McGill University

LATE PLEISTOCENE REEF LIMESTONES, NORTHERN BARBADOS, W.I.

by

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ABSTRACT

Separate reef complexes formed on either side of the northern Barbados, pre-Pleistocene, structural arch, during marine transgressions 83,000 and 104,000 years ago. Late Pleistocene uplift has exposed both these reefs, and also a narrow fringing-reef deposited during the short, eustatic, high stand of sea level, 60,000 years ago.

Pelsparite crusts surrounding late Pleistocene, reef corals were cemented in the marine, diagenetic environment. Pleistocene limestones, presently in the intertidal and supratidal zones, contain Mg-calcite and aragonite cements precipitated from salt spray.

Pleistocene limestone in surficial, calcareous crust profiles is altered by solution, brecciation, recrystallization, micritization, and boring. Calcite, precipitated as micrite, needles, and flower spar, forms cement, oolite-like particle coatings, pelletoids, and crusts.

Solution and recrystallization of scleractinian corals in the vadose, diagenetic environment is controlled by coral microstructure. Concomitant solution of aragonite and precipitation of calcite, beginning at the centre of the trabecula, transforms each original trabecula into a clear, central canal surrounded by a ghost, fibrous texture.

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CHAPTER 1 - INTRODUCTION

PURPOSE

In recent years, improvements in underwater exploration techniques have resulted in increased understanding of modern carbonate depositional environments. These findings have, in turn, greatly enhanced our ability to specify more accurately similar ancient depositional environments. The most sensitive indicators of ancient environments, however, the animals themselves, are often extinct and, during transition from loose sediment to hard limestone, their remains undergo many changes that frequently obscure and mask their original characteristics.

Many of the cement textures and alteration fabrics observed in ancient limestones are similar to those being produced today during the diagenesis of relatively young Pleistocene deposits. This similarity suggests that many of the changes that take place early in the history of a limestone may be among the most important. The limestones on Barbados are a series of separate reefs, perhaps representing deposition spanning the entire Pleistocene. The island is one of the few localities where carbonates, made up of essentially modern constituents, are exposed in three dimensions and are changing under known conditions to produce many of the textures and fabrics found in ancient limestones.

This study is a detailed investigation of the late Pleistocene limestones on the northern part of Barbados (Fig. 1). The geologic history, and especially reef development, is the result of the interaction between worldwide late Pleistocene sea level fluctuations and local tectonics. Two late Pleistocene reef complexes are described and emphasis is placed on the correlation between modern and Pleistocene fabrics and sediments. Four specific diagenetic problems are examined: (1) submarine lithification, (2) intertidal and supratidal lithification, (3) subaerial accretion of calcareous crusts, and (4) scleractinian coral diagenesis.

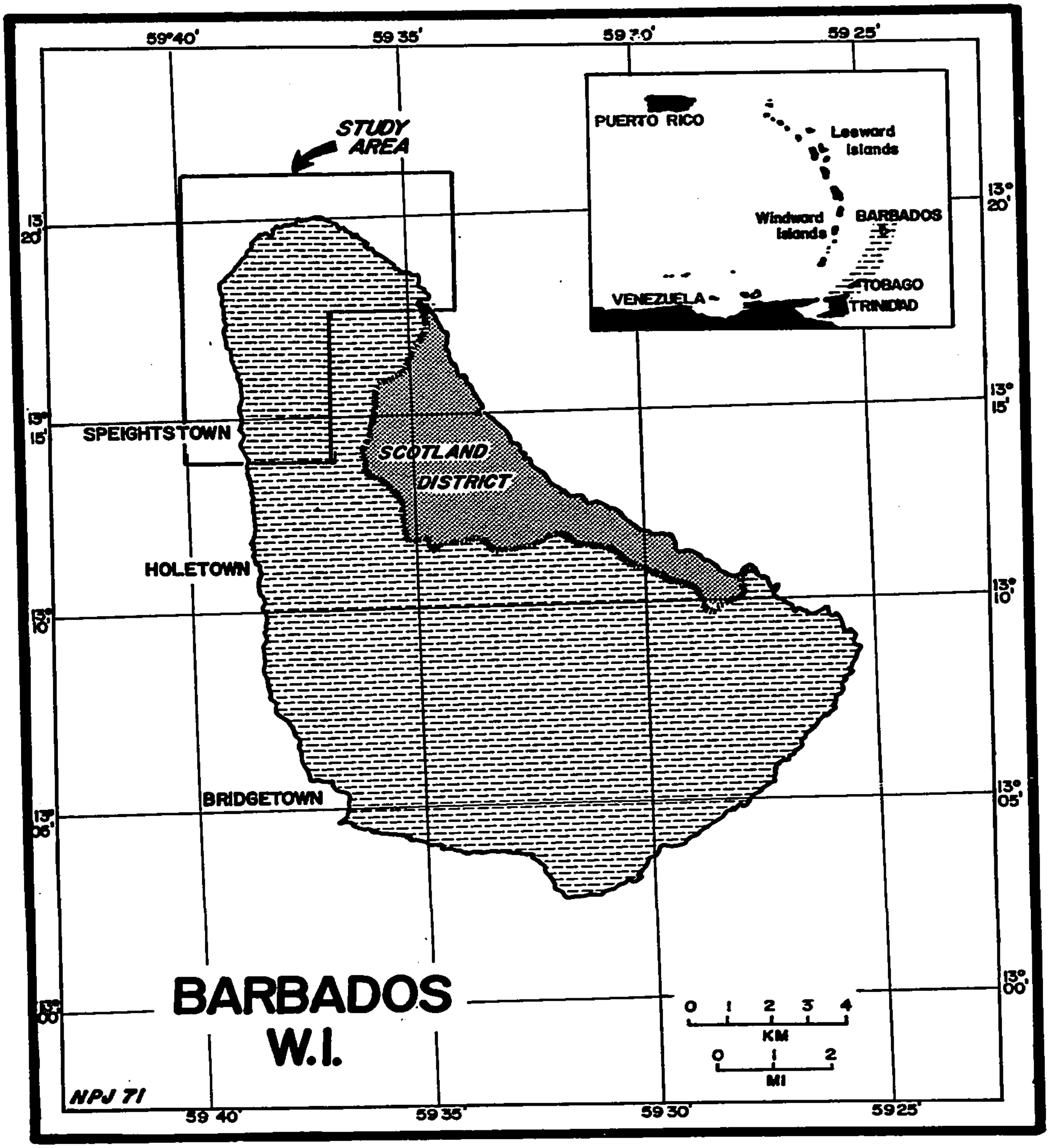

Figure 1. Location map of Barbados and the area encompassed by this study.

The results of this integrated study will be of value in deciphering reef development and recognizing environments of deposition and diagenesis in ancient limestones.

GEOLOGIC SETTING

Barbados, the easternmost island of the Caribbean, has, because of its Tertiary sediment core and superbly exposed Pleistocene limestones, been the subject of several geological investigations. In the past, most interest has centred around the Tertiary sediments (Jukes-Brown and Harrison, 1891; Trechmann, 1937; Senn, 1940, 1946, 1948; Beckmann, 1953, 1956; Kugler, 1961; Saunders and Codry, 1965). In the last decade, with renewed interest in carbonate sedimentation and the application of radiometric dating to late Pleistocene deposits, the Pleistocene limestone veneer, or "Coral Cap", has come under closer scrutiny (Russell, 1966; Mesolella and others, 1969, 1970).

The island is an emergent portion of the north-south trending submarine ridge of Tertiary rock curving northward from Trinidad and Tobago (Fig. 1). Tertiary strata strike northeast (Trechmann, 1937; Senn, 1946) and maintenance of this orientation to depths of over 4,650 meters (15,000 feet) (Baadsgaard, 1960) is an indication of the regional nature of the structural pattern. The geology of the ridge itself is extremely complex. Deep tests drilled on the island penetrate large scale faults and overturned sequences (Baadgsgaard, 1960). This complex structure may be caused by the compression of the continental margin as two crustal plates collide (Schneider, 1969). The 3,350 meter (10,800 feet) test at Friendship, on northern Barbados, encountered approximately 125 meters (400 feet) of Oceanic Formation overlying an extensive clastic sequence of the Scotland Formation. The 3,225 meters (10,400 feet) of Scotland Formation seems to

TABLE 1

FORMATIONS ON BARBADOS

ERA	PERIOD	EPOCH		FORMATION		MEMBER		THICKNESS IN METERS		LITHOLOGY
CENOZOIC	QUATERNARY	HOLOCENE								
		PLEISTOCENE		CORAL ROCK FORMATION		CORAL LS. MBR.		80	100	Massive coral and coral-algal limestone
						AMPHISTEGINA LS. MBR.		20		Well-bedded foraminiferal limestone
	TERTIARY	PLIOCENE								
		MIOCENE								
		OLIGOCENE	UPPER	BISSEX HILL FORMATION				21		Algal limestones and Globigerina marls grading up into Globigerina marls and lenses of Globigerina limestone
				RIVER ESTATE GLOBIGERINA MARLS				1000 ?		Globigerina marls and beds of Globigerina limestone
			MIDDLE							
			LOWER	OCEANIC FORMATION		CODRINGTON COLLEGE MBR.		130	600 - 650	Well-cemented clayey Globigerina marls
							MUD-FLOW	55		Dark grey, pebbly silt with blocks of oil sand
		EOCENE	UPPER			BATH MBR.	UPPER	55		Greyish Radiolaria-Globigerina marls
							LOWER	50		Radiolaria-Globigerina marls and volcanic ash beds
						MT. HILLABY MBR.	UPPER	340		Radiolaria marls and clays with interbeds of volcanic ash
			MIDDLE				LOWER	21		Radiolaria-Globigerina marls
								5		Globigerina marls and marlstones
				JOES RIVER FORMATION				0 - 500		Dark grey pebbly silts with green clay pebbles and blocks of tar sand
				SCOTLAND FORMATION	UPPER	FRESH WATER LS.		?	1650 - 2000	Blocks of limestones with freshwater molluscs
						MT. ALL MBR.		520		Interbedded silty and sandy shales and sands
						CHALKY MT. MBR.		100-230		Coarse sands, gritty silts, lenses of concretionary calcareous grit
						MURPHYS MBR.		70-110		Interbedded silts and fine sands
			LOWER		LOWER	MORGAN LEWIS MBR.		460-520		Grey silty and sandy shales with green clay inclusions and brown claystone nodules
						WALKERS MBR.		520-560		Grey silty and sandy shales with green clay inclusions and brown claystone nodules interbedded with sands
		PALEOCENE		Blocks in Joes River and probably present in oil well						
CRETACEOUS										

(from Macintyre, 1967)

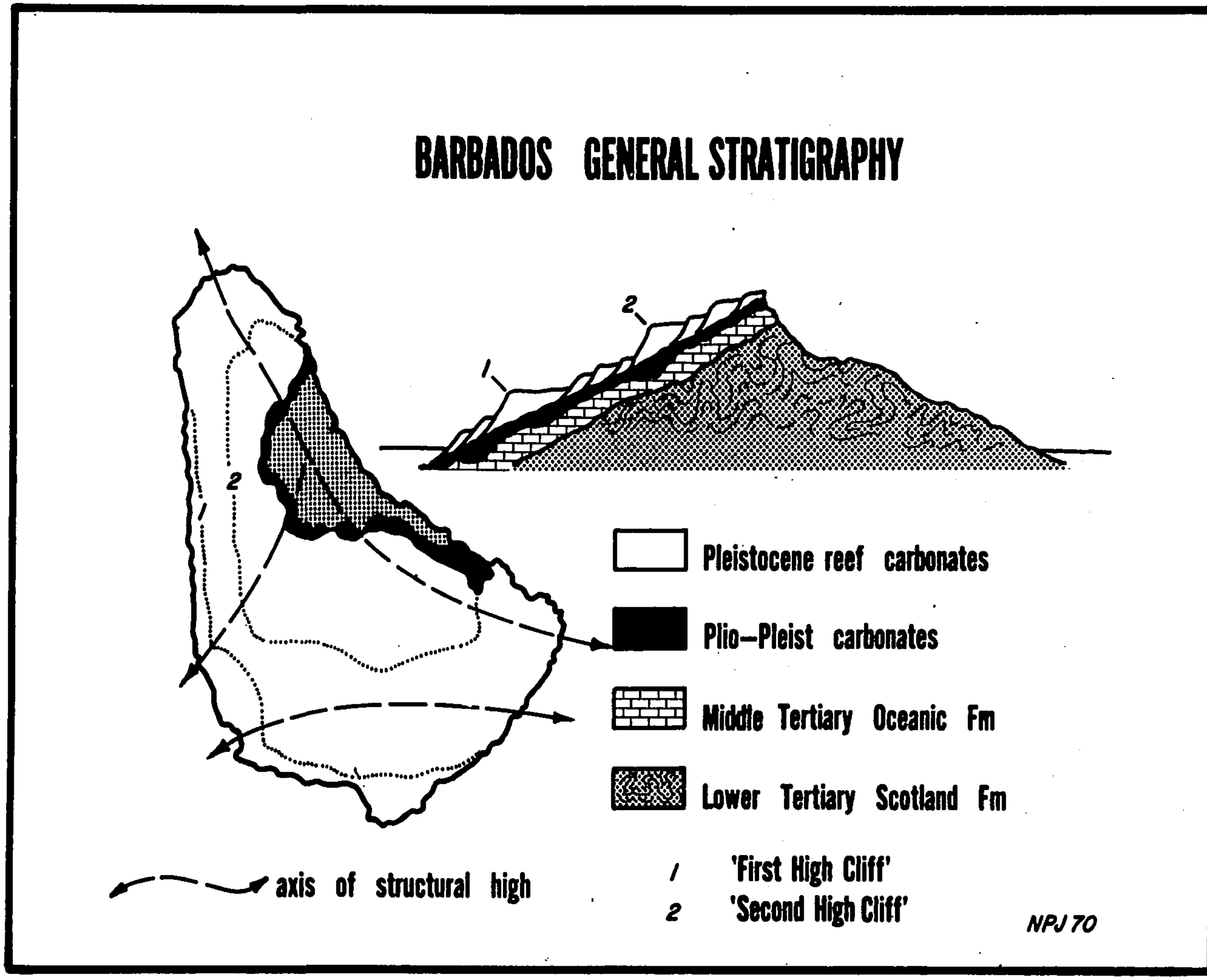

Figure 2. General stratigraphy of Barbados.

be all overturned and to contain at least three major thrust sheets (Baadgsgarrd, 1960).

Barbados can be separated into two distinct physiographic regions: (1) the Scotland District, underlain by outcropping Tertiary strata and (2) the Coral Cap, underlain by a succession of terraced Pleistocene limestones which rise to 330 meters (1070 feet) above sea level (Fig. 1).

The Tertiary succession exposed in the Scotland District and in various wells is outlined in Table I. In general, a basal sequence of Lower to Middle Eocene clastics (Scotland Formation) is overlain by Middle Eocene to Miocene marls and limestones (mainly Oceanic Formation).

The island appears to have been uplifted more or less continuously throughout the Pleistocene. A coral reef grew around the emergent portion of the island during each eustatic high stand of sea level, yielding a Pleistocene terraced limestone veneer over the core of Tertiary strata, with each terrace representing a single high stand of sea level (Broecker and others, 1968; Mesolella and others, 1969, 1970). This interpretation has evolved from radiometric dating of laterally continuous lower terraces on the southern part of the island. The lowest reef terrace is about 83,000 years old and each higher reef terrace is slightly older than the one below. Two terraces, the "First High Cliff" and "Second High Cliff" (Senn, 1946) (Fig. 2, 3), have greater relief than the others and stand out as continuous features around most of the island. The First High Cliff (average crest elevation 34 meters) (120 feet) is a 127,000 year old reef complex. Two younger terraces, 104,000 and 83,000 years old, lie below it. Between the First and Second High Cliffs are a series of terraces dated between 170,000 and 230,000 years old. The Second High Cliff (average crest elevation 150 meters) (480 feet) and higher terraces appear to represent reef complexes formed more than 250,000 years ago. Original depositional

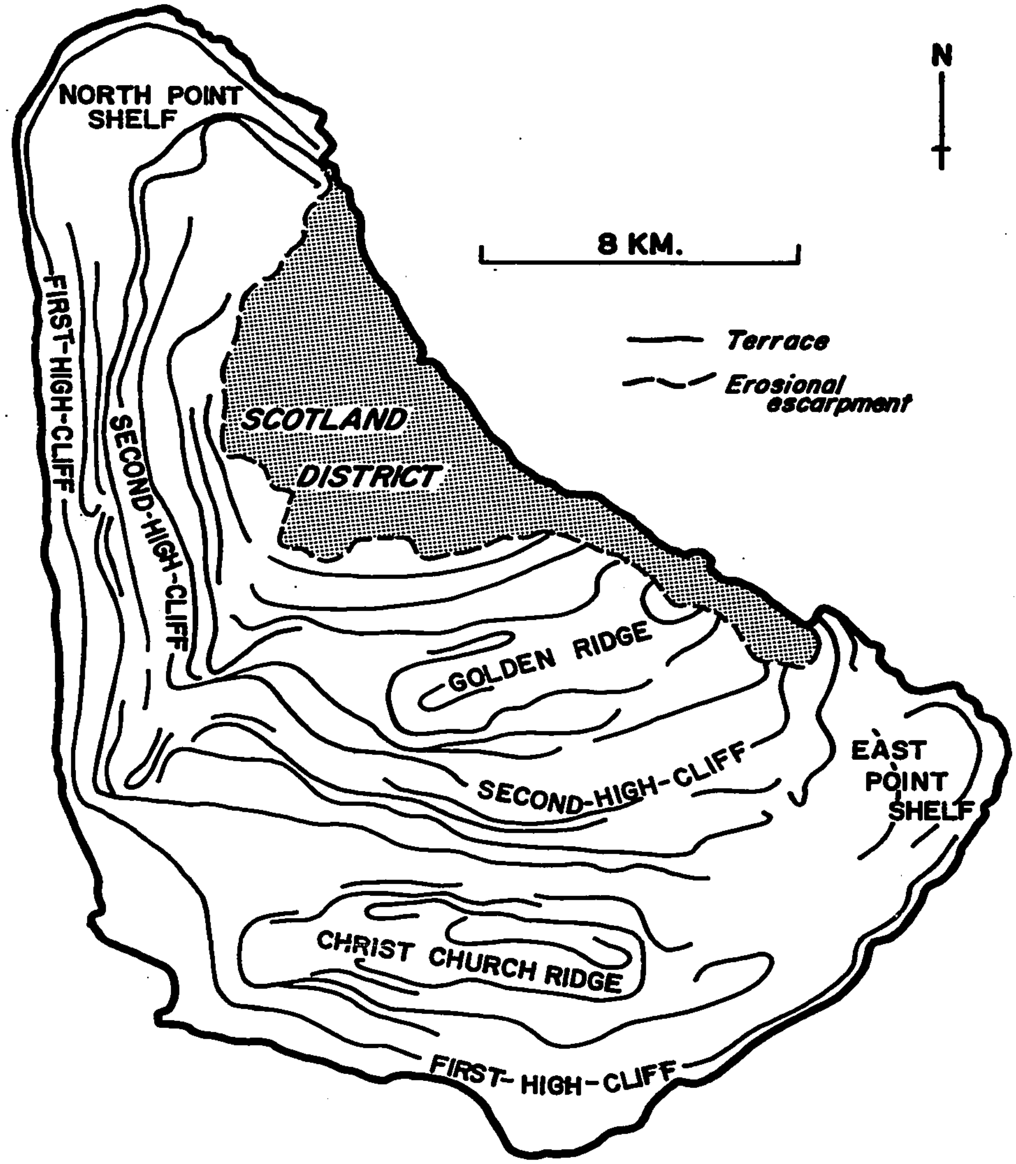

Figure 3. Areal distribution of certain prominent Barbados reef terraces (after Mesolella and others, 1969).

topography of the reef terraces has been modified to varying degrees by subsequent wave abrasion when they were sea cliffs and, later, by subaerial solution.

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CHAPTER 2 — STRUCTURE AND STRATIGRAPHY

INTRODUCTION

In northern Barbados, sea cliffs, 15 to 30 meters (50 to 100 feet) high, bound a flat, rolling plateau (Plate 1A) that rises gently to approximately 62 meters (200 feet) elevation at the base of the Second High Cliff (Fig. 3). The Second High Cliff has roughly the same shape as the present shoreline, sweeping in a gentle arc from the northeast Scotland District around to form the long, straight cliff paralleling the western coast.

Unlike most other parts of the island, the plateau below the Second High Cliff, the "North Point Shelf" of Mesolella and others (1969), is not terraced. Only on the southwestern side of the plateau do terraces appear and southward they eventually become distinct physiographic features. The North Point Shelf is not simply Pleistocene limestone, as suggested by Mesolella and others (1969), but contains numerous scattered Tertiary outcrops of differing lithology (Fig. 4), implying underlying topographic relief of some complexity.

The reportedly late Pleistocene limestones below the Second High Cliff on northern Barbados were mapped in detail in order to provide a stratigraphic and structural framework in which to conduct investigations of reef development and carbonate diagenesis. Stratigraphy determined from field studies was, where possible, augmented by radiometric dating of late Pleistocene *in situ* coral skeletons.

TERTIARY

Introduction

Initial fieldwork and earlier reports (Trechmann, 1937) indicate small inliers of Tertiary strata on the North Point Shelf (Fig. 4), suggesting

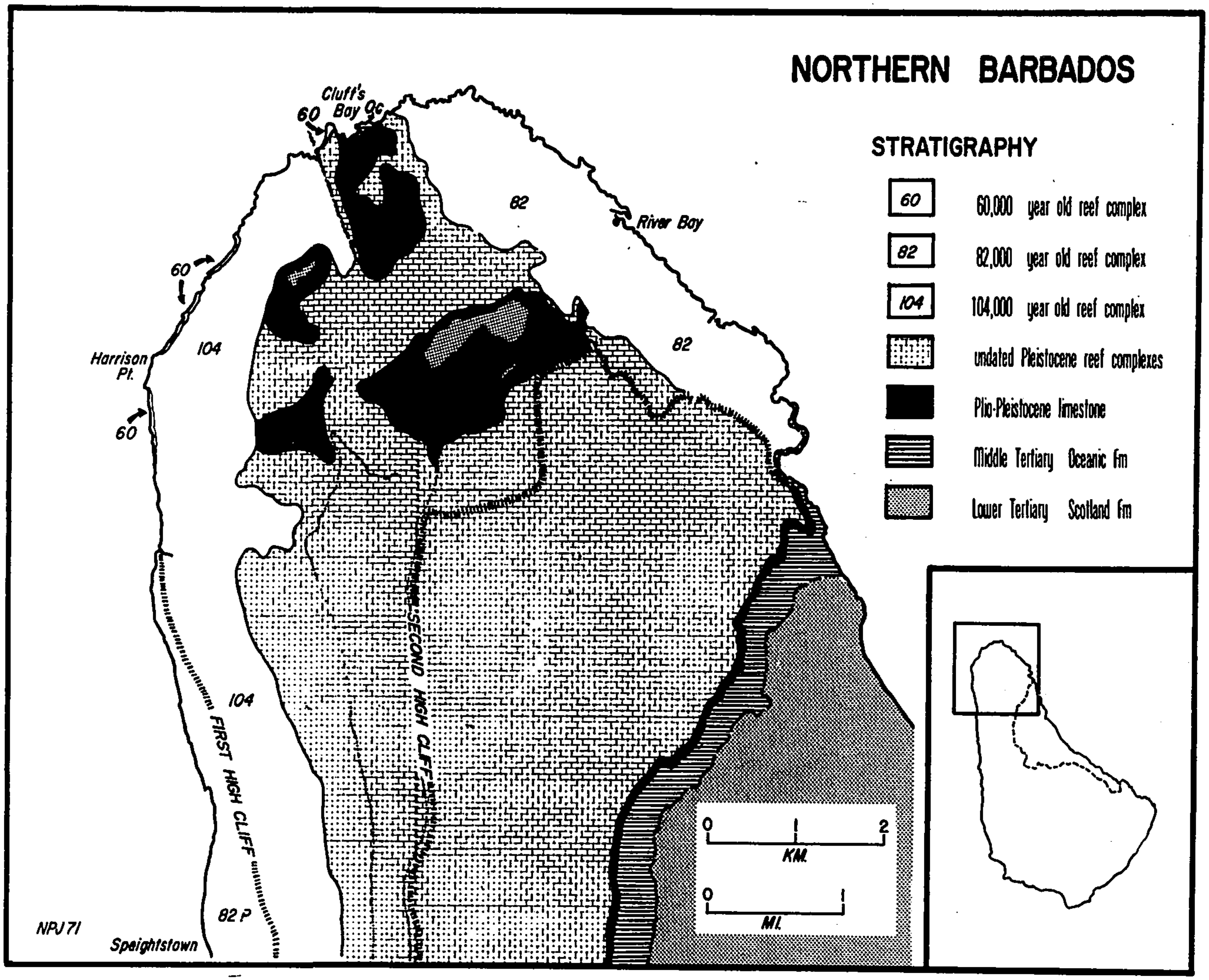


Figure 4. Geologic map of northern Barbados.

that Tertiary sediments throughout this area may be near the present topographic surface. Such topographically high, Tertiary substrata would undoubtedly have influenced the distribution and form of subsequent late Pleistocene reef development.

As the northern end of the island is dry, many water wells have been dug. Senn (1946), who logged some of these wells and obtained data on many others, divided the structure of northern Barbados into elements trending northeast-southwest -- the Mt. Poyer Syncline and the Crab Hill Anticline. Since then, however, many more wells have been dug yielding much more information. Correlation of surface and subsurface data indicates that Tertiary outcrops are eroded tops of three separate pre-Pleistocene highs, with individual reliefs of over 45 meters (150 feet). These highs, for the purposes of discussion, are given the names "Spring Hall Platform", "Crab Tree Ridge", and "Cluff's Arch" (Fig. 6). These highs also appear as primary and secondary groundwater divides (Tullstrom, 1964).

Inspection of the structure contour and isopach maps prepared from water well data (Fig. 5, 6) indicates that these three highs together make up the northern extension of the north-south ridge that forms the backbone of Barbados. The buried portion of this large structure underlying the North Point Shelf is herein called the "St. Lucy Arch" (Fig. 5).

Spring Hall Platform

At the foot of the Second High Cliff, near Spring Hall Factory, is an extensive area of Scotland Formation sandstone. These poorly lithified, fine to medium grained clastics (Plate 2B) with indistinct bedding range in colour from dark brown to green to yellow and are partially covered by patches of Plio-Pleistocene limestone. These sediments form a flat-topped

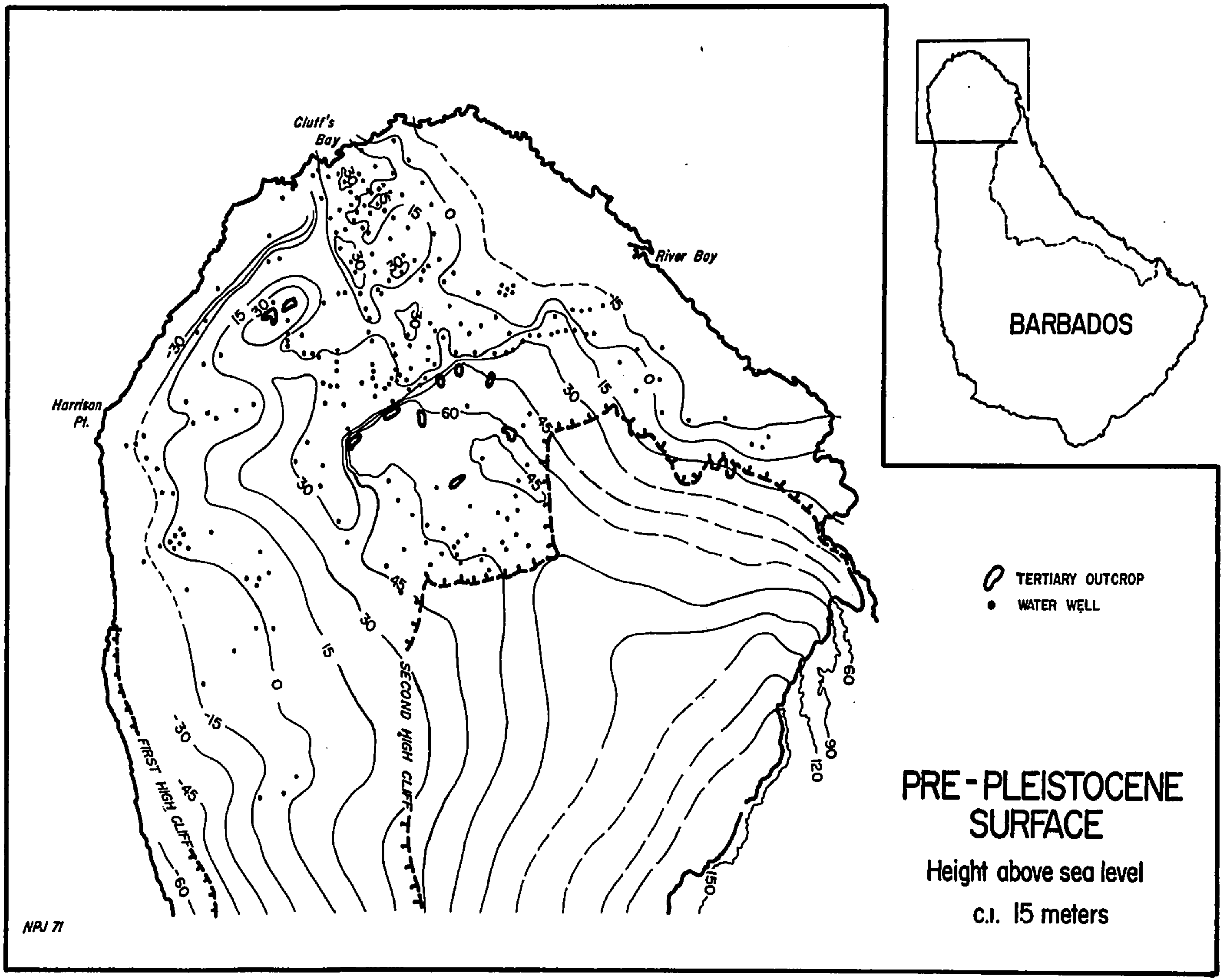


Figure 5. Contour map of pre-Pleistocene surface, northern Barbados.

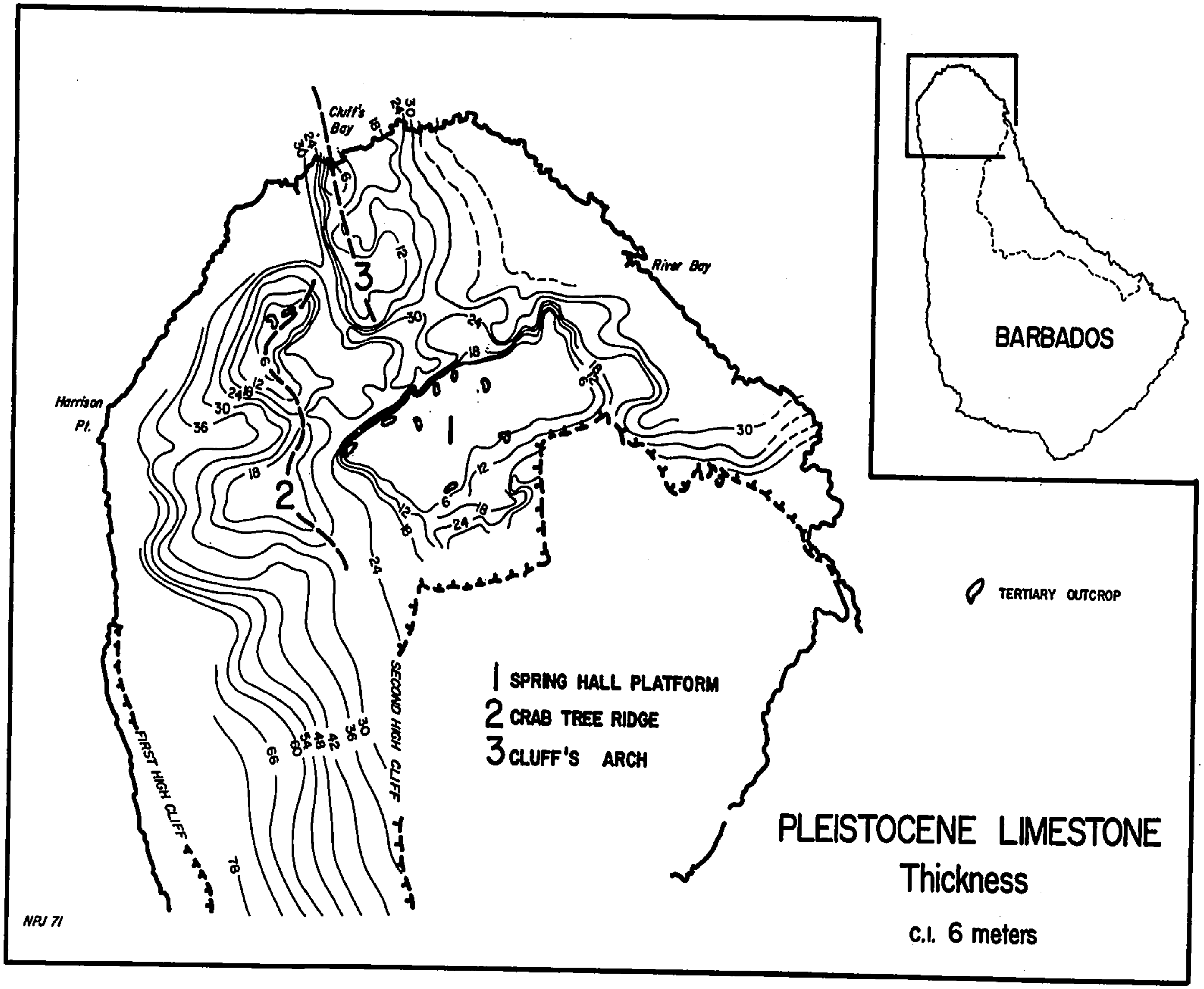


Figure 6. Isopach map of Pleistocene limestone, northern Barbados.

arch which dips steeply along its northern flank, over 45 meters (150 feet) within a distance of 200 meters. The eastern flank dips gently at 37 meters per kilometer (200 feet per mile) and the western side is separated from the southern extension of Crab Tree Ridge by a depression.

Crab Tree Ridge

Silts and clays of the Scotland Formation, containing layers of brown, clay-ironstone concretions are exposed at the top of Crab Tree Hill. This outcrop is the northern end of an ill-defined ridge running parallel to the western shore. It is separated from the Oceanic Formation of Cluff's Arch by a depression which may, in part, be fault controlled. North of Crab Tree Hill, the pre-Pleistocene surface dips gently northward and then abruptly plunges to over 62 meters (200 feet) below sea level within a distance of 400 meters.

Cluff's Arch

The shoreline at Cluff's Bay is normal to this arch and exposes an excellent cross-section of the north-south trending structure. The core of the arch is Oceanic Formation. While the contact between Oceanic and overlying Pleistocene limestone on the western flank dips steeply at over 70 degrees, the contact on the eastern flank dips more gently at about 20 degrees (Fig. 7). The bay is eroded in non-resistant rocks of the Oceanic Formation. Undermining by wave action has resulted in large scale slumping of the upper part of the exposure and overlying Pleistocene limestones, so that large blocks have moved down to sea level.

The Oceanic Formation is buff, well bedded *Globigerina* chalk. Bedding is made up of chalk units 30 to 40 cm thick, separated by bands of dark brown, silt to fine sand, 5 to 6 cm thick (Plate 2A). These dark bands are ascribed to ash falls (Senn, 1946) and locally exhibit graded bedding. Burrows in the chalk beds are filled with dark brown, clastic material.

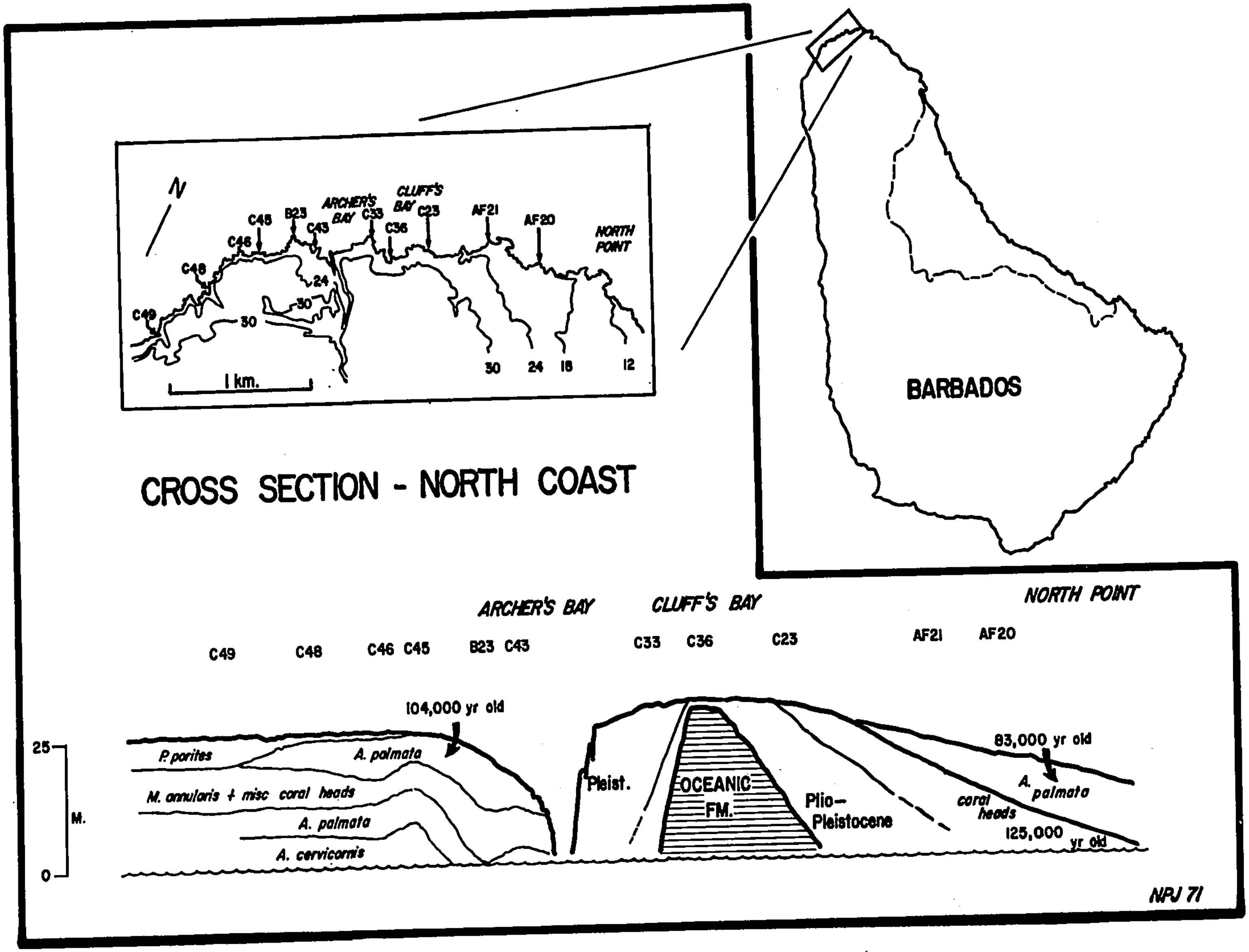


Figure 7. Cross-section along the north coast of Barbados, compiled from measured sea cliff sections.

As the Oceanic Formation at Cluff's Bay cannot be traced to dated outcrops in the Scotland district, foraminifera from the Cluff's Bay section, and from a 31 meter (100 feet) deep well, 0.4 kilometers (1/4 mile) south of the bay, were examined (see Appendix E). The age range of the diagnostic foraminifera found in nine samples studied is indicated in Table 2 (after Bolli, 1957). The fauna suggest that these sediments are Middle Eocene (Lutetian) in age and more specifically belong to the _Globigerapsis kugleri_ zone (Bolli, 1957). The uppermost sample (C36-1) may belong to the slightly younger, _Globorotalia lehneri_ zone. On the basis of Bandy's (1964) subdivision of Tertiary foraminiferal zones, these sediments would be placed in the _Globigerina frontosa_ zone, at the base of the Middle Eocene.

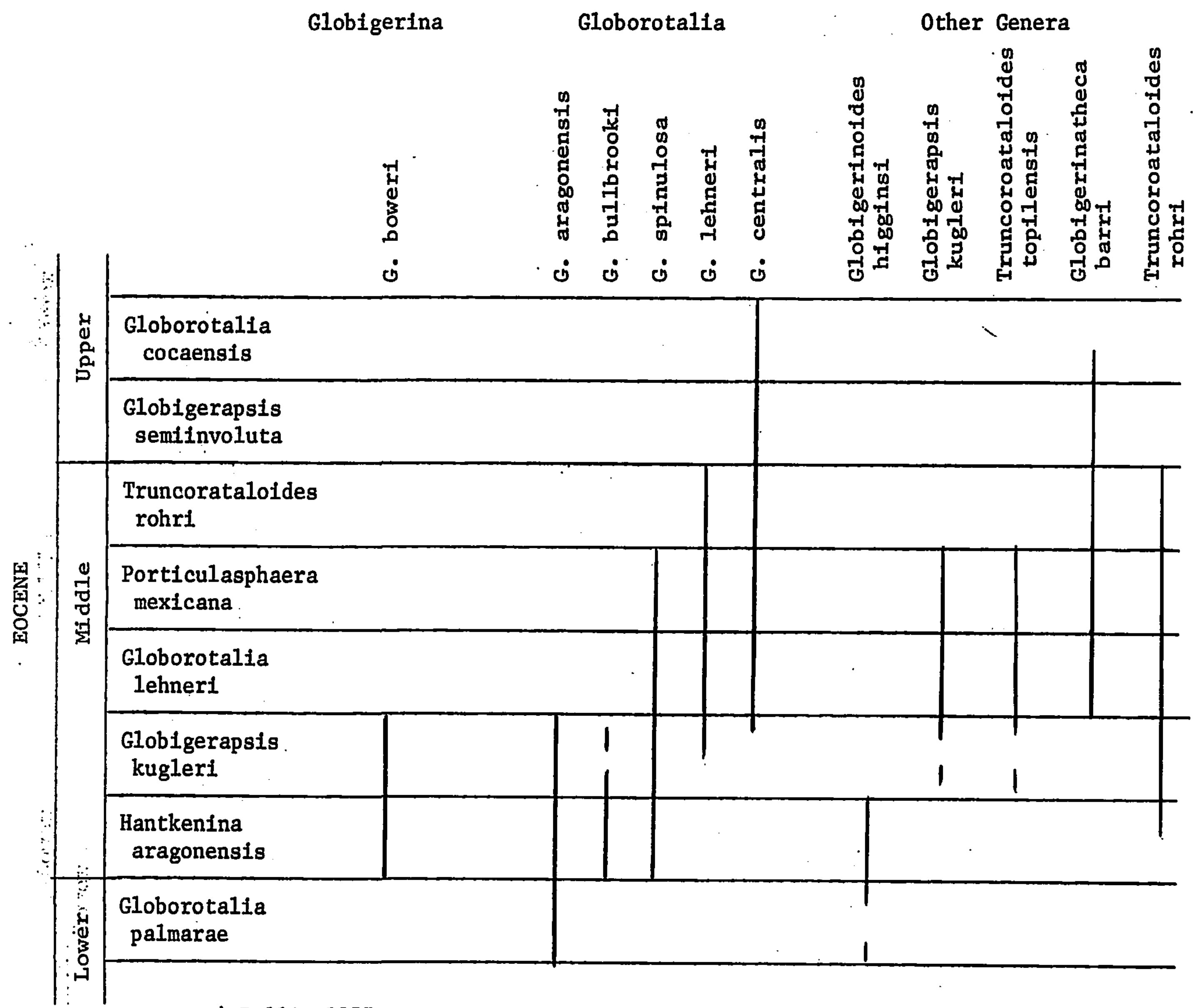
Saunders (1965, p. 448) indicates that calcareous siltstones exposed at Mount Hillaby, the oldest known sediments of the Oceanic Formation, belong to the _Porticulasphaera mexicana_ zone. The discovery of these older marls at Cluff's Bay, clearly two zones lower and nearly at the base of the Middle Eocene stage, indicates that parts of the Oceanic Formation are older than hitherto determined. This discovery also suggests that the underlying Scotland Formation is almost entirely Lower Eocene in age.

BASAL PLEISTOCENE

Contact

The pre-Pleistocene surface at all localities is irregular (Plate 2C) with pockets of conglomerate (Plate 2D) in places up to 0.5 meters thick. Clasts are invariably Scotland Formation, and vary in composition from well lithified, coarse conglomerates to siltstones. In most exposures, limestone rests directly upon the eroded surface and angular fragments of sandstone up to 0.3 meters (1 foot) in diameter are found as high as 2 meters (6 feet) above the contact. The basal limestone contains terrigenous grains but these disappear within a few centimeters.

TABLE 2 – AGE LIMITS* OF DIAGNOSTIC FORAMINIFERA FOUND IN OCEANIC FORMATION AT CLUFF'S BAY



* Bolli, 1957

Lithology

Trechmann (1937, p. 338) noted that, wherever the Pleistocene limestone-Tertiary contact is seen on Barbados, (except along the northeast coast, see Chapter 3) basal Pleistocene lithologies are different from the main mass of coral limestone above. Although large diagnostic fossils are rare and their condition poor, Trechmann collected a representative assemblage from these "basal Pleistocene" limestones. The most noticeable fossils are several species of Haliotis (abalone), the gastropod Pleurotomaria, and the bivalve Meicardia. Trechmann (1937, p. 358) concluded that, on the basis of these and other fossils, the limestone might be pre-Pleistocene, possibly Pliocene, in age. Since the exact age is somewhat uncertain, these sediments will be called, until more detailed paleontological study is carried out, Plio-Pleistocene.

Senn (1946) confirmed Trechmann's (1937) observations and divided the Pleistocene "Coral Cap Formation" into a thick, widespread, upper "Coralline Limestone member" encompassing all reef complexes and a lower, much thinner, "Amphistegina-limestone member". This lower member is a well-bedded limestone characterized by calcareous algae and numerous tests of the large lentiform foraminifer Amphistegina lessonii d'Orbingy.

Tertiary inliers on northern Barbados are overlain by the Plio-Pleistocene Amphistegina-limestone member. The areal distribution of this member was studied in detail to delineate the form of pre-Pleistocene highs (Fig. 4). On northern Barbados, this member can be divided into two informal units--a lower, thin, phylloid algal unit and a thicker, Amphistegina calcarenite unit.

Phylloid algal unit.--This unit covers the pre-Pleistocene surface as a veneer, from 0.3 to 1 meter (1 to 3 feet) thick, in all exposures on northern Barbados except along the northeast coast, below the 83,000 year old reef complex. Its thickness is apparently independent of the topography of the underlying surface. Irregular laminae (2 to 10 cm thick) of crustose red coralline algal plates (Plate 2E) and interstitial geopetal sediments constitute up to 60 per cent of the rock. These laminae are separated by pockets of calcisiltite and fine grained calcarenite and lenses and irregular bands of coarser grained calcarenite.

The thin (0.24 to 1 mm) crustose red algal plates constitute a self-supporting structure by forming domes over undulations and protuberances in the underlying plates (Plate 3A, B). The structure of the rock resembles the Pennsylvanian phylloid-algal limestones of the mid-continent, rich in Archeolithophyllum (Wray, 1964). The specific identification of these crustose red algae is difficult as most specimens appear infertile and lack the diagnostic conceptacles. The hypothallus makes up most of the individual plates and the majority of specimens exhibit a cell arrangement reminiscent of Lithothamnium (Johnson, 1961; Ginsburg and others, 1971a). About 20 per cent, however, display a hypothallic arrangement more akin to Lithophyllum (Johnson, 1961; Ginsburg and others, 1971a). Most plates are encrusted with at least one and, rarely, up to ten layers of Lithoporella and occasionally the foraminifera Gypsina. Original sediment, shell fragments and algal plates are extensively bored, resulting in numerous random, circular to ovoid holes, 0.1 to 0.4 mm in diameter. Many algal plates are fractured and fragmented.

Sediment deposited with these plates is a biomicrite whose most conspicuous faunal elements are planktonic foraminifera, mollusc debris and fragmented algal plates. Most of the matrix between these plates, however, is micrite pellets and minor allochems, which later filtered into borings, fractures and primary voids, creating an excellent geopetal fabric (Plate 3B, C). Intercalated bands of fine to medium grained intrabiosparites become more common towards the top of the unit. Skeletal fragments (5 to 30 per cent) in these intrabiosparites are dominantly mollusc debris, *Amphistegina*, planktonic foraminifera and occasional echinoid fragments. Intraclasts are, for the most part, fragments of either crustose coralline algae with cement and micrite intact or pelsparite (Plate 3D) identical to that between adjacent algal plates, indicating both early, possibly submarine, lithification and erosion.

Amphistegina calcarenite unit.--The phylloid algal limestones grade into a calcarenite, rich in *Amphistegina*, which is relatively thin over pre-Pleistocene topographic highs but is up to 15.5 meters (50 feet) thick (Plate 2F) in intervening depressions. The rock is composed dominantly of *Amphistegina* and assorted allochems (40 per cent) in a varied matrix of either micrite, pelsparite, or biocalcisiltite and planktonic foraminifera (Plate 3E, F). Calcarenites become cleaner towards the top of the unit.

Although the numerous large foraminifera make this lithology easily recognizable, it is the assorted allochems that distinguish it from other calcarenites. The allochems are fragments of red algae and intraclasts with only minor skeletal debris. Red algal fragments are dominantly ripped-up clasts of crustose corallines, similar to the phylloid algae below, and occasional articulated corallines which become dominant towards the top of the unit. Intraclasts are varied in composition but can be broadly grouped into (1) pelsparite, (2) *Homotrema rubrum* and micrite, (3) micrite envelopes surrounding varied fragments and (4) large composite grains of foraminifera, red algae and micrite or crustose red algae and cement coated with micrite. These intraclasts are clearly related to adjacent or immediately underlying sediment. Also conspicuous is the lack of terrigenous grains, so common in younger Pleistocene limestones.

Areal Extent

Tertiary inliers are surrounded by the Plio-Pleistocene units which reflect the shape of the underlying pre-Pleistocene highs. In several areas, water well data suggests a pre-Pleistocene high rising to within a few feet of the present surface but there is no record of Tertiary outcrop. Detailed investigation of limestone outcrops in such regions reveals that they belong to the Plio-Pleistocene, and permits a better delineation of the buried pre-Pleistocene surface. In addition, results of these investigations suggest that Plio-Pleistocene units form a large part of the exposed limestone on the North Point Shelf (Fig. 4).

These limestones illustrate the complex structural history of the area. At Cluff's Bay, the well-bedded Amphistegina calcarenite is slightly undulatory but in general dips to the east between 4 degrees and 13 degrees, while the steeper contact of the pre-Pleistocene surface dips at 17 degrees, indicating that Cluff's Bay has been more or less structurally stable since early Pleistocene, and, if it was uplifted, the entire area moved as a unit. The Amphistegina calcarenite bounding the northern outcrop limit of the Scotland Formation, on the Spring Hall Platform (Fig. 4), however, dips steeply to the north at between 15 degrees and 30 degrees, indicating that at least part of the pre-Pleistocene topography observed may be due to tectonic movement since early Pleistocene.

LATE PLEISTOCENE REEF COMPLEXES

The sequence of reef complexes in the form of terraces below the Second High Cliff along Barbados' west coast is less than 250,000 years old (Mesolella and others, 1969). Radiometric ages of several of these terraces, from localities just north of Bridgetown, and experience gained from southern Barbados, where morphology and chronology of the reef terraces were in most

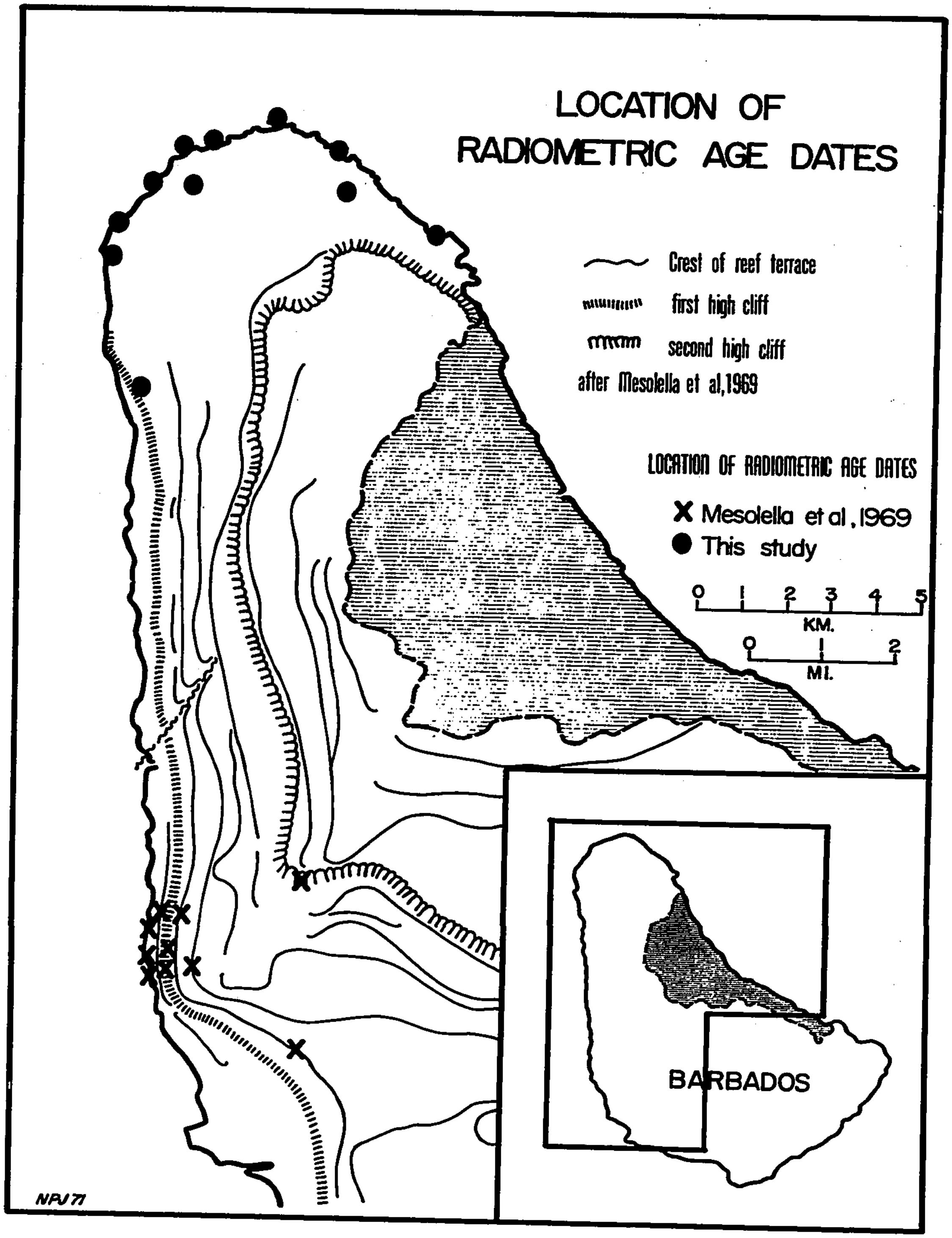


Figure 8. Localities of radiometrically age-dated Pleistocene material from western and northern Barbados (all studies).

cases synchronous, have been used to postulate reef terrace chronology along the west coast (Mesolella and others, 1969). Radiometric dating was not possible for most of the terraces along the west coast because the relatively high rainfall in this area has accelerated equilibration of the original coral skeletal aragonite to calcite (Matthews, 1968), making the corals useless for age determinations. Only on the relatively dry North Point Shelf, where many of the younger corals are still aragonite, can reliable age dating be carried out.

These terraces were mapped in detail from Holetown north in order to ascertain what happens to the lower terraces as they approach the North Point Shelf and disappear. Limestones on either side of the St. Lucy Arch were radiometrically age-dated (Fig. 8) to confirm that carbonates on the northern part of the island could be correlated with those to the south and that reef complexes on either side of the arch were the same age.

West Coast Terrace Series

Below the Second High Cliff, on the west coast, terraces are relatively continuous morphological features (Fig. 9). The First High Cliff stands out as a distinct physiographic feature, with a relief of 16.5 meters (50 feet) or more, while the terraces lying above and below are more subtle, with local relief of 6.2 meters (20 feet) or less. Russell (1966) and Mesolella (1967) confirmed that the leading edge of each terrace is a massive series of large corals, dominated, in most cases, by Acropora palmata, the species characteristic of the living crest on Caribbean reefs. The stony, leading edge of the terrace has only a thin soil cover with sparce vegetation, mainly sour grass. The thicker soils, over the back-reef, are planted in cane. The terraces are, therefore, easily discernable both in the field and from aerial photographs (Plate 1B).

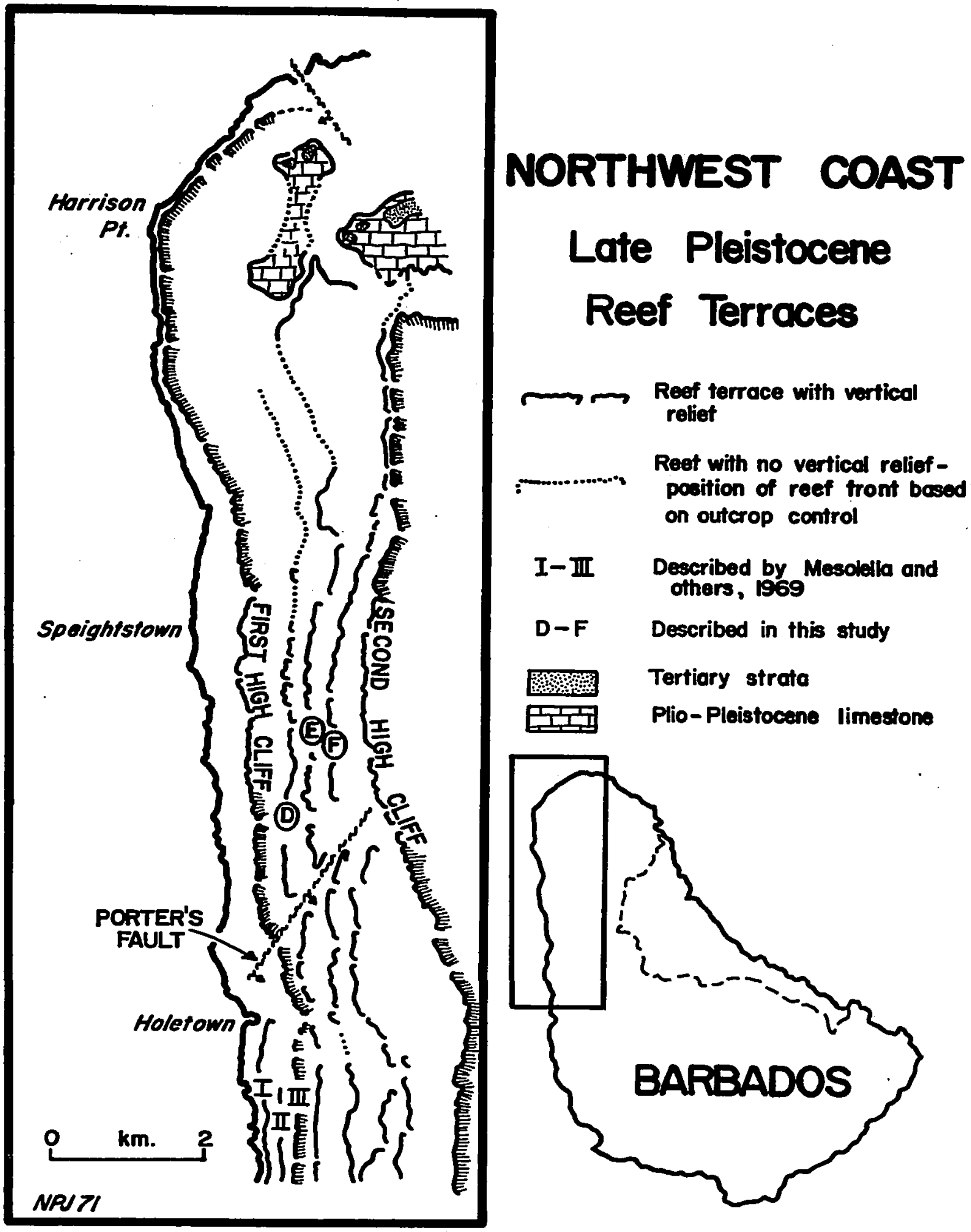


Figure 9. Areal extent of late Pleistocene reef complexes along the northwest coast of Barbados.

The terrace series is cut by a fault at Holetown, near Porter's Factory, which is termed "Porter's Fault" (Fig. 9). This fault is reflected both in the pre-Pleistocene surface and the terraces themselves. Present relief on the pre-Pleistocene surface indicates sinistral movement and vertical offset of about 31 meters (100 feet). The Second High Cliff arches slightly over Porter's Fault but it, and the terraces above, are not affected. Terraces below the Second High Cliff are deflected by the fault (Fig. 9) but most can be traced across it. The two terraces below the First High Cliff cannot be mapped with any certainty north of Porter's Fault.

Between the First and Second High Cliffs, north of Holetown, three terraces can be mapped. These are, for the most part, very low risers composed of corals characteristic of the reef crest. The back-reef facies can only locally be discerned. These terraces will be labelled "D", "E", and "F" (Fig. 9) so that they are not confused with the terrace numbering system of Broecker and others (1968).

Terrace F.--Exposures are dominated by the presence of *Acropora palmata* in the reef crest position and occasional outcrops of the deeper water *cervicornis* zone. The terrace lies at an elevation of between 93 meters (300 feet) and 100 meters (320 feet) and comes very close to the base of the Second High Cliff north of Speightstown (Plate 1C).

Terrace E.-- The crest of this terrace lies between 74.5 meters (240 feet) and 80.5 meters (260 feet) above sea level. Terrace E, often lacking continuity and definite relief, is difficult to trace laterally on the basis of morphology alone. On the basis of composition, however, it is distinctive and easily differentiated from other terraces. While the reef crest of most reef terraces is composed of *Acropora palmata*, the crest of Terrace E north of Holetown is made up of flat and columnar *Montastrea* annularis colonies, often surrounded by crustose red algal nodules (rhodolites; Bosellini and Ginsburg, 1971). Surface mapping of the distinctive reef crest, often exposed only in low outcrops, indicates that the poorly developed reef can be traced as far north as the southern end of the Crab Tree Ridge (Fig. 6, 9).

Terrace D.--Terrace D lies at an elevation of between 56 meters (180 feet) and 62 meters (200 feet). The reef crest is dominantly *Acropora palmata* but the fore-reef *Acropora cervicornis* community is commonly also exposed. Beach calcarenites of the First High Cliff complex overlie these facies in several localities (Fig. 16). The reef facies loses its topographic expression northward and can only be traced by close facies control a little north of Colleton. In line with the extension of the reef facies to the north is an area of Plio-Plëistocene *Amphistegina* limestone on Crab Tree Ridge suggesting that the reef may die out against this buried high.

First High Cliff.--The reef complex can be traced without difficulty across Porter's Fault although it is highly dissected. Along most of its length, road cuts expose a massive *cervicornis* zone capped by a relatively narrow, reef crest *palmata* zone. A deeper-water, coral community of large, rounded heads can be seen at the foot of the *cervicornis* zone. North of Speightstown the terrace veers westward (Fig. 9) and post-depositional erosion has removed progressively more of the seaward edge of the *cervicornis* zone. The terrace becomes part of the sea cliffs a few miles north of Speightstown and erosion along these sea cliffs has cut back all of the *cervicornis*-zone revealing the underlying limestones as well. At several localities, cliffs exhibit a massive *palmata* zone resting on a well-indurated *A. cervicornis*-rich limestone. The contact between the two illustrates numerous subaerial weathering features indicating a period of subaerial exposure between periods of reef accretion (Plate 30).

Facies associated with the First High Cliff complex are readily mapped due to extensive outcrop. Where the First High Cliff becomes part of the sea cliffs, the back-reef facies undergoes a change from dominantly lagoonal sands with minor corals to a <u>Porites porites</u> zone fringed in the landward position by an algal ball (rhodolite) zone that can be traced northward (Fig. 15; for detailed facies discussion see Chapter 3). Cliffs along the coast, continuous with the First High Cliff, are composed of a massive <u>palmata</u> zone with numerous channels filled with <u>P. porites</u> debris apparently washed in from the back-reef. Most late Pleistocene limestones exposed on the western side of the North Point Shelf are part of the First High Cliff reef complex.

The reef facies of this complex was radiometrically dated at five localities (see Appendix F). In all cases, the coral species analysed was <u>A. palmata</u>. These analyses yield an average Th^{230}/U^{234} age of 104,000 $\pm$ 4,000 years B.P. and an average Pa^{231}/U^{235} age of 100,000 $\pm$ 4,000 years B.P. (Appendix F). Clearly, this reef complex, at an average elevation of 31 meters (100 feet), is not the same age (125,000 $\pm$ 6,000 years old) as the First High Cliff south of Porter's Fault but, rather, corresponds nicely to Terrace II of Broecker and others (1968) which is 104,000 years old and, around most of the island, lies at an elevation of about 18.3 meters (60 feet).

As demonstrated in the sea cliff sections, these limestones are not thick and were deposited by a high stand of sea level following subaerial exposure of an underlying reef complex. This underlying reef is correlated with the 125,000 year old complex on the basis of the following evidence: (1) it is a well-developed complex whose reef facies occupy approximately the same geographic position as those above; (2) it forms the base upon which the 104,000 year old complex grew, thus determining to a great degree its morphology; (3) it is separated from the overlying complex by a period of subaerial erosion; and (4) it is in line with the First High Cliff to the south. In this area of Barbados, the 125,000 year old complex was covered by the 104,000 years B.P. sea level high stand and a relatively thin, but laterally extensive, reef complex accumulated on this foundation (Fig. 13).

Northeast Coast

The northeast coast below the Second High Cliff is a broad plateau that slopes gently eastward towards sea cliffs which are being rapidly eroded (Plate 1E). These sea cliffs display a thick reef facies consisting of corals and sediment that are, for the most part, little altered and poorly lithified, suggesting they are relatively young. These sediments rest on well-lithified limestones, except in Gay's Cove where they directly overlie the Tertiary, Oceanic Formation (Plate 5A). Detailed mapping of their complex facies (see Chapter 3) reveals that these sediments belong to one laterally continuous complex and make up most of the limestone exposed on the northeast coast.

Differential movement during uplift is indicated by a fault at River Bay (Fig. 14). This structure strikes obliquely to the coast and rocks on the seaward side have suffered a vertical offset of at least 6.2 meters (20 feet). The upthrown block on the seaward side forms the partial barrier to River Bay.

In situ coral skeletons were selected from three widely separated areas within this complex for radiometric dating (Fig. 8). Specimens were taken from (1) the _palmata_ zone of the barrier-reef facies, (2) the coral-knob zone of the back-reef facies, and (3) the fringing-reef facies.

These samples yield an average Th^{230}/U^{234} age of 82,000 $\pm$ 2,000 years and an average Pa^{231}/U^{235} age of 82,000 $\pm$ 1,000 years B.P. (Appendix F). This reef complex appears to be the same age as the lowest reef terrace near sea level along the south and southwest coasts of the island (Broecker and others, 1968).

The shape of the 83,000 year old limestone body along the northeast coast is like a wedge, with its feather edge lying along the top of the St. Lucy Arch and thickening eastward (Fig. 14). Uplift and erosion along the northeast coast have combined to expose not only the 83,000 year old reef complex, but the underlying sediments as well. In the northern part of the northeast coast, the 83,000 year old reef complex is underlain by a calcarenite sequence more than 20 meters (60 feet) thick (Fig. 7). The upper part of the underlying calcarenite contains numerous large heads of *Montastrea annularis* (Plate 5C). While well-indurated reef limestones underlying this complex to the west cannot be used for radiometric dating because all aragonite has inverted to calcite, along the sea coast such diagenesis has been arrested, and hence coral skeletons can be utilized. Underlying reef carbonates are accessible along the sea coast near North Point and one of the large *M. annularis* colonies 4.6 meters (15 feet) below the contact was secured for dating (Fig. 34). This sample yields a radiometric Th^{230}/U^{234} age of 127,000 $\pm$ 3,000 years B.P. and a Pa^{231}/U^{235} age of 124,000 $\pm$ 5,000 years B.P. (Appendix F) indicating that the upper part of the underlying limestone in this area was formed during the same high stand of sea level as the First High Cliff on other parts of the island, but here it is buried <u>below</u> a younger complex.

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Northwest coast fringing terrace

Occurrence and dating.--A narrow, discontinuous terrace lies at the foot of Pleistocene limestone cliffs along the northwest coast (Plate 4A). This terrace is best developed in bays but headlands are often notched at a similar elevation (Plate 4B). The terrace rises from sea level at Maycock's Bay (Fig. 10) to about 4.5 meters (17 feet) above sea level at Cluff's Bay. As wave action along this coast is strong, much of the terrace has been eroded.

Where best exposed on the northern coast, the terrace differs in internal composition from older reef terraces described by Mesolella and others (1970). It is built on a wave-cut platform eroded in Tertiary or older Pleistocene strata. The sediment, which has accumulated to a thickness of up to 4 meters (15 feet) on this platform, is divisible into coral and sand facies (Fig. 11). The seaward part is a massive, shallow water, reef limestone dominated by the corals *Acropora palmata* and large columnar *Montastrea annularis* (Plate 4E) which are common forms on the crests of Caribbean reefs today. Other corals include occasional large *in situ* heads of *Porites astreoides* and small banks of *Porites porites*. The poorly-bedded, carbonate sand facies contains abundant molluscs (Plate 4D) especially the land snail *Helix isabella* and the marine gastropod *Cittarium (Livonia) pica*.

Samples of the coral *P. astreoides* and the gastropod *Cittarium (Livonia) pica* were analysed to date the terrace. The fossils yielded an average Th^{230}/U^{234} age of 61,000 $\pm$ 2,000 years B.P. and an average Pa^{231}/U^{235} age of 59,000 $\pm$ 3,000 years B.P. (Appendix F). The narrow range of dates clustered around 60,000 B.P. obtained by both methods of dating indicates their reliability. The coral dates are more reliable than those obtained from *Cittarium pica* because the gastropods are likely

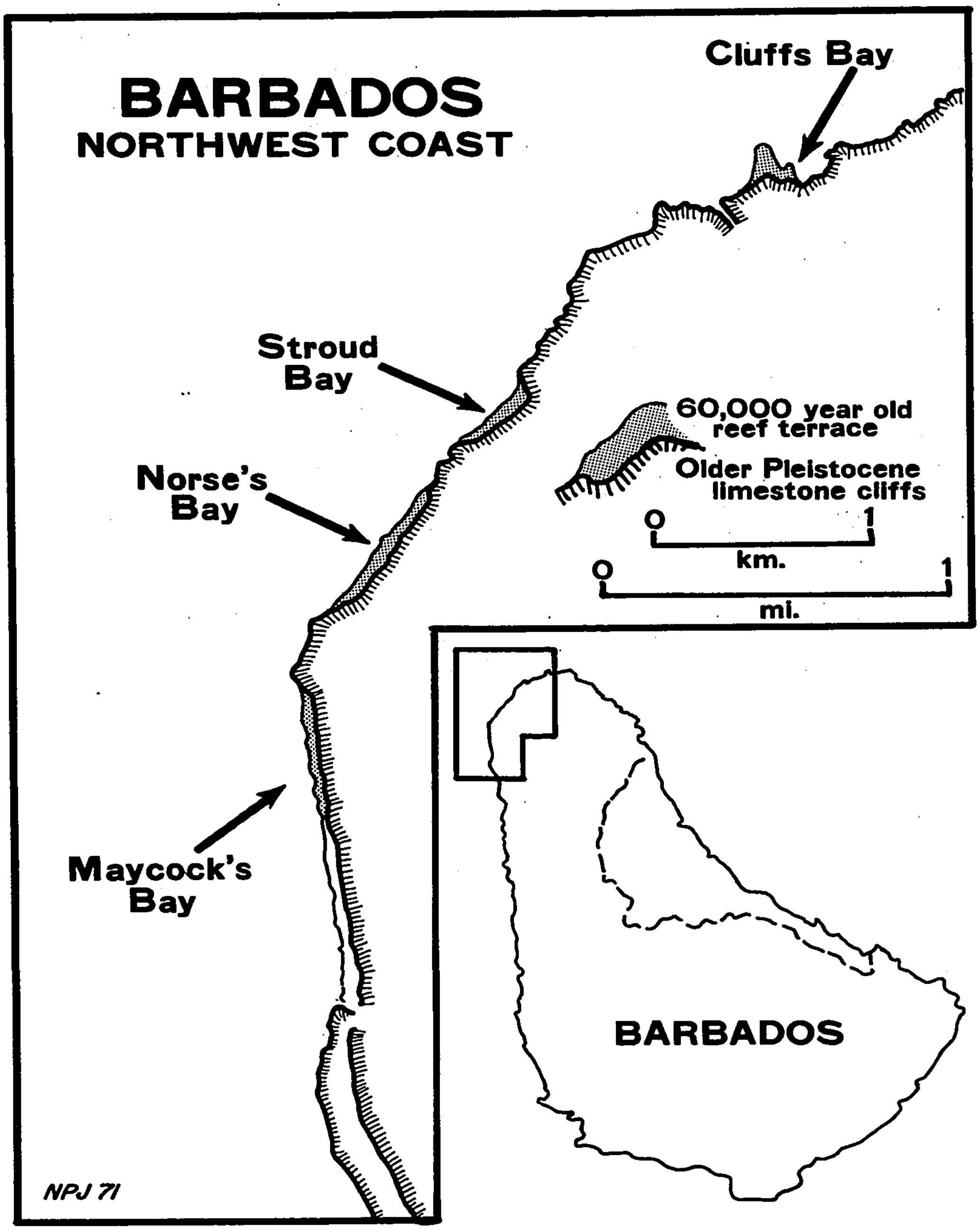

Figure 10. Localities of 60,000 year old reef terrace along the northwest coast of Barbados. Cross-section in Figure 11 taken at Cluff's Bay.

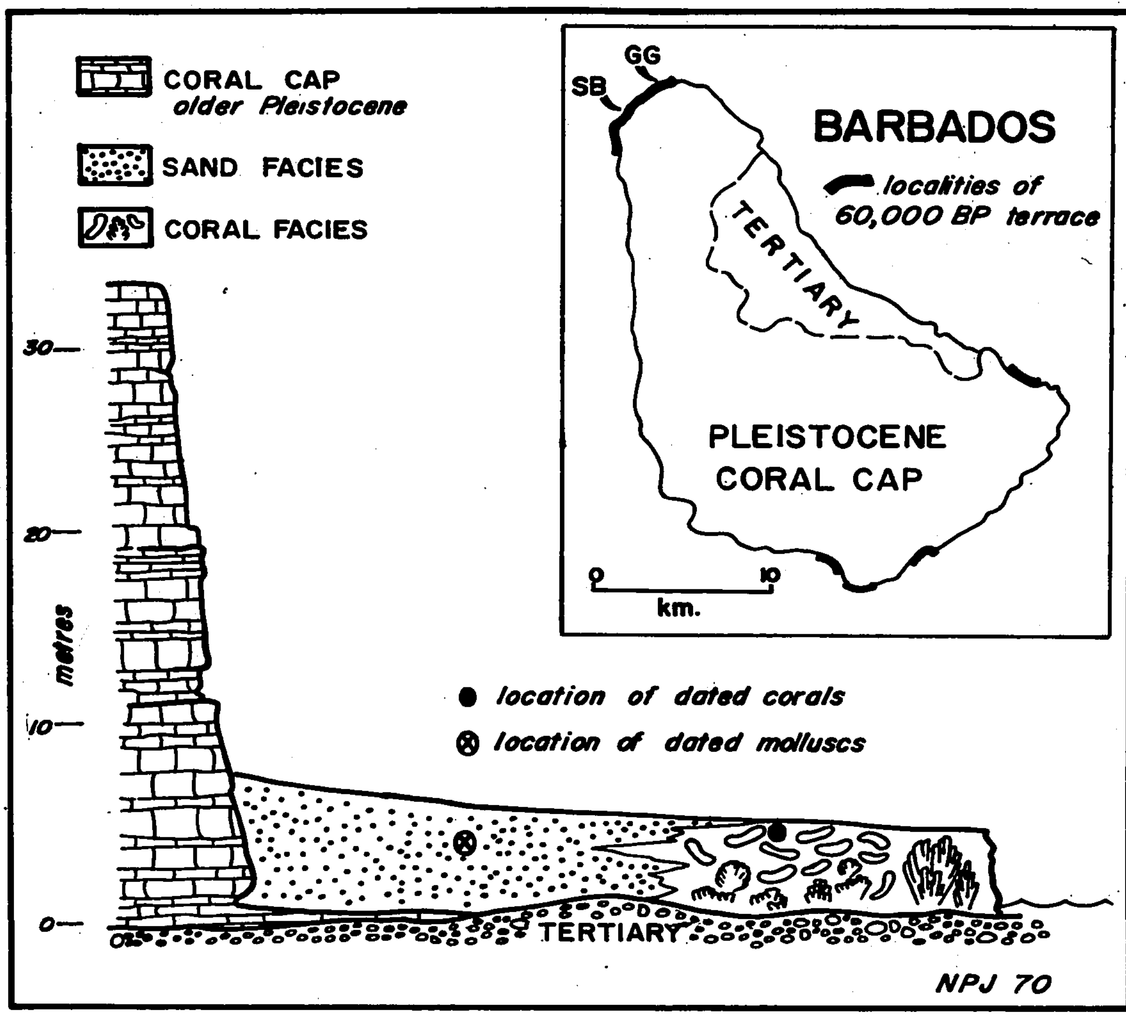

Figure 11. Cross-section and areal distribution of 60,000 years B.P. reef terrace, at Cluff's Bay, Barbados. SB, GG on index map indicate location of samples dated. Exposures on southern part of Barbados are described by Trechmann (1937). Width of terrace varies from 3 to 30 meters.

to contain uranium taken into their skeletons shortly after fossilization (Broecker, 1963; Thurber and others, 1965; Osmond and others, 1970) even though they are still pure aragonite and have retained the striking exterior markings and shiny interior mother of pearl.

Trechmann (1937) has described beds rich in the land snail *Helix isabella* as forming a veneer along the coast on the south and east sides of Barbados. These beds, 0.5 to 3.5 meters above sea level, contain a mixed land and marine mollusc fauna as well as corals. Since they are found at or near the present coast and are different in composition from the Pleistocene limestones, he believed they were deposited subsequent to formation and uplift of the entire Pleistocene Coral Cap. Field investigation of these deposits indicates that they are, as Trechmann's descriptions suggest, essentially the same as those sediments forming the dated terrace fringing the northern part of the island. Although not dated, the similarity of stratigraphic position and composition suggests they were deposited during the same high stand of sea level.

Contemporaneous late Pleistocene marine terraces.--Marine terraces formed during early Wisconsin time, although rare, have been reported from other parts of the world. Shoreline deposits in coastal Georgia suggest one marine transgression between 25,000 and 30,000 years B.P. and another between 40,000 and 48,000 years B.P. (Hoyt and others, 1965). Radiometric dating of interglacial shoreline deposits in Alaska indicates a high stand of sea level between 40,000 and 50,000 years B.P. (Karlstrom, 1965). In New Guinea a complex series of reef terraces suggests three separate marine transgressions at (1) 29,000 years B.P., (2) 35,000 to 50,000 years B.P., and (3) 65,000 years B.P. (Veeh and Chappell, 1970). On the central Ryukyu Islands in the western Pacific, two separate limestone units have dated at 42,000 and 67,000 years B.P. (Konishi and others, in press) (Fig. 12--bar represents range of ages reported for each deposit, not error in single age determination).

<u>Additional evidence of late Pleistocene climatic changes</u>.--Comparison with late Pleistocene climatic events determined by other studies reveals the importance of this terrace. Wisconsin chronology and climatic fluctuations are based largely on continental stratigraphy which records the presence of two major glaciations ("Classical" and "Early" Wisconsin; Flint, 1963). The Plum Point interstadial (25,000 to 35,000 years B.P.) and Port Talbot interstadial (45,000 to 55,000 years B.P.) separate the two major Wisconsin glaciations, while the St. Pierre interstadial (60,000 to 65,000 years B.P.) records a boreal period during the post-Sangamon glacial advance (Fig. 12) (Goldthwaite and others, 1965; Dreimanis, 1969).

The pattern of climatic fluctuations is reflected in deep sea sediment (Ericson and Wollin, 1964; Emiliani, 1966, 1970), but the exact dates of these temperature fluctuations are still unresolved (Rona and Emiliani, 1968; Broecker and Ku, 1969). The times of climatic fluctuations obtained from deep sea cores have, however, been correlated with the Barbados terraces by Broecker and others (1968), and so are used here in Fig. 12.

High stands of sea level (interglacials) 80,000 years and older are in good agreement with the insolation curve predicted by the "Milankovitch Hypothesis". Unfortunately, few radiometric ages are available for the younger, mid- to late Wisconsin interstadials, except as noted above. The insolation curve suggests warm periods (but not as warm as the Sangamon) should be present at approximately 33,000, 60,000 and possibly 48,000 years B.P. (Mesolella and others, 1969).

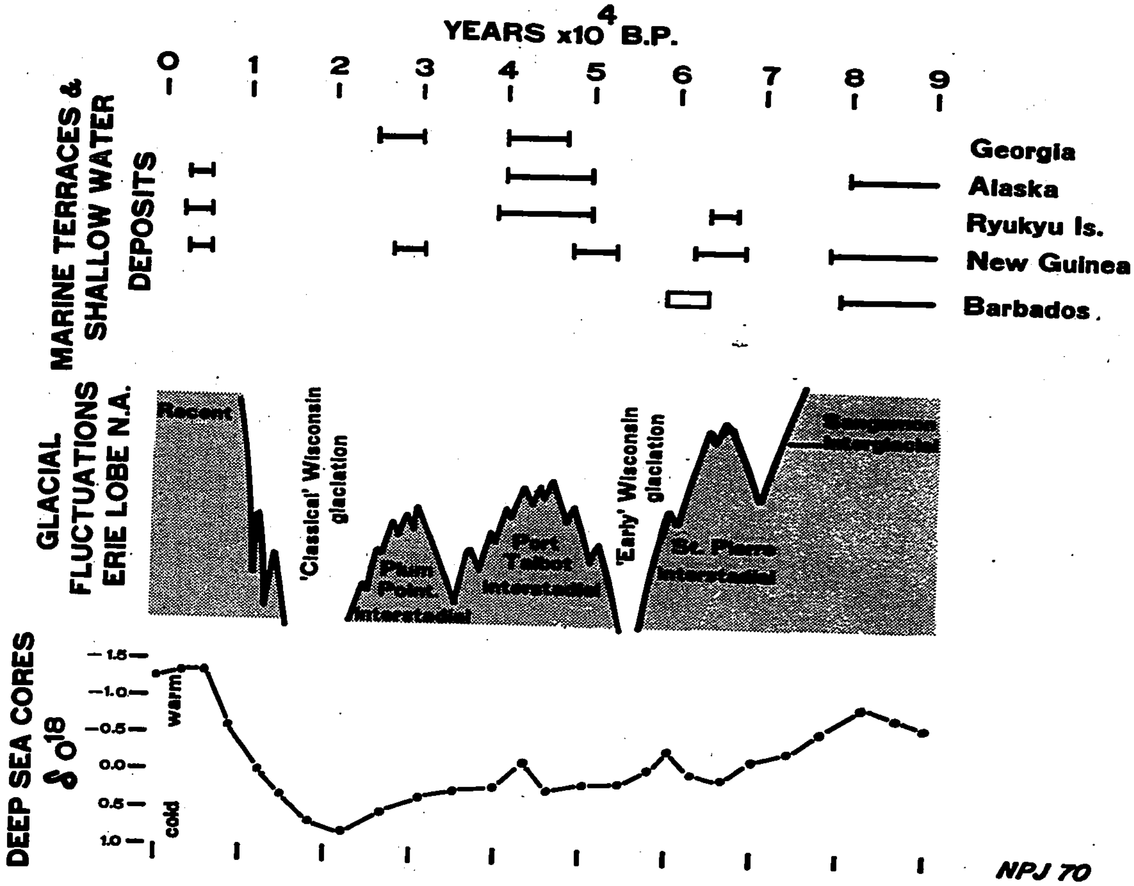

Figure 12. Ages of uplifted marine terraces correlated with Pleistocene climatic fluctuations. Marine terrace data from Georgia (Hoyt and others, 1965), Alaska (Karlstrom, 1965), Ryukyu Islands (Konishi and others, 1971), New Guinea (Veeh and Chappell, 1970), and Barbados (Broecker and others, 1968; this study). The bar represents the range of ages reported for each deposit, not error in single age determination. Glacial chronology after Dreimanis (1970). Deep-sea core δO^{18} data after Broecker and Ku (1969).

Therefore, the occurrence of a 60,000 years B.P. terrace on northern Barbados is not anomalous, but fits both the glacial and deep sea chronology and the predicted solar insolation curve.

In Barbados, the 60,000 year old terrace probably represents the sea level high stand between 60,000 and 65,000 years ago. The younger high stands may be represented as part of the shallow water erosional terrace that extends up to a mile offshore from the west coast (Macintyre, 1970).

SUMMARY AND DISCUSSION

1. The broad platform on northern Barbados is underlain by the extension of a north-south ridge of deformed Tertiary strata that forms the core of Barbados. This northern part of the ridge is called the "St. Lucy Arch". The flanks of the arch dip gently to the east and west but the core is dissected into three distinct, partially buried, highs (Fig. 6). The sediments making up the core of one of these highs, exposed at Cluff's Bay, are Globigerina chalks (Middle Eocene (Lutetian), Globigerapsis kügleri zone). These are the oldest beds of the Oceanic Formation so far recorded, extending the age of these world famous sediments over a slightly wider range, and restricting the underlying Scotland Formation to the Lower Eocene.

2. Overlying the pre-Pleistocene surface is a conglomerate, with clasts derived mainly from the Scotland Formation clastics. The presence of boulders of Scotland Formation in the overlying Plio-Pleistocene limestone units suggests that initial carbonate sedimentation began in some areas while erosion was continuing in others, perhaps on the topographic highs. Erosion along with subsequent tectonic activity may be responsible for the highly dissected nature of the St. Lucy Arch.

3. Plio-Pleistocene carbonates constitute a greater part of the limestones on the North Point Shelf than previously supposed. They are divided into two units--(1) a thin, basal, phylloid crustose red algal unit forming a more or less continuous mantle over the pre-Pleistocene surface and (2) an upper, thicker, *Amphistegina* calcarenite unit which is thickest in lows on the pre-Pleistocene surface.

4. The areal distribution of Plio-Pleistocene and Tertiary rocks shows that the late Pleistocene outcrops cannot be traced across the St. Lucy Arch. Radiometric age dating of corals from the widespread limestones on either side of the arch indicates that limestones forming most of the outcrop along the western edge of the platform were formed during a sea level high stand 104,000 years ago and are not comparable with the limestones making up most of the sediment on the eastern part of the platform deposited during the subsequent high stand of sea level 83,000 years ago.

5. The sequence of reef complexes on most of Barbados appears to record a late Pleistocene history of periodic deposition on a constantly rising substratum (Mesolella and others, 1970), but stratigraphy of the same reef complexes on northern Barbados records a history of periodic deposition on a substratum undergoing sporadic uplift. Warping of northern Barbados sometime between 105,000 and 125,000 years ago resulted in relative depression of the area. High stands of sea level 104,000 and 83,000 years ago transgressed part way across the North Point Shelf and accompanying reef deposition buried pre-existing reef complexes. Subsequent increased uplift raised these later reef complexes to heights above comparable deposits on other parts of the island. This relatively greater uplift along the northwest coast has resulted in the subaerial exposure of the pre-

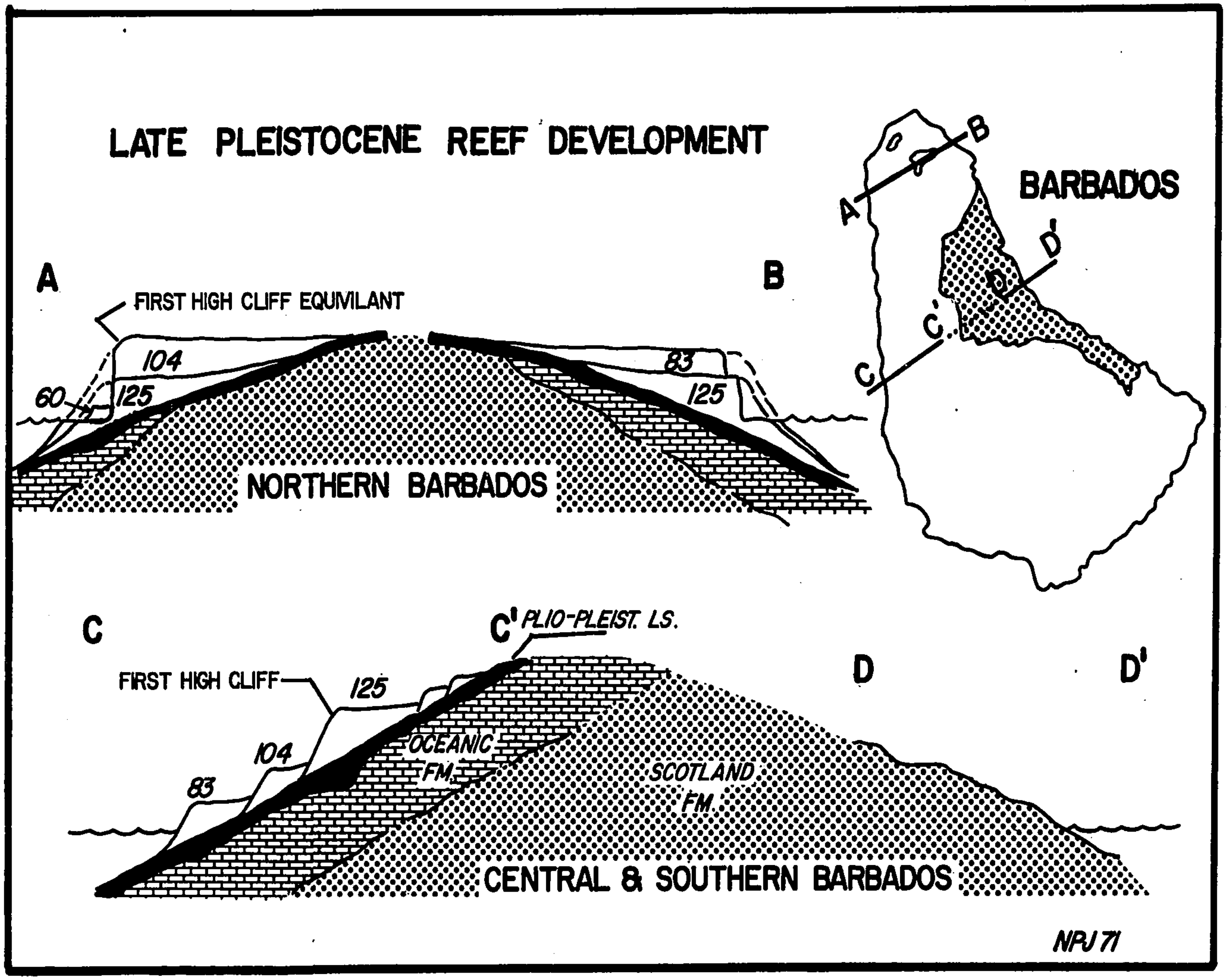

Figure 13. Diagrammatic comparison between late Pleistocene reef stratigraphy on northern Barbados and central and southern Barbados. Radiometric age of reef complexes x 10^3 years.

viously unreported 60,000 year old reef terrace which formed below present sea level (Fig. 13).

6. A narrow, discontinuous reef terrace, 2.5 to 4.5 meters above sea level, and radiometrically dated at 60,000 ± 2,000 years B.P., fringes the northwest coast of Barbados. This terrace is distinct from older terraces and can be correlated lithologically and stratigraphically with similar terraces some 32 kilometers (20 miles) distant on the southern part of the island. Marine terraces dated at 65,000 years B.P. on New Guinea and 67,000 years B.P. on the Ryukyu Islands were probably deposited during the same sea level high stand.

These data, along with dates of other terraces formed during the mid- and early Wisconsin throughout the world, and coupled with continental glacial and deep sea core stratigraphy, indicate that sea level stood relatively high at three separate times during the Wisconsin about 30,000, 48,000 and 60,000 years B.P. As these periods were not as warm as the interglacials, sea level did not rise to a level corresponding to the present sea level. Consequently deposits are only observed in areas that have undergone some subsequent tectonic uplift.

Variations in climate may be controlled by changes in solar insolation (the Milankovitch Hypothesis). Calculations suggest that warm periods, although not as warm as interglacials, should have occurred about 33,000, 60,000 and possibly 48,000 years ago (Veeh and Chappell, 1970). The close agreement between the times of the warm periods discussed above and the times of those predicted by the Milankovitch Hypothesis lends support to those who feel that large variations in solar insolation may initiate glaciation.

CHAPTER 3 - LATE PLEISTOCENE REEF COMPLEXES

INTRODUCTION

Owing to the unique conditions necessary for exposure of Pleistocene limestones, few have been described in detail (Stoddart, 1969). A reconnaissance study of all the reefs on Barbados was carried out by Mesolella (1968) and sediment composition of some selected reef complexes was determined by Kiesewetter (1968). From these investigations a general model of reef development was proposed (Mesolella and others, 1970). None of the Pleistocene reefs on the island has been subjected to detailed examination, due mainly to lack of continuous exposure.

Uplift and subsequent erosion of the late Pleistocene reef complexes (104,000 years B.P. and 83,000 years B.P.) on northern Barbados has created extensive outcrop which can be examined in detail. The 83,000 year old complex, in particular, displays a sequence of facies that reflects the response of animal communities and sedimentary regimes to a slowly rising sea level. As the animals that inhabit the reef ecosystem today are essentially the same as those of 100,000 years ago, comparison can be made between late Pleistocene fossil and modern living communities. These two reef complexes are described from the point of view of stratigraphy, facies development, and sediments.

83,000 YEAR OLD REEF COMPLEX, NORTHEAST COAST

This reef complex is exposed in excellent, but often inaccessible, outcrop along the sea cliffs (Plate 1D). These cliffs are parallel to the facies trends and are mostly cut into the reef facies (Fig. 31). Bays and river valleys, at right angles to the coast, yield excellent cross-sections of the complex (Fig. 32). There are also many smaller outcrops on the North Point Shelf that are well exposed due to the arid climate and lack of vegetation.

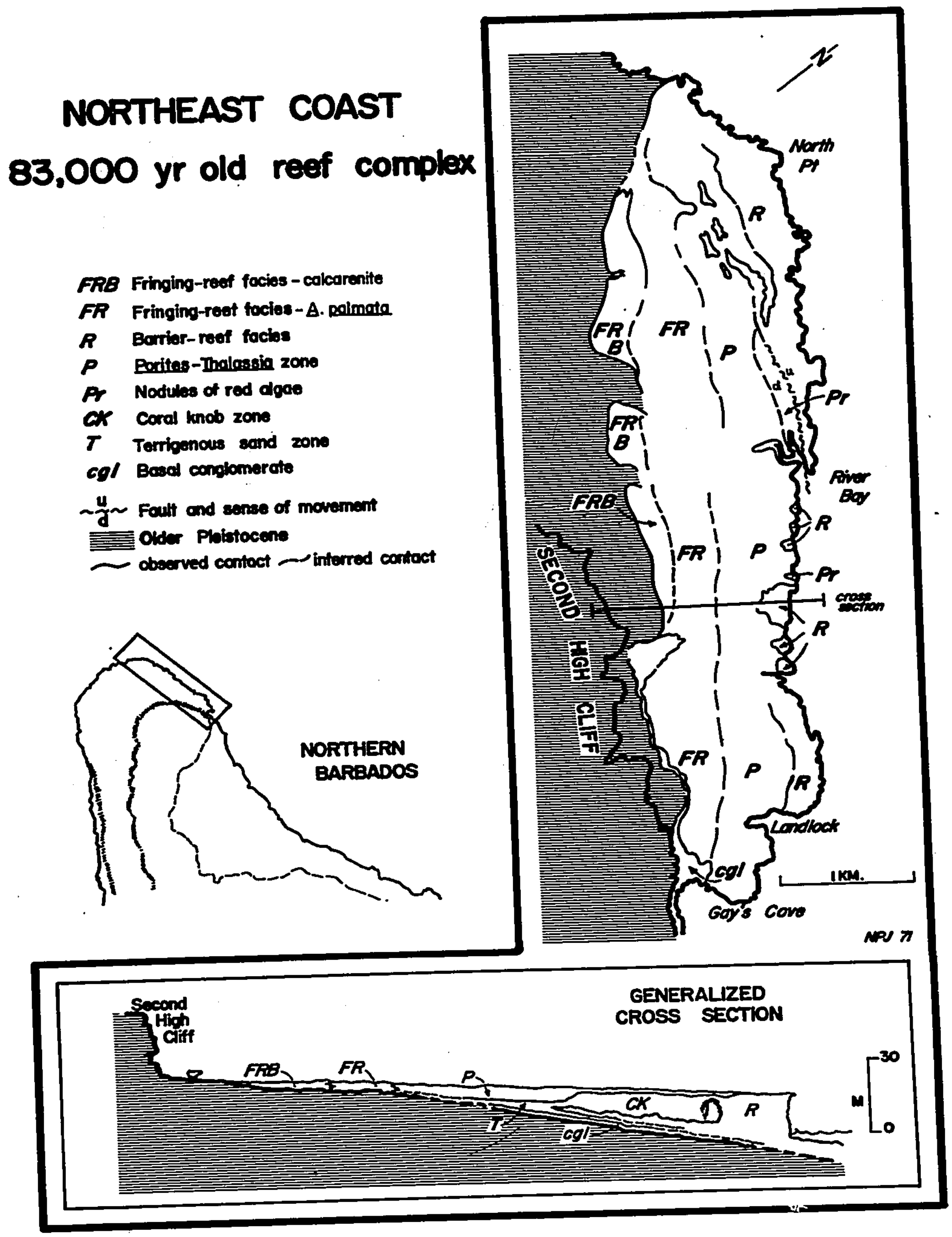

Figure 14. Surface facies distribution and generalized cross-section of 83,000 year old reef complex, northeast coast, Barbados.

Stratigraphy

The underlying surface of the reef complex is formed of Tertiary and older Pleistocene sediments. Although the contact exhibits evidence of subaerial and extensive biological erosion, no fossil subaerial calcareous crusts were found. The shape of the limestone body is that of a wedge thickening eastward, with the thin edge parallel to the axis of the St. Lucy Arch. On the northern coast, the 83,000 year old limestones overlie a thick sequence of corals and calcarenites. The top of the older limestones is marked by a present-day, erosional bench (Plate 5C), frequently pictured in studies of the island (Price, 1962). A coral some 3.7 meters (15 feet) below this bench was dated at 125,000 years B.P. On the southern part of the northeast coast (Gay's Cove to The Landlock), the 83,000 year old limestones overlie chalks of the Tertiary Oceanic Formation, much younger than those exposed at Cluff's Bay (Plate 5A).

Facies

The lithologies of the reef complex cannot easily be divided into separate parts (Fig. 14) but, in general terms, the limestone can be broken into a thin, basal unit and an overlying, thicker, reef unit. The basal unit, directly overlying the older Pleistocene limestone and Tertiary strata, is made up of calcarenites and conglomerates which, in the eastern part of the area, grade up into a coral-rich lithology. The overlying reef unit is divisible, on the basis of corals and sediments, into three separate facies--(1) a barrier-reef facies, (2) a back-reef facies and, (3) a fringing-reef facies. The barrier-reef facies is, in turn, divisible into two zones--(a) the <u>palmata</u> zone and (b) the <u>cervicornis</u> zone, in which the corals are almost exclusively <u>Acropora palmata</u> and <u>Acropora cervicornis</u>. The back-reef facies is divisible into three zones--(a) the coral-knob zone, made up of scattered, rounded, coral heads in calcarenite and calcilutite, (b) the terrigenous sand zone, and (c) the Porites-Thalassia zone, which overlies the terrigenous sand zone and, in the upper parts of the reef complex, overlies the coral-knob zone as well. The narrow, fringing-reef facies is developed in the uppermost part of the complex and is composed of a reef zone and back-reef zone.

Basal Unit

A veneer of conglomerate (Plate 5B) and calcarenite covers much of the eroded pre-reef surface (Fig. 14). Conglomerate is most common over the western, landward, part of the pre-reef surface and clasts are derived from all known Tertiary sediments, various older Pleistocene limestones and fragmented caliche crusts. Sedimentation was not continuous as many of the pebbles on the upper surface of the conglomerate are extensively bored by molluscs and sponges (Plate 5F). This conglomerate grades eastward into a poorly sorted, coarse calcarenite made up of intraclasts, articulated coralline algae, minor coral, and red algal nodules.

In the eastern, seaward, part of the area, the basal calcarenite is overlain by coral-calcarenites consisting of about 40 per cent Acropora palmata fronds, Montastrea annularis (Plate 5D, 5E) and scattered Diploria in a matrix similar to the calcarenite described above, but with fewer intraclasts. Instead, the dominant allochems are Homotrema and red crustose algal fragments.

The eastern, seaward, section of coral-calcarenites passes upward without break into the barrier-reef facies of the overlying reef unit. In contrast, the basal unit and the overlying back-reef facies of the reef unit are separated by a distinct boundary, with the upper surface of the basal unit coated by crustose red algae (Plate 5E). This break in sediment deposition, marked by the crustose red algae, suggests that, during initial stages of barrier-reef growth, open ocean waves swept across the back-reef area, encouraging crustose red algal growth and sweeping away most loose sediment.

Reef Unit

Barrier-reef facies.--(a) Palmata zone (Fig. 14) - The reef front of this complex is composed of a massive accumulation of *Acropora palmata* (Plate 6C). This *A. palmata* grew and/or was scattered over an area about 0.53 kilometers (1/3 mile) wide, 6.5 kilometers (4 miles) long, forming a deposit over 12 meters (40 feet) thick. The *palmata* zone appears to have remained in one position throughout most of the reef development and formed a massive wall, composed almost exclusively of *A. palmata* fronds stacked one upon the other. Individual fronds are up to 0.3 meters (1 foot) thick, often over 1.2 meters (4 feet) wide, and weigh hundreds of pounds. Encrustations of red algae on the upper surface of many fronds (Plate 8A, 32C) indicate they were encrusted in growth position, like those now growing off the north coast of Jamaica (personal observation). In almost all samples examined, the red algae was *Lithophyllum* with up to 10 per cent additional strands of *Lithoporella*. Many of the *A. palmata* fronds are inverted (Plate 6B), indicating that they were broken and tumbled from their growth position before burial. Repeated boring by the gastropod *Lithophaga* (Plate 8A), the sponge *Cliona*, and eunicid worms (James, 1970) weakened these large structures and made them amenable to mechanical breakage. Tight packing of the structure is well demonstrated by the numerous smaller, immature fronds that are wedged between the larger fronds, resembling a fieldstone fence. Stability of this structure is enhanced by the *in situ* cementation of some of the inter-reef sediment (see Chapter 4).

Sediment between the A. palmata fronds is mainly calcilutite and calcisiltite, characteristically containing whole, unabraided, pelecypod valves, rods of coralline algae (especially Amphiroa), and tests of Homotrema rubrum. In calcarenite lenses and pockets, the grains are predominantly well-sorted coral fragments (Plate 7E, 7F) with an average grain size of 0.25 mm. Accessory grains are composed of mollusc, Amphiroa, and Homotrema rubrum fragments.

(b) Cervicornis zone – Leeward, behind the abundant A. palmata, are accumulations of Acropora cervicornis (Plate 9D, 9E, 9F). This delicate coral is commonly characteristic of modern fore-reef areas (Plate 9C; Goreau, 1959; Mesolella, 1967; Stoddart, 1969) but appears to be abundant behind the palmata zone in this Pleistocene reef. Whereas A. cervicornis is often a delicate form in the back-reef environment of many modern coral reefs (Kornicker and Boyd, 1962), large sticks (up to 0.94 meters long) (Plate 9F) are found behind this Pleistocene reef crest. These larger, more sturdy, Pleistocene forms appear to represent adaptation to vigorous water movement in the shallow water, reef crest environment. In most outcrops the delicate raised polyps, so typical of Acropora species, are still superbly preserved. This, along with evidence of in situ submarine cementation of some cervicornis sticks (Chapter 4), indicates that these corals grew in situ and were not transported to their current position from the fore-reef. Storm activity (Ball and others, 1967; Perkins and Enos, 1968; Stoddart, 1969) appears to have resulted for the most part in transport of A. palmata fronds behind the reef crest, yielding interbeds of A. palmata in this cervicornis zone (Plate 6D).

Sediment in the cervicornis zone is essentially the same as in the palmata zone, with the addition of minor amounts of echinoid and peneropolid foraminiferal debris to the coarse fraction. Some parts of the sediment are mottled and, in these areas, the mottles are composed of pelsparite.

Massive colonies of Montastrea annularis (Plate 8D) reach heights of 9.5 meters (30 feet) or more and widths of 7.7 meters (25 feet) in the barrier-reef facies. These colonies, although scattered throughout the facies, are most common either bordering depositional channels which trend at right angles through the barrier-reef facies, or in the zone between the barrier-reef and back-reef facies (Plate 8E, 9B).

Back-reef facies.--Immediately behind the barrier-reef facies lies a massive calcisiltite-calcarenite with scattered coral knobs. The lower part of this facies grades laterally westward into a well-bedded, terrigenous sand. The terrigenous sand and coral-knob zones are overlain by a lithology made up almost entirely of Porites sticks (Fig. 14).

(a) Coral-knob zone - The part of the coral-knob zone adjacent to the barrier-reef facies consists of scattered (30 per cent) coral knobs in a mottled sand (Plate 11, 1D). Large, tall colonies of Montastrea annularis grow from underlying Acropora palmata mounds and may be up to 3 meters (10 feet) high. Scattered among these colonies are round Diploria heads (Plate 11A). In the upper part of the zone, corals are smaller and M. annularis assumes an encrusting "hat-like" form (Plate 11C). This "hat-like" growth form of M. annularis is characteristic of the back-reef environment in many modern coral reefs (Plate 11D). The presence of a similar coral growth form in both Holocene and Pleistocene back-reef facies emphasizes the usefulness of various coral growth forms as indicators of specific reef environments.

Particularly common in the middle and upper parts of the unit are Porites astreoides, Porites porites, Siderastrea, Eusmilia (Plate 11F) and Isophyllia.

Sediment between corals in the back-reef facies is mottled and changes in composition vertically. Brown, terrigenous sand at the bottom of the unit grades upward into white calcilutite. In the lower half of the unit, sediment mottling is very striking with white blebs and tubes of calcilutite set in a matrix of poorly lithified brown sand. This texture, similar to modern "bioturbites" (Imbrie and Buchanan, 1965), is likely due to the action of burrowing animals. These animals (probably the shrimp <u>Calianassa</u>; Shinn, 1968a), appear to have created a network of open tubes in the brown, terrigenous sand below the sea floor. When the animals later deserted these galleries, the fine, carbonate sediments then being deposited on the lagoon floor filtered down into the holes and filled them. This resulted in the present-day texture of brown sand with irregular brown blebs and tubes (Plates 12D, 12E, 12F). At the top of the unit, the lack of contrast between burrow-fill and surrounding calcilutite makes these mottles difficult to discern.

Coarsest sediment, dominantly quartz grains (Plate 13C) with up to 20 per cent micritized, carbonate particles (Plate 13D), occurs at the base of the coral-knob zone. This sand grades up into a micrite with silt to fine sand sized skeletal debris (Plate 13F) of miliolid foraminifera, molluscs and crustose red algae, but little or no quartz. Sediment in the upper part of the zone, and in the white mottles, is pelleted (0.02 to 0.04 mm) micrite with minor skeletal debris. Many coral knobs are surrounded by a narrow zone of medium grained calcarenite reflecting local production of abundant skeletal material.

(b) Terrigenous sand zone - Overlying the conglomerates of the basal unit, in the western, or landward, part of the back-reef facies, are brown, terrigenous sands (Plate 5D). These sands were derived from nearby, poorly lithified, Lower Eocene, Scotland beds. Terrigenous sedimentation does not appear to have affected coral growth as scattered heads of <u>M. annularis</u> and <u>Diploria</u> are underlain and enclosed by the sand. These sands contain progressively more carbonate towards the barrier-reef facies and away from the

Scotland beds. In the lower part of the zone, sands are well laminated. Near the top of the zone, laminae are disrupted by calcite cemented tubules (Plate 12A, 12B).

(c) Porites-Thalassia zone - During the major part of reef history, a Porites biotope developed landward of the coral-knob zone. The species of Porites is difficult to identify, but the relatively long, slender nature of the sticks suggests it is Porites porites var. furcata. Profusion of these sticks (Plate 14A) indicates rapid and massive growth. Interspersed with the Porites sticks are small accumulations or patches of accessory corals (Plate 14D) such as Eusmilia, Agaricia agaricites, Siderastrea, and Manicina aerolata. Especially prominent are the relatively large number of molluscs, particularly the gastropods Strombus (Plate 14E) and Bulla, and the bivalves Chione cancellata and Codakia orbicularis. Towards the upper part of the zone, these skeletons are segregated into beds and lenses up to 0.45 meters (1-1/2 feet) thick.

The matrix between these pelecypod shells and Porites sticks grades from a muddy calcarenite at the base (Plate 15A, 15B) to a well-washed calcarenite at the top (Plate 15C, 15D). Many (up to 30 per cent) of the silt to fine sand sized fragments are again micritized peloids of unknown origin. In the cleaner, better sorted, upper portion of the zone, most grains are coral and accessory mollusc fragments.

Porites porites var. furcata is one of the most common corals in the back-reef environment of modern coral reefs. This form is found in water up to 20 meters (62 feet) deep (Goreau and Wells, 1967), but grows best in depths of less than 3 meters (10 feet) (Voss and Voss, 1955; Kornicker and Boyd, 1962). The growth of this coral is particularly prolific where the sea grass, Thalassia testudinum is abundant (Plate 14C; Margalef, 1962; Rigby and McIntire, 1966; Turmel and Swanson, 1970).

In modern reefs, *Thalassia* beds are distributed either in a patchwork pattern, alternating with open sand (Kornicker and Boyd, 1962) or in linear trends parallel to the reef tract. As this grass does not contain any skeletal hard parts, it leaves no trace in the fossil record and its presence is only indicated by the generally fine sediment (Ginsburg and Lowenstam, 1958; Humm, 1964; Land, 1970b) and associated fauna. Besides *Porites porites* var. *furcata*, this environment is also inhabited by several species of gastropods and bivalves, the green alga *Halimeda*, assorted sponges and holothurians (Supko and others, 1970), and the corals *Diploria* (Rigby and McIntire, 1966), *Manicina aerolata* and *Siderastrea* (Squires, 1958; Patriquin, 1971), which often assumes a "ball-like" growth form. Of these, the molluscs contain the most characteristic hard parts, and the most diagnostic of these are the bivalves *Codakia orbicularis* and *Chione cancellata* (O'Gyper and Wacasey, 1967; Moore and others, 1968; Taylor and Lewis, 1970). The gastropods *Strombus* and *Bulla* are, if not diagnostic, very common forms.

To summarize, the similar association of the above Pleistocene molluscs and corals, along with their position relative to surrounding sediments and facies, suggests that the deposit represents a *Porites-Thalassia* community growing in very shallow water.

Fringing-reef facies.--At the top, landward (western) edge of the complex are discontinuous coral accumulations, generally less than 3 meters (10 feet) thick and rarely more than 50 meters (162 feet) wide. These coral patches are fronted by scattered *Acropora palmata* in calcarenite (Plate 14F) and localized on laterally persistent, underlying topographic highs. The *Acropora palmata* fronds are not coated with red algae, seldom bored, and rarely in growth position. Westward, directly behind these *A. palmata* accumulations, is a mottled calcarenite, characterized by small *Siderastrea* heads and numerous *Strombus* shells.

These small, coral patches, themselves broadly divisible into a reef (*A. palmata*) and back-reef (calcarenite) zone, appear to represent a fringing-reef facies adjacent and parallel to the axis of the relatively high St. Lucy Arch. The relationship between this facies and the *Porites-Thalassia* zone of the back-reef facies is not clear except in one section (B6 to B12 - Fig. 35), where the *A. palmata* grades eastward into calcarenite, which in turn grades into the *Porites-Thalassia* zone.

104,000 YEAR OLD REEF COMPLEX, NORTHWEST COAST

Stratigraphy

This reef complex forms the major part of the First High Cliff north of Holetown (see Chapter 2 for detailed discussion) and is deposited, for the most part, on a surface that was exposed to subaerial weathering long enough to develop caliche-like calcareous crust profiles (see Chapter 4).

Facies

Limestones of the 104,000 year old complex can be divided into a reef facies and a back-reef facies (Fig. 16). Unlike the 83,000 year old reef complex on the northeast coast, no basal clastics were observed. The reef facies can be subdivided into a western, *cervicornis* zone and an eastern, reef crest, or *palmata* zone. The back-reef facies can be subdivided, from west to east, into--(a) a near-reef zone, (b) a stick-coral zone, and (c) a nearshore calcarenite zone. These zones change northward into (d) a *Porites*-bank zone, and (e) a rhodolite, or red algal nodule, zone (Fig. 15).

Reef Complex

Reef facies.--(a) *Cervicornis* zone - This zone, consisting of numerous *Acropora cervicornis* sticks in a fine grained matrix, forms the western edge

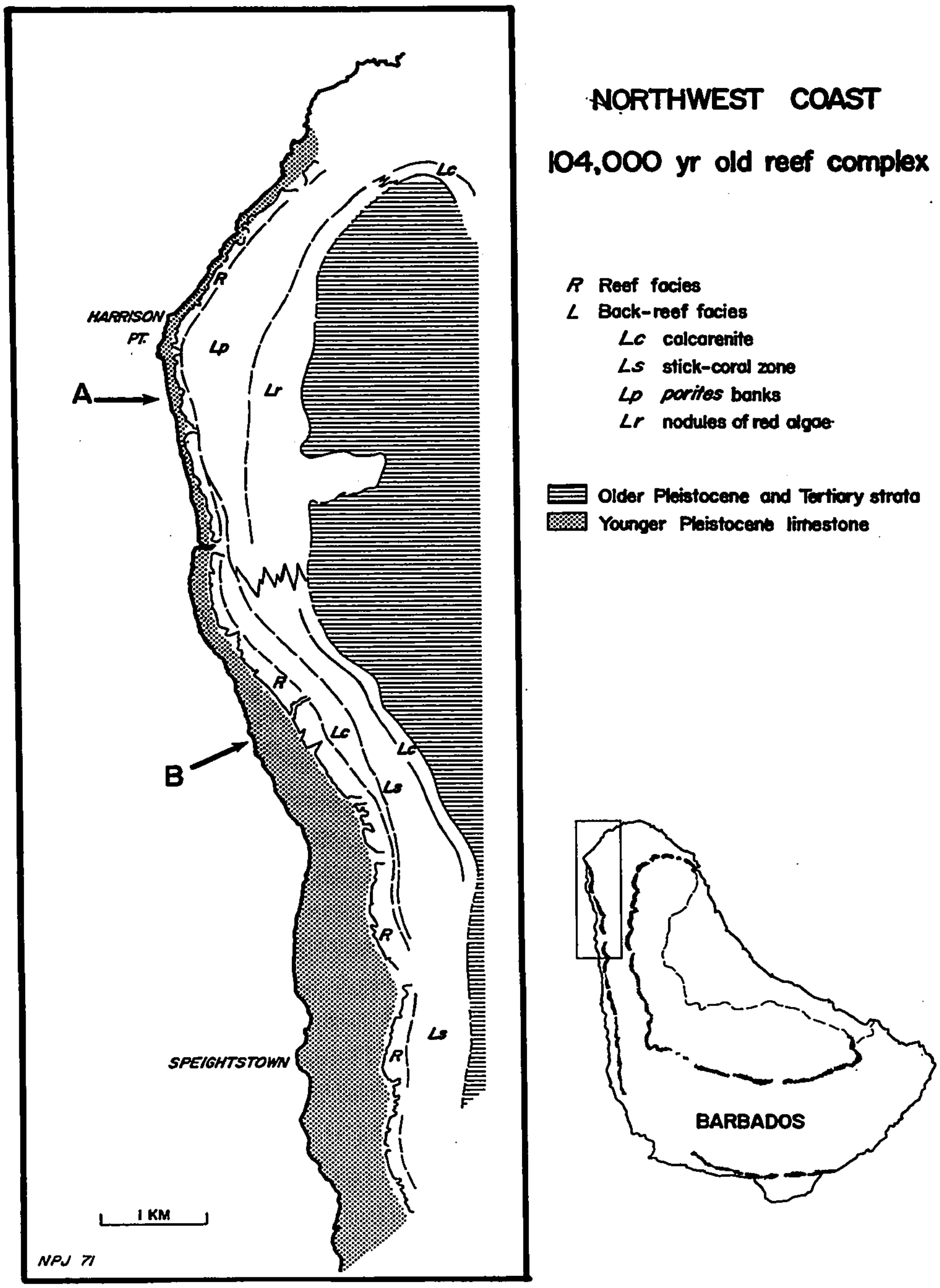

Figure 15. Surface facies distribution of 104,000 year old reef complex, northwest coast, Barbados. A and B are lines of section illustrated in Figure 16.

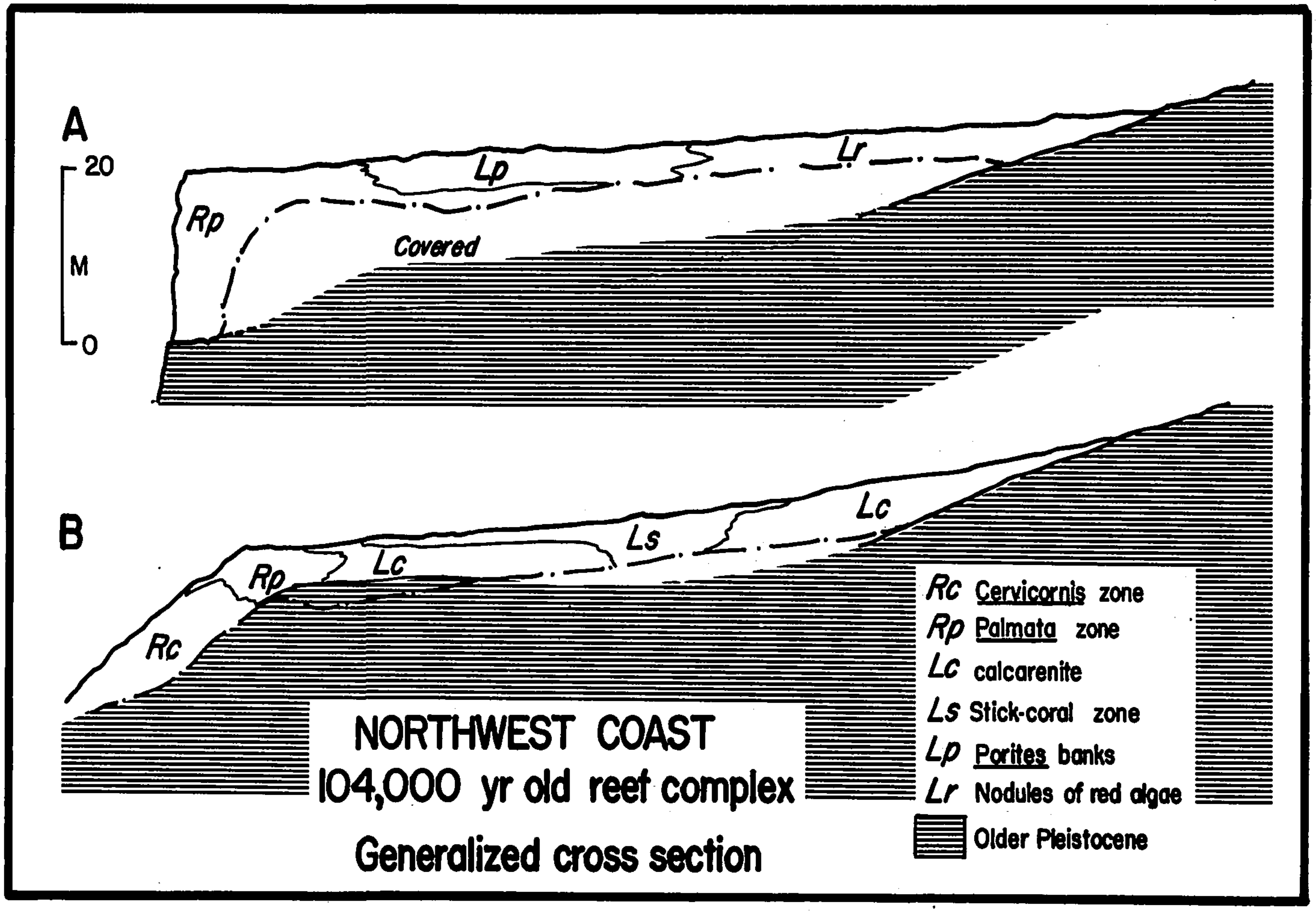

Figure 16. Generalized cross-sections of 104,000 year old reef complex, northwest coast, Barbados. Position of sections illustrated in Figure 15.

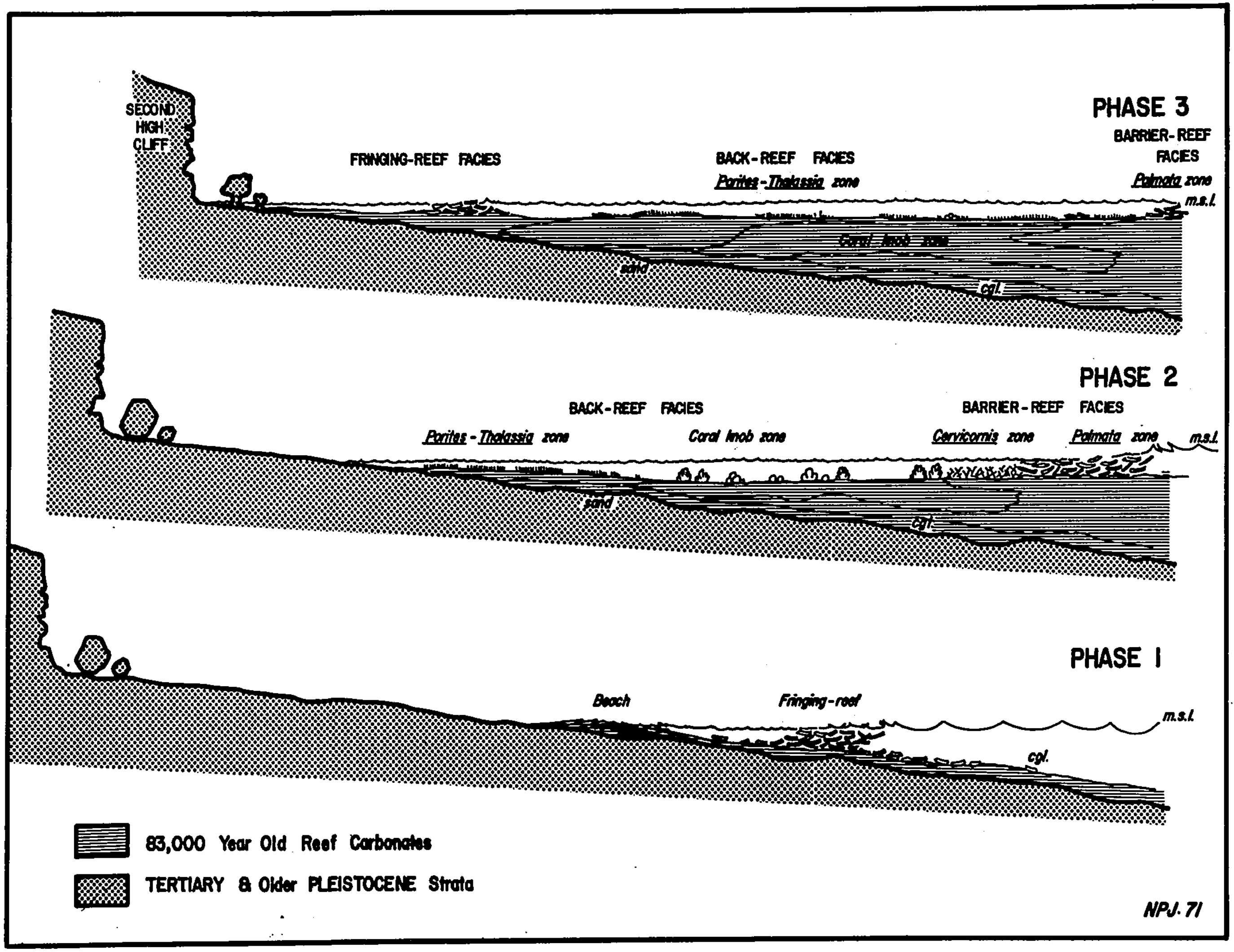

Figure 17. Inferred development of facies geometry during various phases of reef growth as sea level rose and transgressed over older strata along the northeast coast of Barbados, about 83,000 years ago.

of the reef facies (Fig. 15, 16). Many *A. cervicornis* sticks (Plate 32D) are individually coated with a thin rind of red algae. Between sticks, the matrix is, for the most part, a calcarenite with up to 30 per cent carbonate mud. The bimodal calcarenite contains a coarse mode (1.5 to 0.5 mm) of unabraided, articulated, coralline algae (Amphiroa; Plate 10A) and mollusc fragments with a fine mode (0.3 to 0.2 mm) dominated by coral fragments (Plate 10B). Calcilutite, when present, is usually silt sized fragments of red algae, foraminifera, and corals in a micrite matrix.

(b) *Palmata* zone - This reef crest accumulation is well exposed in outcrop and directly overlies a pre-existing *cervicornis* zone of the underlying reef. The base of the *palmata* zone, best exposed near Harrison Point, consists of separated fronds of *Acropora palmata*, encased in a cross-bedded, terrigenous sand. The size and packing of coral fronds increases upwards until the top of the zone is an accumulation of tightly packed corals with much less matrix than at the base. The increasing density of corals upwards appears to reflect a relative increase in *A. palmata* growth as the reef developed.

Terrigenous sand, most common at the base of the *palmata* zone, is derived from Scotland Formation beds exposed nearby. Sediment between the coral fronds becomes finer and more calcareous upwards. The limestone matrix is characteristically bimodal, composed of whole, unabraided skeletons of *Homotrema*, *Amphiroa*, and molluscs (up to 30 per cent) in a fine sand to mud sized matrix (Plate 7). The finer mode is dominantly very fine sand to silt sized grains of degraded skeletons of the above, as well as echinoid fragments and planktonic foraminifera in a matrix of 3 to 6 micra micrite. Occasional calcarenite lenses are composed of *Homotrema* and blockly coral fragments with scattered, round to ovoid (0.14 to 0.6 mm in diameter) pellets, composed of micrite and calcisiltite.

Back-reef facies.--(a) Near-reef zone - Directly behind the palmata zone of the reef facies is a narrow deposit of overturned, Diploria and Montastrea annularis heads with pockets of Acropora palmata, Porites astreoides and Porites porites. These corals are surrounded by a medium grained calcarenite made up of coral and mollusc fragments and large pelecypod valves.

This coral-rich deposit grades landward (east) into a brown, fine grained calcarenite that is alternately well laminated or bioturbated (Plate 16A). In this calcarenite are scattered, overturned, coral heads along with large, pelecypod shells. Large fragments of Amphiroa and Homotrema reflect the proximity of this calcarenite to the reef facies (Plate 15F). Most of the grains are detrital quartz, crustose red algae, and coral (Plate 15E, 17A).

(b) Stick-coral zone - This zone forms the central part of the back-reef facies and is the most widespread back-reef lithology (Fig. 15) south of Speightstown. In places, this zone onlaps westward over the near-reef zone.

The stick corals, Acropora cervicornis and Porites porites, are accompanied by scattered, small Siderastrea and Montastrea annularis in the "hat-like" growth form. Coral sticks are commonly encrusted with other corals such as Porites astreoides. Strombus and large bivalves are intensely bored by the sponge, Cliona. The matrix varies in composition from a mottled calcilutite with accessory silt sized skeletal fragments (Plate 17B) to a calcarenite similar in composition to calcarenites just behind the reef facies.

(c) Nearshore calcarenite zone - The landward side of the back-reef is characterized by calcarenites. Fine grained, nearshore calcarenite contains up to 40 per cent small, whole, planispirally coiled foraminifera of several different species (Plate 17C, 17D). Most of the remaining grains are crustose red algae, often in well-rounded grains, and detrital quartz. These calcarenites grade eastward into, and are interbedded with, cross-laminated, medium to coarse, well sorted, well rounded calcarenites (Plate 16D).

These cross-laminated calcarenites are the easternmost, and topographically highest, deposits of the complex, and they dip seaward (west) at about 10 degrees. They also overlie the weathered surface of an older reef complex (Plate 17C). These calcarenites are dominated by crustose red algae fragments and whole and broken Amphistegina foraminifera, and are characterized by numerous large intraclasts, generally of mud and algae or mud and Homotrema (Plate 17E, 17F). The geometry, stratigraphy, and composition of these calcarenites are similar to those of modern beach calcarenites.

(d) Porites-bank zone - North of Maycock's Bay, the back-reef facies changes to a series of Porites porites banks (Plate 16E) that grade eastward to a rhodolite zone. P. porites mounds are generally 0.9 to 1.2 meters (3 to 4 feet) high, up to 4.7 meters (15 feet) long, and have accreted one on top of another to yield a deposit over 3.7 meters (12 feet) thick. The matrix between these corals is terrigenous sand.

(e) Rhodolite zone - Over half of the rhodolite zone consists of algal nodules, averaging 10 centimeters in diameter, and thin crustose algal plates in a calcarenite. Rhodolites are mainly Lithothamnion, Archeolithothamnion, minor Lithoporella, red algae, the encrusting foraminifer Homotrema, and Gypsina surrounding a nucleus of coral, mollusc or other red algae (Plate 10E, 10F). The irregular algal plates were bored and the holes subsequently filled with mud. The calcarenite matrix is mainly smaller, algal nodules and calcarenite, whose allochems are red algae, occassional Halimeda, Amphistegina, and Gypsina plana with accessory mollusc fragments, quartz, Homotrema and planktonic foraminifera.

DISCUSSION

Reef Growth

83,000 year old reef complex.--Extensive erosion along the northeast coast has cut deeply into this reef complex and underlying strata. The variation in facies geometry and sediment composition illustrates the establishment and development of this reef complex during one major transgression of the sea, about 83,000 years ago. On the basis of facies variation, three phases of sedimentation can be discerned--(1) deposition of sands and conglomerates and widespread growth of *Acropora palmata* and *Montastrea annularis*; (2) development of a reef in which reef and back-reef facies are discernable; and (3) growth of a narrow, fringing-reef (Fig. 17).

The complex thickens eastward and is wedge-shaped in cross-section (Fig. 14), suggesting that, as sea level rose, it transgressed onto an eastward-sloping surface. Erosion during this transgression appears to have removed the Plio-Pleistocene limestone and created local topographic relief of 2.5 meters or more in the soft marls of the Oceanic Formation. The thin, basal blanket of sands and local conglomerates derived from Tertiary and older Pleistocene sediments represents deposition during initial encroachment of the sea onto this sloping surface.

A relatively thin (1 to 6 meters), laterally continuous, deposit of *Acropora palmata* and accessory *Montastrea annularis* overlies the conglomerates and calcarenites in the eastern part of the area (Fig. 32). The upper surface of the coral-rich lithology is irregular, with corals heaped into mounds 2.0 to 2.2 meters high. This distribution of *A. palmata*, over a relatively wide area at the base of the 83,000 year old reef complex, is in contrast to the position of *A. palmata* as a narrow zone in the reef facies of most Pleistocene reefs on Barbados (Mesolella, 1967). A. palmata, characteristic of the modern reef crest zone (Goreau, 1959; Stoddart, 1969), rarely grows in water deeper than 9 meters and is most prolific in depths of 5 meters or less. The widespread, Pleistocene, 83,000 year old deposit may represent A. palmata growth in shallow water during the initial stages of marine transgression over the sloping land surface. As sea level rose and the shoreline moved westward, the zone of prolific A. palmata growth, limited to shallow water, also moved westward, creating a relatively thin, laterally continuous, slightly diachronous deposit.

The barrier-reef facies of the next phase appears to have been localized at the eastern, or seaward, edge of the A. palmata deposit described above.

The reef facies is a thick (up to 10 meters) wall of A. palmata, built up during a slowly rising sea level. This is in no sense a narrow reef facies of some ancient reefs (Stanton, 1967) and also many of the leeward Barbados Pleistocene reefs (Mesolella, 1968), but is a massive accumulation of one dominant coral species.

While the massive, A. palmata reef, with its accessory Acropora cervicornis and M. annularis, developed without interruption on the A. palmata and M. annularis rubble, or pavement, of the basal unit, the upper surface of the pavement, at the base of the coral-knob zone, is coated with crustose red algae, indicating a period of non-deposition.

The initial back-reef facies, scattered heads of M. annularis and Diploria in calcarenite, appears to represent an open lagoon. This coral-knob zone grades landward into a nearshore, terrigenous sand zone with few corals. The supply of sand from the Scotland Formation was cut off soon after establishment of the coral-knob-terrigenous sand zonation. The terrigenous sand zone was replaced by a calcarenite rich in Porites

porites which appears to represent a very shallow water, Porites-Thalassia community. A very shallow water environment is also reflected by the shape of the encrusting, "hat-shaped" M. annularis in that part of the coral-knob zone adjacent to the Porites-Thalassia zone. The relatively thick, 4.6 meters (15 feet), nature of the Porites-Thalassia zone suggests deposition kept pace with a slowly rising sea level. The transgression of the shallow water, Porites-Thalassia zone, eastward over the adjacent coral-knob zone and finally over part of the barrier-reef facies (Fig. 17), may reflect a stillstand at the highest point of sea level rise during the 83,000 years B.P. transgression.

Porites sticks were subjected to more wave action during this last phase of deposition and sorted into beds alternating with lenses of shells. Porites sticks and accompanying larger, skeletal remains were also washed into surge channels running across the A. palmata, barrier-reef, and in these channels were coated with red algae to form rhodolites.

During this last phase of reef growth, a series of narrow, A. palmata, fringing-reefs, with a narrow back-reef, grew more or less parallel to the trend of the reef complex, but some 0.8 kilometers (1/2 mile) behind the barrier-reef (Fig. 14). Growth of this second, much smaller, A. palmata reef may be related to minor fluctuations of sea level during the final stages of the high stand. This reef may represent a short rise of sea level, and deepening of water, which enabled A. palmata to grow and form a series of small reefs west of the main, drowned, barrier-reef facies. The discovery of two separate palmata zones in the 83,000 year old reef complex points up the danger of assigning a separate interglacial high stand to every occurrence of A. palmata.

104,000 year old reef complex.--Most exposures of this reef complex are either shallow, road outcrops, mainly exhibiting back-reef sediments, or sections down the face of the First High Cliff, exposing sediments of the reef facies. There is not enough vertical exposure to permit division of the complex into separate phases of growth. The shallow, back-reef outcrops do, however, indicate a marked lateral variability. Crustose red algae and rhodolite sediments, in the northern part of the complex, grade south into calcarenites (Fig. 15). The centre of the back-reef further south is rich in delicate stick-corals and fine grained calcisiltites and calcilutites. The change from rhodolites to calcarenites occurs opposite the area where the Second High Cliff swings abruptly eastward. The back-reef sediments in the lee of the Second High Cliff may have been protected from the Atlantic waves that come from the east. Fine to medium calcarenites and delicate stick corals developed in this quieter, leeward environment. Sediments on the open, North Point Shelf were subject to much more turbulent conditions, especially condusive to the growth of crustose red algae. A similar zone of turbulent sedimentation has been described from the lee of a modern windward reef by Rigby and McIntire (1966, p. 29). Red algal nodules formed on the shallow (3 meters or less) flats behind the reef are kept in constant motion by the strong waves that continuously sweep across the reef flat. Similar conditions can reasonably be inferred to have existed on the North Point Shelf about 104,000 years ago.

During the final stages of reef growth, the shallow, lagoonal facies transgressed seaward as in the younger 83,000 year old complex. The *Acropora cervicornis*, lagoonal, stick-coral zone migrated westward over the adjacent back-reef calcarenites. The *palmata* zone also transgressed westward slightly over the adjacent, seaward, *cervicornis* zone.

Sediments

One hundred twenty thin sections were examined to determine the composition of sediments from the various facies and zones. Sandstones (sediments containing over 50 per cent terrigenous grains) are excluded from the following discussion. Sediments contain all the major skeletal allochems recognized in modern reefs, except the green alga Halimeda which is rare (Mesolella and others, 1970).

Reef sediment.--Sediment between large corals of the reef facies is dominated by fine material, mainly calcilutite and calcisiltite, with occasional pockets and lenses of calcarenite, as noted by other investigators of reef deposits (especially Newell, 1955).

Although fine grained, the sediment is characterized by up to 30 per cent whole or initially fractured skeletons of the articulated coralline alga Amphiroa, the encrusting foraminifer Homotrema rubrum, and miscellaneous large, pelecypod fragments. Both Amphiroa and H. rubrum are common organisms that live on and between large corals in a reef, and so are produced in situ. This strongly bimodal sediment, with its characteristic coarse mode, is easily distinguishable from lagoonal muds.

The grinding together of fronds under surf action causes the delicate, raised polyps of Acropora species to be broken off and produces grains about 0.25 mm in diameter (Folk and Robles, 1964). Calcarenites associated with the reef facies reflect this breakdown as they are almost exclusively coral grit with an average grain size of 0.25 mm.

Sediment between Acropora cervicornis sticks is essentially the same but contains sandier interbeds and the coarse mode is dominated by Amphiroa with little Homotrema.

The articulated coralline alga Amphiroa and the foraminifer Homotrema secrete skeletons of Mg-calcite, while corals and many molluscs precipitate an aragonite skeleton. In the subaerial, diagenetic environment, Mg-calcite skeletons generally alter to calcite relatively rapidly, while aragonite skeletons equilibrate more slowly, often losing many of their original skeletal structures (see Chapter 4 - Introduction). Fine grained, calcareous sediments also appear to equilibrate relatively rapidly in the subaerial, diagenetic environment (Matthews, 1968). Consequently, the chances are good that the skeletal structure of Amphiroa and Homotrema will be preserved during inversion to calcite in the subaerial, diagenetic environment, and survive to be useful indicators of the reef facies.

Back-reef sediment.--In the 104,000 year old reef complex, the calcarenites reflect proximity to the reef, or to the shoreline. Grain size is coarse, both directly behind the reef, and in beach sands, and progressively finer towards the centre of the back-reef. Calcarenites on the reef side of the lagoon are dominated by reef-derived components. Coral is ubiquitous, but Homotrema and Amphiroa decrease in abundance towards the shore so that the fine calcarenites at the centre of the back-reef are mainly mollusc, crustose red algae, and coral fragments. Reef-derived material is not represented in calcarenites near the shore. These calcarenites are composed of small, coiled foraminifera and crustose red algae. Beach calcarenites contain characteristically well-rounded, abraided grains of crustose red algae, Amphistegina, and numerous intraclasts.

Whereas the type of calcarenite grains is easily identified in the well-laminated, back-reef sediments of the 104,000 year old reef complex, mottled sediments in the back-reef environment of the 83,000 year old reef complex were unrecognizable, due to micritization. Most are fine to medium grain sized peloids (McKee and Gutschick, 1969) and these may be formed either by fecal agglutination or micritization of skeletal debris (Swinchatt, 1965; Kendall and Skipwith, 1969; Windland, 1969). The remnant reticulate structure of crustose red algae in many peloid grains suggests that they are degraded skeletal material, rather than fecal pellets.

Mixed terrigenous sand-carbonate sediment.--The relatively large amount of terrigenous sand present as sediment is one of the most interesting features of late Pleistocene reefs of northern Barbados. Mixed carbonate-terrigenous facies are relatively uncommon in recent reef complexes. On the Great Barrier Reef, although the dispersal of terrigenous components is dependent on several factors, the amount of insoluble sediment between reefs is mainly dependent upon proximity to source (Maxwell and Swinchatt, 1970). This is true for northern Barbados, as well, where this sediment reflects the proximity of these reef complexes to a source of sand, the Scotland Formation beds outcropping on the St. Lucy Arch. The amount of sand is relatively low in the upper parts of the 83,000 year old reef complex, but in the 104,000 year old reef complex, sand contribution is significant throughout.

The contribution of terrigenous material to these complexes is substantial, being at least equal to, if not greater than, both coral and *in situ* carbonate production in the lower part of the complex. As a result, the facies distribution might have been quite different, had this sand not been available for resedimentation. The reef complex would certainly not have been as laterally extensive.

CHAPTER 4 - LIMESTONE DIAGENESIS

INTRODUCTION

In recent years, modern environments of carbonate deposition have been given increased attention, in a search for greater insight into the conditions under which ancient limestones were formed. Along with these investigations, an understanding has developed of the great importance of the numerous and varied changes that carbonate sediments undergo soon after deposition. The fabrics and textures generated during early diagenesis often remain unaltered over most of geologic time. The most important of these early changes is the equilibration of carbonate minerals formed in sea water with other fluids at, or near, the earth's surface. Carbonate minerals aragonite and Mg-calcite precipitated in contact with sea water generally equilibrate by changing to calcite.

Carbonate deposits forming today on the sea floor, composed of organically and inorganically derived constituents, are produced by many different organisms and processes, in one of three mineral phases--calcite, Mg-calcite (containing over 4 mole per cent $MgCO_3$), or aragonite. Each constituent, due to its own unique structure and mineralogy, reaches equilibrium with new surrounding conditions in a slightly different manner. These inherent differences result, in part, in the varied states of fossil preservation, replacement textures, and porosity modification, observed in ancient limestones. In an effort to discern with more precision the ways in which diagenesis takes place, relatively young (Pleistocene) limestones, made up of the same constituents as modern carbonate deposits, are being studied in greater detail.

To place these changes in meaningful perspective, Purdy (1968) has introduced the concept of "diagenetic environments". He establishes three different areas in which these alterations occur--(1) subsea, soon after deposition, (2) subaerial, upon exposure to fresh water, and (3) subsurface, or after deep burial. By documenting the diagenetic alterations presently taking place in each of these environments, some of the resultant textures, diagnostic of a specific environment, may be distinguished in ancient rocks.

Sediments in modern, carbonate environments may undergo mineralogic (Schroeder, 1969; Windland, 1969) and textural (Purdy, 1968) changes on the sea floor prior to burial, or be covered without alteration. Once buried, these sediments either remain as loose uncemented particles or become quickly lithified into true limestone (Taft and others, 1968; Shinn, 1969; Taylor and Illing, 1969). Although observed in modern deposits, some of these changes have only recently been discerned in ancient limestones (Purser, 1969; Schmidt, 1969). Recognition of submarine alteration and lithification in ancient limestone sequences has resulted in a re-evaluation of the geologic history of some carbonate successions (Rose, 1970). The uplifted Pleistocene reef limestones on northern Barbados display textures that are similar to those described from synsedimentary, cemented carbonate in modern, coral reefs. Synsedimentary, submarine lithification appears to be important in determining the subsequent diagenetic history of such sediments.

To date, most investigations of limestone diagenesis have been concentrated on those changes that take place when marine deposits are subjected to subaerial, fresh water fluids, on the assumption that it is here that many of the changes occur and that most of the subsequently preserved textures are created. The majority of these studies have been conducted on rocks altered in the upper "vadose" portion of the subaerial, diagenetic environment, but investigations have recently begun in the less accessible, "phreatic" portion of this environment (Land, 1970a). The most notable studies on vadose subaerial diagenesis (Friedman, 1964; Land, 1967; Matthews, 1968, 1969) have concentrated on calcarenites, as this grain size contains the greatest variety of constituents and is most easily studied. From these and other studies (Purdy, 1968; papers in Bricker, 1971) a general scheme of alteration has emerged.

About two-thirds of the calcium carbonate precipitated in the ocean is aragonite. The rest is Mg-calcite; calcite is rare. The first two minerals are unstable with respect to most subaerial fluids and equilibrate to the relatively stable form, calcite. Observations indicate that the microstructure of most Mg-calcite skeletal grains is little affected by this change, suggesting that the ionic exchange is in the form of exsolution (Land, 1967). The alteration of aragonite, on the other hand, as it involves a structural change from orthorhombic to hexagonal systems, may lead to destruction of the original, skeletal texture and preservation of only the external form (Bathurst, 1966; Windland, 1968).

The most stable mineral phases with respect to sea water are aragonite and Mg-calcite (averaging approximately 10 mole per cent $MgCO_3$; Windland, 1969). The solubility of Mg-calcite increases with increasing $MgCO_3$ content so that a Mg-calcite with 7 mole per cent $MgCO_3$ has the same solubility as aragonite. Mg-calcites containing approximately 16 mole per cent $MgCO_3$ are about twice as soluble as aragonite and four times as soluble as calcite with respect to fresh water (Chave and others, 1962). Under ideal conditions, Mg-calcite constituents with 7 mole per cent $MgCO_3$ or greater will, therefore, equilibrate more rapidly than those of aragonite. This is confirmed from studies of late Pleistocene limestones in the vadose, diagenetic environment. While aragonite is still in the process of alteration, most Mg-calcite grains have completed equilibration to calcite. Thus the mineral phase, and hence the particles made up of the minerals, react at varying rates when in contact with fresh water, yielding contrasting end products.

While most studies have been carried out on calcarenites, the other two main components, mud and large skeletal constituents, have not received as much attention. Fine calcareous sediment, possibly because of its inherent mineralogy and fine grain size which--(1) is more reactive and (2) provides a greater number of nucleation sights per unit area than calcarenites, appears to equilibrate more rapidly than the coarser sediment (Chave and others, 1962; Matthews, 1968).

Large, skeletal constituents, mainly molluscs (calcite and aragonite) and corals (aragonite), are extremely important not only as major contributors to the reef but also as indicators of ancient environments and chronology. The processes of alteration that lead to the preservation of the mollusc skeleton have been documented, in a general way, by Bathurst (1964). The myriad of coral textures was long ago superbly outlined by Cullis (1904). Since then, there has been little attempt (except Land, 1967) to ascertain how the structural alteration of aragonite to calcite takes place in corals while, at the same time, preserving the delicate microstructure more or less intact. Consequently, some of the corals within the late Pleistocene limestones under study were investigated in an attempt to ascertain the ways in which these changes take place. Hopefully, some of the fabrics seen in the preserved skeletons of more ancient forms could, as a result of this study, be illucidated more clearly.

As our knowledge of these early diagenetic changes increases, it appears that in each diagenetic environment a separate series of alterations takes place. We do not yet have the background of petrographic information needed to identify these different environments with precision from textures alone. Any other information, therefore, that will give us clues as to the early diagenetic history of the rock, is invaluable.

On the presently exposed surface of many uplifted, Pleistocene limestones, a series of hard, calcareous crusts is developed, below which is a secondary zone of alteration. Although these crusts have been reported from many areas (Multer and Hoffmeister, 1968), their petrographic characteristics are unknown. In order to establish useful criteria for recognition of these diagenetic crusts, and to differentiate them from other similar features, subaerial crusts from Barbados were investigated and compared to similar crusts from other areas. These crusts were then compared to fossil examples to see how these features altered during diagenesis, and what textures would be preserved in the fossil record.

MINERALOGY OF PLEISTOCENE LIMESTONES IN THE VADOSE ZONE

The degree to which any Pleistocene carbonate has equilibrated with surrounding vadose fluids is reflected by the amount of change in its original mineralogy. On Barbados, in the subaerial diagenetic environment, the degree of equilibration appears dependent upon two factors--(1) age of the limestone, and (2) climate (Matthews, 1968). While most carbonate on the island has altered to calcite, portions of the younger, Pleistocene reef complexes often contain appreciable amounts of aragonite and sometimes Mg-calcite. Young, Pleistocene limestones in areas of relatively high rainfall have a greater proportion of calcite than limestones of the same age in relatively dry areas.

Northern Barbados contains limestones of all ages and is an area of relatively low rainfall (145 centimeters/year or less) and high evaporation. The only limestones that still contain any unstable carbonate minerals are associated with the late Pleistocene (104,000 years B.P. and younger) reef complexes; minerals in all others have completely equilibrated to calcite (Appendix C). Constituent particles in calcarenites and calcilutites from the 104,000 year old reef complex are mainly calcite with only scattered grains of coral retaining their aragonite mineralogy. The mineralogy of large, coral colonies in the reef complex is less consistent. Although numerous corals are still aragonite and many have completely altered to calcite; the majority are in a transitional stage, partly aragonite and partly calcite. The number of calcite corals increases southward towards areas of higher rainfall (over 150 centimeters/year) and relatively low evaporation.

Sediments deposited about 83,000 years ago, along the northeast coast, have partially equilibrated with subaerial fluids. Most Mg-calcite have altered to calcite. Aragonite constituents have either remained unchanged, completely dissolved, or are in the initial stages of alteration to calcite. The majority of the corals in this complex are still aragonite but many illustrate the initial stages of solution and calcite precipitation.

In the 60,000 year old, fringing-reef terrace, along the northwest coast, all the corals are still aragonite, and sediments, for the most part, are made up of their original sedimentary mineralogy.

SUBMARINE LITHIFICATION

Most of the sediment matrix between corals in the 83,000 year old reef complex is either unlithified or poorly cemented. In the reef facies, however, sediment between *Acropora cervicornis* sticks, and beneath *Acropora palmata* fronds, is occasionally very well lithified. The mode of occurrence, and petrographic texture, of this well lithified sediment (discussed below) is similar to syn-sedimentary, lithified, modern reef carbonate, suggesting that the Pleistocene sediment was prelithified in the submarine environment.

Cervicornis Zone

The long, slender coral sticks in the cervicornis zone are often superbly preserved, still retaining their delicate surface polyps. In some areas, numerous sticks are surrounded by a uniform brown or grey, very fine grained, well lithified matrix in the form of a crust, up to 3.5 centimeters thick, with a lumpy exterior (Plate 18B). These well lithified crusts contrast sharply with surrounding crumbly, mottled calcilutite or poorly lithified calcarenite.

Most of the crusts occur near the base of the section, and contain up to 1/3 silt sized quartz grains, which gives them a grey colour. Crusts found near the top of the section, with less than 10 per cent accessory, silt sized, quartz grains, are buff-brown in colour. Although X-ray diffraction indicates that the majority of these crusts are calcite, some of the buff-brown crusts are Mg-calcite.

Mg-calcite crusts.--In cut section, the crusts are composed of highly irregular laminae (2 to 3 centimeters thick) (Plate 18D) which are the expression of alternating areas of densely packed and widely spaced pellets. Individual pellets range in size from 9 to 60 micra (Plate 19C), are ovoid to round in shape, and are composed of micrite less than 1.5 micra in size. Areas of close and widely spaced pellets are separated by sharp boundaries. Each pellet is surrounded by a fringe of spar from 2 to 6 micra thick, which cements the rock tightly. The crystals in this fringe are very irregular, but dentate, Mg-calcite scalenohedra can occasionally be discerned growing normal to the pellet wall (Plate 19D). This cement is easily discernable in the wider spaced pellets, but in the areas of merged pellets it is hard to differentiate from the pellets. On the electron microprobe, both pellets and cement contain 11 to 16 mole per cent $MgCO_3$. Because cements precipitated in the vadose zone are generally calcite and the surrounding sediment is unlithified, these crusts, therefore, probably were cemented prior to uplift into the subaerial environment.

Modern analogues.--Submarine lithification is currently being recorded from the reef facies of several modern reefs (Macintyre and others, 1968; Land and Goreau, 1970; Ginsburg and others, 1967, 1971b). Of particular interest is the massive cementation of the *cervicornis* zone in vigorously growing reefs off the north coast of Jamaica (Land and Goreau, 1970). Investigations by the author indicate that the form of submarine cementation in northern Jamaica is strikingly similar to that in the Pleistocene of Barbados.

Acropora cervicornis sticks (Plate 18A), coated by lithified, Mg-calcite-rich, pelleted micrite, are common in the Jamaican reefs. The pellets are platy Mg-calcite (Plate 19A, 19B), similar to the surrounding scalenohedral Mg-calcite cement, which contains about 18 mole per cent $MgCO_3$ (Land and Goreau, 1970). This laminated to massive pelsparite displays a smooth to knobbly, outer surface.

Petrographic comparison between a section cut from the sample (Plate 18A) figured in Land and Goreau (1970, Fig. 5, p. 460), and the buff-brown, Mg-calcite, Pleistocene samples from Barbados, indicates similar size, composition, and arrangement of pellets, as well as similar cement characteristics (Plate 19A, 19B, 19C, 19D). It appears, then, that these Mg-calcite, Pleistocene crusts, surrounding *A. cervicornis* in the 83,000 year old reef complex, are the manifestation of submarine lithification.

Calcite crusts.--The more common calcite crusts display the same laminated texture, and are also pelsparites (Plate 19E). Upon initial examination, the calcite crusts appear petrographically identical to the

Mg-calcite crusts. The crystal size of the pellets is, however, slightly larger, up to 5 micra in size. Cement between pellets is approximately the same size, averaging 3 to 8 micra. Overlap in crystal size between pellets and cement makes it difficult to pick out the boundary between the two. Cement crystals are again just one layer thick, but more equant than the Mg-calcite forms. The centre of most small voids is occupied by relatively large (up to 60 micra), calcite crystals.

The similarity between the position, form, and texture of Holocene and Pleistocene Mg-calcite, pelsparite crusts, and the Pleistocene calcite crusts described above, suggests that the calcite crusts may have been lithified by Mg-calcite in the submarine environment. Subsequent uplift and exposure to subaerial, vadose fluids has altered most of the original Mg-calcite to calcite. Equilibration is, however, not complete in this relatively young (83,000 year old) reef complex, and so some crusts still retain their original, Mg-calcite mineralogy.

Palmata zone

Acropora palmata fronds in the 83,000 year old reef complex, at Jordan's Cowpen along Barbados' northern coast, although surrounded by poorly lithified calcarenite, are directly underlain by a well-cemented, calcilutite layer (Plate 18E, 18F) which, depending upon the size of the coral, may be up to 2 centimeters thick. This grey, calcite, pelsparite layer, with a knobbly exterior, is petrographically identical to the calcite pelsparite surrounding *Acropora cervicornis* sticks (Plate 19F) in other parts of the reef. Like the calcite crusts associated with *A. cervicornis*, the crusts below *A. palmata* may have been lithified in the submarine environment by Mg-calcite prior to being uplifted into the subaerial, vadose zone, and altered to calcite. The possibility of submarine lithification is enhanced by the fact that borings of the date mussel Lithophaga and eunicid worms penetrate both the pelsparite and the coral. These cavities are now partially filled with carbonate sediment similar to poorly lithified sediment surrounding the corals, suggesting that the pelleted crusts were lithified early, certainly prior to sedimentation between fronds.

Discussion

The accretion of this reef facies along the northeast coast was due not only to coral growth and minor binding by algae and foraminifera, but also, significantly, to syn-sedimentary cementation. Such fabrics are neither seen in the 104,000 year old complex, nor previously reported from the Pleistocene of Barbados.

The origin of the pelleted micrite crusts on Jamaica is not indicated by Land and Goreau (1970), although isotopic data confirms that the cement is precipitated from sea water. In the water-filled cavities of the Jamaican reefs studied to date, the lithified crusts commonly coat the bottoms and sides of the holes, and accrete upwards. The crusts on Barbados, however, have no preferred orientation, and those associated with Acropora palmata coat the undersides of the fronds.

Occurrence of crusts similar to those from Jamaica, in both Acropora cervicornis and Acropora palmata zones in the Pleistocene of Barbados, illustrates that this form of submarine lithification is not restricted to the A. cervicornis and lower reef zones off northern Jamaica, but is widespread both in space and time.

When Mg-calcite grains alter to calcite, in the subaerial, vadose, diagenetic environment, the change is probably one of magnesium exsolution with no discernable void stage (Land, 1967). Consequently, when a Mg-calcite, submarine, lithified carbonate alters to calcite in the vadose zone, it should remain tightly cemented. Well cemented, calcite, pelsparite crusts in the 83,000 year old reef complex, originally cemented in the submarine environment, have since altered to calcite, without appreciable textural change, thus confirming this hypothesis.

The Mg-calcite nature of the crusts assures that the fine textures of the rock, like the fine textures of many Mg-calcite fossils, will be preserved upon inversion to calcite. The major textural change occurring during equilibration is the increase in crystal size of the calcite within the micrite pellets, often rendering discrimination between pellet and cement difficult.

INTERTIDAL AND SUPRATIDAL CARBONATE PRECIPITATION

Introduction

Diagenesis of Barbados Pleistocene calcarenites, now in the vadose zone, has been the subject of several investigations (Matthews, 1967, 1968, 1969; Harris and Matthews, 1968; Windland, 1969). Most studies have, to date, centred on material collected from road cuts, quarries, and occasionally drill holes, in areas flushed only by fresh water. These sediments are cemented exclusively by calcite. There has been little detailed examination of rocks lying in the vadose zone, and yet bathed in sea water instead of fresh water. On northern Barbados, most of the Pleistocene outcrop that faces the open sea is either sprayed or washed with salt water almost continuously.

Pleistocene limestones, now in the intertidal and lower, supratidal zones along the northwest coast, are partially cemented by Mg-calcite. The surface of Pleistocene limestones along the top of the cliffs on the northeast coast is occasionally coated with a thin crust of aragonite cement. Both of these cements appear to be precipitating from sea water, either splashed or sprayed onto the rock.

Northwest coast

The narrow, 60,000 year old, fringing-reef terrace, 0 to 4.5 meters above sea level, along the northwest coast, lies on a bench eroded into older Pleistocene limestones (see Chapter 2). Along most of the terrace, the reef facies has been eroded so that the present, seaward edge is a 60,000 year old calcarenite with scattered coral heads, overlying an older, *Acropora cervicornis*-rich calcarenite. The upper meter of the younger calcarenite exhibits extensive, calcareous, caliche-like crust development which is also being eroded (Fig. 18). Along most of its length, the terrace is either bathed in salt spray or, in some cases, washed by waves during high tide (Plate 20A).

X-ray diffraction analysis of sediments making up the seaward, eroding edge of the exposure indicates Mg-calcite, aragonite, and calcite in variable amounts.

Petrography.--Thin sections were cut from the rocks in this zone to more specifically determine the spatial arrangement of these minerals. Sections were stained with Clayton yellow (specific for magnesium), which imparts a red colour to any Mg-calcite present on the slide (Windland, 1969). On the basis of colouration, the distribution of Mg-calcite, calcite, and aragonite in a thin section could then be determined with relative precision.

(a) The upper 1.5 meters of the *Acropora cervicornis*-rich limestone underlying the 60,000 year old reef terrace is relatively well-lithifed, very fine to medium grained calcarenite, in which *A. cervicornis* sticks have been dissolved and the holes often filled with younger geopetal sedi-

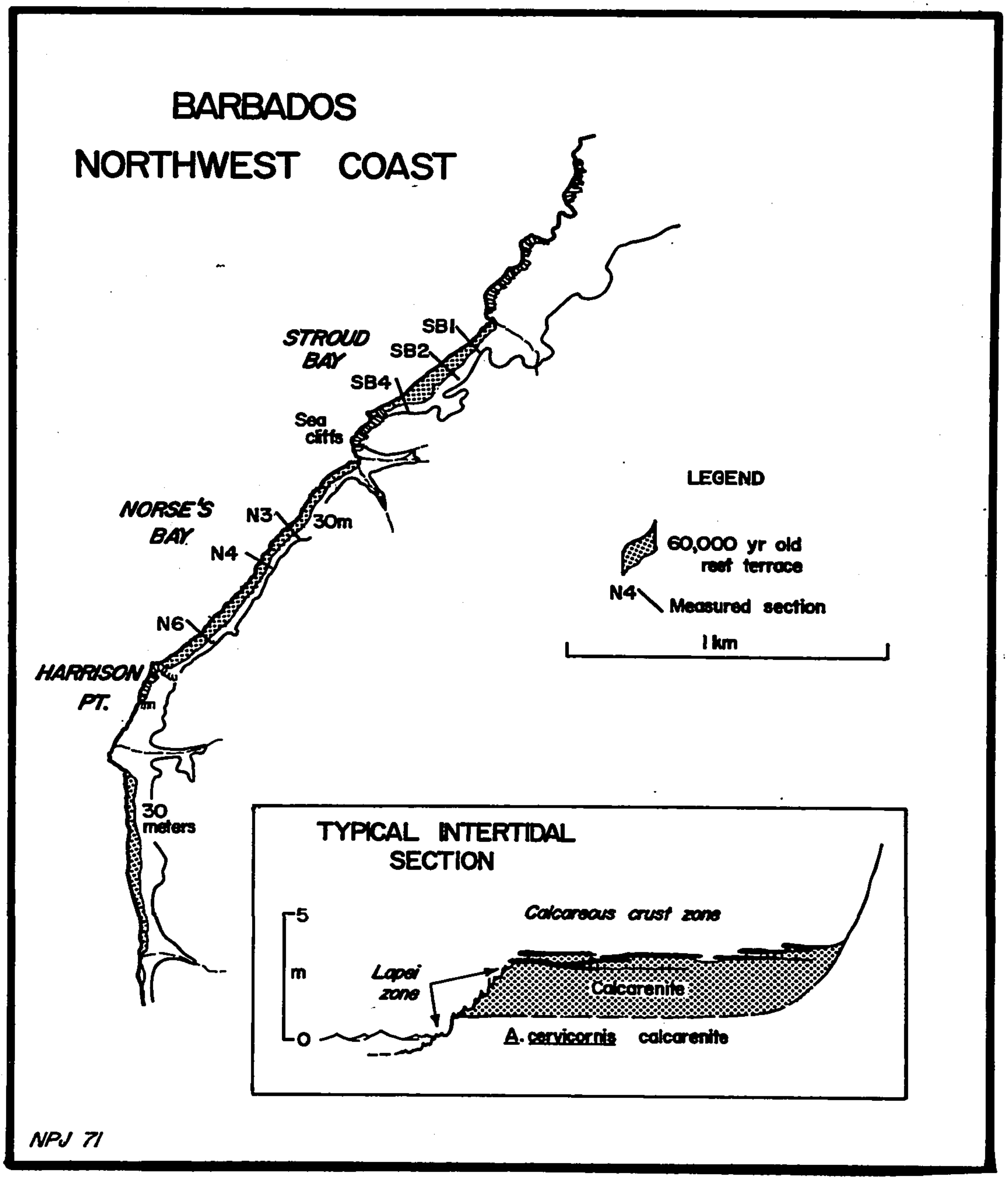

Figure 18. 60,000 years B.P. reef terrace along the northwest coast, Barbados. Intertidal calcarenites in the lapei zone are lithified by Mg-calcite cement.

ment. All the allochems (mainly crustose and articulated red algae, Homotrema, miliolid foraminifera, and minor echinoid fragments) have altered to calcite. There are accessory voids that resemble coral and mollusc fragments.

These grains are cemented by a thin rind of calcite cement which varies in thickness from 15 to 60 micra, but averages 30 micra (Plate 20C). The cement is relatively isopachous, but in some cases fills entire voids. The larger voids are filled with fine sediment which postdates the calcite cement (Plate 20B). As this fine sediment stains pink, much of it may be Mg-calcite. Succeeding the rind of calcite cement is a brown, fine, crystalline cement, averaging 50 micra thick (Plate 20D), which stains bright red, indicating Mg-calcite (Fig. 19). Often the tips of the calcite scalenohedra in the first stage cement also stain bright red.

(b) Grains in the overlying, 60,000 year old calcarenite are coarser (0.5 to 2.0 mm) in size, very well rounded, and well sorted. The sand is mostly (15 to 30 per cent each) articulate red algae (Amphiroa) peneropolid foraminifera, coral, molluscs, and intraclasts with accessory (5 to 30 per cent) Homotrema. Crustose red algae, echinoids, Amphistegina foraminifera, detrital quartz, and reworked calcareous crusts are found in minor amounts. The grains are of varied mineralogy, and the coral and mollusc fragments, although still aragonite, are often bored.

Samples from this unit, taken from just below the calcareous crusts to just above the underlying, older, A. cervicornis sand, illustrate a complex series of diagenetic fabrics. Although grains just below the calcareous crusts are often calcite, coated with a rim of calcite cement up to 100 micra thick, most of the grains retain their original mineralogy, Mg-calcite and aragonite. Occasionally, calcite cement in the upper parts

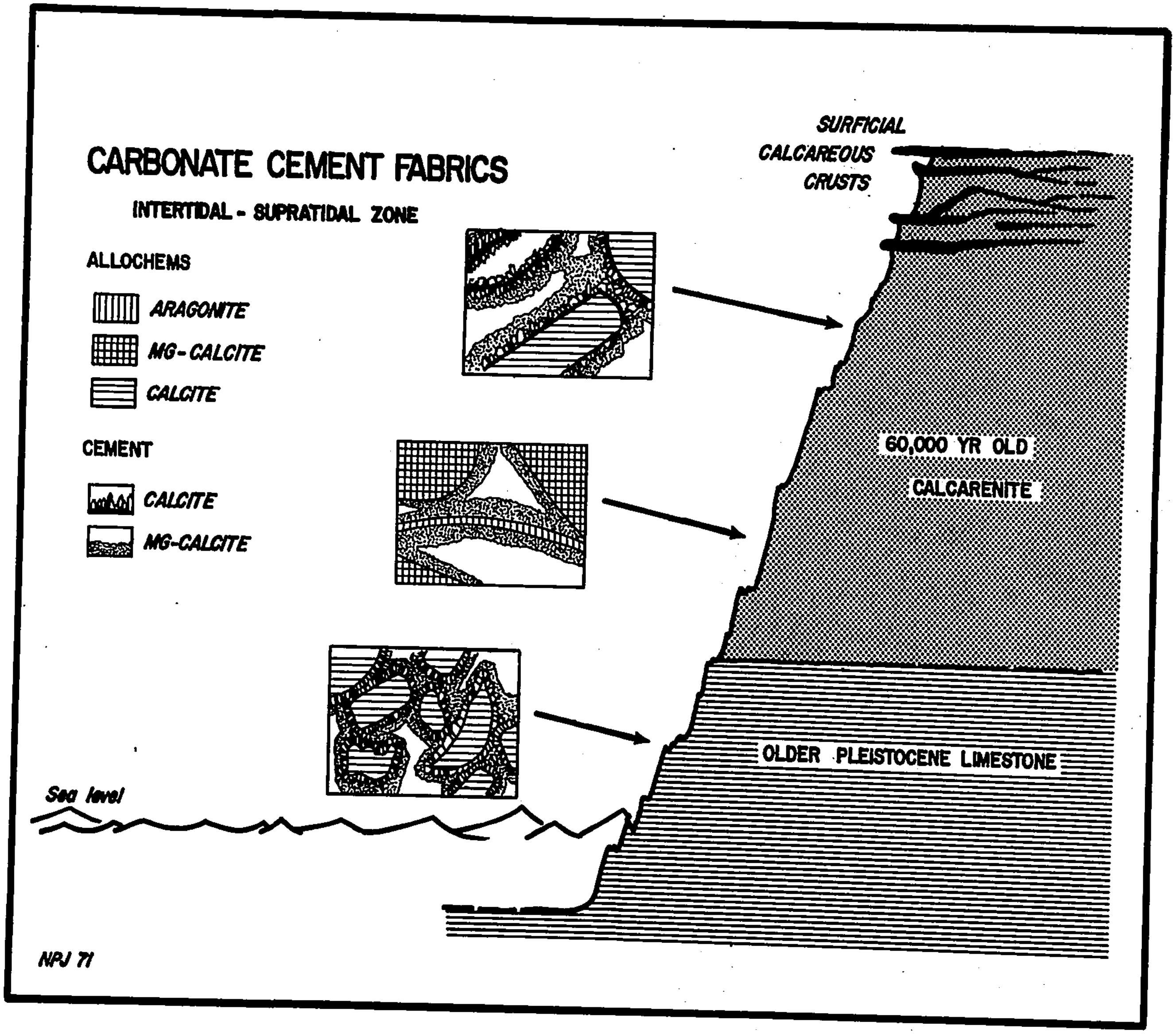

Figure 19. Sketch of cement fabrics in the intertidal-supratidal zone at Norse's Bay, Stroud Bay and Cluff's Bay, Barbados. See Figures 10 and 18 for localities.

of the unit coats Mg-calcite grains; however, the final cement stage throughout most of the deposit is Mg-calcite, precipitated either as fine, crystalline cement following calcite, or directly upon Mg-calcite and aragonite grains, or as epitaxial continuations of pre-existing calcite scalenohedra (Plate 20E, 20F; Fig. 19). At the base of the deposit, Mg-calcite mud is present between grains, and mud and grains are subsequently cemented by a thin, Mg-calcite, cement rind.

The sequence of cements in this unit is often complex. Some coral fragments, for example, are discernable only by their external shape. These coral grains have their original pores filled with calcite, and solution of the skeleton was followed by Mg-calcite precipitation in the resultant void. The resulting texture is a Mg-calcite, coral fragment surrounded by calcite cement.

In the subaerial crusts zone above, voids are often lined with a late stage, Mg-calcite cement.

Discussion.--The last stage of cementation, Mg-calcite, occurs throughout those lithologies directly exposed to sea water, including subaerial caliche crusts. As these porous rocks are today in continual contact with sea water, it is likely that this cement, like submarine, Mg-calcite cement, is precipitated from sea water. The position of these rocks, in the intertidal and supratidal zone, is analagous to the location of many beachrock occurrences throughout the world (Stoddart and Cann, 1965). In beachrock, grains are often cemented together by Mg-calcite (Emery and Cox, 1956; Kaye, 1959; Russell, 1962; Alexandersson, 1969; Gavish and Friedman, 1969; Taylor and Illing, 1969). Grains in beachrock, however, are for the most part Recent or Holocene. Analagous, intertidal, Mg-calcite cementation of already partially lithified, porous rocks, as described above, has not been reported to date.

When correlated with the known geological history of this area since the Sangamon, these textures reflect Pleistocene sea level variations (see Chapter 2). The basal, Acropora cervicornis-rich calcarenites were deposited when sea level stood relatively high, sometime during the Sangamon interglacial, possibly as much as 125,000 years ago. Subsequent lower sea levels, during glacial periods prior to 60,000 years ago, exposed these sediments to subaerial diagenesis. Under conditions of fresh water percolation, unstable sedimentary minerals equilibrated to calcite, and the sediments were partially cemented with calcite. These sediments were buried by a thin cover of reef-associated calcarenites, deposited during a relatively high stand of sea level about 60,000 years ago. After deposition, sea level dropped, and during the following Wisconsin glacial period, these younger sediments were exposed to subaerial diagenesis, under conditions similar to those on northern Barbados today. This time, exposure resulted only in calcite cementation and partial alteration of grains in the upper few feet of the younger calcarenite, and did not affect the rest of the unit. Both of the above units are now being eroded and lie in the intertidal zone, where a last stage, Mg-calcite cement is being precipitated in the pores.

Although this diagenetic environment appears to be a narrow, restricted one, when viewed in the perspective of geologic time, it may be more important. Although transgressing seas are often accompanied by beach sedimentation, this is not always the case. As such a sea slowly transgressed over bedrock, precipitation of Mg-calcite may take place as a last stage, vadose, diagenetic event before complete submersion. Since Mg-calcite is unstable when in contact with fluids other than sea water, the cement will alter when this rock is placed in another diagenetic environment. It may dissolve or, like Mg-calcite allochems in the vadose zone, quickly alter to calcite, resulting in a limestone whose upper surface is very well lithified. In a limestone sequence, such beds would be difficult to distinguish from those lithified in the submarine environment.

Northeast coast

On the surface of 12 to 25 meter high sea cliffs along the northeast coast, surface outcrops and boulders are veneered with patches of a thin, pearly white to grey, smooth coating (Plate 21B). Where boulders or outcrop stand above the generally flat surface, this coating occurs only on the windward side of the rock; the leeward, protected side remains dark brown or black. Coatings, varying in thickness from a few micra to 1.5 mm, are found on fossil coral, well-cemented limestone, and subaerial, calcareous crusts. These coatings occur up to 0.4 kilometers (1/4 mile) inland.

Petrography.--In thin section, the white crusts appear as a series of parallel laminae, averaging 0.04 mm thick (Plate 21C). Each laminae is composed of aragonite needles growing upward, perpendicular to the rock surface (Plate 21D). Laminae may separate stages of needle growth, or be merely fine inclusions through which needles continue to grow. Individual stages of aragonite crystal growth vary from 0.03 to 0.16 mm in thickness. Each stage of crystal growth is initiated by nucleation on a new surface, from which a series of radiating bundles of needles grow. Mutual interference during growth, between all needles except those growing normal to the nucleating surface, results in preferential growth upward.

Discussion.--Large swells from the open ocean, breaking against these cliffs, throw large amounts of spray into the air (Plate 21A).

Easterly trades carry this spray across the North Point Shelf. When the spray is blown onto the surface, it evaporates, and aragonite appears to be precipitated.

The similarity of these aragonite, cement crusts to both beachrock and submarine, aragonite cements (Ginsburg and others, 1971b) is striking. This cement, along northeastern Barbados, has obviously been precipitated from evaporating sea water in the subaerial environment. Aragonite cementation of beachrock, due to periodic wetting of the rock by seawater, followed by drying and evaporation, has long been postulated, but never proven (Stoddart and Cann, 1965). The stable carbonate phase expectedly precipitated from seawater is aragonite (Windland, 1969). This appears to be the first recorded occurrence of aragonite, precipitated by seawater evaporation in the subaerial environment.

SURFICIAL CALCAREOUS CRUSTS

Introduction

Irregular, dark brown bands of dense, micritic limestone are found sporadically distributed along the contact between different reef complexes, in the Pleistocene sequence on northern Barbados. These structures are restricted to the upper meter or so of the buried complex. Surface outcrops in the same area are often coated with a similar, dark brown crust, or series of crusts, while adjacent rock is altered to a white, chalky limestone. These surficial crusts are strikingly similar to those buried in the Pleistocene sequence, and apparently akin to others forming today on the surface of Pleistocene limestones in Florida (Multer and Hoffmeister, 1968). Such similarities suggest that these fossil crusts record subaerial exposure of limestone, under conditions similar to the relatively dry, seim-arid climate of northern Barbados today. If we were able to recognize with certainty similar horizons in ancient carbonates, they would then be an invaluable aid in determining whether or not a limestone succession has been exposed to subaerial diagenesis under a semi-arid, tropical climate.

Surficial zones of calcareous accumulation (caliche), associated somehow with the soil-forming process, are common in many arid to semi-arid areas in lower latitudes. Although their field occurrence has been described in detail from numerous areas, along with their chemistry and theories as to their formation, few, if any, attempts have been made to document their petrographic characteristics and, in turn, relate these to the mode of formation. This is most important because, if they are to be used as criteria for subaerial exposure of sedimentary successions in the fossil record, then their petrographic and stratigraphic characteristics must be known.

Surficial calcareous crusts from three areas on northern Barbados--the central part of the North Point Shelf, the northeast coast, the northwest coast fringing-reef terrace--were examined in detail. To ascertain that the microscopic fabrics observed were common with other areas, similar phenomena from the Florida Keys and the "Nari limecrusts" of the Middle East were also studied. Mineralogy of the crusts was determined by X-ray diffraction, and elemental composition was ascertained semi-quantitatively by electron microprobe. Petrography was done on thin sections impregnated with epoxy resin.

Description

Most limestone outcrops on northern Barbados, whether exposed or below a thin soil cover, are coated with one, or several, hard, brown, calcareous crusts. Limestone under these crusts is altered to chalky carbonate. Together the calcareous crusts and underlying carbonate make up a semicontinuous "calcareous crust profile". This profile rises and falls with the present topography, and is variable in thickness and development. The areal distribution of various calcareous crust profiles on northern Barbados is illustrated in Fig. 20.

The thickest and most extensive development is at the surface of the poorly lithified, 83,000 year old, reef-associated carbonates, along the northeast coast (Plate 1D, 22A). The surface of the calcareous crust profile is a hard, partially brecciated, brown crust (Plate 22B). Below this surficial crust, numerous other crusts, separated by chalky carbonate, are developed (Plate 22C). Although roughly horizontal, these secondary crusts pinch and swell, are undulating in cross-section, and often merge with one another (Plate 22D). Crusts at or near the surface are relatively hard, but those below become more friable and softer with depth. Each crust is relatively uniform, ranging from 0.5 to 5.0 cm in thickness, and either aphanatic or laminated in cross-section. The number of crusts, and the depth to which they occur, increases towards the coast. The crusts, well-lithified compared to the underlying sediment, tend to weather in relief (Plate 22A, 22C).

Sediment between and below these crusts is crumbly, chalky carbonate (Plate 23D). This carbonate may extend to a depth of 3 meters or more, and contains several narrow, poorly developed, brown, calcareous bands. Corals and large molluscs such as Strombus appear more resistant to alteration, and often remain unaltered, except for brecciation, in a groundmass of chalky carbonate. Laminae of numerous small nodules or coated grains occur between crusts in the upper part of the profile (Plate 23A).

In parts of the reef complex, the original limestone is very well-lithified calcilutite. In these areas, the carbonate between crusts is not crumbly, but brecciated, and the cracks between fragments are filled with dark brown, calcareous material (Plate 23B). The profile in these areas is relatively thin, rarely exceeding one meter.

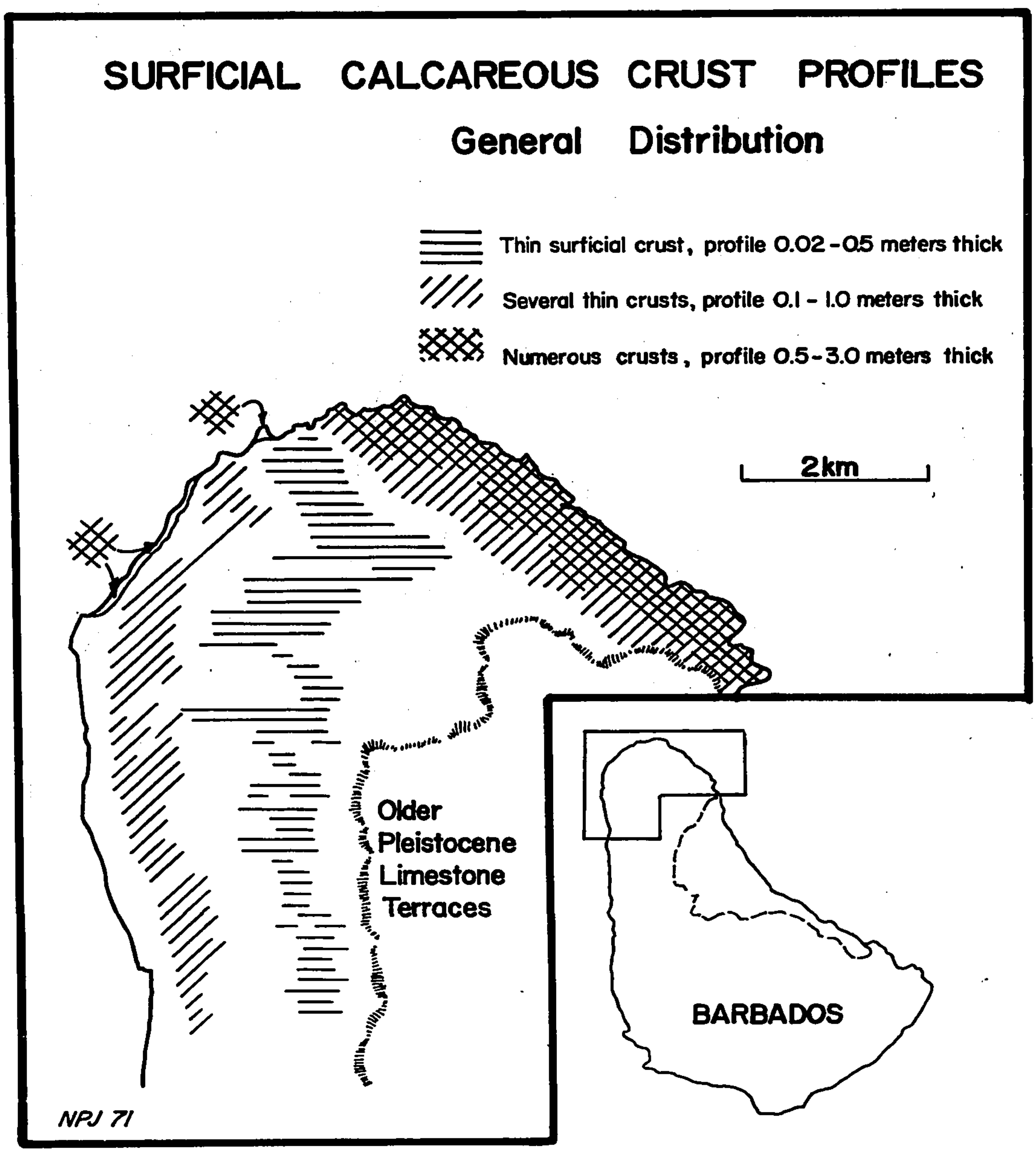

Figure 20. General distribution of surficial calcareous crust profiles on northern Barbados.

A zone of calcareous crusts is also developed on the surface of the 60,000 year old reef terrace, 0 to 4.5 meters above sea level, along the northwest coast (Plate 22E). Here calcareous crusts and altered limestone occupy the upper 0.5 to 1 meter of the unit. Unlike the thick development along the northeast coast, where chalky carbonate grades downward into unaltered calcarenite, the base of the surficial profile is bounded by a single, thin crust averaging 0.5 to 1.0 centimeter in thickness (Plate 23C). Calcarenites below this crust are little altered, except for occasional solution, and still retain their original, unstable mineralogy. The rest of the profile above this basal crust is a series of calcareous crusts in a brown, carbonate matrix. While the crusts exhibit the same geometry as those along the northeast coast, the carbonate matrix between crusts is different. At the base of the profile, the matrix consists of allochems, similar to those in the calcarenite below the bottom crust, but each allochem is coated with brown carbonate. Between these coated grains is a brown, calcilutite matrix. Coated allochems become less important upwards, and the matrix between crusts, at the top of the profile, is a brown calcilutite, either unlithified or very well cemented.

In the back-reef facies at Goulding's Green, next to the base of the cliff, calcareous crusts are also developed throughout the 4.5 meter thick calcarenite, and all the allochems, still Mg-calcite and aragonite, are coated with brown, microcrystalline carbonate (Plate 28A).

In the central part of the North Point Shelf (Fig. 22), a relatively thin profile of alteration is developed, at the surface of the well-lithified, older Pleistocene carbonates (Plate 22F). The upper surface is a thin, hard, brown crust averaging 2 to 20 centimeters thick. Below this crust, the limestone is altered to a chalky carbonate. The relict sediment texture often remains visible, however, as large allochems and corals appear more resistant to alteration. The depth of alteration below the surface rarely exceeds 0.5 meters.

Other Calcareous Crust Profiles

Surficial, calcareous-crust profiles, similar to those on northern Barbados, are common in many arid to semi-arid areas in lower latitudes. In North America, the most extensive of these deposits are found in the southwestern U.S.A. desert area, where they are called "caliche deposits". Aristarain (1970, p. 201) has defined caliche deposit as

> a body resulting from the epigenetic accumulation of calcium carbonate (calcite) in unconsolidated sediments under conditions derived from soil processes in climates where moisture is deficient during all seasons.

Indurated portions of caliche deposits are called "calcrete" (Lamplugh, 1907), while the friable parts are referred to as "caliche" in Texas (Blank and Tynes, 1965) or "chalk" (Nelson, 1959) elsewhere. A special variety of carbonate, that forms by surface or near-surface alteration of permeable carbonate rocks, distinguished by a fine network of veins which surrounds unreplaced remnants of the original rock, is termed "Nari" (Sanders and Friedman, 1967).

Following soil horizon terminology, the caliche profile forms in the Cca horizon which, because of its uniqueness, has been designated as the K-horizon (Gile and others, 1966). Although this is a useful term for soil scientists, in its original definition it is rather restrictive and, therefore, following Reeves (1970), the more general term "caliche deposit", as defined above, will be used.

Reeves (1970) considers that the caliche deposits of the southwestern U.S.A. evolve with time from a simple, thin, incompetent, soil horizon to a hard, massive limestone. "Young" caliche is generally a crumbly, white carbonate enclosing masses of parent material. "Mature" caliche consists of an upper crust and accessory horizontal stringers of carbonate, surrounded by a profusion of small nodules and relatively well-cemented carbonate. "Old" caliche consists of a completely indurated horizon. Such a sequence of "young", "mature", and "old" caliche can only develop if the profile remains covered by soil; once exposed the profile is rapidly lithified.

Caliche profiles developed on northern Barbados appear somewhat similar to the "young" to "mature" caliche stages described above. Unlike the profiles described by Reeves (1970), however, those on Barbados are exposed, and yet are not indurated.

Caliche-like crusts, developed on Pleistocene limestones, have been described along the shoreline and upper, supratidal zone in the Bahamas (Newell and Rigby, 1957; Kornicker, 1958; Supko and others, 1970), Puerto Rico (Kaye, 1959), and Florida (Multer and Hoffmeister, 1968). On the basis of texture and thickness, Multer and Hoffmeister (1968) recognized three general forms of crusts and, in order of decreasing volumetric abundance, these are:

(1) Porous laminated crust--poor, vague laminations made up of 5 to 20 per cent horizontal root tubes, organic debris, bioclastic and lithoclastic fragments. This appears to have formed under a thick, aggrading forest cover with the porous nature due to solution of organic debris and oolitic rock upon which it is developed.

(2) Dense laminated crust--good, sharp laminae, made up of 0 to 5 per cent organic debris, bioclastic and lithoclastic fragments with rare solution holes. This crust seems to have formed under a thin soil or on exposed bedrock receiving periodic drainage from adjacent soil patches and its denser nature is the reflection of more frequent wetting and drying.

(3) Laminated microcrystalline rind--sharp laminae composed of ghost pellets in a dense tan microcrystalline calcite mosaic. This rind is generally at the base of any crust in direct contact with the bedrock and fills deep cracks and coral calices. This crust develops independently of soil and diurnal variations in pH; microbal activity and evaporation of ascending capillary water are thought to be responsible for precipitation of this crust in subaerial, sublittoral and upper littoral zones.

These crusts appear to have counterparts on northern Barbados. The Florida "dense laminated crust" is similar to crusts developed on older, well lithified, Pleistocene limestones in the centre of the North Point Shelf. The Florida "laminated microcrystalline rind" at the base of many crusts is identical to the thin crust found at the base of profiles along the northwest coast of Barbados.

Formation

The ideal environment for caliche formation in general is neither too arid nor too humid. Too little moisture allows only surficial accumulation of carbonate, while too much water and relief causes regional leaching of soil solubles (Reeves, 1970; Krumbein, 1968). The rate and degree of profile development depend mainly upon --(1) the rate and amount of infiltrating water (Reeves, 1970), and (2) the amount of $CaCO_3$ in, or being added to, the soil. As the local relationship between precipitation, temperature, runoff, and relief is critical, caliche does not characterize any particular climatic zone, provided there are alternating, short periods of rainfall and intense evaporation. Conditions on northern Barbados appear to be well suited for caliche development.

<u>Meteorology</u>--On the eastern fringe of the Antilles arc, weather is dominated by easterly trades which blow the year round. Although the temperature is relatively constant on Barbados (δT = 3.9 degrees Fahrenheit), precipitation is not. During the wet season, July to December, over 75 per cent of the total precipitation falls. Superimposed upon this moisture variation is the precipitation imbalance due to the topography of the island itself. The high (up to 340 meters) central axis of the island, oriented north-south normal to the trades, forces surface air upward as it passes over the island, causing most of the moisture to fall on the highlands themselves, or along the west coast (Rouse, 1962).

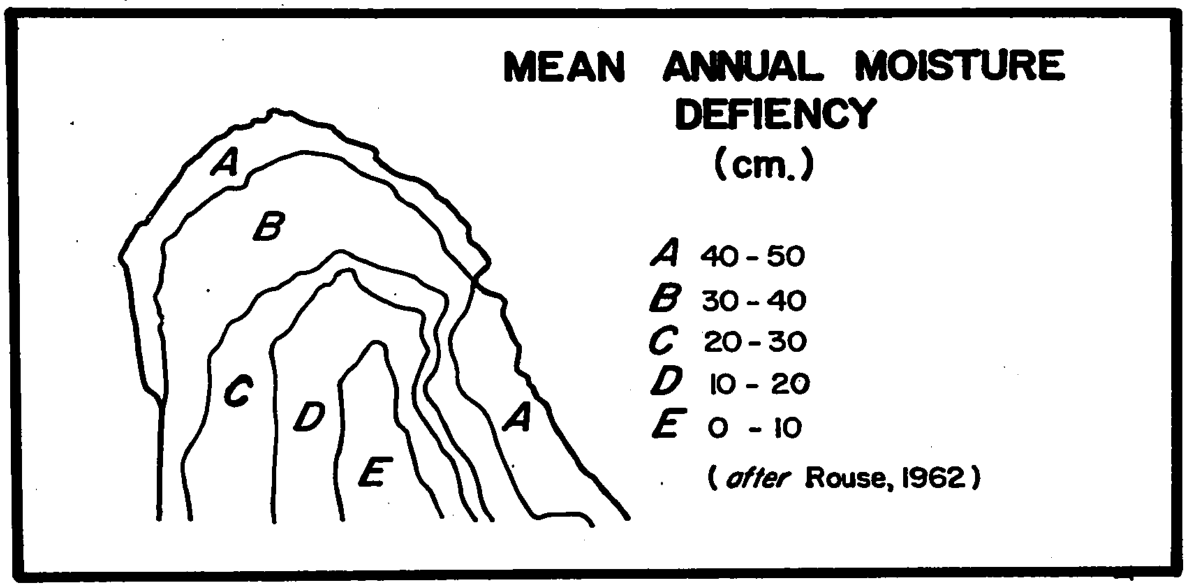

Figure 21. Map of mean annual moisture deficiency (in centimeters) for northern Barbados (after Rouse, 1962).

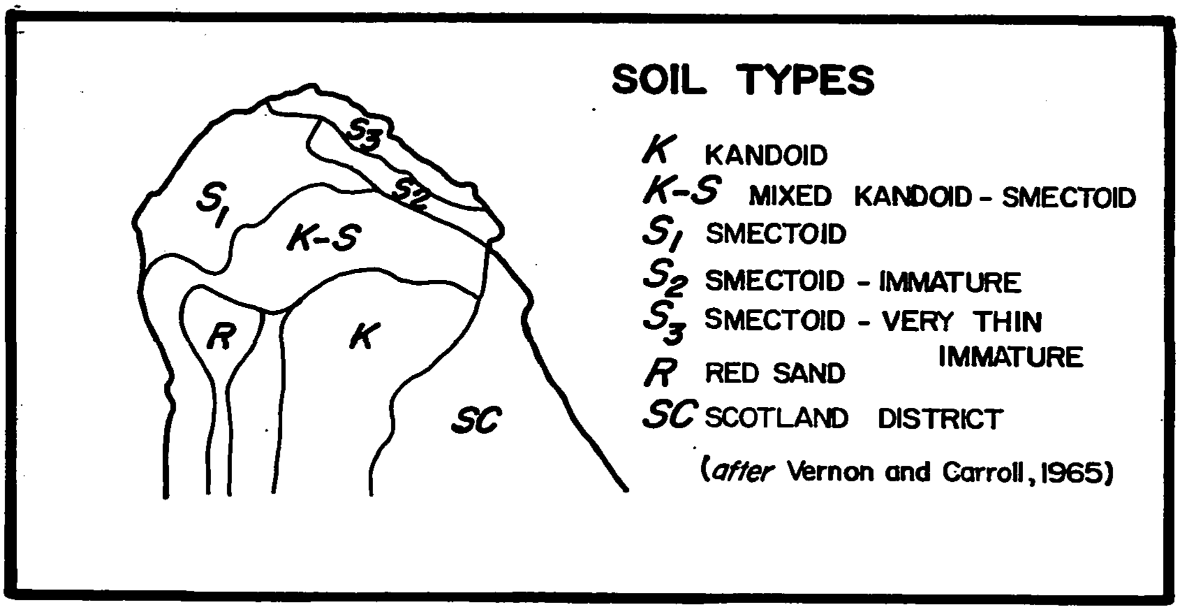

Figure 22. Areal distribution of soils on northern Barbados. Kandoid, a latosol of kaolin and metahalloysite clays; Smectoid, a grumusol of montmorillinoid clays (after Vernon and Carroll, 1966).

Mean annual rainfall figures are misleading as deviations of up to 70 per cent from mean values, especially in low rainfall areas, have occurred in the present century (Rouse, 1962). Rainfall on the northern plain varies from 110 to 145 centimeters per year. In this area, most of the rain falls as heavy showers, lasting for less than 1/2 hour, but these showers may yield up to 1.2 centimeters of rain. These downpours are followed by long periods of intense evaporation (Randall, 1968).

The mean annual moisture deficiency (evapotranspiration-precipitation) in the area varies from 40.6 centimeters to 58.5 centimeters (Fig. 21, after Rouse, 1962). Randall (1968), however, considers that this is an under-estimation, as the continuous winds, which vary from 13.5 to 7.8 miles per hour, are strongest in the driest months, and cause greater evaporation. In any case, the dry, semi-arid nature of the area is reflected in the relatively poor crops and abundant prickly-pear cactus near the sea cliffs. Daily soil temperatures (Rouse, 1962) vary from 62 degrees to 89 degrees Fahrenheit, and can remain as high as 86 degrees as deep as 20 centimeters (8 inches) in the soil.

Source of calcium carbonate--In most areas of extensive caliche-crust formation, there is an external source of $CaCO_3$. Desert loess is an important (and probably dominant) source of carbonate, with amounts of up to 3,000 tons/acre having fallen in certain areas (Ruhe, 1967). This, however, does not apply on Barbados. Although fallout of windblown dust from Africa has been recorded (Prospero, 1968), its effect is difficult to evaluate. This fallout may add considerable material to the soil as suggested from the soils of Bermuda (Bricker and Mackenzie, 1970).

The soils themselves, regardless of origin, are a source of $CaCO_3$. The distribution of soil types is illustrated in Fig. 22 (after Vernon and Carroll, 1965). The black soil on the North Point Shelf is relatively thin and dominated by montmorillonite-type, clay minerals. Towards the northeast coast, as organic content of the soil decreases, the soil becomes grey-brown in colour and fringing the coast is only a thin, immature veneer over the limestone, typical of sterile soils exposed to strong winds and salt spray. The exchange capacity for cations, especially Ca and Mg in these soils, is high, and carbonate averages 15 per cent throughout.

Another, and perhaps dominant, source of $CaCO_3$ is wind-blown, salt spray. A wind, freshly entering the northeast coast, contains as much as 200 mg NaCl/square foot, while air blowing off the island, on the west coast, contains only 10 mg NaCl/square foot, indicating that a substantial portion has been dropped on the North Point Shelf. The effect of this salt spray near the coast is twofold--(1) high salinity in the area prevents growth of vegetation, which in turn does not anchor the soil; thus the thin soil is blown away, and bedrock exposed (overgrazing by sheep and goats in the last few hundred years may have aided this process); (2) spray adds $CaCO_3$ to the surface, thereby increasing the $CaCO_3$ content of the near-surface waters. The increase in thickness and development of caliche towards the northeast coast appears to reflect this addition of $CaCO_3$ by salt spray.

Mineralogy and Chemistry

Throughout this study a total of 53 samples of calcareous crusts were routinely analysed for carbonate mineralogy by X-ray diffraction. In each case, these calcareous crusts were found to contain only calcite.

To determine the elemental composition of these crusts, five samples (two from the northeast coast, one from the northwest coast and two from the centre of the North Point Shelf) were selected and analysed for manganese, iron, strontium and magnesium by electron microprobe. The amount of manganese is very low, and does not vary from sample to sample. An average of 200 ppm iron is found in the caliche. This is equal to, or less than, the iron con-

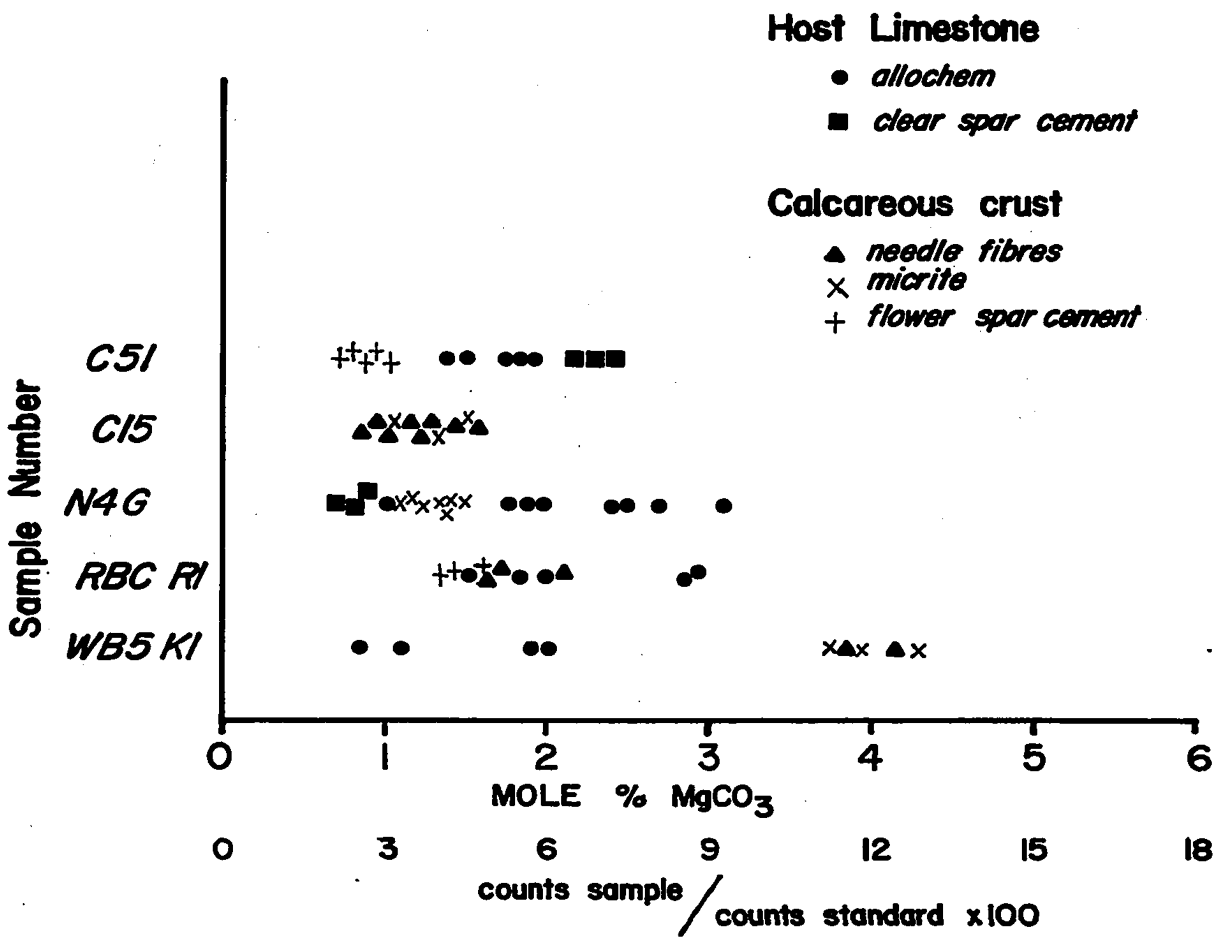

Figure 23. Mole per cent of $MgCO_3$ in calcite from surficial calcareous crust profiles and adjacent host limestone. Samples C51 and C15 are from thin crusts at centre of North Point Shelf, N4G from sediment between crusts along northwest coast (see Figure 18), RBC1 and WB5K1 from crusts and sediment along northeast coast.

tent of surrounding Pleistocene limestone allochems and calcite spar, indicating that the brown, carbonate colour is not due to iron. Strontium distribution is related to the original sedimentary mineralogy, and is only high in those allochems that have not yet equilibrated to calcite. In most samples, $MgCO_3$ content ranges from 0.5 to 2.0 mole per cent, slightly less than adjacent, Pleistocene, limestone allochems and spar cement. Along the northeast coast, however, the sample of caliche bathed in salt spray contains between 3.5 and 4.5 mole per cent $MgCO_3$ (Fig. 23).

Petrography

Calcareous crust profiles are formed in the uppermost part of the vadose, diagenetic environment, at or near the air-rock interface. The interstitial fluids in this zone are subject to rapid fluctuations in composition, movement, and temperature. Superimposed upon these fluctuations are the physical and biological effects of soil formation. Field examination of the profiles indicates that the above factors combine to both alter original limestone and precipitate new carbonate. The precipitated, carbonate crystals combine to form a series of textures characteristic of crust profiles. Alteration and precipitation, however, are not mutually exclusive, as alteration of newly precipitated carbonate may occur several times, creating a complex set of overlapping textures. The following textures are not unique to the calcareous crust profiles on northern Barbados, but also occur in thin sections of either Florida crusts or Middle East limecrusts, or both (Table 3).

Alteration Fabrics

<u>Solution and brecciation</u>--(Plate 24A, 24B) The soft, chalky sediment under and between the crusts is a highly fractured, original, carbonate sediment. Cracking takes place either as--(1) fracturing of micrite or calci-

TABLE 3 – MICROSCOPIC TEXTURES OBSERVED IN HOLOCENE AND PLEISTOCENE CALCAREOUS CRUST PROFILES FROM BARBADOS AND OTHER AREAS

	Northern Barbados central part of area	Barbados northeast coast	Barbados terrace fringing northwest coast	Florida	Israel	Fossil occurrence northern Barbados
ALTERATION						
Micritization		x	x	x		
Solution	x	x	x	x	x	
Brecciation	x	x	x	x	x	
Neomorphism	x	x		x	x	
Boring	x	x	x	x		
PRECIPITATION						
Small tubules	x	x	x	x		
Root? tubes	x			x		x
Cement						
random needle fibres	x	x	x	x	x	
flower spar	x	x	x	x	x	
clear spar		x	x	x	x	
Tangential needles	x	x	x	x	x	
Coatings						
fractures	x	x	x	x	x	
pelletoids	x	x	x	x		x
allochems	x	x	x			x
fragmented limestone		x	x			
Crusts						
laminated micrite and needles	x	x	x	x	x	x
merged pelletoids	x	x	x	x		x
laminae of calcite spar	x	x		x	x	
Micrite						
micrite	x	x	x	x	x	x
pelletoids		x	x	x		

siltite, (2) fracturing of microspar, (3) separation of grains from the matrix, (4) fracturing of allochems. Extensive fracturing is the result of solution or dessication or both. Solution creates voids in dense limestone and, in doing so, is also a local source of $CaCO_3$.

Recrystallization--In crust profiles, the most common form of recrystallization is the change of 1.5 to 3 micra micrite to 6 to 10 micra microspar (Plate 24C). Folk (1965) noted that this change is most common when limestones are subjected to fresh water, especially when in contact with organic material. The fresh water, organic-rich conditions near the ground surface on northern Barbados create an ideal environment for this change.

Micritization--Particles and allochems in calcareous crusts are often coated with microlaminae of brown micrite. The boundary between particle and coating is generally fuzzy and gradational (Plate 24E, 24F). The irregular boundary is often marked by small cusps, with points towards the coating, suggesting the original grain is being altered to micrite. In some allochems, small parts of the original allochem can be observed in the coating. This is particularly noticeable at the contact between coating and nucleus in coated microspar fragments. At the contact, microspar crystals float in a micrite matrix (Plate 24D). In coated, Amphistegina grains, crystals of the separated test fragments in the coatings can be easily identified, because they are in optical continuity with the remaining part of the test (Plate 25A, 25B).

Although micritization is a relatively common diagenetic process in the marine environment (Kendall and Skipwith, 1967; Windland, 1969), the persistent association of calcareous crust profiles and wholly or partially micritized particles suggests that micritization is a common process in this near-surface, vadose, diagenetic environment as well.

In some crusts, well-sorted, skeletal, calcarenite grains are coated with micrite laminae (Plate 28C). Adjacent grains display no skeletal nucleus, and the particle is a coated, micrite pelletoid. Such pelletoids may represent completely degraded (micritized), skeletal particles. The upper parts of many crusts are composed almost exclusively of pelletoids that become less common as the crust grades downwards into original calcarenite. The pelleted micrite may represent not only micrite precipitation in the upper parts of the crust, but also degradation of original particles to create a homogeneous texture.

In summary, micritization appears to take place in calcareous crust profiles, and may completely alter a calcarenite to a dense pelsparite.

<u>Boring</u>.--Original sediment, especially skeletal allochems, is often bored by organisms, creating circular tubes averaging 20 to 25 micra in diameter. Boring is most common on the periphery of grains, but, in places, entire grains are almost completely destroyed, and only a network of holes remains (Plate 25C). Bored particles are most common a few centimeters below ground, and occur in roughly horizontal zones, a few centimeters thick, below the laminated crusts. In the Florida crusts, however, these holes extend into the crust itself, indicating destruction of the crust after formation. Holes are identical in diameter to the calcareous tubules described below, and occasionally are continuous with them.

<u>Root tubes</u>.--Brown, circular, root tubes, generally 1 to 3 mm in diameter, occur in many crusts and associated features (Plate 25E, 25F). In some areas, these tubes penetrate the soft, chalky carbonate in great profusion.

Calcite Cement Textures

In all of the crusts examined, the mineralogy of newly precipitated carbonate was calcite. This calcite occurs in a variety of crystal forms--(a) tangential needles, (b) random needles, (c) flower spar, and (d) micrite. Most of these crystal forms do not occur in the underlying, vadose zone. These crystals, while characteristic in themselves, also combine to form larger structures, such as coated particles and crusts, which typify caliche profiles.

Micrite.--The bulk of most deposits is made up of 1 to 3 micra, brown micrite. This micrite is not uniform, but is distributed in irregular patches, exhibiting a clotted texture (Plate 26A), with the irregular, dense clots up to 0.1 mm in diameter. These denser areas grade into sharp, round to ovoid "pelletoids" that range in size from 0.03 to 0.5 mm (Plate 26B, 26C). Most pelletoids larger than 0.5 mm are coated with a rind of tangential needles.

Random needle fibres.--(Fig. 24; Plate 26D, 26E, 26F) A common form of $CaCO_3$ precipitated into void spaces is a mesh of acicular, randomly oriented, calcite laths. These needles are from 30 to 125 micra long, and from 1.5 to 4 micra wide. The mineralogy of these crystals was checked by staining, X-ray diffraction, and electron microprobe. When immersed in Fiegel's solution, the crystals were partially stained in some samples, and not stained at all in others. As this stain is based on the relative reactivity between aragonite and calcite, it is not definitive in the case of fine crystals (Purdy, 1968). X-ray diffraction of several whole rock samples, where all other components are calcite, yielded no trace of aragonite. Electron microprobe analysis yielded very low strontium content, and magnesium content too high for aragonite. It is concluded, therefore, that these acicular crystals are calcite.

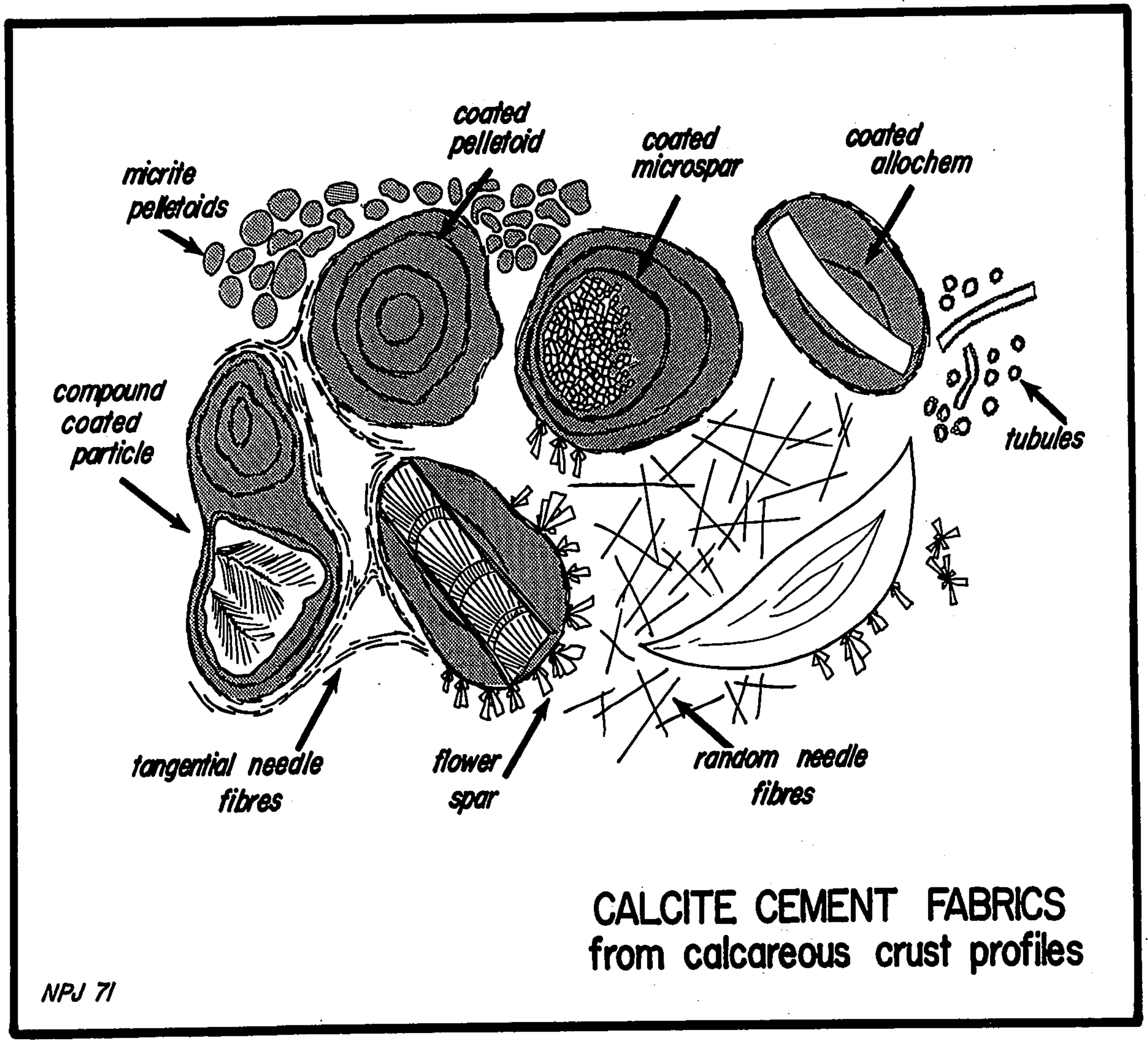

Figure 24. Sketch of typical subaerial calcareous crust fabrics.

The number of these crystals in a void varies from a few scattered needles, to a tight mesh of numerous crystals, where the void space between crystals has almost disappeared. The number and density of needles varies, from void to void, in the same rock. These crystals appear to undergo diagenesis by thickening up to 20 micra, while the length remains the same. Dense precipitation of these needles creates a tightly cemented rock.

Supko (1971) has described similar fabrics from Bahamian calcarenites. Occurrence of these cements in the subsurface, along with their aragonite mineralogy, suggests that they formed in the phreatic zone. He suggested the name "whisker crystals" for this cement. Ward (1970) observed similar cements, near present and ancient weathering surfaces and soil zones developed in and upon Holocene and Pleistocene Yucatan aeolianites. These cements, in contrast, are calcite and he has, following cement terminology of Folk (1965, p. 25), called them "needle fibres". As the fabrics of Barbados most resemble, texturally, mineralogically, and environmentally, those described by Ward (personal communication), his terminology will be followed and they will be called "random needle fibres" (to differentiate them from tangential needles).

Similar needles, 10 to 300 micra long and 2 to 5 micra thick, are commonly found between pebbles in surficial gravels from western France (Cailleux, 1965). Where numerous, they form a felt or crust ("tripoli de Nanterre") that is 0.1 to 5 mm thick, mainly around the lower parts of pebbles, and may cement sand grains and pebbles together. Analagous needles have been described from Hungary (Kirvan, 1958). Interestingly, Cailleux (1965) noted the apparent lack of needle crystals in warm climates, and feels they may be characteristic of cold climates.

<u>Tangential needle fibres</u>.--Particles and walls of microfractures are plastered with acicular needles of calcite, 9 to 30 micra long, and 1 to

2 micra thick, oriented tangential to the coated surface (Plate 27C). Stacked laths may form cement crusts up to 50 micra thick. These needles also form a ramifying texture in the voids, and create a self-supporting structure (Plate 27A, 27B). The crystals are calcite, with the C-axis also aligned parallel to the long axis of the crystal.

Flower calcite.--(Plate 27D, 27E, 27F) In these crusts, drusy calcite assumes a habit different from that in the major part of the vadose zone below. This cement is in the form of brown, relatively elongate, single crystals of calcite. These crystals occur in bunches at regularly wide-spaced intervals on the grain boundary and, from each of these points, three to four crystals grow outwards in a fan. Flower calcite forms on grain boundaries, previously precipitated, clear, calcite spar, or on fine, heterogeneous particles in the voids. Continued precipitation results in a void, filled with a tight, interlocking mesh of relatively random, elongate crystals, and readily distinguishable from the clear, calcite mosaic.

In cracks, these bladed crystals grow close together, and result in a row of single, brown, calcite crystals that either meets a similar set from the other side, or extends across the void.

Coated particles.--Particles in the profile are often coated with calcite in the form of light and dark brown rings, similar to marine oolites. The nucleus can be--(1) original skeletal grains (Plate 28B), (2) micrite pelletoids (Plate 28C, 28D), (3) fractured microspar (Plate 28E), (4) fractured grains and micrite. The dark and light laminae have a different fabric. The thinner, dark laminae contain many needles (identical to those that form tangentially to void walls), oriented tangentially to the nucleus. The light brown laminae are loosely packed, 1.5 to 2.5 micra, crystals of calcite, similar to the brown micrite. On smaller particles, there is usually just one rim of tangential needles, but on larger coated grains up to 7 dark laminae have been observed. The size of these coated grains depends upon the size of the nucleus, and so these vary between 0.04 and 4.0 mm, which ranges from the defined size of oolites to pisolites. In late Pleistocene, reefal carbonates, calcite coats both Mg-calcite and aragonite allochems. The tendency of precipitation is towards the creation of spherical particles. With elongate nucleii, such as mollusc fragments, the coating normal to the long axis of the shell may be up to ten times thicker than over the ends. These coatings may be partly degradational, as well as accretionary.

Crusts.--Crusts, although exhibiting a similar external expression of a brown, irregular, dense calcite, vary in internal composition. The most common crust is made up of numerous, alternating, light and dark laminae. In many crusts, these light and dark laminae are alternating bands of brown, microcrystalline calcite (0.1 to 0.15 mm thick) and thinner, calcite laminae (0.06 mm) of small needle fibres oriented parallel to the laminae. Although this is the principal fabric of most crusts, bands of bladed calcite spar (similar to flower calcite), closely packed pelletoids (occasionally cemented by clear drusy calcite), closely packed, well-cemented, coated particles, and clear calcite spar are common accessory fabrics. These latter, accessory textures form thin crusts, identical to the "microcrystalline rind" of Multer and Hoffmeister (1968).

Intimate association of crusts and coated particles is illustrated, as thinner crusts and rinds often merge with particle coatings (Plate 28F). Coatings along fractures, running normal to bedding, also merge with particle coatings.

Tubules.--In the upper parts of the alteration zone, usually just below the hard, calcareous crust, there are often observed numerous ramifying tubes, coated with fine calcite (Plate 29). These tubes have an internal diameter of 10 to 15 micra, an external diameter of 15 to 20 micra, and are 50 to 120 micra in length. They are straight, curved to slightly sinuous, singular and branched, occur between original allochems, and can be seen to continue into allochems as borings. Tube walls are made up of small, equant calcite crystals, 1.5 to 2.5 micra in size. Rarely, walls contain small needles, 1.5 to 2 micra wide, and 6 to 8 micra in length. Decalcification reveals an organic residue, along the calcified periphery of each tube.

Ward (1970) has described similar tubules as an interlocking network, enveloping grains and partly filling interparticulate areas, and associated with fossil, weathered surfaces in Pleistocene calcarenites from Quintana Roo, Mexico. These tubules are slightly smaller, 5 to 15 micra in diameter, with a wall thickness of 1 to 2 micra. He postulates that, owing to the absence of light in this environment of formation, they cannot be due to blue-green algae, but more likely to the root hairs of angiosperm, dune plants.

The tubules Ward (1970) describes do not appear to penetrate grains, as do the tubules observed on Barbados (see Plate 25C). The tubules from calcareous crust profiles on Barbados strongly resemble the slightly smaller (9 to 12 micra diameter) tubes of blue-green algae (especially Schizothrix), which not only have calcified sheaths, but also create a ramifying network of borings in limestone surfaces in intertidal areas. Krumbein (1968) notes that the microflora of Israel "Nari limecrusts" is dominated by blue-green algae. The exact origin of these enigmatic, yet characteristic, structures remains unresolved, and requires further study.

Origin of Cements

The most common form of calcite cement in the vadose zone is the rhombohedron, as drusy blades (Folk, 1965), rhombic mosaics (Perkins, 1968), and epitaxial growths on single crystal allochems. The dominance of somewhat aberrant, calcite crystal morphologies in crust profiles indicates conditions of formation which differ from those in most of the underlying, vadose zone. Can these crystal morphologies be reconciled with known environmental conditions and, in turn, can they tell us more about the formation of the basic structures?

Inorganic precipitation.--Most studies on carbonate precipitation to date have been on the physiochemical controls which specify the mineral phase (Murray, 1954; Fyfe and Bischoff, 1965; Taft, 1967). Little experimental data is available for the different calcite morphologies expected under various physiochemical conditions. Integration of those few experiments on calcite precipitation with data available on the precipitation of crystals in general (Buckley, 1951; Strickland-Constable, 1968) does, however, yield a relatively consistent picture.

Variation in crystal habit, due to increased velocities of specific crystal face growth, may be due to any one of the following factors--

(1) Evaporation versus heating--Crystals that form by slow changes in temperature, as opposed to slow evaporation, tend to have slightly different face development (Buckley, 1951).

(2) Composition of solute--Specific crystal forms can be encouraged by growing them either in different solutes, or in water with other dissolved substances ("Syncrystallization"; Buckley, 1951). A good example of this is aspirin, which grows as needles in water, but as plates in other solutions. Calcium carbonate, separated from a bicarbonate solution in which a minor, but ever increasing amount of SO_4 is present, undergoes a progressive change in crystal form. At very low concentrations, the primary rhomb is precipitated, but as the SO_4 concentration is increased, the rhomb becomes steeper and the crystals are elongated (Buckley, 1951).

Water

Usdowski (1963) has found that the Mg:Ca ratio of the solute also affects the crystal form of calcite. If the Mg:Ca ratio is between 1:1 and 1:16 (salinity of 3.6 ^{oo}/o), optically negative spherulites, with no visible, radial, fibrous structure (5 to 10 micra diameter), are formed, while if the Mg:Ca ratio is between 1:16 and 1:64, a fine, granular precipitate, approximately 1 micra in diameter (micrite), is formed. In fresh water over the range 1:1 to 1:64, a granular precipitate of crystals, averaging 10 micra in size, is precipitated.

(3) Supersaturation--Crystals grow normally at low supersaturations, but if precipitated from highly supersaturated solutions, they exhibit abnormal growth forms, such as needles, tubes, dendrites, etc. Ice grows in its normal form as plates at low supersaturations, while at high supersaturations it grows as needles, hollow prisms, dendrites or prismatic columns. These different forms are produced over strictly delineated temperature ranges (the supersaturation being varied independently of the temperature((Strickland-Constable, 1968). In alum, the complexity of the crystals decreases with increasing saturation, so that certain faces (100 and 110) have a better opportunity to appear at higher degrees of supersaturation (Buckley, 1951).

Fluids at or near the air-rock interface may be expected to display rapid and extreme variations in supersaturation. These may be brought on by rapid temperature fluctuations and periods of rain alternating with intense evaporation. The addition of seawater solubles in the form of salt spray, as on northern Barbados, will also affect the composition of the solute.

Among the different abnormal crystals, produced under the above conditions, are dendrites, spherulites (radial and concentric) and whisker crystals (random needle fibres). Dendrite growth takes place in the labile condition, and the regular branching is probably due to the successive depletion in the neighbourhood of each freshly grown branch. Dendrites are usually regularly branched, but many workers include crystal needles in this category as they are initial forms of dendrites. Flower calcite from Barbados is very similar in form to many dendritic crystals.

Concentric spherulites are formed by successive shells of crystals, laid down at more or less regular intervals, from the central core. Regions of dense crystals are separated by areas of loosely packed crystals. Buckley (1951) considered that the rings of densely packed crystals are the result of crystallization under labile conditions (very high supersaturation), while loosely packed crystals form during times of metastable (low supersaturation) conditions. The concentric laminae, coating particles with brown calcite on Barbados, display similar crystal shells that may well have formed by this mechanism.

The random needle fibres, from calcareous crusts on Barbados, appear very similar to the more widely known "whisker crystals". Whisker crystals are defined as being less than 100 micra in diameter, grow to great length, are constant in cross-section, and possess properties of great strength. The mechanism of whisker crystal formation is far from being understood (Strickland-Constable, 1968). Whisker crystals most commonly form on metals. When other compounds such as KCl, $CaSO_4.2H_2O$, and NaCl are saturated at high temperatures and allowed to cool, they also form whisker crystals and needles. After formation, whisker crystals often thicken, usually by spreading uniform layers from one end. In summary, both the random and tangential needle fibre crystals from Barbados, by their dimensions and subsequent diagenesis, are similar to "whisker crystals".

Organic control.--All crystals observed forming the basic elements of crusts, and precipitated in the surrounding limestone, might be explained in the light of physiochemically controlled precipitation. However, as these crusts are intimately involved with soil formation, and much of the carbonate precipitation takes place within the rhizosphere (Burgess and Raw, 1967, p. 53), the role of organisms must also be considered. Unfortunately, even less is known of the precipitation of $CaCO_3$ by microfauna and flora.

Chemical decalcification of the brown carbonate in the crusts and coated particles reveals large amounts of residual organic material between the crystals. Conversely, bleaching altered the colour of the crusts to grey, indicating that the brown colour is organic, similar to the findings of Multer and Hoffmeister (1968) on the Florida crusts.

Initial investigations of the "Nari limecrust" (Israel) by Krumbein (1968) indicated that the crust contained a well-developed microflora, consisting of autotrophic and heterotrophic bacteria, fungi, and actinomyceta, but is dominated by green and blue-green algae. As culture experiments on the flora indicated that they could produce large amounts of calcite, it is possible that such a flora may produce, or be involved in the production of, caliche carbonate.

Ward (1970), on the basis of similarity in size and arrangement of the needle fibres to fungal hyphae, suggests that the calcite crystal precipitation is in some way associated with fungae. The larger tubules as well, whatever their origin, are also related to organic processes of some kind.

Buried Fossil Caliche Profiles

Buried crusts are visible at several localities, and in all cases underlie the 104,000 year old reef complex. The same fabrics occur in fossil buried and Holocene, surficial crusts.

In the field, the buried crusts consist of a band, or series of bands, of hard, extremely dense limestone at the boundary between two facies (Plate 30A to 30D). Within the well-lithified limestone are a series of brown, highly irregular laminae, separating buff to cream, dense limestone, which grades downward into recognizable marine lithologies. At one locality, the lithology underlying the crust is still relatively crumbly, altered, chalky material and weathers recessively (Plate 30A), in a similar fashion to carbonate below modern crusts.

Exposure of these crusts is not good enough to ascertain their lateral extent. As they are not present at all contacts they may have developed only locally and/or have been partially eroded by the transgressing sea.

At one locality (US-1), the crust zone also contains irregular cavities up to 30 centimeters in diameter. These cavities are flat-floored and coated with a brown crust (Plate 30E, 30F), similar to the more common, horizontal crusts.

Cores in the Pleistocene succession on the Florida Keys reveal fossil laminated crusts within the marine, Key Largo limestone. These crusts lie below the dated (95,000 years B.P.) portion of the Key Largo limestone.

In thin section, the dense, brown crusts from Barbados consist of-- (1) interlaminated, brown micrite and tangential needles (Plate 31F), (2) irregular root tubules surrounded by tangential needles and filled with clear, spar mosaic, (3) thin bands of clear calcite and brown calcite, 0.1 mm thick (Plate 31E). The cream to buff limestone is made up of brown, micrite pelletoids and allochems coated with layers of tangential needles and brown micrite (Plate 31A to 31C).

Once buried by younger, reefal limestones, these crusts pass into the main body of the vadose, diagenetic environment. Because of their calcite mineralogy, crust-associated fabrics are stable in the presence of vadose fluids, in contrast to the original, sedimentary mineralogy of the particles they often enclose, and so should be well preserved. This is well illustrated in the diagenesis of coated, aragonite allochems. Now in the vadose zone, the aragonite allochem dissolves and subsequent precipitation of void-filling calcite takes place, while the stable calcite coating remains, unaltered (Plate 31D). These surficial calcareous crusts will, then, remain in the geologic record, as criteria of subaerial exposure under semi-arid conditions, unless the whole rock is crystallized and all fabrics lost.

Summary and Discussion

1. Surficial, calcareous crust profiles developed on the Pleistocene limestones of northern Barbados are similar to "caliche" deposits. The extent of profile development is a function of age and induration of the host limestone, local topography, meteorology, and amount of external $CaCO_3$ available. All crusts are calcite, but they contain a wide range of crystal morphologies. Calcites in areas bathed in salt spray contain up to 4 mole per cent $MgCO_3$.

2. Many of the calcite, crystal morphologies present in the calcareous crust profiles are similar to those precipitated from highly supersaturated solutions. Similar crystal habits can also be obtained from solutions that contain large amounts of other ions, such as Cl^- and $SO_4^=$. Rapid fluctuations in temperature, rainfall, and evaporation may result in supersaturation of near-surface fluids. Material may also be added to

these solutions by rainfall and salt spray. The presence of organic material, in both fossil and Recent crusts, also suggests that organisms such as algae, fungi, and bacteria may aid in inducing carbonate precipitation.

3. In the upper part of the vadose zone, the host limestone is--

(a) Brecciated, both on a macroscale, creating actual breccias, and on a microscale, creating chalky, crumbly carbonate.

(b) Recrystallized, with aggrading crystallization of micrite to 6 to 10 micron microspar, which is characteristic of crust profiles.

(c) Micritized, with degrading crystallization of original limestone to micrite, especially in the form of pelletoids.

(d) Bored, which in some cases completely destroys original allochems and leaves only a series of ramifying tubes. This boring is accomplished by the same plant or animal responsible for the production of fine tubules.

4. The zone of calcareous crust accumulation possesses a unique set of cement fabrics and textures, identical to those in caliche profiles from other areas, but completely different from those in the underlying, vadose zone. The crystals of the crusts and associated features are in the form of--(a) flower spar, (b) needles, both as large (up to 160 micra) random needles and small (up to 30 micra) tangential needles, and (c) micrite. These basic crystals combine to form a series of textures (Fig. 25)--

(a) Void-filling cement, dominantly flower spar and random needle fibres;

(b) Coated particles, varied nucleii enclosed in alternating laminae of micrite and tangential needle fibres;

(c) Crusts, formed from the same basic arrangement of needles and micrite, but augmented by addition of coated particles, cement, and pelletoids;

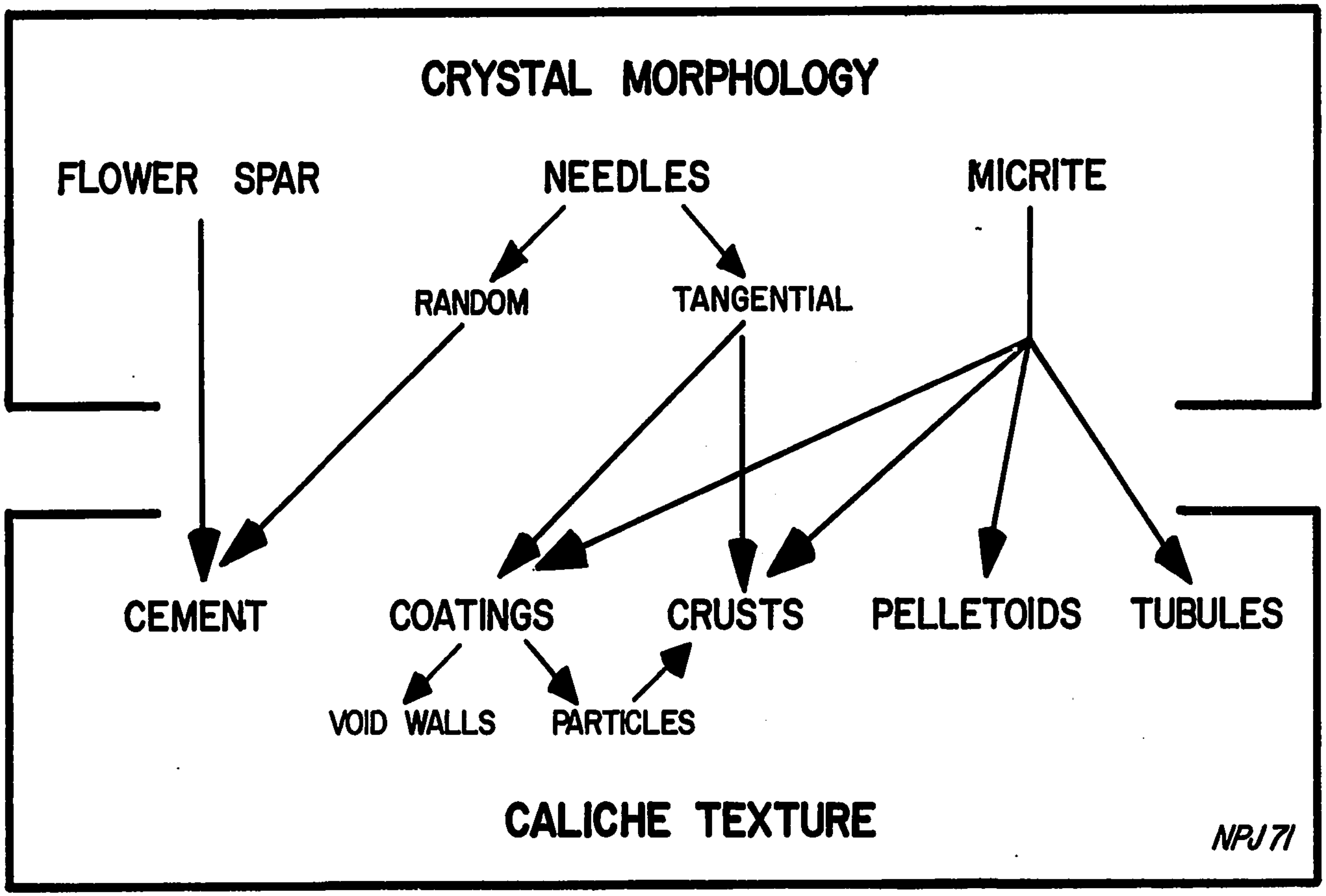

Figure 25. Summary diagram of calcareous crust fabrics and textures.

(d) Pelletoids, of both precipitated micrite and degraded particles, often coated by at least one layer of tangential needle fibres.

Finally calcite is also precipitated around the filaments of a series of ramifying tubules which are continuous with allochem borings.

5. Since the precipitated crystals described above are calcite, they are likely to be preserved, along with other calcite textures, in the fossil record. Textures in pre-Pleistocene deposits resembling the crusts and coated grains, have generally been ascribed to marine sedimentation. With increased realization of the importance of subaerial diagenesis in altering and lithifying limestones, enigmatic, fossil textures are undergoing re-examination, and many can be directly related to near-surface, diagenetic phenomena (Swineford and others, 1958; Shinn, 1968b; Thomas, 1968; Dunham, 1969; Kendall, 1969). Documentation of these calcareous crust fabrics and textures on northern Barbados should aid in the recognition of fossil, calcareous crust profiles, which are diagnostic of the subaerial, vadose, diagenetic environment.

CORAL DIAGENESIS

Introduction

Corals, the frame builders of Recent, Pleistocene, and many older reefs, are also the largest blocks of monomineralic material in these reef complexes. In situ skeletons of coral, along with sediment derived from them, make up in many cases over 80 per cent of the bulk of the reef facies. It is well known that aragonite skeletons change to calcite in the subaerial, diagenetic environment, and that many of the original coral textures are retained in the new calcite forms. The actual process of transformation itself, however, has been little studied.

Previous Studies

Transition of aragonite to calcite must take place in the presence of an aqueous solvent (Fyfe and Bischoff, 1965), at the temperatures and pressures near the earth's surface. The transition from an orthorhombic to hexagonal structure appears to take place as--(1) dissolution-reprecipitation, a process in which the aragonite dissolves, a void is produced into which subsequent precipitation of calcite takes place, and most original textures are destroyed, or (2) inversion, theoretically a process by which skeletal aragonite spontaneously alters to calcite without production of a discernable void space, is not rigorously isochemical, and results in preservation of original texture (Land, 1967).

Matthews (1968) has postulated that the present mineralogy of late Pleistocene, aragonite skeletons in the subaerial, vadose, diagenetic environment on Barbados reflects--(1) the amount of vadose water available, and (2) the kinetics of water transport through the sediment. The aragonite-calcite transformation is retarded in areas of relatively low rainfall and high evaporation because of little vadose water, and many corals are still aragonite. The transformation is more rapid in areas of higher rainfall, but the present form of the coral is dependent on the kinetics of water movement through the sediment. If undersaturated water enters the sediment and passes through rapidly, only solution of aragonite may occur, and so the corals are dissolved. If, on the other hand, water passes through slowly, solution of aragonite, and concurrent precipitation of calcite, may occur and the coral will be altered to calcite.

Harris and Matthews (1968) suggested that, in some areas, water transport is sufficiently slow in the vadose zone that aragonite to calcite solution-reprecipitation is operating at greater than 90 per cent efficiency, within a few hundred feet of the outcrop surface.

Pingitore (1970) studied the species Acropora palmata from Pleistocene reefs on Barbados and attempted to quantify the processes involved in filling primary, coral voids with carbonate cement. He concluded that, in the marine environment, pores may be filled with precipitated aragonite needles. In the subaerial environment, as the substitution of calcite for aragonite appears to be a volume for volume change, the excess 8 per cent $CaCO_3$, left over after the coral has changed from aragonite to calcite, is precipitated as calcite, void-fill cement. He did not consider the problem of alteration, except to note how well original textures are preserved in the calcite forms.

Macroscopic Diagenetic Textures

The most abundant corals in the late Pleistocene reefs are Acropora palmata, Acropora cervicornis, and Porites porites. A. palmata was selected for detailed study because of its abundance in the reef facies, and because this facies is well exposed (Plate 6). The Acroporidae (late Cretaceous to Recent) contain over 125 living species representing about 25 per cent of living coral species (Vaughan and Wells, 1943). These are perhaps the most successful family of the Scleractinia, due to their light, very rapidly growing skeleton and enormous numbers of small polyps which form large colonies (Wells, 1956).

The climate on northern Barbados is relatively dry compared to other areas of the island (Rouse, 1962; see also discussion of subaerial crusts). Many late Pleistocene corals in this area are still aragonite, while others are in transition, containing both aragonite and calcite, and some are completely changed to calcite. In places along the west coast, between Speightstown and Holetown, and in some older Pleistocene limestones on the North Point Shelf, the corals have been completely dissolved (Plate 32D, 32F).

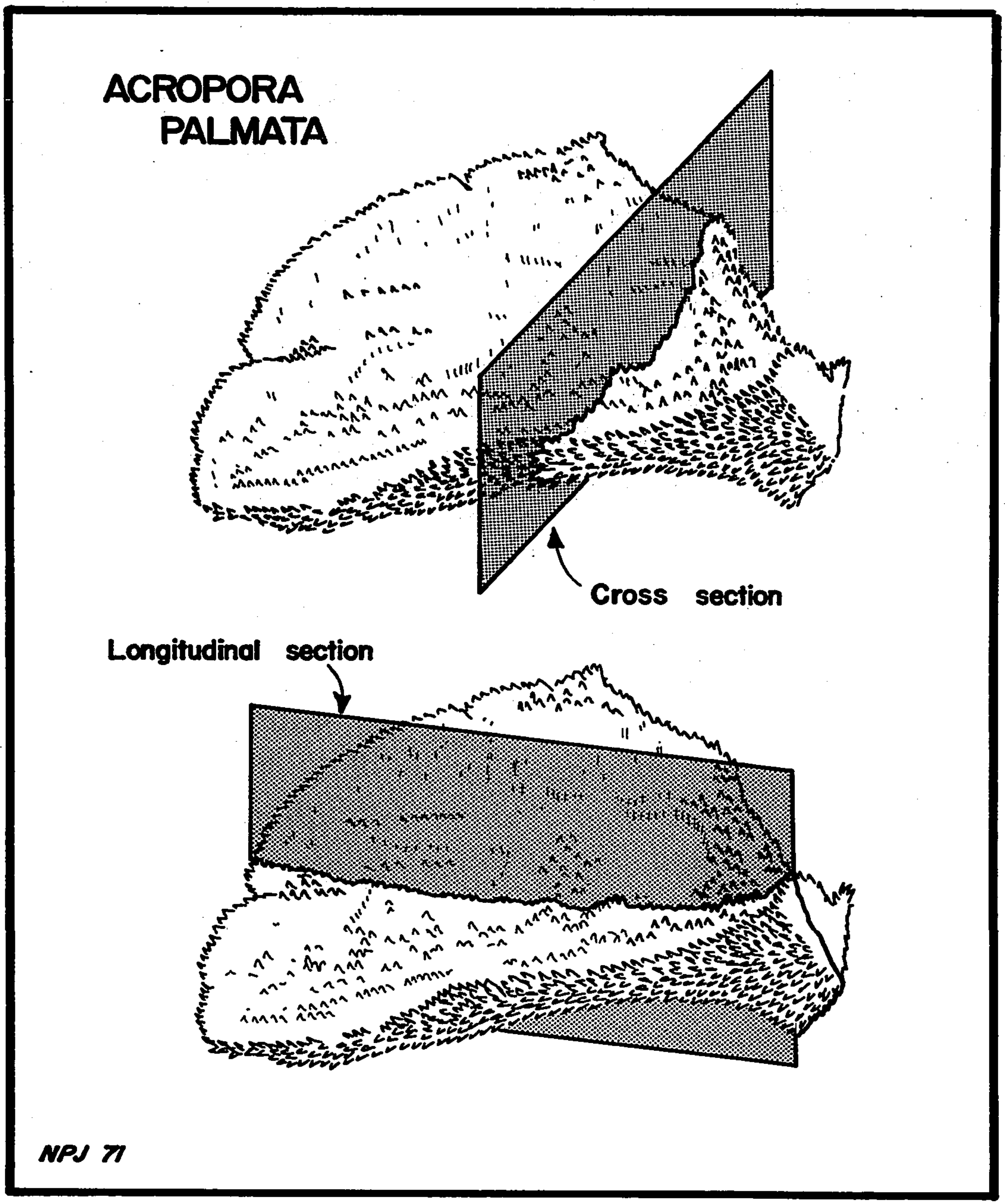

Figure 26. Individual branch or frond of Acropora palmata, illustrating the location of longitudinal and cross-sections in Figures 27 and 28.

In transitional forms, the zone between good, rhombic calcite and aragonite is occupied by a powdery white, "chalky" area of variable thickness. The "chalk" can easily be scraped out with a fingernail and is readily discernible from dense, well-crystalline aragonite. This "chalky" material is present in all corals undergoing alteration. In some specimens aragonite is absent and the coral consists of calcite and "chalk", while in others no calcite or aragonite is present and the coral is almost all "chalk".

Separate mineral phases are present as two discrete areas in the coral frond, and never as scattered, random domains. The calcite or "chalk" is located either in the centre part of the coral frond (axial alteration) (Plate 32B), or as a thick rim along the top of the frond (dorsal alteration) (Fig. 27; Plate 32C). This fabric implies that alteration moves outward from the centre of the frond, or down from the top of the frond, as a "diagenetic front", similar perhaps to a metamorphic front.

To better quantify these specific spatial arrangements of aragonite and calcite, over 450 fronds, from 13 separate localities in the 83,000 year old and 104,000 year old reef complexes, were investigated. The coral structure could only be determined when the frond was broken open, as most fronds are black and coated with a thin (1 to 2 mm) layer of fungi or algae. The mineralogy of every broken frond was recorded (Table 10; Appendix G). Those corals in transition (over 250) were studied in detail and the spatial arrangement of minerals (whether the change was from aragonite to "chalk", "chalk" to calcite, or aragonite to "chalk" to calcite) was recorded, along with the presence or absence of red algal encrustation on the upper surface of the frond.

These detailed observations reveal several regional trends. In the 104,000 year old reef complex, the relative number of calcite corals increases from about 30 per cent on the comparatively dry, North Point Shelf,

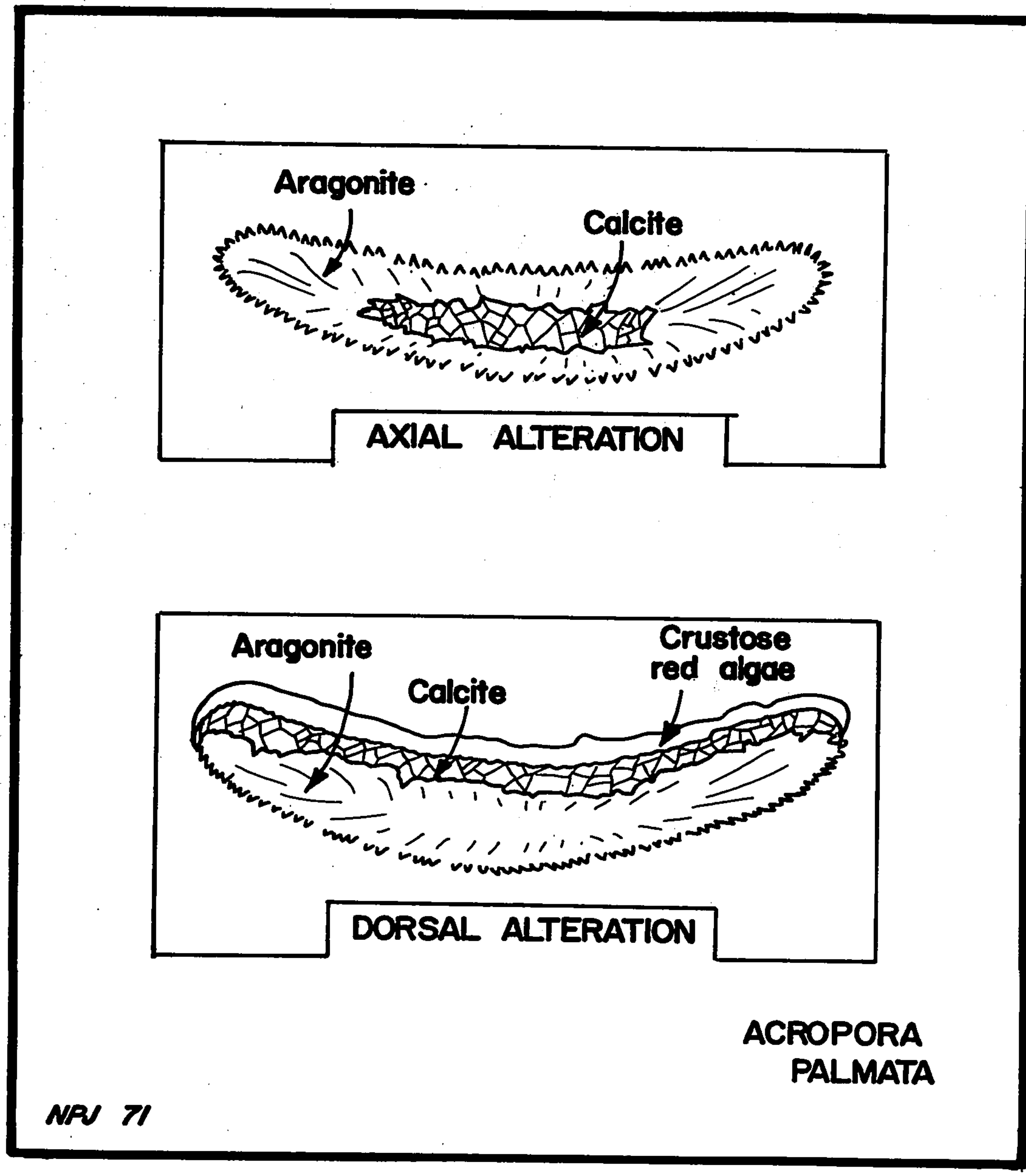

Figure 27. Cross-section of Pleistocene Acropora palmata illustrating the location of new calcite in partially altered aragonite corals. When the new calcite is located at the centre of the frond the mode of alteration is called "axial"; when the new calcite is located along the upper portion of the frond the mode of alteration is called "dorsal".

to over 70 per cent near Holetown, a distance of 7 kilometers to the south. Corals in the 104,000 year old complex, on the whole, contain more calcite than the younger corals on the northwest coast.

Of over 250 corals in transition (excluding those recorded as all "chalk") over 70 per cent exhibit axial alteration. While only 16 per cent of those corals exhibiting axial alteration are encrusted with red algae, over 85 per cent of corals showing dorsal alteration are algal-coated. In several algal-encrusted examples, both dorsal and axial alteration are observed, but dorsal alteration is further advanced. These data suggest that, in general, alteration commences in the axial region of the frond, but if encrusted on the upper surface with red algae, alteration begins adjacent to the algae. The red algae, due to its Mg-calcite mineralogy, equilibrates more rapidly in the subaerial environment than aragonite, and during this change clearly initiates alteration of the adjacent, aragonite, coral skeleton. Initiation of alteration in the centre of the frond is governed by some as yet unspecified, internal, skeletal control.

The widespread "chalky" state of the corals always occurs as an intermediary stage between aragonite and calcite, and appears to be an important key in understanding the process of alteration. This "chalky" appearance is not unique to corals and is found in many pre-Recent aragonite fossils. Land (1967) noted this material and stressed its importance, but did not know its origin. Schlanger (1963), in a study of Pleistocene corals from the Bikini and Einewetok boreholes, noted that the boundary between original aragonite and replacing calcite closely resembles a styolitic seam, and is occupied by a thin film of powdery aragonite. He concluded that, under the action of subaerial solutions, the aragonite evidently breaks down into a powder, and is then dissolved and replaced by the more coarsely crystalline calcite. The "chalk" phase also occurs in corals from Florida and Jamaica Pleistocene limestones (personal observation).

Samples illustrating this material in all degrees of development were collected, and each sample examined under the binocular microscope. The crumbly, soft, "chalky" carbonate occurs first in the centre of each small, structural element of the coral. In extremely crumbly samples, the centre of each structural element is completely dissolved and only the aragonite adjacent to each pore remains. This chalky material never originates adjacent to the pore wall. The microarchitecture of the coral itself apparently possesses structural inequalities which make some parts of the skeleton more susceptible to "chalkification", and hence alteration, than others.

Coral Microarchitecture

Acropora palmata (Lamarck) is a scleractinian coral in which small, widely-spaced polyps are connected by a tangle of communicating tissue (coenosarc). Each individual corallite is composed of three structural elements, septa, dissepiments, and theca (or wall), and is joined to other corallites by coenosteum (Fig. 28; Plate 32A). As dissepiments in the Acroporidae are characteristically poorly developed, the main elements are septa, theca and coenosteum.

Scleractinian corals are composed of fine, individual crystals, or "fibres", of aragonite (Plate 36B). Each fibre, in the form of a lath, blade, or needle, is from 0.5 to 2 micra in thickness (Wise, 1969). Fibres are combined in compact bundles, called sclerodermites (Wells, 1956) (also referred to as spherulitic arrays, Sorauf, 1969; or fasciculi, Wise, 1969), 5 to 25 micra in diameter. Crystallization of a sclerodermite proceeds outward from a point centre of calcification, until crystal fibres coalesce with those from a neighbouring centre.

Septa.--Septa are the first skeletal structures to appear after deposition of the basal plate, and all other skeletal parts are subsequent

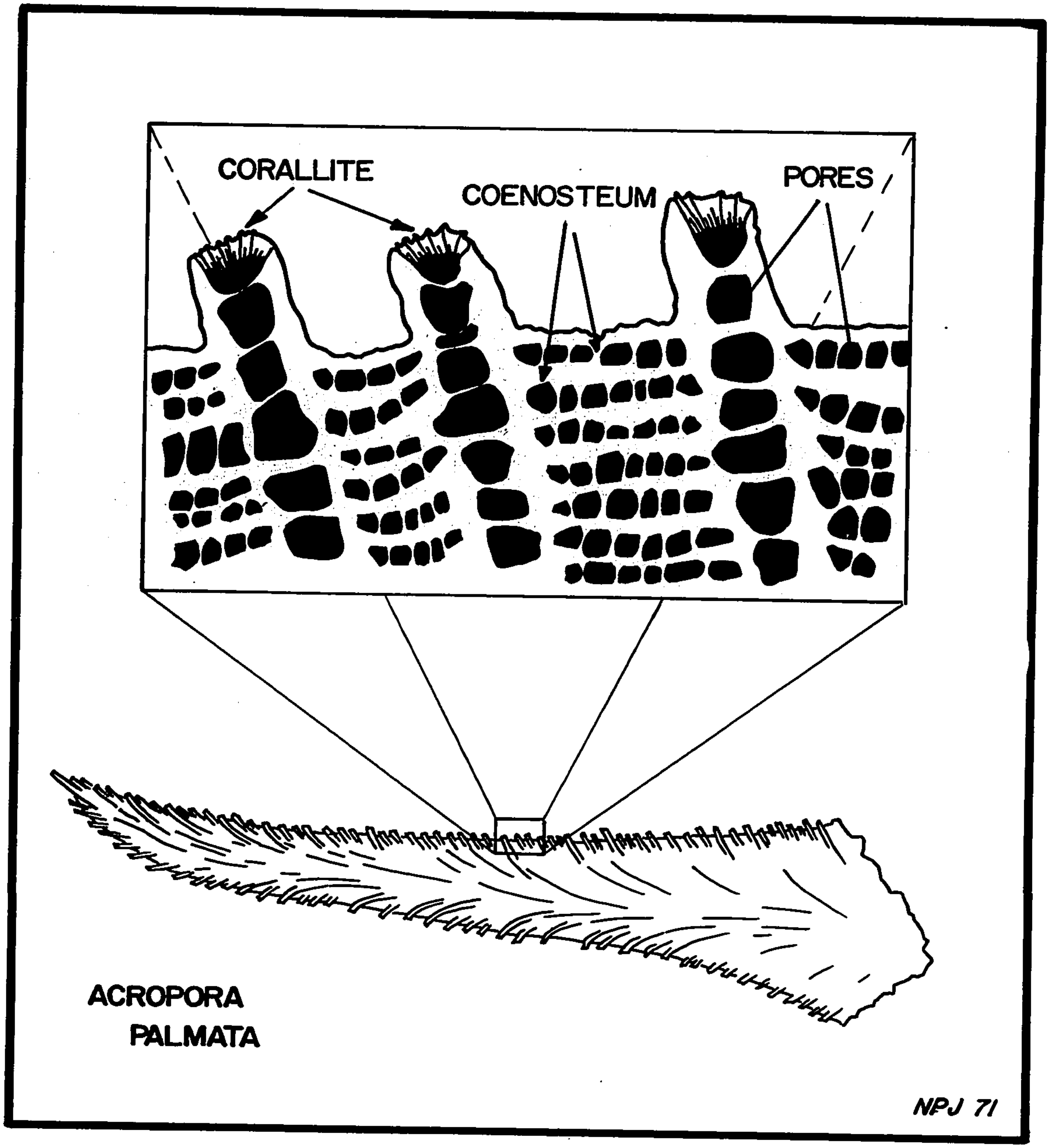

Figure 28. Principal morphologic units of Acropora palmata.

to the septa and of secondary importance. In the septa, sclerodermites are usually stacked one on top of the other to form a pillar or spine called a "trabecula". The axial part of this spine is formed of a series of centres of calcification which, although discontinuous, in a single trabecula, forms a dark, irregular line in thin section which is referred to as the "centre of calcification" (Plate 33A, 33B, 33C). The septum is a pallisade of trabeculae (Fig. 29). In the Acroporidae, each septum contains 6 to 8 of these trabecula, which are relatively far apart, resulting in a fenestrate structure with a well-developed dentition at the top. Spaces between trabecula are filled, but only partially so, leaving the septum relatively porous (Fig. 29). As trabecular arrangement in the septum varies consistently from group to group in the scleractinia, it is the basis for classification.

Theca.--Septa are often joined by rods or bars connecting opposed faces. Such simple "synapticula" are formed by the joining of two highly divergent trabeculae in adjacent septa, and may include one or two extra sclerodermites. This horizontal, rod-like, structure also develops more profusely to form the corallite wall ("synapticulotheca") in the Acroporidae (Fig. 29). The highly porous wall is designed to enable direct communication between the gastrovascular cavity and coenasarc.

Coenosteum.--In the groups Poritidae and Acroporidae, the lower part of the coenosarc is modified into a tangle of minute communicating canals ("canaliculae") with ramifying vertical and lateral connections. The calcified material ("coenosteum") laid down around this soft tissue consists of discontinuous, vertical trabecula , united horizontally by rods in more or less distinct laminae (Fig. 28).

Trabecula.--From the above it can be seen that the trabecula are the most important skeletal elements in the Acroporidae, as columns in the septa,

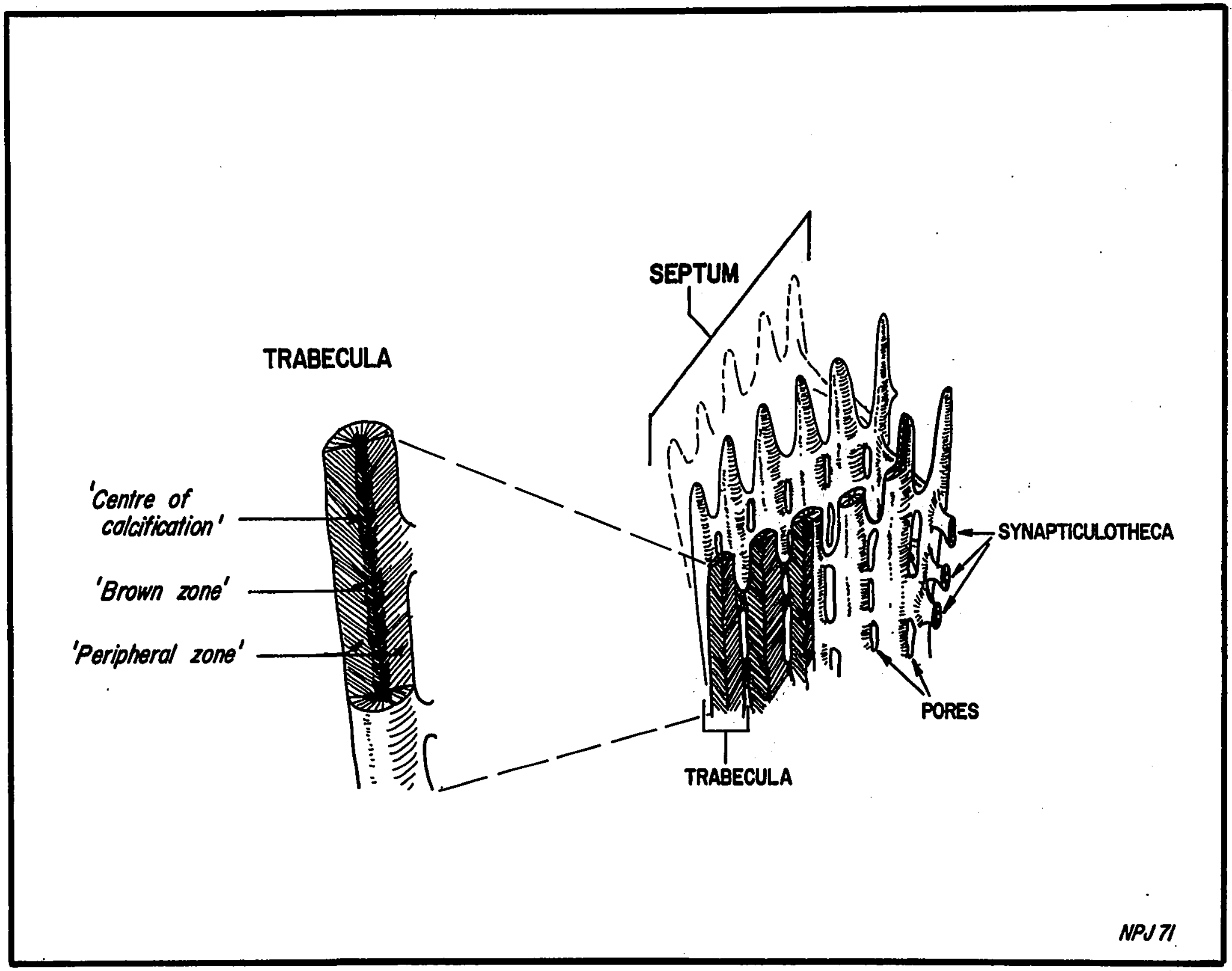

Figure 29. Septal structure and trabecular composition of Acropora palmata. Trabecular nomenclature after Wainwright (1964).

as bars in the theca, and as rods and spines in the coenosarc. The microstructure of the scleractinian trabecula has been studied by Wainwright (1963, 1964). Detailed petrographic, chemical, and X-ray microradiographic analysis (Wainwright, 1964) revealed that each trabecula is composed of three parallel areas--(1) the centre of calcification, (2) a brown zone, and (3) the peripheral zone (Fig. 29). The centre of calcification and brown zone contain, on the average, 6 per cent less aragonite than the peripheral zone, suggesting submicroscopic, intercrystalline spaces may be present there. The centre of calcification is composed of small, 1 micron or less, randomly oriented crystals of aragonite (Plate 36A). This appears as a dark line when viewed in thin section (Plate 33C). When immersed in bromoform, which has a refractive index (1.595) among those of aragonite (α=1.530, β=1.680, γ=1.685), the dark line does not alter optically. Hence the submicroscopic, intercrystalline spaces are filled, perhaps with soluble, organic material or water absorbed onto the crystal faces, enhancing the observed, optical properties. Surrounding the centre of calcification, in sections 30 to 60 micra thick, is a zone of brown colour. When immersed in bromoform, this zone imbibes bromoform slowly, and in time becomes optically indistinguishable from the surrounding peripheral zone, indicating that it contains submicroscopic, intercrystalline spaces which are filled with air in dried specimens. X-radiographic pictures indicate this zone to be transitional, possessing both the random, small crystals of the centre of calcification and the highly oriented, aragonite needles of the peripheral zone. The peripheral zone, which makes up most of the trabecula, is composed exclusively of aragonite needles (Plate 36B).

Petrography

To ascertain the nature of the "chalk" and the aragonite-calcite transition, thin sections were cut of corals in many stages of alteration. Since most changes take place on a microscopic scale, broken surfaces were also examined under the Scanning Electron Microscope. Specimens illustrating alteration from aragonite to "chalk" were examined first to discern the development of this phase. The boundary between this and calcite was then investigated, in an attempt to more accurately determine the nature of the mineral change.

Chalk.--A series of broken slabs and accompanying thin sections from selected Acropora palmata samples, ranging in composition from good aragonite, to samples displaying minor "chalkification", to corals with little original aragonite and all "chalk", were studied. Thin section examination confirmed that the alteration of aragonite to "chalk" occurs first at the centre of each trabecula. When "chalkification" is extensive the original coral structure remains, but each elementary, trabecular column has a hollow centre with up to 70 per cent of the aragonite removed. Alteration was never observed to take place from the pore walls inwards.

Of particular interest are those regions of the coral adjacent to crustose red algae. The red algae, because it was originally Mg-calcite, has rapidly altered to calcite. In the original coral pores, a mosaic of clear, calcite spar has been precipitated. The coral skeleton, however, is altered to "chalky" aragonite, with the centre of each trabecula and part of the surrounding aragonite needles removed. No calcite has been precipitated within the coral skeleton.

In impregnated thin section, the white, crumbly, chalky material appears dark (Plate 33E), and similar in form to the aragonite. Crystal boundaries are ragged, with irregular, individual needles of aragonite (Plate 33F). Under the Scanning Electron Microscope, this irregular texture is clearly visible. Aragonite is no longer in the form of clear, vitreous, tightly packed crystals, but rather needles are etched, dog-eared, and separated from one another (Plate 37). X-ray powder patterns of small groups of these crystals confirm that they are aragonite, with a trace of NaCl, a common accessory in marine skeletons.

The lack of small crystals of calcite in the "chalky" carbonate suggests that this phase of coral alteration is solely the result of solution. This solution does not occur in a random fashion, but is selective, first dissolving the centre of each trabecula (Plate 33D), and then creating a small, elongate void between individual, long, parallel, aragonite needles (Plate 37). This latter process is analagous to the common petrographic technique of etching thin sections, the most reactive part of the mosaic being the crystal contacts. In the coral skeleton, the c-axis of aragonite is parallel to the long axis of the needle. Dickson (1965, p. 491) noted that calcite reacts considerably faster on faces parallel to the x-axis than on those normal to it. Fyfe and Bischoff (1965, p. 3) record the same phenomenon for aragonite, in observing the relative lack of reactivity of the (001) face in aqueous solutions. Thus, the preferential reactivity of those crystal faces of aragonite parallel to the c-axis may enhance solution between needles.

Calcite.--Calcite corals are made up of a mosaic of relatively large crystals, up to 5 mm in size. The original, spherulitic texture of bundles of aragonite needles is preserved in ghost form, so accurately, in many cases, that under plane light the presence of calcite can only be discerned by the crystal boundaries (Plate 34C, 34D). Under crossed nicols each calcite crystal extinguished on its own and the sweeping extinction of the spherulitic aragonite array has gone. Large calcite crystals do not extend into the original pores, but do cut across delicate internal microstructures.

Trabecular structure itself is of particular interest. The original, dark line outlining the centre of calcification is no longer present, but is occupied, in most cases, by a narrow canal of clear calcite (Plate 34D). The remainder of the trabecula retains the ghost texture of aragonite needles.

"Chalk"-calcite.--Those corals that have not entirely altered to calcite always reveal, at the contact, a zone, sometimes only a few microns wide, of "chalky" aragonite, indicating partial solution of the original skeleton. The boundary is a relatively straight line exhibiting extensions or protuberances ahead of the main frond (Plate 34A, 34B). These leading, calcite zones almost always occur in the central area of the trabecula, along the dark line (Plate 34B). In several samples where the central dark line has been replaced by calcite, the structure is now a canal of clear calcite surrounded by aragonite (Plate 34F). Once established in this central area, alteration widens outward towards the wall, always proceeded by a thin zone of "chalk". This is well illustrated in some specimens where the trabecula is all calcite, except for the very outer part fringing the pore, which is still "chalk" and has not yet altered to calcite (Plate 34A, 38).

The boundary between calcite and partially dissolved needles of aragonite was studied on the Scanning Electron Microscope. At a magnification of 6000x, there is no discernible, void stage between the end of an aragonite needle and the calcite crystal. The needles abut directly against the faces of large, calcite crystals, and traces of the aragonite needles can be detected in some calcite crystals.

Alteration Process

The alteration of aragonite is occurring on an ultramicroscopic scale (ultrascale) and somehow involves encorporation of aragonite crystals into the calcite structure, slightly prior to, or during, the actual change. This change may be true, spontaneous inversion (Land, 1967), but the predominant mode of alteration, observed in all samples on a macro- and microscale, is one of solution and precipitation. From the above petrographic and S.E.M. observations, an alternative process, based on solution-reprecipitation on an ultrascale, is proposed to account for the observed microtextures.

The initial reaction is one of solution at the boundaries between adjacent, aragonite needles, creating "chalky" aragonite, with calcite precipitated locally in adjacent voids, again between aragonite needles. In this way, the aragonite needles are encased in calcite, preserving the microtexture. Solution-reprecipitation of the less reactive parts of the aragonite, now surrounded by calcite, continues, and the microvoid is back-filled with precipitated calcite growing epitaxially on the pre-existing large, calcite crystal. In this way, the calcite crystals grow as an entity and the microtexture of the skeleton is preserved.

Other Scleractinian Corals

The process of aragonite solution and calcite replacement observed in _Acropora palmata_ also occurs in other coral species on northern Barbados. _Acropora cervicornis_ illustrates identical macro- and microtextures (Plate 35A, 35B, 35C). _Porites porites_ and _Montastrea annularis_ (Plate 34E, 34F) undergo the same stages of alteration as _Acropora palmata_, even though they have slightly different microstructures, with trabecular elements often widely separated.

These observations suggest that, in the subaerial, vadose, diagenetic environment, this sequence of alteration is widespread in most Pleistocene corals.

Discussion

Observations of the process of alteration taking place in Scleractinian coral skeletons, now in the subaerial, vadose, diagenetic environment on northern Barbados, have several, widely applicable implications--(1) Solution of aragonite corals is controlled by skeletal microstructure; (2) Alteration to calcite, like solution, begins at the centre of each trabecula; (3) on a larger scale, solution and replacement begin at the centre of each coral frond; and (4) the calcite texture does not exactly mimic the original, aragonite texture and may be characteristic of coral diagenesis in the subaerial, diagenetic environment.

1. Solution of the coral skeleton is not a random process but starts in the centre of each trabecular element. This area of the skeleton, containing numerous, small, intercrystalline pores, is slightly less dense than most of the trabecula. Apparently, fluids initially migrate through the coral, via these submicroscopic pores, and enlarge them by solution of the fine crystals. With continued solution, this central axis is opened to form a small channel, and solution of the aragonite needles can begin. Aragonite needles are separated from one another by preferential solution along the crystal boundaries, creating the "chalky" aragonite so common in Pleistocene corals. If the kinetics of solute movement are such that reprecipitation of calcite will not take place, i.e. the water remains undersaturated, then the coral will slowly be dissolved.

2. Solution of aragonite will be accompanied by adjacent reprecipitation of calcite if the surrounding fluids remain supersaturated with respect to calcite. The stages of alteration are controlled by the relative solubility of specific areas of the coral microstructure. As the zone of calcite precipitation moves through the coral, it is preceeded by one of aragonite solution. First, the fine crystals in the central, dark line in each trabeculae are dissolved, and calcite is precipitated in the void, creating a canal of clear calcite up to the edge of the aragonite needles. The solution

of the aragonite needles surrounding this calcite then occurs. First by solution between crystals, local precipitation of calcite in these voids, and then reaction of the aragonite needles now encased in calcite, the front moves slowly towards the edge of each trabeculae. This process of solution-reprecipitation on a microscale preserves the structure of the coral. This two stage process, first of solution-reprecipitation in the region of fine, microcrystalline crystals, and second the more involved process of changing the aragonite needles, results in a unique texture. Each trabeculae becomes a canal of clear calcite, reflecting the first stage, surrounded by a relict, fibrous texture reflecting the second stage. Although the fibrous, aragonite structure is clearly a ghost texture, the clear, central canal of the trabecula is a diagenetic, and not an original morphological, texture (Fig. 30).

3. Solution and recrystallization generally begin in the axial region of each <u>Acropora palmata</u> frond. When the upper surface of the frond is coated with crustose red algae, however, recrystallization commences in the part of the coral skeleton immediately adjacent to the red algae. The axial portion of the coral frond is made up of long, thin trabecula with widely spaced, thin tabulae. In contrast, the peripheral part of the frond is made up of thicker trabecula, sometimes unconnected, and accessory, random sclerodermites. Since solution or recrystallization starts in the centre of each trabecula, the axial region, with many thin trabecula, may be more conducive to fluid migration than the periphery of the coral, and so may be altered first.

4. Many corals from ancient and Pleistocene deposits in other areas retain a dark axis in their trabecula after they have been altered to calcite. This texture is not observed in Scleractinian corals, now in the subaerial,

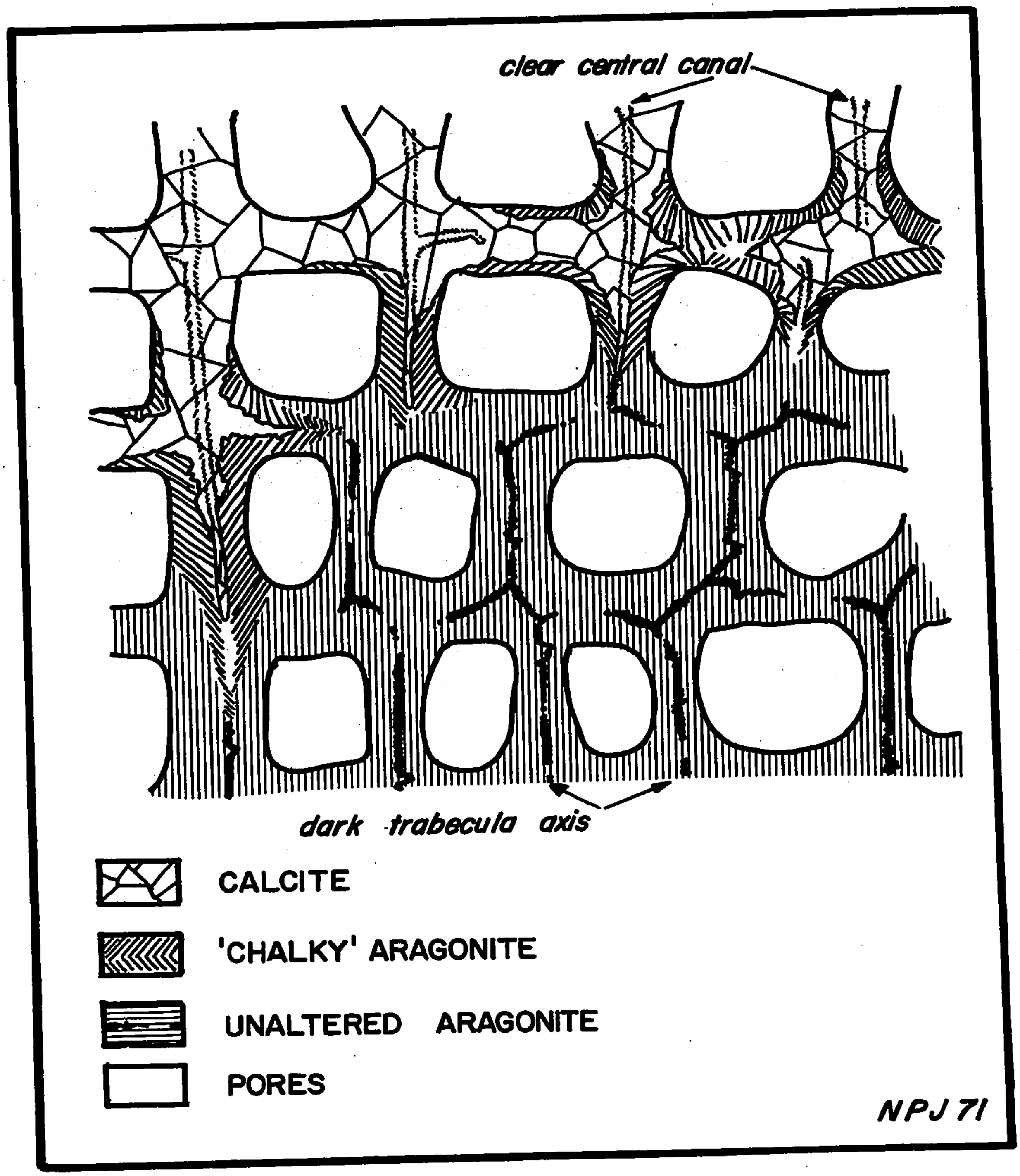

Figure 30. Diagrammatic representation of recrystallization contact, Acropora palmata.

vadose, diagenetic environment on northern Barbados. The reason for this is uncertain, and the problem awaits further study. This texture may, however, reflect alteration in another diagenetic environment, such as the subaerial, phreatic zone or deep subsurface.

Other Colonial Calcareous Skeletons

Rugose corals.--Scleractinian corals first appear in the fossil record during the mid-Triassic. An important question in the evolution of anthozoan corals is the relation of scleractinians to Paleozoic, rugose forms. Even though rugose and scleractinian corals have many analagous structures, several are specific, and the lack of corals in the Permian and lower Triassic does not allow us to trace the possible evolution from one to the other. It is thought that rugose corals secreted a calcite skeleton, because the microstructure is so well preserved.

As in the scleractinia, one of the basic structural elements in rugosan microarchitecture is the trabecula. In many forms these are monacanthine trabecula , illustrating the same, dark, "centre of calcification", and fibrous radiating structure, as present in living scleractinia. Other forms, however, illustrate a holocanthine trabecula in which the axial part of the trabecula is recrystallized to clear calcite, causing the septa to be a series of seemingly structureless rods of clear calcite, termed "holocanths", set in lamellor to fibrous sclerenchyme (Hill, 1956). This calcite, coral structure is very similar to calcite, scleractinian corals that have changed from aragonite to calcite in the vadose, diagenetic environment.

This textural similarity suggests that the recrystallization yielding the holocanth trabeculae in rugose corals may represent a change similar to that in the scleractinia, which obliterates the primary, dark, trabecular axis. This interpretation yields three important conclusions-- (1) this feature, which is common to specific rugose families, is, as Hill (1956) suggested, a diagenetic, and not a morphologic, feature; (2) the "holocanth" represents the alteration of a specific, microarchitecture unit; and (3) the skeletal mineralogy of those corals exhibiting this texture was aragonite, and not calcite.

Tabulate corals.--Preliminary observations of certain portions of the tabulate, coral skeleton also indicate a tripartite division of the skeleton. Transverse sections of *Favosites*, a common, Paleozoic tabulate, reveal an intercoralline wall structure consisting of five parts--(a) a central zone of yellowish, translucent calcite, (b) two thin, opaque lines adjacent to the central zone, and (c) two fibrous zones in which the apparent orientation of the "fibres" is normal to the wall (Swann, 1941). This description is obviously again nearly identical to the microstructural elements seen in the calcite, Pleistocene, scleractinian corals.

Examination of *Thamnopora*, another tabulate coral, from the fore-reef deposits of Upper Devonian reef complexes in western Canada, reveals a similar texture (Plate 35D, 35E, 35F). It is very difficult, strictly on the basis of calcite microstructure, to differentiate the scleractinian and rugose forms.

Stromatoporoids.--Stromatoporoids, an extinct group of colonial animals, with a calcareous skeleton, and massive, laminar, cylindrical, or dendroid growth forms, were the dominant reef-building organisms during the middle Paleozoic. Although the geologic range of the enigmatic group is Cambrian to Cretaceous, they have been divided into two groups, true Paleozoic stromatoporoids, and late Paleozoic and Mesozoic forms ascribed mainly to the Sphaeractinoidea (St. Jean, 1960).

These fossils appear to have a microstructure resembling corals. They are built of concentric laminae, separated by transverse, radial pillars. Laminae may contain a fine axial line of clear calcite, which is particularly common in the genera Stictostroma, Trupetostroma, Stromatoporella and Clathrocoilona (Stearn, 1966). Lecompte (1956) believes the light colour is the result of bleaching; St. Jean (1960) suggested that the colour is inherent and a generic characteristic; while Stearn (1966) feels it may be the joining, during preservation, of a line of cellules. The fine, axial line of clear calcite is also similar to the clear calcite axis of many coral trabecula, and so may be a diagenetic texture.

The rod-like pillars of some genera illustrate a fasciculate or "water-jet" structure made up of fibres radiating upwards and outwards from a granular axis. This is particularly characteristic of Mesozoic sphaeractinoids, appears to be due to the growth of fibrous crystals from a central axis, and is strikingly similar to the trabecula of corals. This structure has also been observed in Paleozoic forms, particularly the genera Stromatopora, Actinostroma, Taleastroma, and Syringostroma (Stearn, 1966).

Hartman and Goreau (1966, 1970) have recently rediscovered a group of living, calcareous, coralline sponges (Sclerospongiae) which bear certain striking resemblances to the stromatoporoids. The fasciculate, aragonite microstructure laid down by these Recent sponges is similar in pattern to that of Mesozoic forms. The fasciculate structures of Ceratoporella, Stromatospongia, Hispidopetra, Goreauiella and Merlai, in particular, match the microstructure of sphaeractinoid forms very well. The aragonite, like coral skeletons, is in the form of spherulitic arrays, often forming elongate, "water-jet" structures similar to trabeculae.

There is considerably difference among specialists as to which stromatoporoid microstructures are primary, and which are secondary. Similarity between the clear, central canal, surrounded by an apparent, ghost, fasciculate structure, and the altered, aragonite, trabecular structure of scleractinian corals, indicates that the clear, central canal is a secondary diagenetic feature. This suggests that many of the Paleozoic forms may have been aragonite, and strengthens the possibility that the animals were similar to modern Sclerospongiae.

Conclusion.--There may be several processes that produce a calcite trabecula with a clear, central canal. The similarity between calcite trabecula formed when aragonite, scleractinian corals alter to calcite, in the subaerial, vadose, diagenetic environment, and the calcite trabeculae of various, large, colonial organisms throughout space and time, suggests that the mode of alteration described above may have been common among a relatively large group of animals. If so, aragonite mineralogy in the Paleozoic may have been, as it is today, a dominant mineral in the skeletons of massive, colonial, reef-building organisms.

CHAPTER 5 - SUMMARY

GEOLOGIC EVOLUTION OF NORTHERN BARBADOS

The broad, flat, northern Barbados platform is underlain by the St. Lucy Arch, a north-south trending structure of Tertiary strata. Those parts of the arch exposed by erosion reveal both Lower Eocene (Scotland Formation) clastics and Middle Eocene to Miocene (Oceanic Formation) *Globigerina* marls. The oldest beds of the Oceanic Formation (Middle Eocene, *Globigerapsis kugleri* zone) outcrop along the north coast at Cluff's Bay. Pleistocene (partly late Pliocene?) limestones unconformably overlie the older, Tertiary strata. The erosional, pre-Pleistocene surface is mantled by a thin, relatively extensive, Plio-Pleistocene limestone, characterized by phylloid red algae and the foraminifer *Amphistegina*. Following deposition of the Plio-Pleistocene limestone, and throughout most of early and middle Pleistocene time, there was little or no sedimentation on the North Point Shelf. Extensive, reef-associated, carbonate deposition did not begin until late Pleistocene time. Four reef complexes, of varying sizes, were deposited during separate high stands of sea level, about 125,000, 104,000, 83,000, and 60,000 years ago.

On southern Barbados, these late Pleistocene, reef complexes form distinct terraces, with each younger terrace lower in elevation than its predecessor (Fig. 13). On northern Barbados, however, the younger, 104,000 and 83,000 year old reefs appear to have buried the 125,000 year old reef complex (Fig. 13). These different stratigraphic relationships suggest that either the relative rate of uplift in northern Barbados was substantially lower than in southern Barbados, or northern Barbados was depressed following growth of the 125,000 year old reef complex. Thus, while the 104,000 year old high stand of sea level rose only to within 12 meters of the 125,000 years B.P. reef complex on southern Barbados, the sea transgressed over the 125,000 years B.P. reef complex on northern Barbados. Likewise, the 83,000 year old high stand of sea level did not reach the top of the 104,000 year old reef complex on southern Barbados, but it transgressed over the 125,000 year old reef complex along the northeast coast. Subsequent to reef growth 83,000 years ago, the relative rates of uplift in northern and southern Barbados seem to have been reversed. The 104,000 year old reef complex, for example, now lies at a higher, 31 meter, elevation along the northwest coast, in contrast to an elevation of only 18.5 meters on southern Barbados. The complex history of reef development and tectonic uplift on northern Barbados clearly demonstrates the hazard of using tectonically active areas to determine absolute heights of sea level rise during the Pleistocene.

The upper part of the 104,000 year old reef complex is divisible into a reef facies and back-reef facies. The reef facies is comparable to the general model proposed by Mesolella and others (1970), with a _palmata_ zone grading seaward (west) into a thick, _cervicornis_ zone. The back-reef facies, however, displays marked lateral variation. The dominantly calcarenite lithologies, with delicate stick-coral growth (_Acropora cervicornis_ and _Porites porites_) in the centre of the lagoon, change northward to a series of _Porites porites_ banks and red algal ball (rhodolite) calcarenites (Fig. 15). The rhodolite zone may reflect the more turbulent, open water conditions on the North Point Shelf, north and northwest beyond the protecting influence of the Second High Cliff. The stick-coral zone in the centre of the back-reef transgressed westward during the final phase of reef growth, and partially covered some back-reef calcarenites.

The 104,000 year old high stand of sea level is not recorded on the northeast coast, but, during the following warm period about 83,000 years ago, the sea transgressed over the eastern part of the North Point Shelf and resulted in the formation of an extensive reef complex. A blanket deposit of sands and conglomerates was laid down during the initial transgression (Fig. 14). A widespread unit of *Acropora palmata* and other corals, deposited on top of these basal sediments, appears to represent a poorly established, partially transgressive, reef facies. This *A. palmata*-rich limestone served as a base upon which, as sea level continued to rise, a true barrier-reef, with recognizable facies, developed. The barrier-reef facies of this complex is a massive *A. palmata* deposit containing scattered *Montastrea annularis* with *Acropora cervicornis* developed in a leeward position. Reef growth kept pace with rising sea level and resulted in a wall of *A. palmata*, the exposed portion of which is up to 11 meters thick and contains huge *M. annularis* colonies equally high. After initial establishment of the barrier-reef, the back-reef was a lagoon of scattered coral heads grading landward into a terrigenous sand. During the latter stages of reef growth, the nearshore, terrigenous sand zone was replaced by a *Porites-Thalassia* biotope. When sea level rose to its highest point, this *Porites-Thalassia* zone migrated seaward, burying the lagoon and a part of the reef facies. The final deposit of this complex was a narrow, fringing-reef formed inland from the barrier-reef.

Sediments in and adjacent to the reef facies of both reef complexes are made up of particles produced on the reef, whereas sediment on the landward side of the lagoon is produced *in situ* and shows little reef influence. Reef sediments are characteristically bimodal, with large, whole fragments of *Amphiroa*, *Homotrema* and pelecypods in calcilutite and calcisiltite. On the basis of these larger grains, these sediments can easily be differentiated from lagoonal muds. Carbonate grains in the back-reef of the 104,000 year old complex are easily recognizable, whereas those in the finer, mottled, back-reef sediments of the 83,000 year old complex are often degraded to micrite peloids, likely the result of greater endolithic, organic activity.

Interestingly, much of the reef sediment is reworked, terrigenous, Scotland Formation quartz and feldspar grains. These grains are abundant throughout the reef complexes and are not necessarily characteristic of the beach environment.

Increased late Pleistocene uplift along the northwest coast has exposed a previously unreported, narrow, 60,000 year old, fringing-reef terrace. This young terrace, the first such reported from the Atlantic Ocean, was formed during a short sea level high stand, or boreal period, during the Early Wisconsin regression. Similar terraces have recently been reported from several areas in the Pacific Ocean.

LIMESTONE DIAGENESIS

Submarine Lithification

The importance of forming a wave-resistant structure on the reef edge, to enable subsequent development of the facies mosaic, has been stressed in many studies of coral reefs (Lowenstam, 1950; Ladd and others, 1950). In the past, influenced by the obvious dominance of organic carbonate precipitation, many workers have suggested that large skeletal elements are bound by algae and encrusting foraminifera, to create a strong framework. The discovery of submarine lithification in modern reefs (see earlier discussion, Chapter 4) indicates that there is mortar between the skeletal bricks, and a very rigidly bound framework is created *in situ*. The degree of submarine lithification within modern reefs is difficult to assess, however, because these areas are not easily studied.

Detailed investigation of the interior of the exposed, late Pleistocene (83,000 years B.P.) reef facies on northern Barbados, one of the few so investigated to date, reveals the presence of submarine lithification. Cemented material is in the form of pelleted crusts which drape around *Acropora cervicornis* sticks and bind them together. Similar crusts are also found in association with Acropora palmata fronds, indicating that the phenomenon is commonplace in several areas within the reef facies. In contrast to the generally horizontal, well-laminated, pelleted micrites from subaerial, calcareous crust profiles, these poorly laminated crusts are very irregular, and surround corals only. In thin section, the pellets from submarine crusts are generally much smaller (9 to 60 micra) than caliche pelletoids (30 to 500 micra) and each pellet is surrounded by a fringe of calcite cement.

Identical, submarine, pelsparite crusts, composed of Mg-calcite, are found today cementing growing Jamaican reefs (Land and Goreau, 1970). The presence of identical, synsedimentary cements, in both Holocene and Pleistocene reefs, indicates that submarine lithification is not a phenomenon restricted to local areas in today's oceans, but is relatively widespread, and could be expected in reefs older than Pleistocene. As the original, Mg-calcite, pelleted fabrics in Pleistocene reefs on Barbados have been altered to calcite in the subaerial environment without appreciable loss of fine texture, they should be preserved and recognizable in the geologic record.

Intertidal and Supratidal Calcareous Cements

In the past, great emphasis has been laid upon lithification of carbonate sediments in the meteoric vadose zone, as it is in this environment that, through diagenesis, much cementation takes place. Less attention has been paid to those exposed sediments along the coast where salt spray instead of fresh water is the dominant pore fluid.

Throughout the world, in the intertidal zone of modern seas, layers of Recent, beach sediments are cemented by aragonite and Mg-calcite into beachrock. On the northwest coast of Barbados, the same process is apparently operating, but it is 60,000 year old, and older, Pleistocene sediments that are being further lithified, by precipitation of Mg-calcite. Cementation of these rocks is taking place both in the intertidal and supratidal zones. Many of these sediments have been in the meteoric vadose zone throughout most of their history and are cemented with calcite. New Mg-calcite is now being precipitated on, and in many cases in optical continuity with, pre-existing calcite cement.

The origin of aragonite cement in beachrock is the subject of much debate and controversy. An aragonite crust, up to 1.5 meters thick, is precipitated from evaporating sea spray, blown onto the surface of Pleistocene limestone along the northeast coast of Barbados. This cement is petrographically similar to beachrock cement, and its presence lends support to the theory of evaporating seawater as one of the sources of aragonite, beachrock cement.

Surficial Calcareous Crusts

In warm, semi-arid areas, a series of hard, calcareous crusts, and associated features, are developing at the surface of subaerially exposed limestones. Surficial, calcareous crust profiles (caliche) have been described in a general way and several theories have been proposed as to their origin. The petrographic characteristics of carbonate in calcareous crust profiles, however, have not been described, and it is not known whether crusts from different areas possess similar carbonate textures. On northern Barbados, calcareous crust profiles are developed on the surface of Pleistocene limestones and also occur within the Pleistocene limestone sequence. Thus these calcareous crusts are valuable indicators for subaerial exposure.

Diagenesis in the upper part of the vadose zone involves both alteration of limestone and precipitation of new carbonate. Limestones are altered by solution and brecciation, recrystallization (mainly to microspar), micritization, and boring. New calcite is precipitated in the form of "flower spar", needles, and micrite. These basic crystal types combine to form the following characteristic textures--(1) cement, occurring as flower spar and random needle fibres, (2) coated particles, in the form of various nucleii coated with oolitic laminae of needles and micrite, (3) crusts, and (4) pelletoids, formed from both precipitated calcite and micritized particles.

These textures are not unique to the crusts on Barbados, but are the basic elements of similar crusts and associated lithologies in Florida and the Middle East. Since all of the precipitated carbonate is calcite, these features are likely to remain little affected when buried in the vadose zone, and hence will tend to be preserved in ancient rocks.

Coral Diagenesis

The diagenetic processes that result in the alteration of original, skeletal mineralogy to calcite have been little studied, due to the sluggishness of the reactions involved and the small scale of the textures formed. Although our knowledge of past life forms is dependent upon fossil,calcareous skeletons, there is considerable uncertainty among many workers as to whether the textures observed are truly primary, the product of diagenesis during alteration, or some combination of both.

Pleistocene corals in the subaerial, vadose, diagenetic environment on northern Barbados are presently approaching equilibrium with surrounding vadose fluids, either by dissolving or by altering to calcite. Solution of aragonite corals is not a random process but is strictly controlled by the skeletal microstructure. Solution begins at the centre of each trabecula, a slightly porous area of fine aragonite crystallites, the spaces between which may be partially filled with soluble organic material. Solutions appear to migrate through these small intercrystalline pores and dissolve the fine aragonite crystallites. Following dissolution of the trabecula axis, the surrounding long needles of aragonite begin to dissolve, by solution along the intercrystalline contacts, thus isolating each needle and destroying the dense structure. When solution reaches this stage, the aragonite can be easily scraped away with a fingernail and has a "chalky" appearance.

The stages of alteration to calcite are also governed by coral microstructure. The first aragonite to be replaced is that in the centre of the trabecula. Replacement then proceeds outward at right angles from the axis of the trabecula, until the whole aragonite trabecula is altered to calcite. Replacement never takes place from the pore walls inward towards the axis of the trabecula. The final coral texture is one of large calcite crystals. The original, dark centre of each trabecula is a canal of clear calcite, and the rest of the trabecula displays a ghost texture of fibrous aragonite.

Both solution and replacement of the aragonite coral skeleton begin at the centre of the trabecula and proceed outward towards the coral pores. The similarity between the courses of diagenesis not only indicates that they are controlled by coral microstructure, but also emphasizes the fact that replacement probably involves a solution stage, however small. The existence of a solution stage in the replacement process is also illustrated by the presence of a zone of partially dissolved aragonite, or "chalky" aragonite, often only a few microns thick, between original aragonite and final calcite stages of partially altered corals.

Scanning Electron Microscope photographs of the aragonite-calcite contact in partially altered corals revealed that many of the aragonite needles are partially dissolved and separated from one another. These partially dissolved needles can be traced into the adjacent calcite rhombohedron, where they are enclosed in calcite. This relationship suggests that the $CaCO_3$ dissolved from between the aragonite needles may be locally precipitated before the needles themselves are altered, thus preserving the microstructure of the coral.

Many large colonial organisms (Rugose corals, Tabulate corals, Stromatoporoids) in the fossil record exhibit similar calcite fabrics. These calcite fabrics suggest that originally these organisms may have been aragonite. The manner in which these Paleozoic organisms changed from aragonite to calcite may have been similar to the process outlined above for late Pleistocene corals now in the subaerial, vadose, diagenetic environment.

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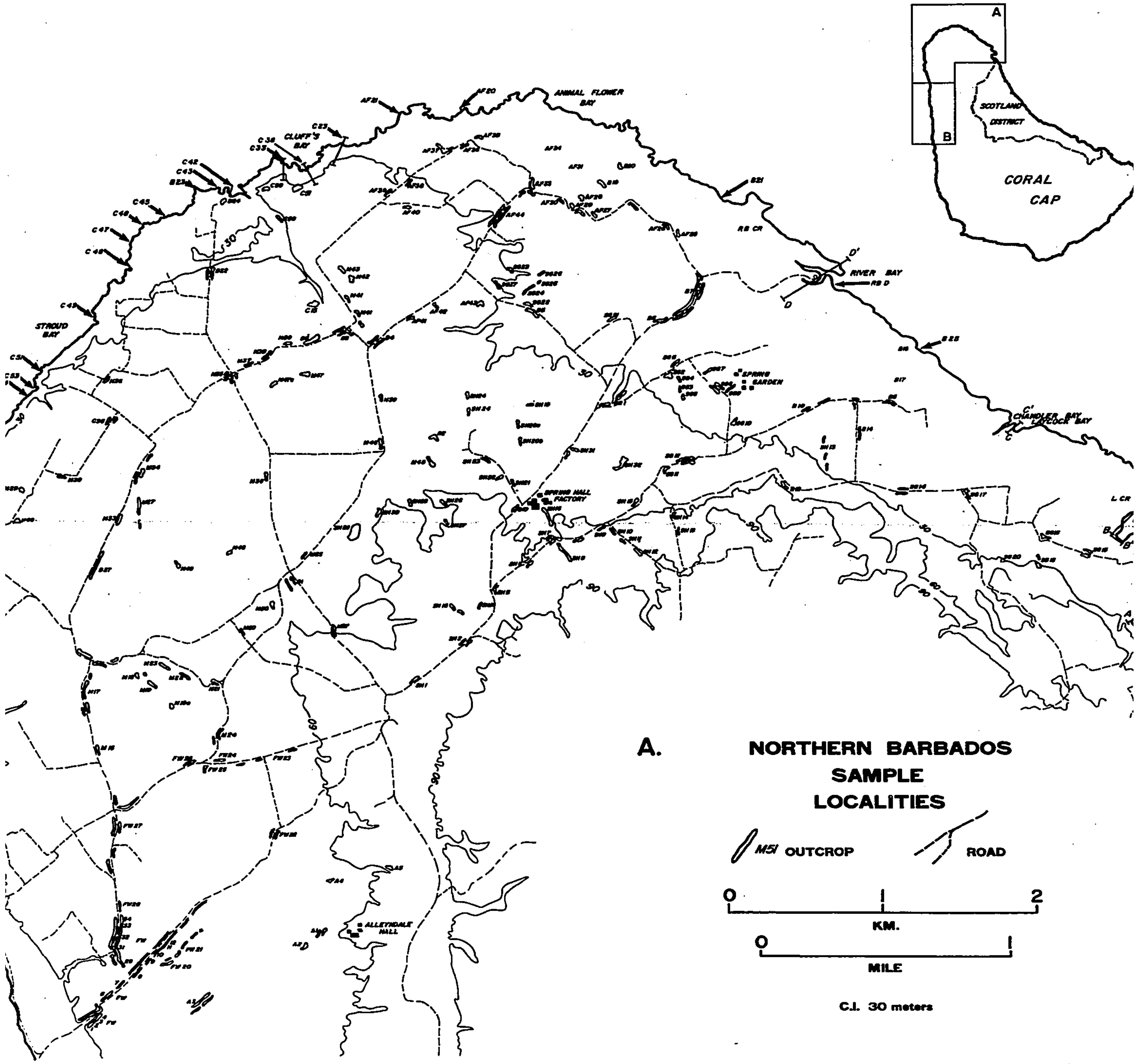
A. NORTHERN BARBADOS SAMPLE LOCALITIES
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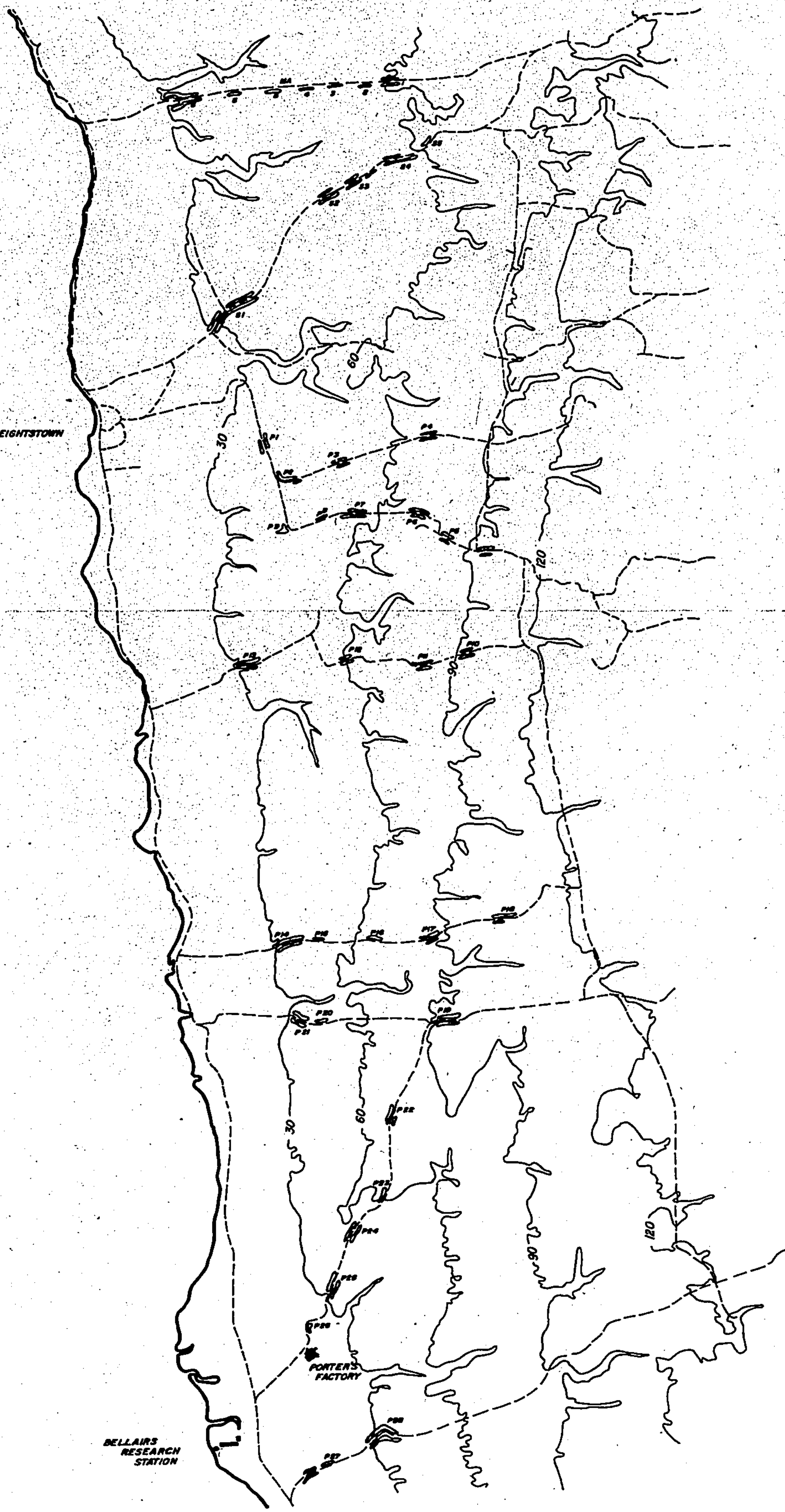
CORAL CAP
SCOTLAND DISTRICT
A
B
ANIMAL FLOWER BAY
CLUFF'S BAY
STROUD BAY
RIVER BAY
SPRING GARDEN
SPRING HALL FACTORY
ALLEYNDALE HALL
CHANDLER BAY
LAYCOCK BAY

C.I. 30 meters


SPEIGHTSTOWN
PORTER'S FACTORY
BELLAIRS RESEARCH STATION
30
60
90
120

McGill University

LATE PLEISTOCENE REEF LIMESTONES, NORTHERN BARBADOS, W.I.

VOLUME II - PLATES AND APPENDIX

by

Noel P. James

A thesis submitted to the faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Geological Sciences

Montreal, Quebec

December, 1971

PLATE 1

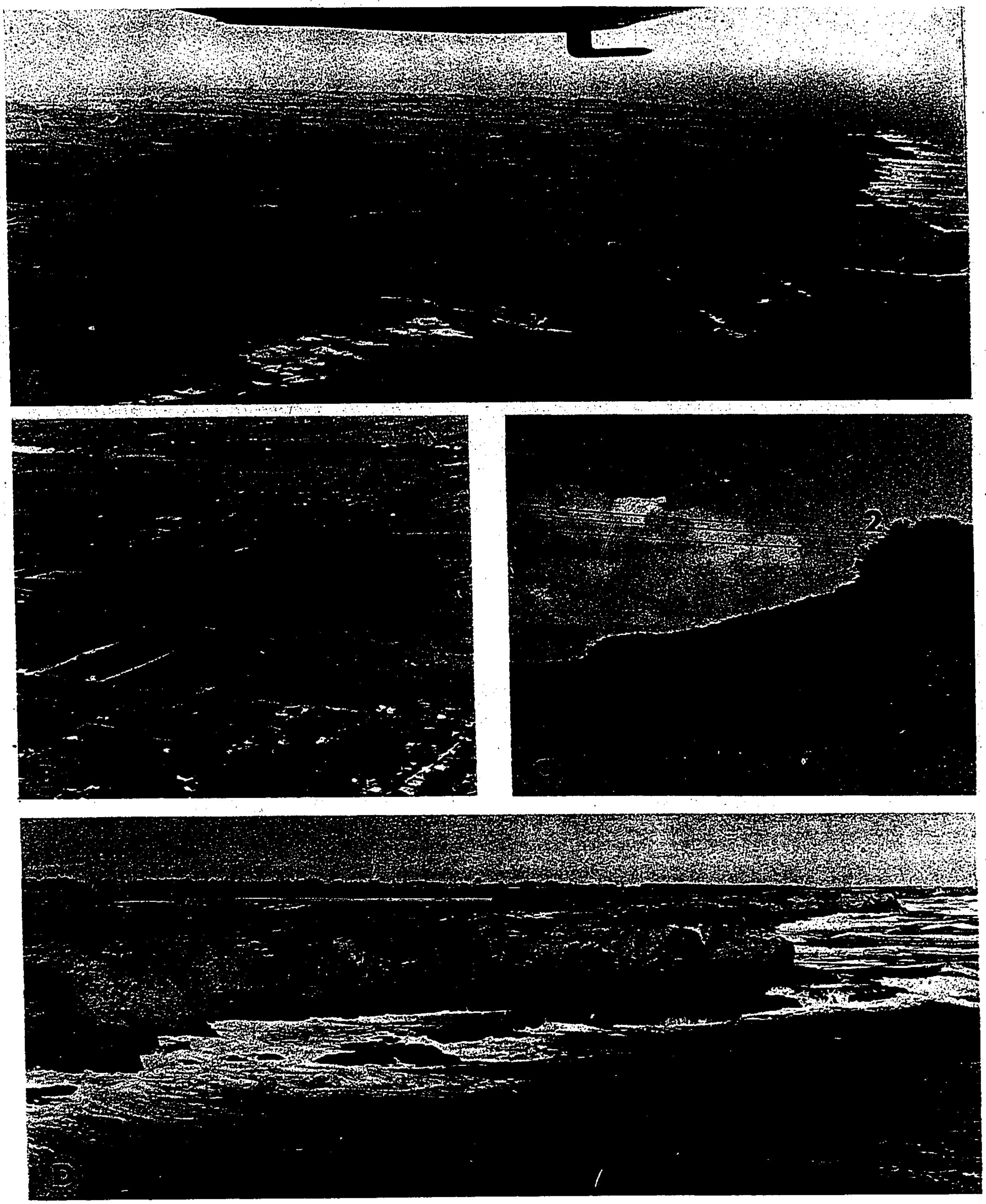
GENERAL PHYSIOGRAPHY

A. Areal view of northeastern Barbados, looking north-northwest. The major escarpment inland (2) is the Second High Cliff, at the foot of which lies the broad, relatively flat, North Point Shelf. This part of the shelf is made up of limestones that were deposited as a reef complex about 83,000 years ago, when the Second High Cliff was a series of sea cliffs, similar to those at the right. The whole area has since been uplifted, exposing the 83,000 year old complex. The bay in the left foreground (G) is Gay's Cove and the bay to the right (L) is The Landlock.

B. Areal view of the west coast of Barbados, near Speightstown, looking east (the ocean is just out of view to the lower left). Arrows indicate the First High Cliff (bottom) and Second High Cliff (top). The cliff face, with bare outcrop and scattered trees, is mainly the reef facies, while the cultivated fields overlie the back-reef facies of each complex.

C. Second High Cliff (2) near Spring Hall Factory. Here a younger terrace (centre, left) has been deposited against the leading edge of the Second High Cliff (Terrace F, Fig. 9).

D. Sea cliffs, about 10 meters high, along the northeast coast near Waites Bay are cut into a back-reef lithology of the 83,000 year old reef complex. Here coral heads (dark irregular patches) lie in a light calcarenite matrix. The upper meter or so displays a well-developed, calcareous crust profile.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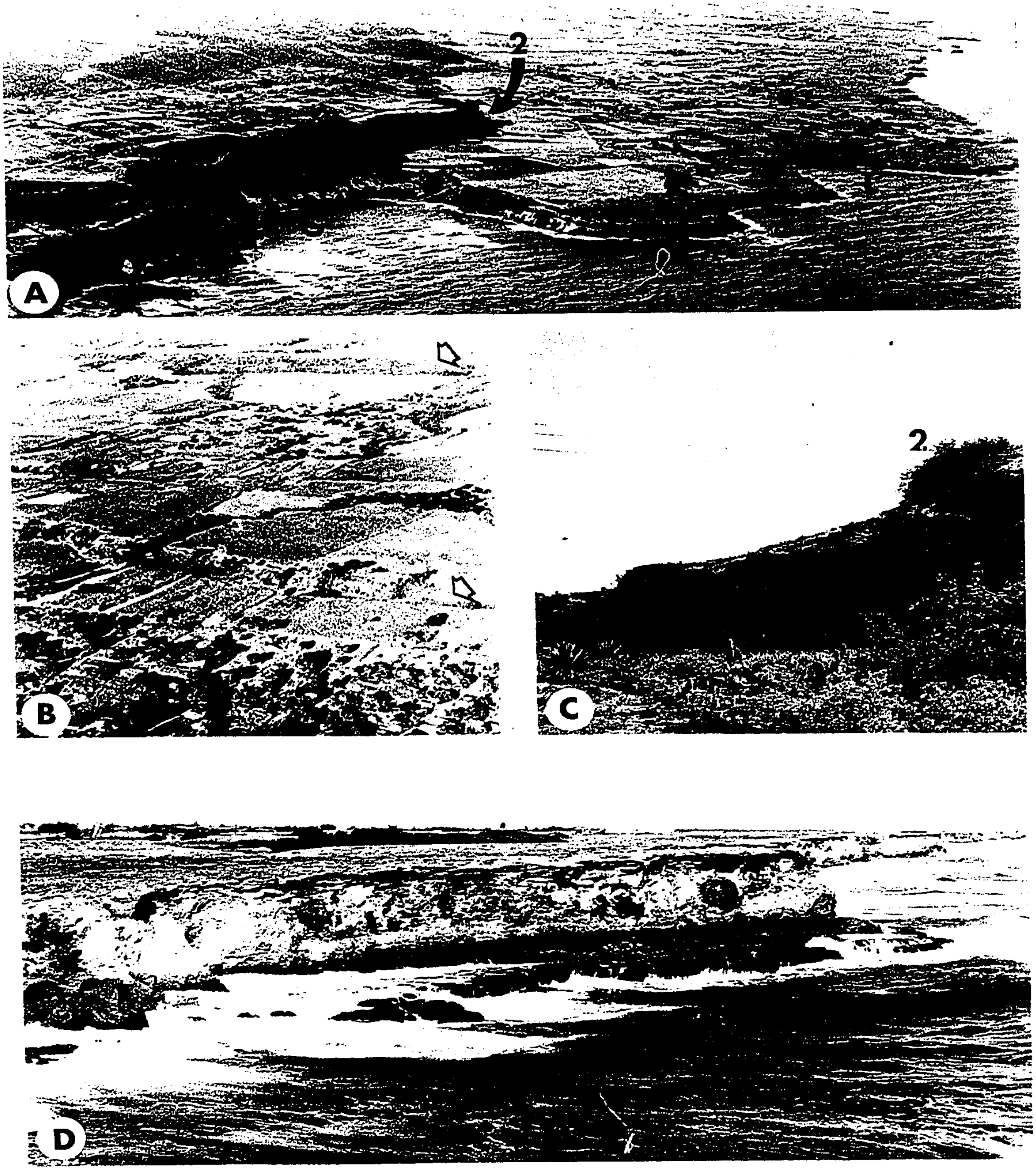
2
A
B
2
C
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PLATE 2

TERTIARY AND PLIO-PLEISTOCENE STRATA

A. Middle Eocene, Oceanic Formation, *Globigerina* chalks at Cluff's Bay. The numerous dark beds, rich in terrigenous sand and silt, may represent volcanic ash falls (Senn, 1946). These beds display small scale faulting (upper left).

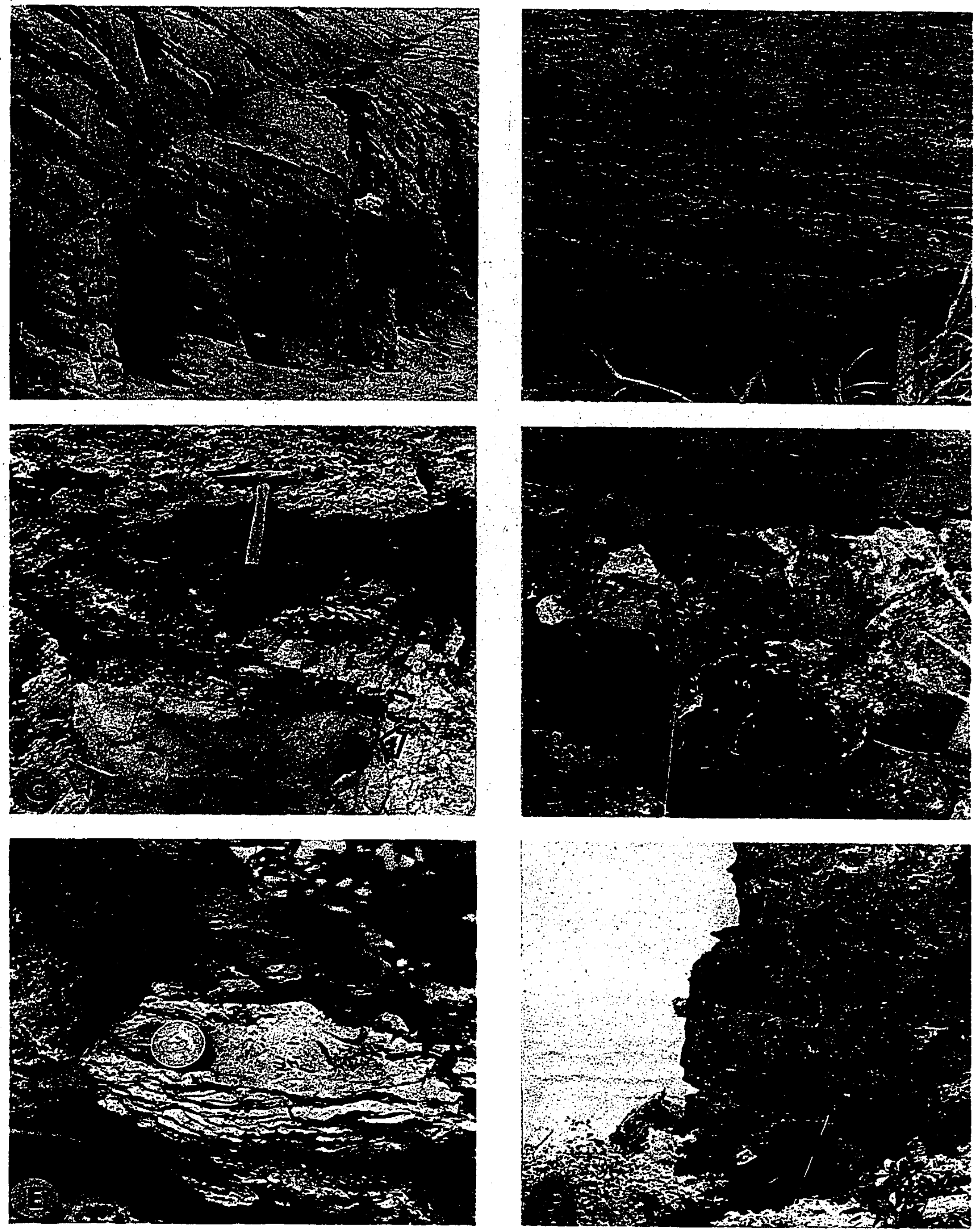
B. Lower Eocene, Scotland Formation, sandstones near Spring Hall Factory (locality SH 30). Fine grained, poorly lithified sands contain many thin irregular micrite laminae.

C. Contact between Middle Eocene, Oceanic Formation, chalks (bottom) and Plio-Pleistocene phylloid algal limestones (top) at Cluff's Bay. Irregular nature of the contact is illustrated by an erosional channel cut into the chalk (arrows indicate channel boundaries, the bottom of the channel is just out of view).

D. Contact between Lower Eocene, Scotland Formation, sandstones and Plio-Pleistocene phylloid algal limestones (a) near Spring Hall Factory. The limestones are underlain by a conglomerate whose boulders (b) are made up of Scotland Formation and whose matrix (m) is micrite with scattered foraminifera.

E. Plio-Pleistocene phylloid algal limestone (locality SH 9) with prominent banding. Diameter of the penny scale is 2 cm.

F. Well bedded sequence of *Amphistegina* calcarenite at Cluff's Bay.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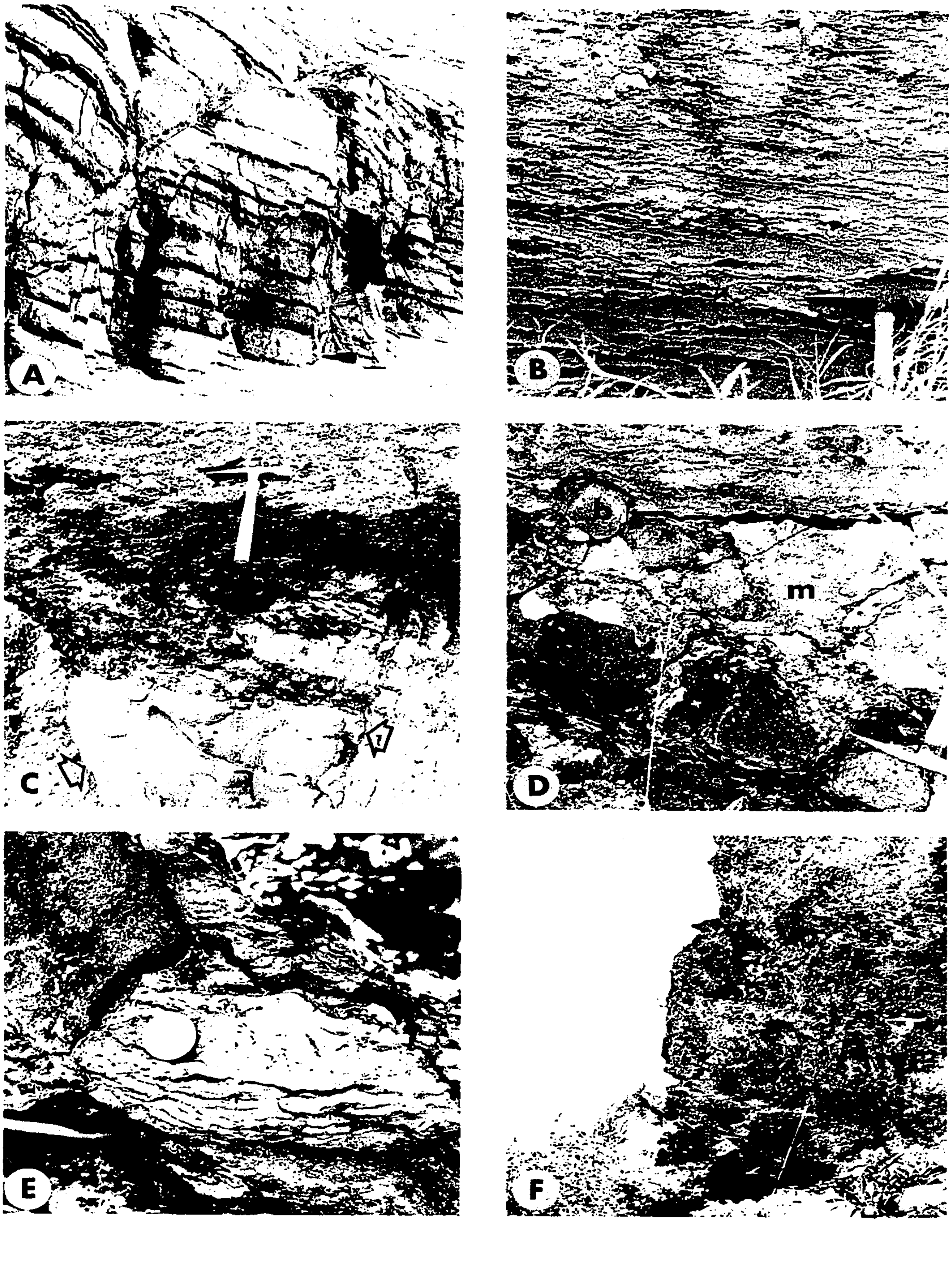
A
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PLATE 3

PLIO-PLEISTOCENE ALGAL AMPHISTEGINA LIMESTONE

Photomicrographs - Plane Polarized Light

A. Phylloid algal limestone. A cross section of crustose red algal plates which appear as dark bands in thin section. Fracture at upper right cuts both foraminiferal micrite and several algal plates. This fracture is filled with the same pelsparite as between the plates in the lower part of the photograph, suggesting early lithification of the foraminiferal micrite (Sample M35 B).

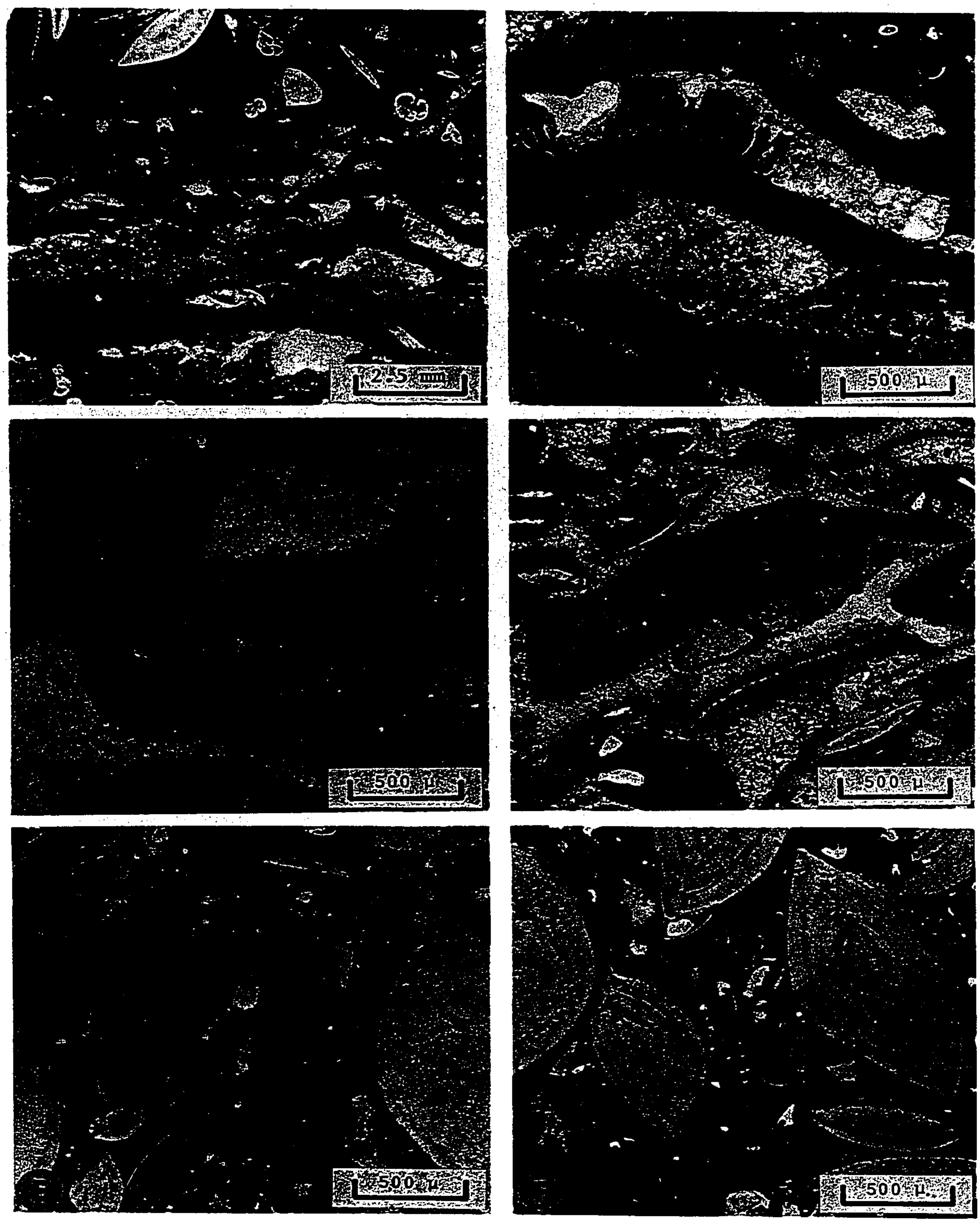
B. Enlargement of lower right hand area in above thin section illustrating pelsparite between the crustose red algal plates.

C. Phylloid algal limestone. Excellent geopetal texture occurs between algal plates. Each void is rimmed with a thin crust (20 micra?) of calcite spar cement which is succeeded by a partial detrital fill of fine pellets (Sample B13 B).

D. Phylloid algal limestone, calcarenite lens. The large intraclast at centre is composed of pelsparite, identical to that between crustose red algal plates in (B) above, suggesting early lithification and erosion.

E. _Amphistegina_ calcarenite. The biomicrite between whole foram tests contains scattered sand sized fragments of crustose red algae (centre) (Sample C24 B).

F. _Amphistegina_ calcarenite. The biomicrite between large lentiform _Amphistegina_ tests contains many planktonic foraminifera and crustose red algae fragments (Sample SG 9).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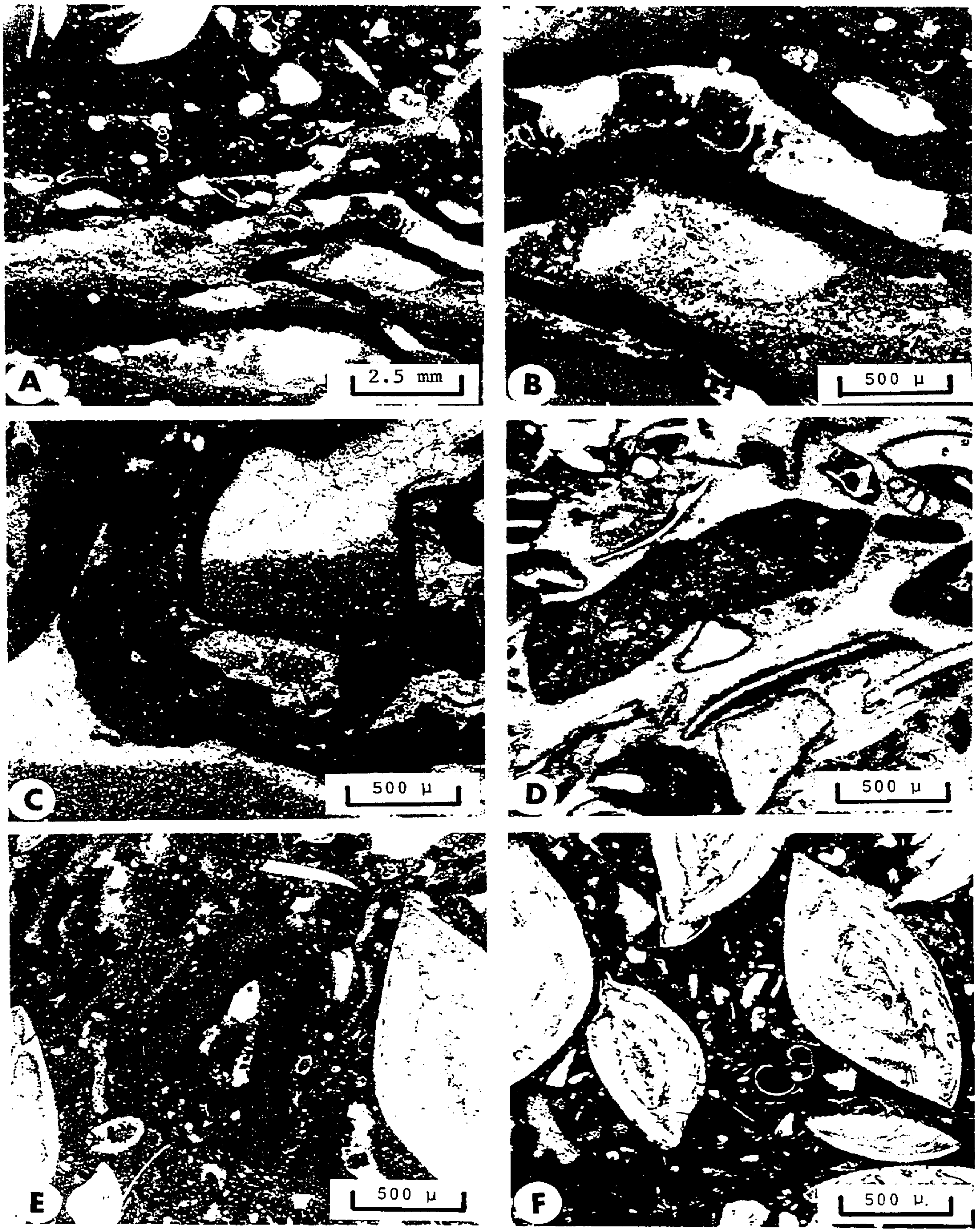
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PLATE 4

60,000 YEAR OLD REEF TERRACE

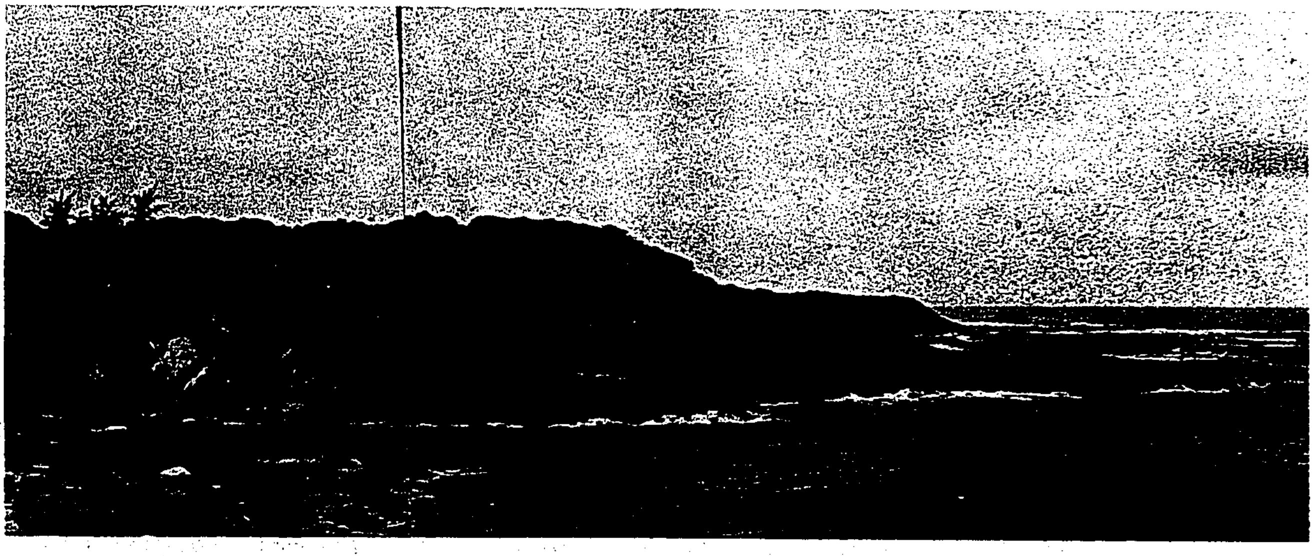
A. Western side of Cluff's Bay. Oceanic Formation (white) at left centre is overlain by Plio-Pleistocene limestones which make up most of the dominant 30 meter high cliff. The platform at right centre (Goulding's Green) is a separate reef terrace formed about 60,000 years ago.

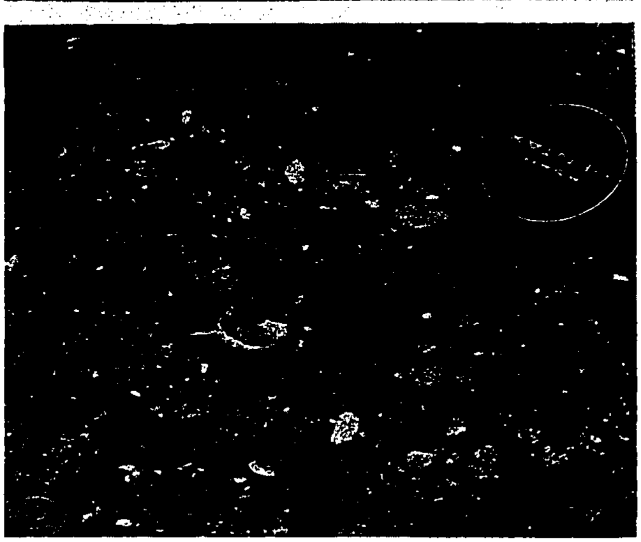
B. Point Harrison as viewed from Norse's Bay. Note notch cut into late Pleistocene limestones on the promontory. The floor of this notch lies at about the same elevation (about 3 meters) as the 60,000 year old reef terrace limestones of Norse's Bay.

C. The 60,000 year old reef terrace is deposited upon a bench cut into older Pleistocene limestone (see Fig. 11). On the landward side of this bench, a notch (illustrated here) is cut into the limestone cliffs. In this example at Goulding's Green the notch is cut into Plio-Pleistocene limestone.

D. Scattered mollusc fragments (white specks) in coarse to medium grained calcarenite of the 60,000 year old reef terrace at Goulding's Green. (Camera lens cover 5 cm. in diameter).

E. Large columns of <u>Montastrea annularis</u>, commonly found in the reef facies of modern and Pleistocene reefs, forming the northern edge of the terrace (Hammer scale).





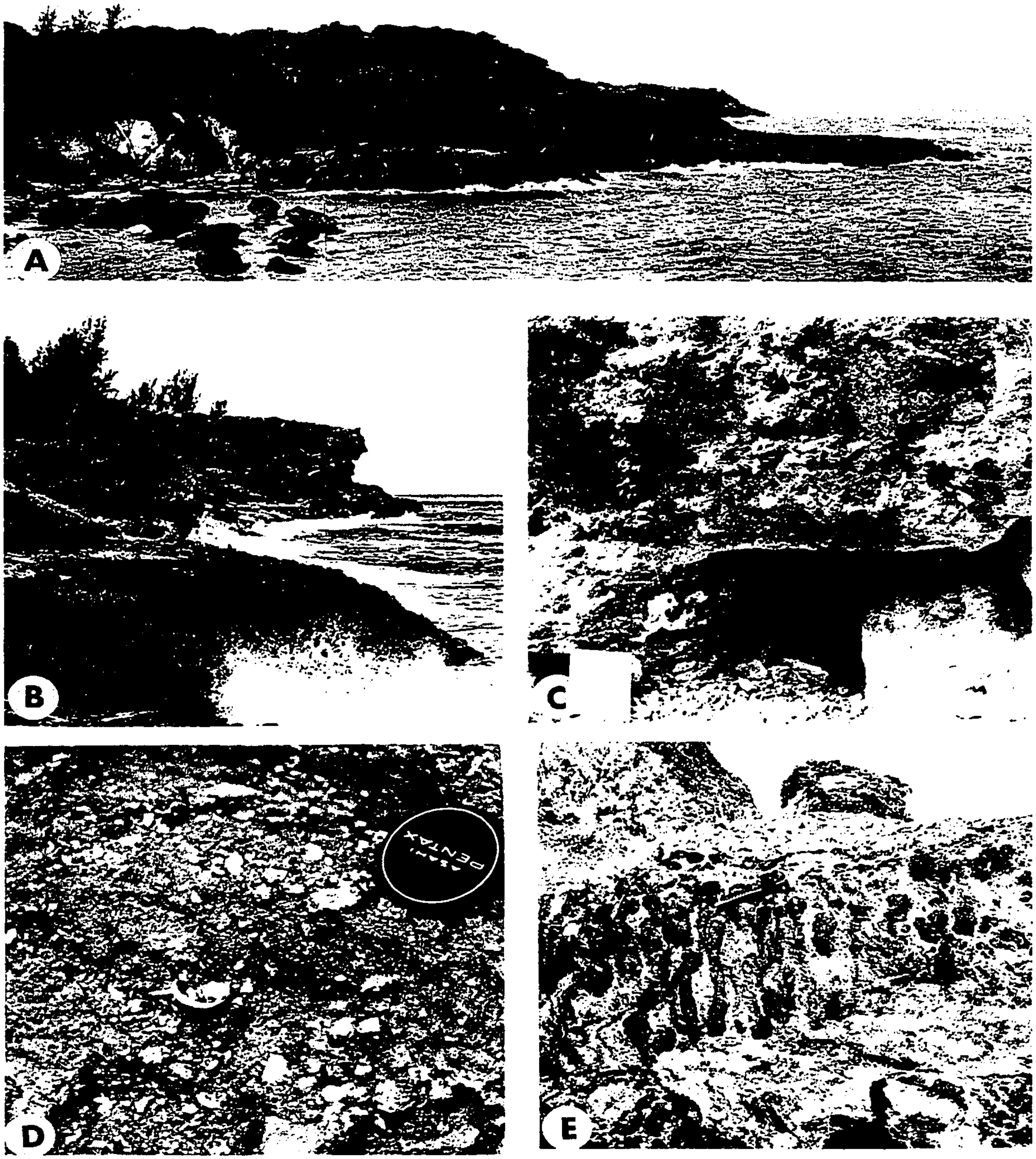

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PLATE 5

83,000 YEAR OLD REEF COMPLEX

BASAL STRATA

A. Sea cliffs, about 20 meters high, forming the northern shore of Gay's Cove (see Plate 1A). Late Pleistocene (83,000 year old) reef limestones overlie tilted, well-bedded, Upper Eocene (Oceanic Formation), _Globigerina_ marls that dip eastward at about 40°. The dark colour of the lower reef limestones is due to the relatively large proportion of reworked Scotland Formation terrigenous grains in the matrix between corals. The contact is irregular.

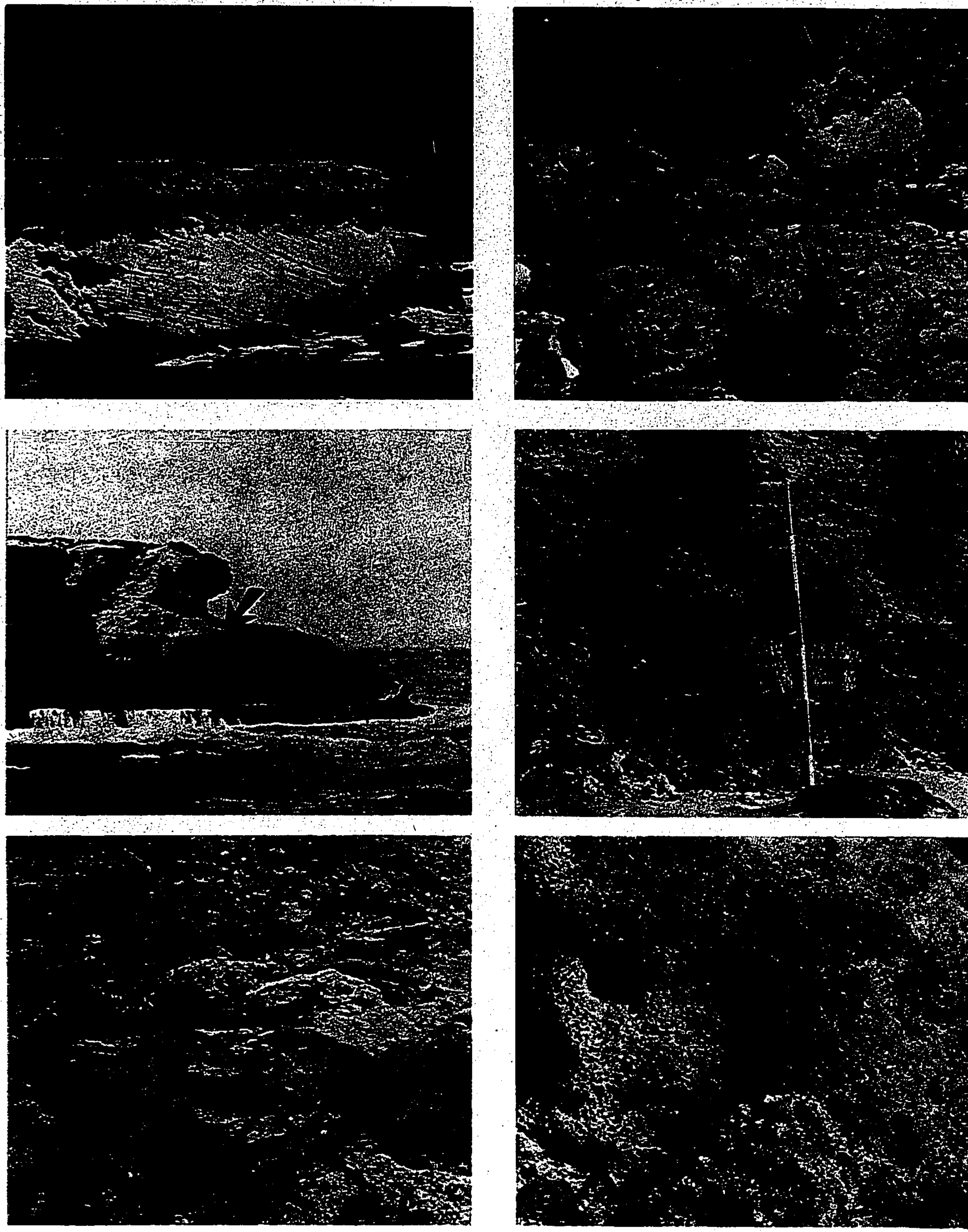
B. Conglomerate at the contact illustrated in (A). White boulders of Oceanic Formation are surrounded by a dark matrix of reworked Scotland Formation sands.

C. Contact (arrow) between 83,000 year old (upper) and 125,000 year old (lower) reef complexes in the 20 meter cliffs at Animal Flower Bay. The younger limestones are not as well lithified as those below and so weather recessively, yielding a good physical expression of the contact.

D. Basal lithologies of the 83,000 year old reef complex at The Landlock. A thin, basal conglomerate is overlain by heads of _Montastrea annularis_ which in turn are covered by a well-bedded, terrigenous sand.

E. Contact, at hammer, between the basal, _Acropora palmata_ lithology and overlying back-reef facies at The Landlock (see Fig. 14). Crustose red algae thickly encrusts the upper surface of the coral.

F. Upper surface of a limestone boulder in the basal conglomerate of the 83,000 year old reef complex. This boulder has been extensively bored by the sponge _Cliona_ (note numerous boreholes) indicating, as does the encrusting red algae in (E), a period of non-deposition. Penny scale is 2 cm. in diameter.



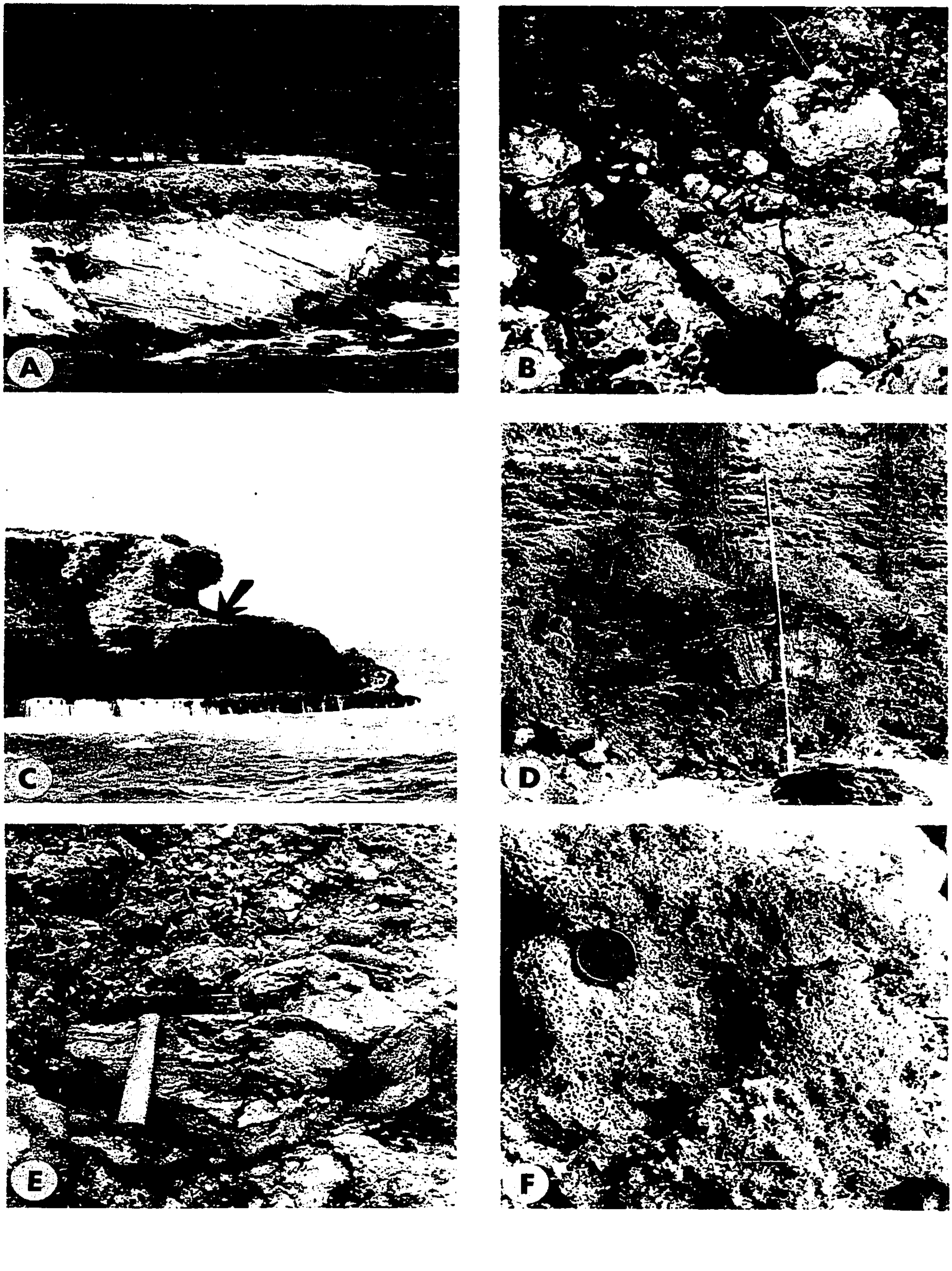

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PLATE 6

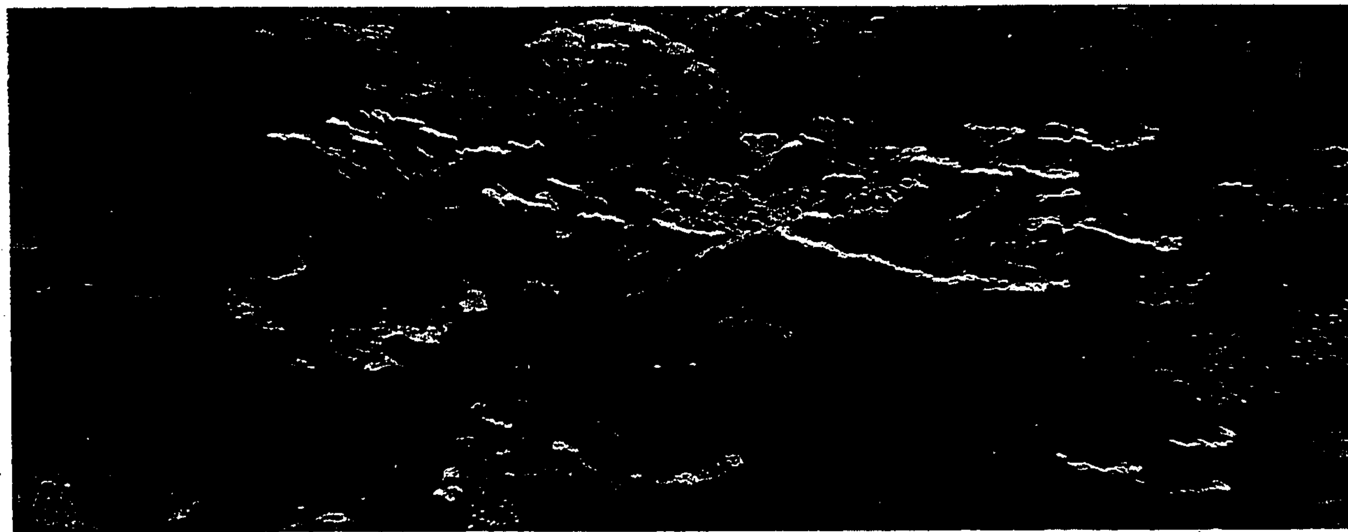
REEF FACIES - PALMATA ZONE

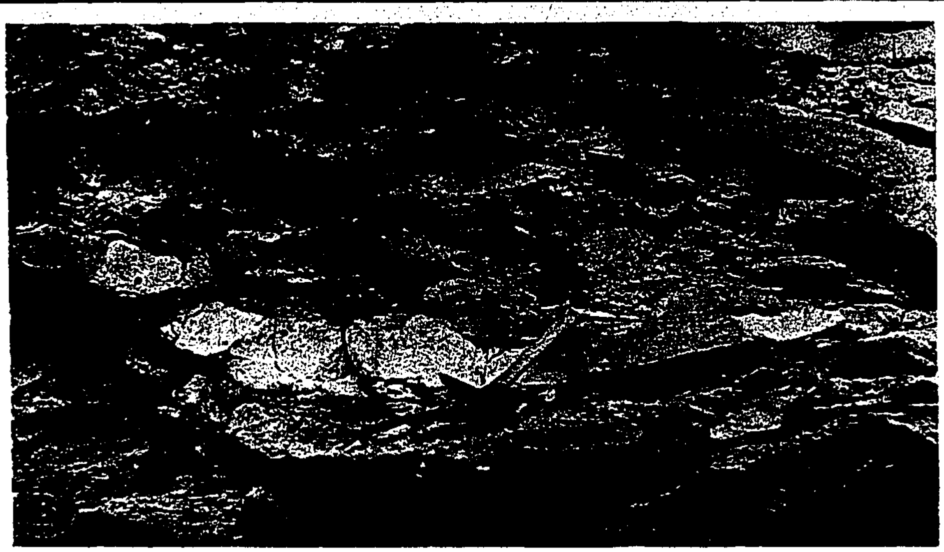
A. A large Acropora palmata colony growing at a depth of about three meters in the reef facies of the Florida reef tract. Each extended coral branch is concave upwards.

B. Cross-section of a large Acropora palmata branch, or frond, in the reef facies of the Pleistocene, 104,000 year old, reef complex (locality FH C51). The large central coral is concave upwards, indicating that it is probably in growth position. The two corals at the right, however, are concave down, suggesting they are not in growth position.

C. Massive accumulation of Acropora palmata fronds in the barrier-reef facies of the 83,000 year old complex (locality AF).

D. Interbedded Acropora palmata (a) in a dominantly Acropora cervicornis (b) reef facies. River Bay.



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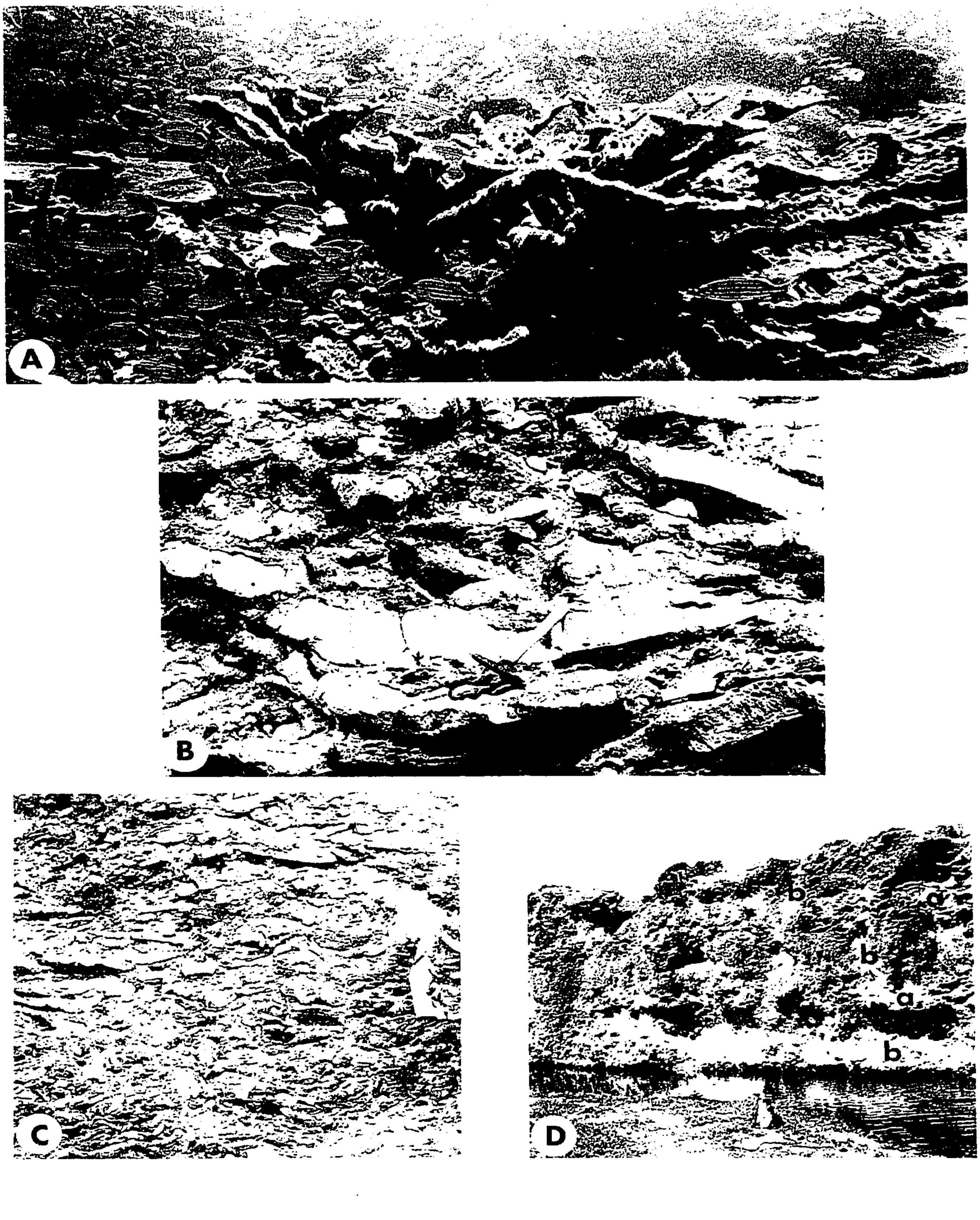
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PLATE 7

SEDIMENT BETWEEN ACROPORA PALMATA FRONDS

Photomicrographs - Plane Polarized Light

A. Large whole sticks of the articulated red coralline alga Amphiroa (lower half) and scattered blocky coral grains (upper right) in a calcilutite matrix, Calcite. (Sample CD 2).

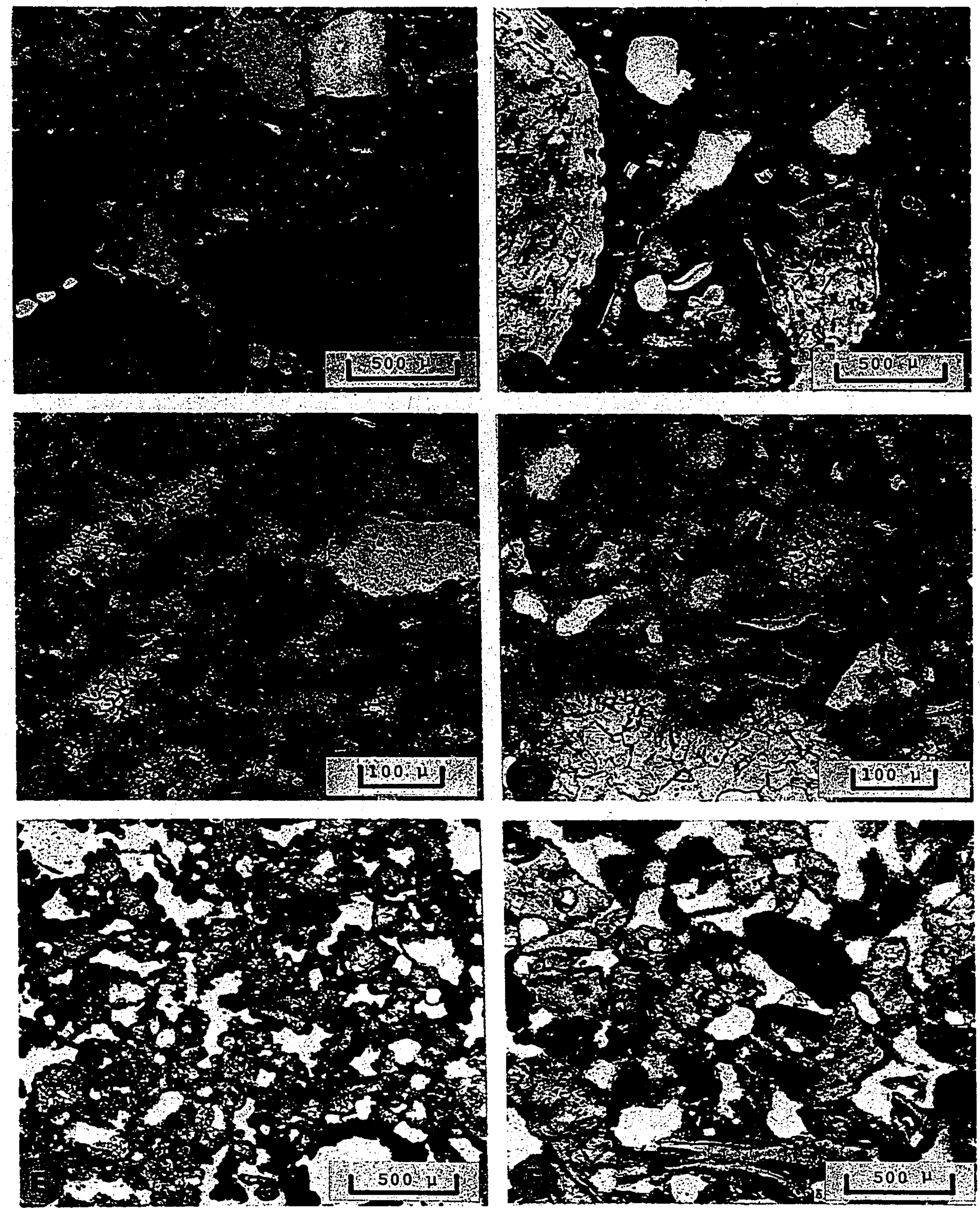
B. Large whole tests of the foram Homotrema (left and lower right) in a calcilutite matrix. Calcite. (Sample P25 A).

C. Calcilutite matrix between large skeletal grains illustrated in (A) and (B). Clear blocky calcite has been precipitated into the voids created when fine aragonite allochems (mainly corals) are dissolved. (Sample FHD 3).

D. Calcilutite matrix between large skeletal grains. One relatively large area (lower left) and numerous small areas of blocky calcite are the result of calcite precipitation into voids created by the solution of aragonite allochems (mainly corals). Contrast with the well preserved textures of the small Homotrema fragment (originally Mg-calcite) above the large area of clear clacite. (Sample FHD 2).

E. Coral calcarenite, with a relatively uniform grain size, in which each grain is now calcite. (Sample AFD2 B9).

F. Well sorted coral calcarenite with accessory dark grains of articulated coralline algae. These coral grains are still aragonite and have not yet altered to calcite. (Sample WB5 G2).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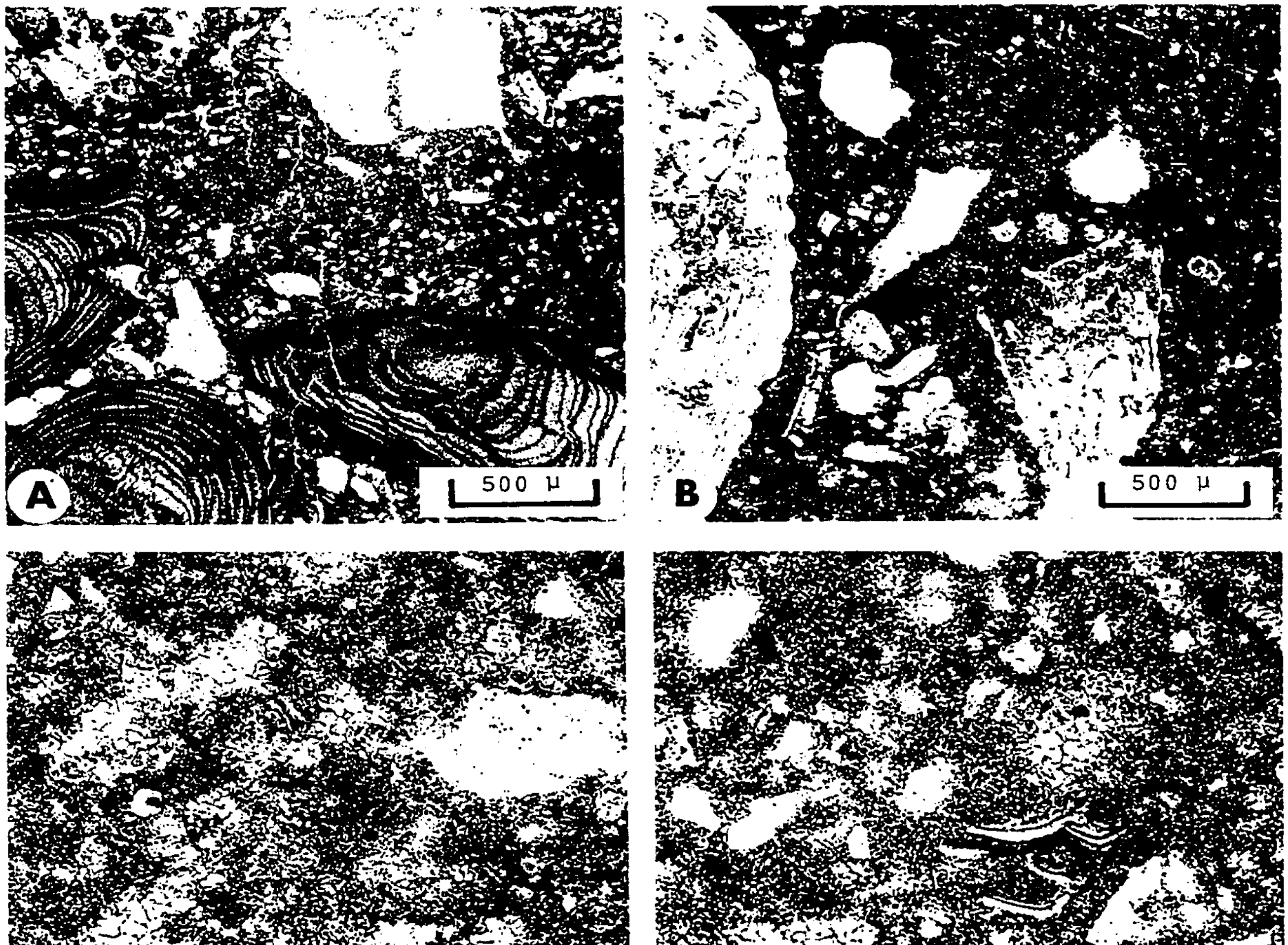
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PLATE 8

REEF FACIES - PALMATA ZONE

A. An Acropora palmata colony in the 83,000 year old reef complex, encrusted with red algae and bored by the date mussel Lithophaga.

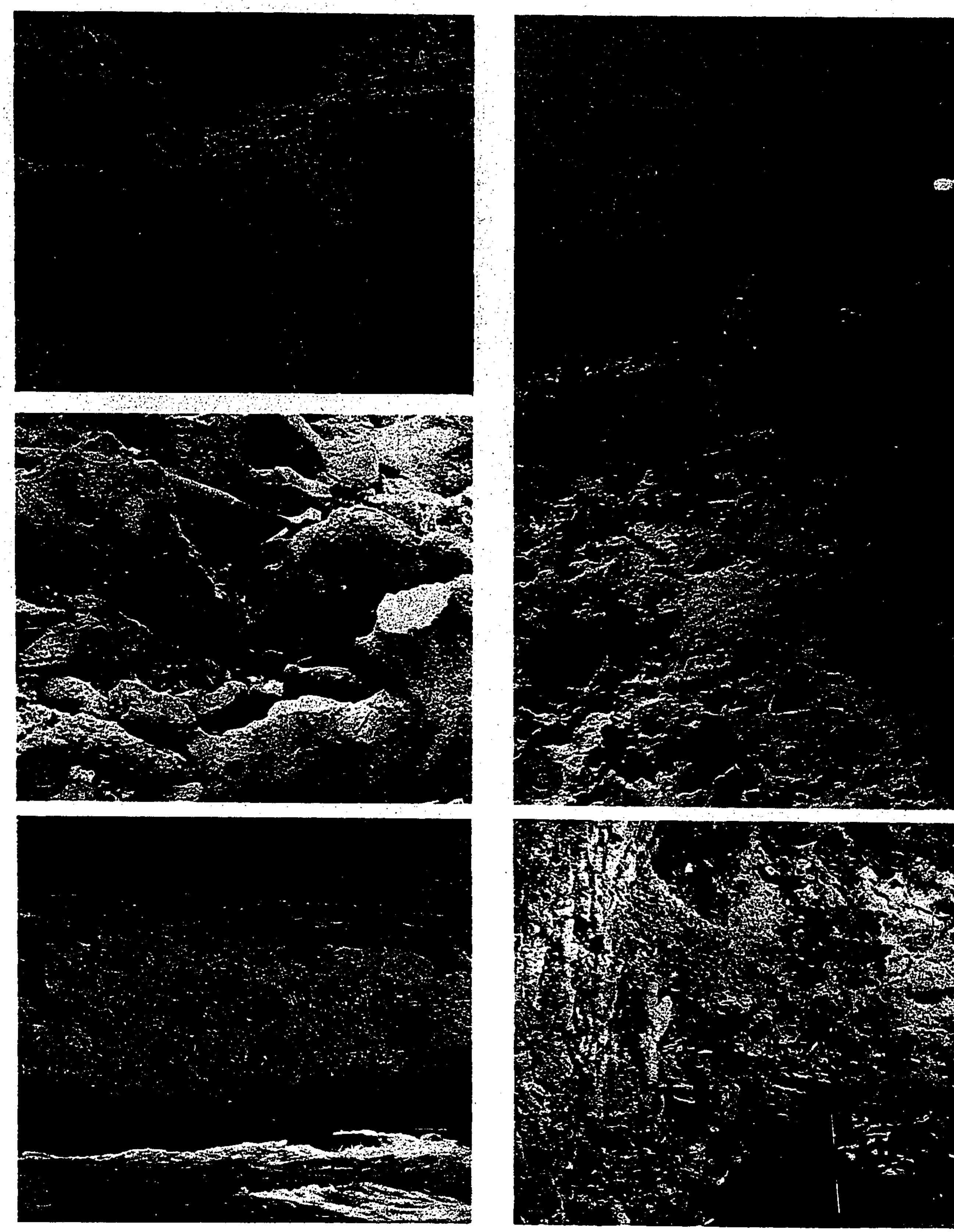
B. Acropora palmata fronds in the 83,000 year old reef complex, viewed from the base.

C. Palmata zone off the north coast of Jamaica (Pear Tree Bottom). The floor between coral colonies, at a depth of about 6 meters, is littered with large, often overturned, broken Acropora palmata branches.

REEF FACIES - MONTASTREA ANNULARIS

D. Sea cliffs, about 12 meters high, forming the northern side of The Landlock. The large Montastrea annularis colony occupies most of the cliff and separates the barrier-reef (right) and back-reef (left) facies. This colony is overlain by a Porites porites-rich lithology (see Plate 14) upon which are developed surficial calcareous crusts.

E. Contact between large Montastrea annularis (left) and massive Acropora palmata (right) lithologies (locality B25). Scale divisions on range pole (lower right) are 1 foot wide.



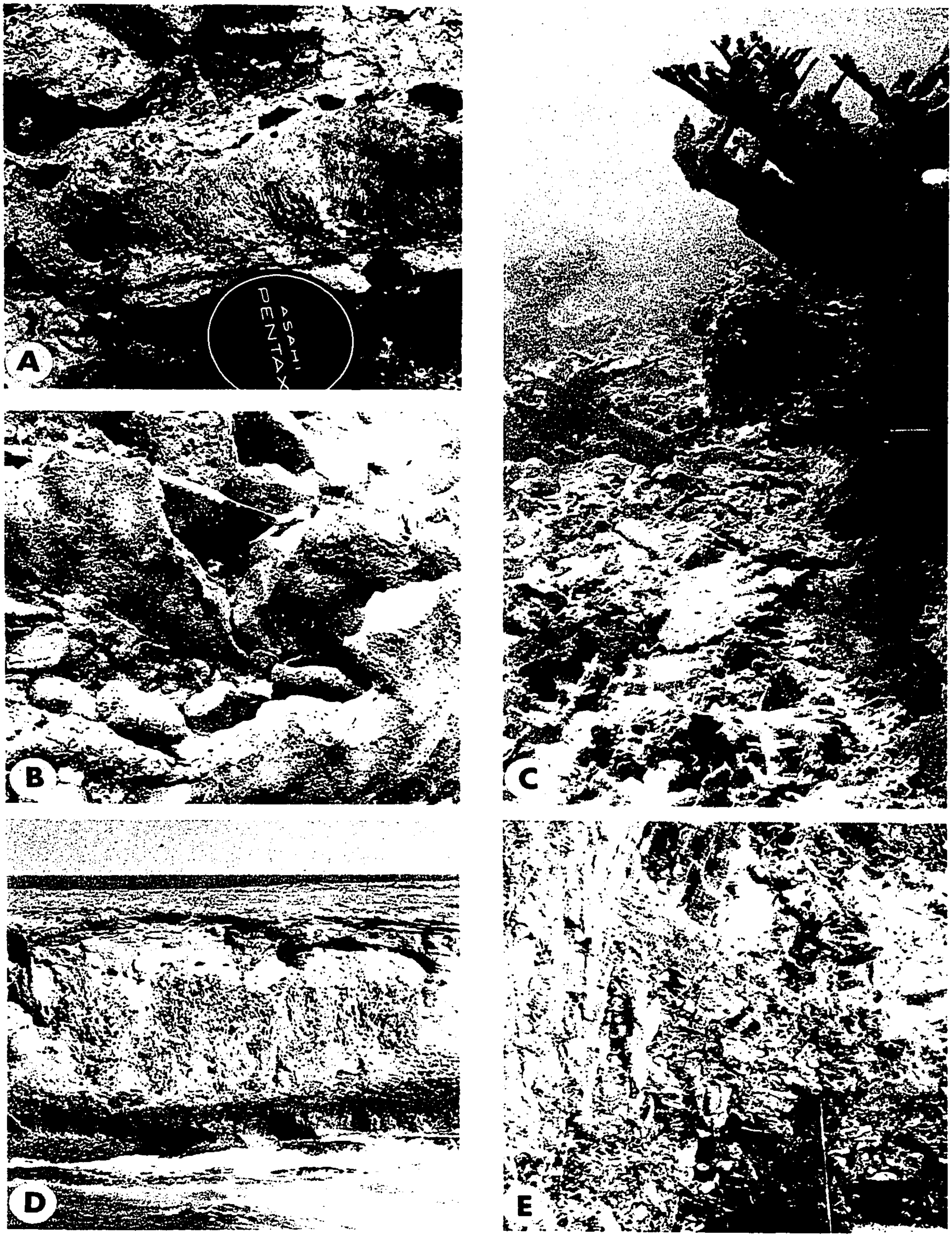

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PLATE 9

REEF FACIES - MONTASTREA ANNULARIS

A. Large Montastrea annularis colony, about 2.5 cm wide, in the reef facies, in about 3 meters of water off the north coast of Jamaica (Pear Tree Bottom).

B. Tall, columnar Montastrea annularis surrounded by Acropora cervicornis in the reef facies of the Pleistocene, 83,000 year old, reef complex. (locality B25).

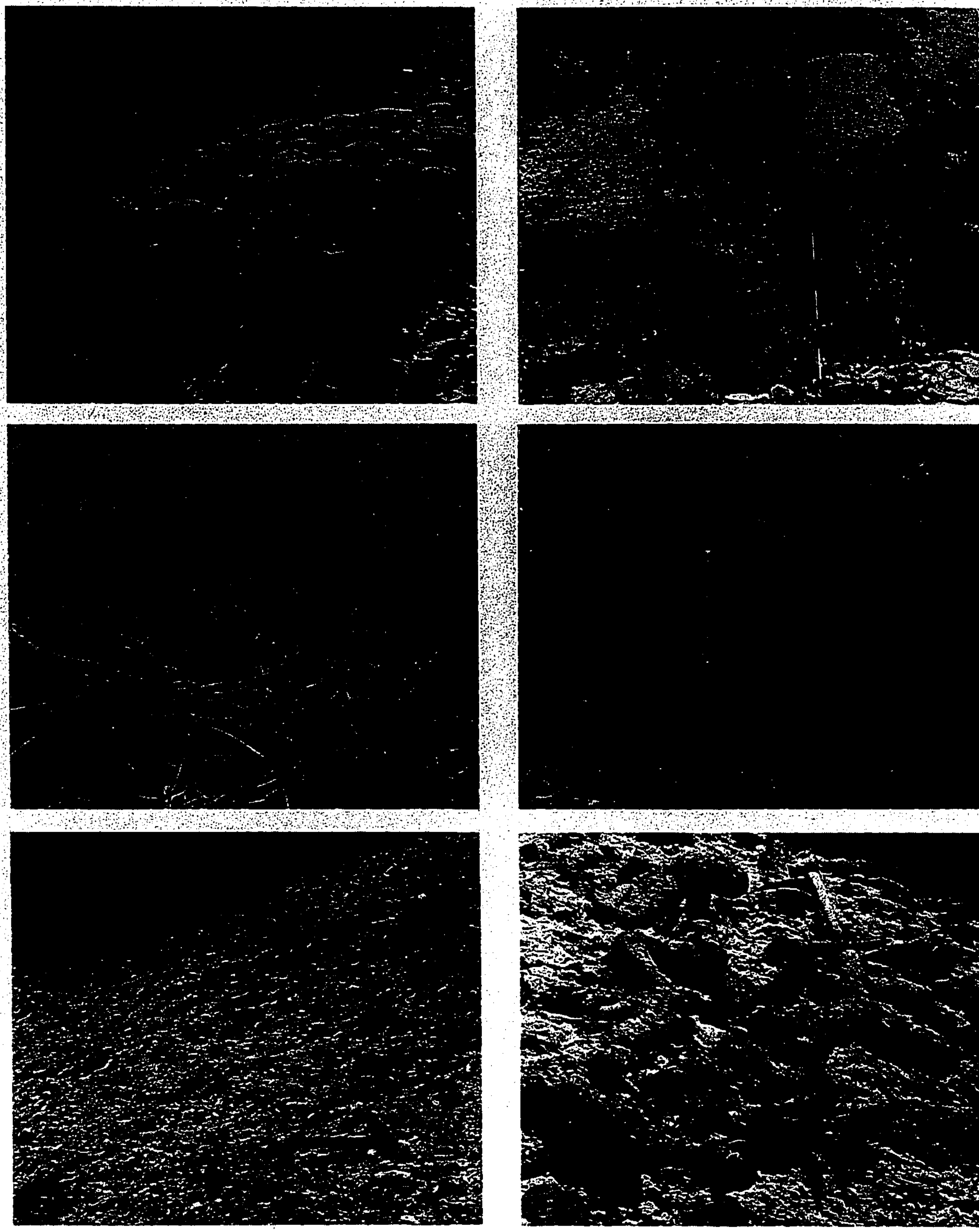
REEF FACIES - CERVICORNIS ZONE

C. Profuse growth of Acropora cervicornis in about 10 meters of water off the north coast of Jamaica (Discovery Bay). Diver at top provides scale.

D. Cervicornis zone in the barrier-reef facies of the Pleistocene, 83,000 year old, reef complex at River Bay, Barbados. Scale division on range pole is 1 foot.

E. Cervicornis zone in the 83,000 year old reef complex at Little Bay, Barbados. Here sticks are weathered out of the poorly lithified matrix.

F. Large Acropora cervicornis sticks to the right of the Montastrea annularis colony in Plate 8D. Compare the size of the coral sticks to those in 9D.



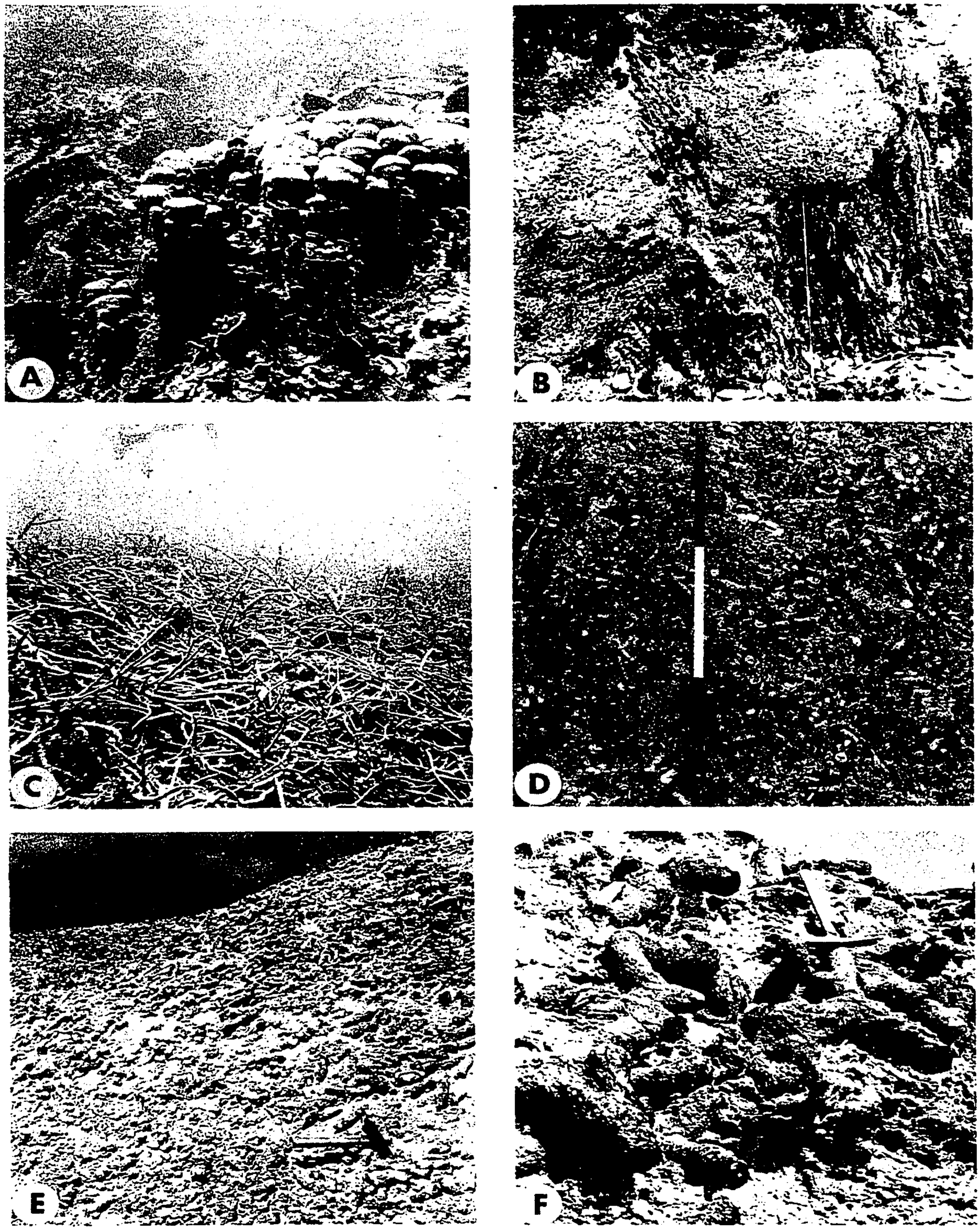

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PLATE 10

SEDIMENT BETWEEN ACROPORA CERVICORNIS STICKS

Photomicrographs - Plane Polarized Light

A. Large rods of the articulated coralline algae *Amphiroa* (upper left) in a matrix of very fine coral and other accessory grains. Calcite. (Sample SD 1).

B. Fine grained matrix of sample illustrated in (A). Clear blocky calcite has been precipitated into voids created by the solution of aragonite coral fragments.

C. Bimodal calcarenite made up of large whole *Amphiroa* rods (lower left) and bivalve particles in a matrix of fine grained coral fragments. (Sample SD 1).

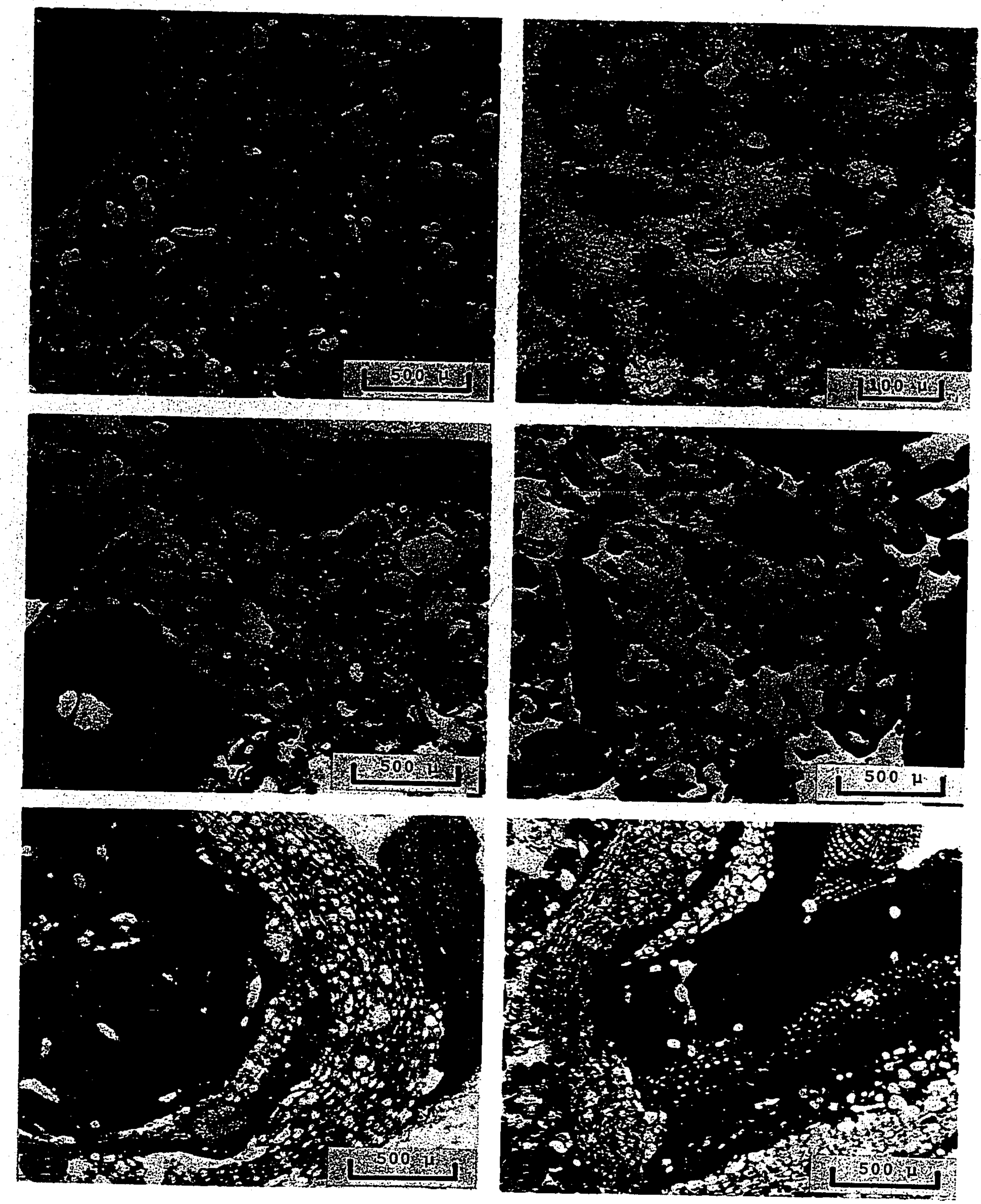
D. Bimodal calcarenite of large *Amphiroa* (right) in a matrix of fine grained coral fragments and miliolid foram tests. (Sample P13 D).

CRUSTOSE RED ALGAL NODULES

Photomicrographs - Plane Polarized Light

E. Red algal ball composed of a central core of crustose red algae (a) encrusted by the foram *Gypsina plana* (b) which is in turn coated with more crustose red algae (c). (Sample M23).

F. A broken fragment of crustose red algae encrusted by the foram *Gypsina plana*. (Sample M19 A).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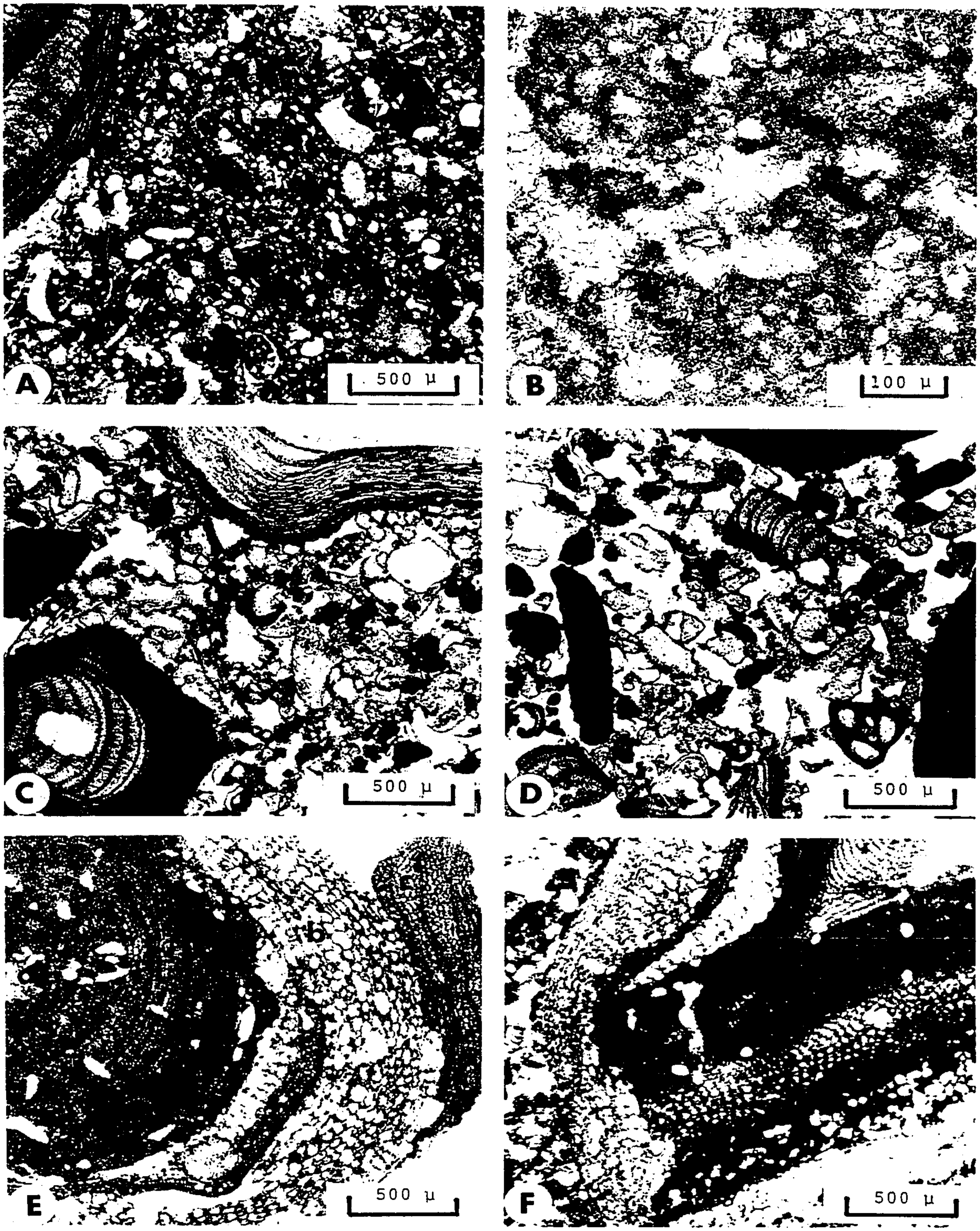
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PLATE 11

83,000 YEAR OLD REEF COMPLEX

BACK-REEF FACIES - CORALS (THE LANDLOCK)

A. Solitary head of Diploria strigosa in mottled calcarenite.

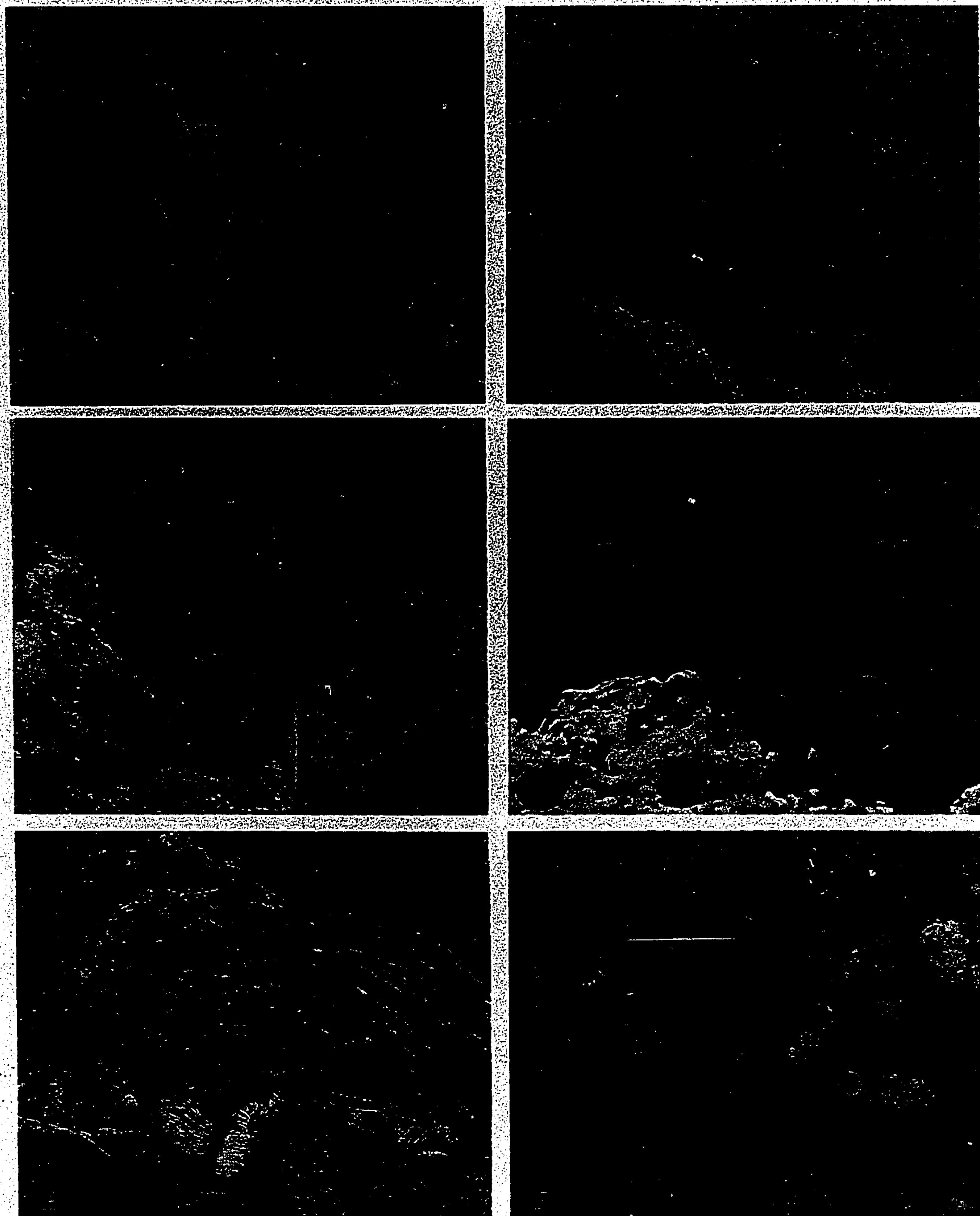
B. Large, rounded head of Montastrea annularis, 1.25 meters high, (compare with Plate 9B) surrounded and covered with small individual "hat-shaped" colonies in growth position.

C. Closer view of columnar "hat-shaped" colonies of Montastrea annularis.

D. Montastrea annularis in the "hat-shaped" growth form at a depth of about 4.5 meters in the back-reef of the Florida reef tract. Compare with the Pleistocene forms in (C).

E. Low, encrusting, sheet-like growth form of Montastrea annularis, 0.25 meters high. Small, attached gastropods are living Littorina.

F. Abundant corallites of Eusmilia fastigiata.



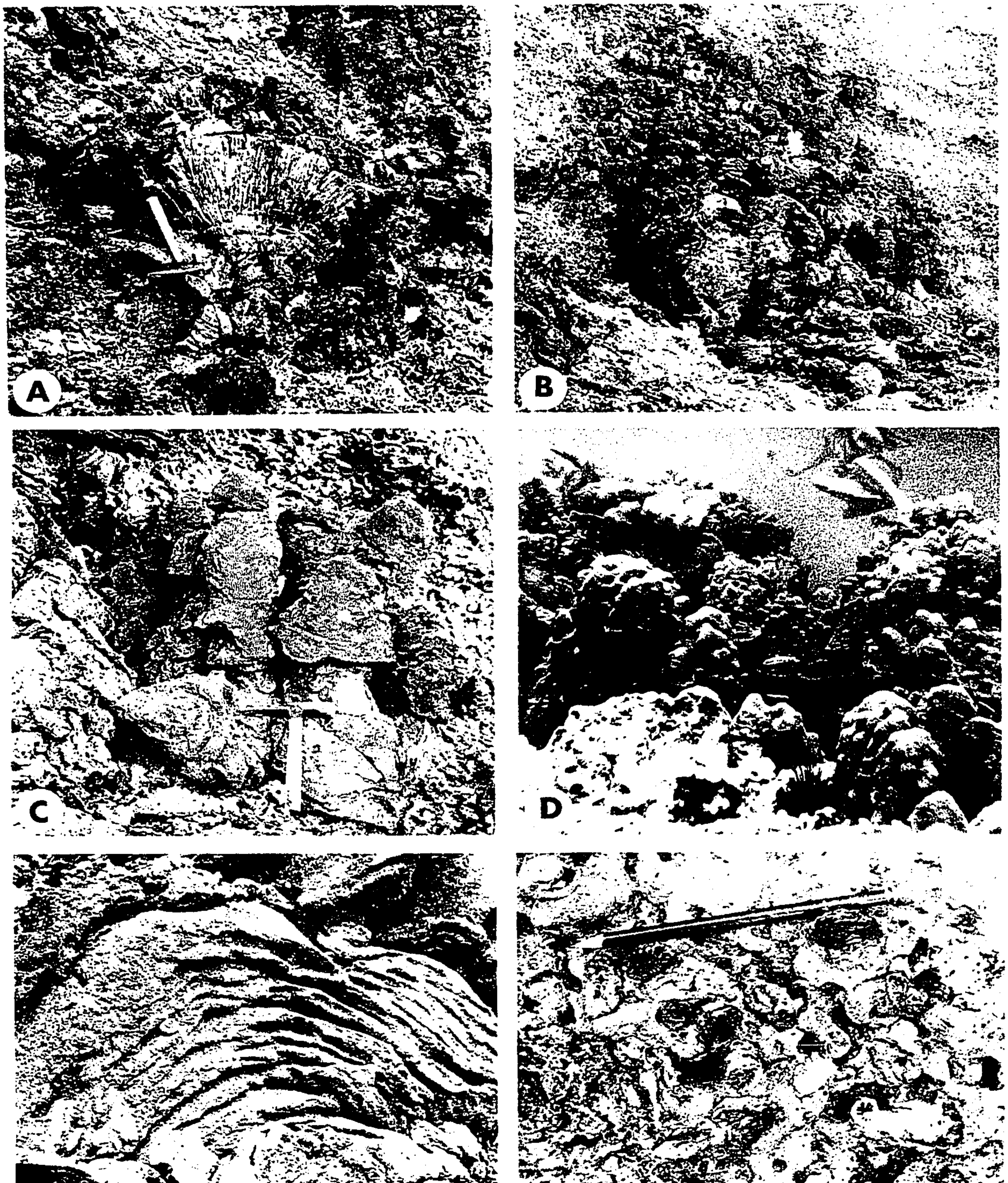

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PLATE 12

83,000 YEAR OLD REEF COMPLEX

BACK-REEF FACIES - OUTCROP OF VARIOUS SEDIMENTS (THE LANDLOCK)

A. Bioturbated terrigenous sand. Note the relatively horizontal laminae disturbed by burrowing animals (see Plate 5D).

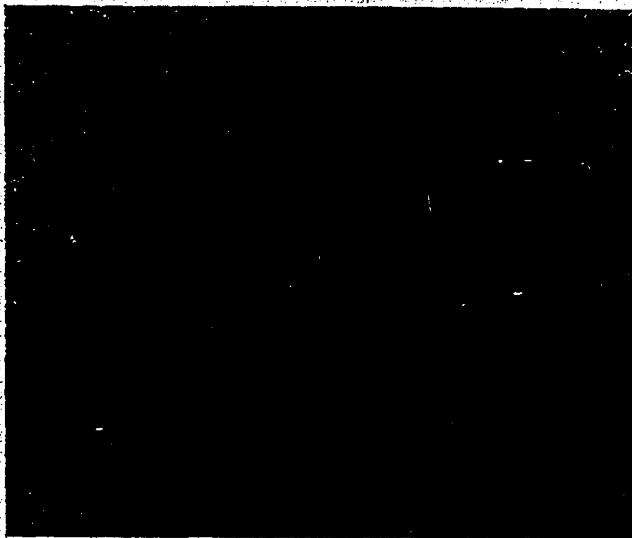
B. Burrows preferentially cemented by carbonate in the terrigenous sand zone.

C. Transition between coarse basal calcarenites and mottled back-reef sediment.

D. Typical mottled lithologies of the back-reef facies. Dark sediment is terrigenous sand and the white mottled material is fine grained carbonate.

E. Close-up view of mottled texture in vertical cross-section showing the more resistant tubular and cross-cutting nature of the white carbonate mottles.

F. Horizontal surface section illustrating the internal nature of the white mottles. Each mottle is lined with fine white carbonate and filled with slightly coarser very fine grained calcarenite. These mottles may represent the holes of borrowing animals (perhaps the shrimp Callianassa) that were later filled with fine carbonate. Penny scale is 2 cm in diameter.





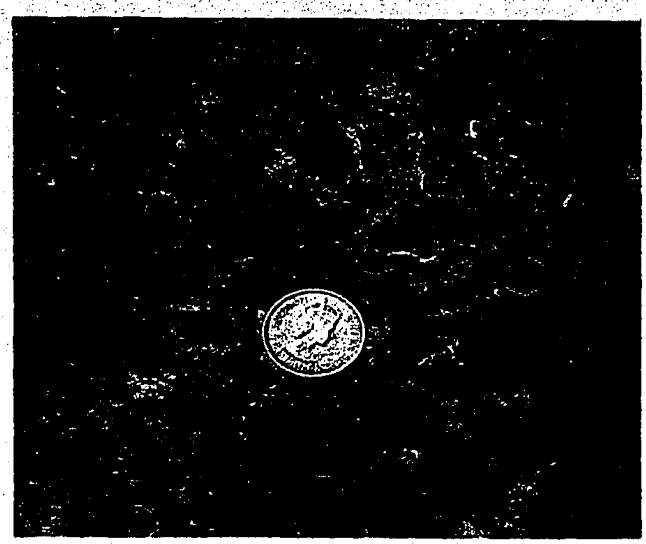




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PLATE 13

83,000 YEAR OLD REEF COMPLEX

SEDIMENTS FROM BASAL PART OF COMPLEX

Photomicrographs - Plane Polarized Light

A. Large, elliptical intraclast typical of the matrix between larger clasts in the basal conglomerate. (Sample GC A2).

B. Calcarenite matrix between large corals in basal unit (see Plate 5D) composed of large Homotrema, red algae (dark grains) and various foraminiferal tests. (Sample GC B4).

SEDIMENTS FROM THE BACK-REEF FACIES

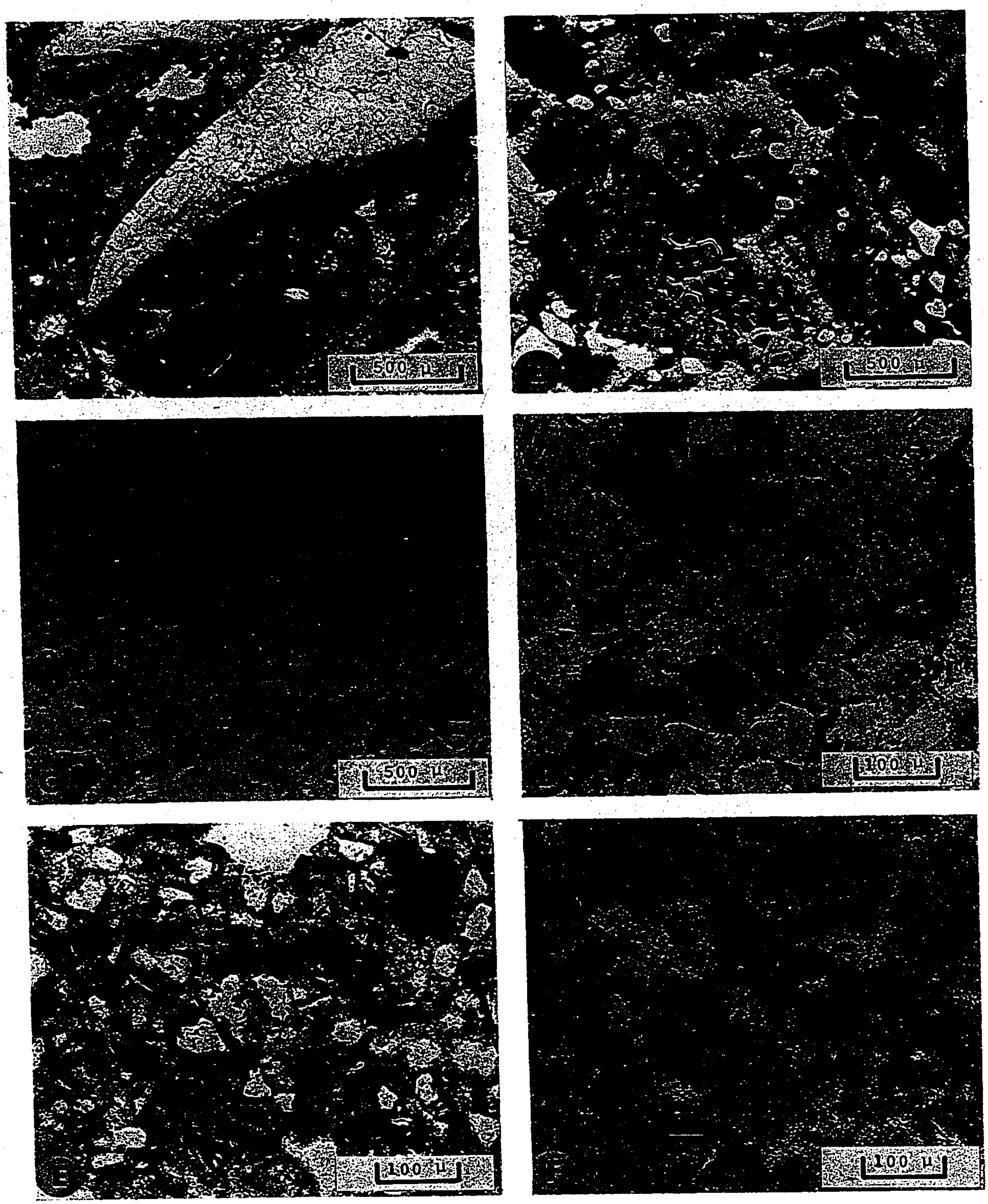
Photomicrographs - Plane Polarized Light

C. Terrigenous sand zone. Unlithified sand made up of reworked quartz and feldspar grains derived from Lower Eocene, Scotland Formation, and scattered carbonate grains. Sample from area illustrated in Plate 12B. (Sample L7).

D. Poorly lithified calcareous sandstone made up of numerous clear, angular, terrigenous grains and scattered dark, unidentifiable microcrystalline carbonate "peloids". Sample from area illustrated in Plate 12A. (Sample L8).

E. Poorly lithified sandy calcarenite with numerous clear terrigenous grains and matrix of dark microcrystalline grains, some of which (upper right) possess the remnant reticulate structure of red algae. This is typical of the sand between the white mottles in Plate 12D. (Sample L19).

F. Fine pelleted microsparite in the white mottles of Plate 12E. (Sample L19).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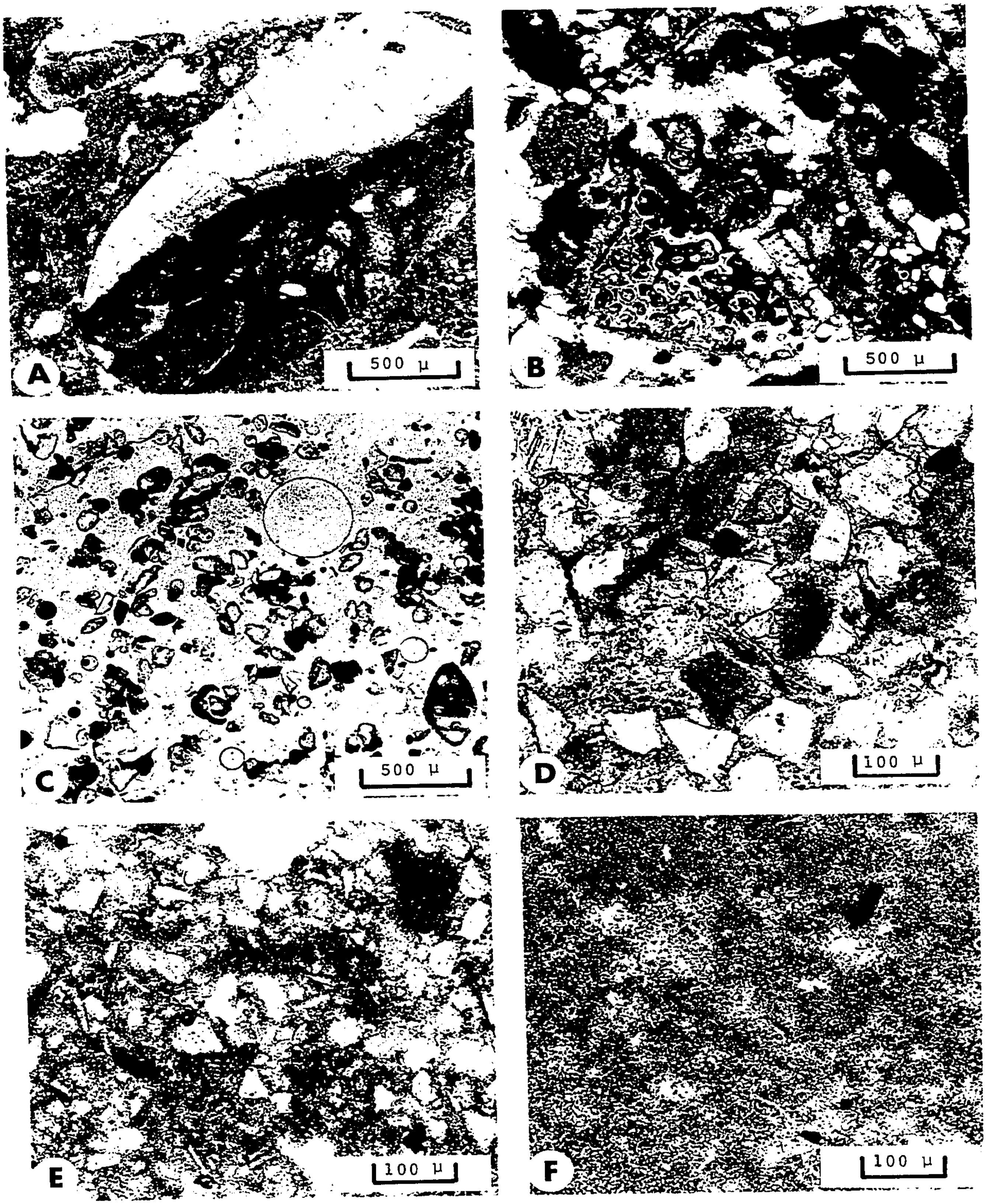
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PLATE 14

83,000 YEAR OLD REEF COMPLEX

BACK-REEF FACIES - PORITES-THALASSIA ZONE

A. Cliff section, 10 meters high, at Laycock Bay, in which a massive *Acropora palmata* lithology is overlain by a *Porites porites* lithology. The whole section is capped by subaerial, calcareous crusts.

B. Horizontal surface of the *Porites-Thalassia* zone with a profusion of small, fragmented, coral branches (locality RB C5).

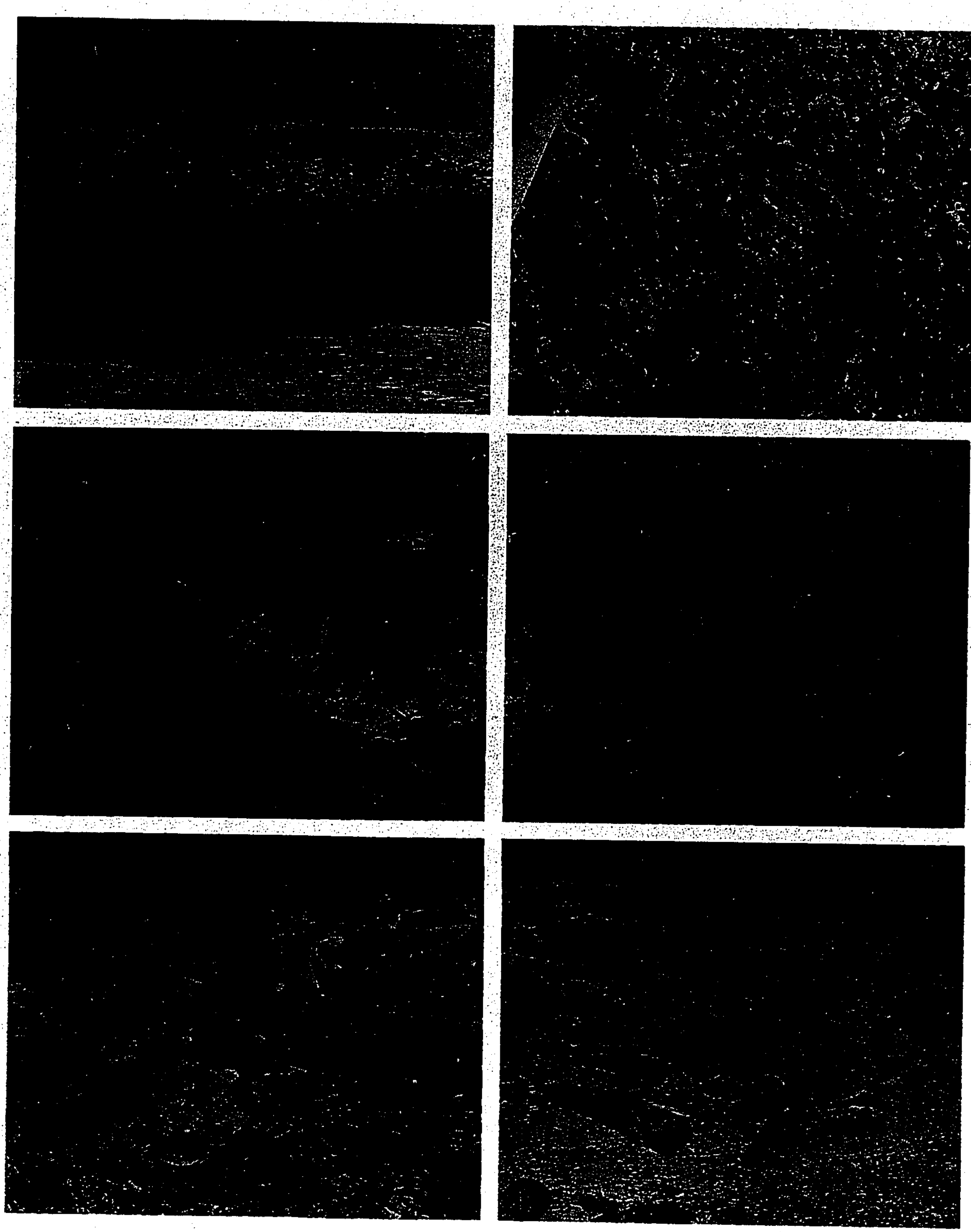
C. *Porites-Thalassia* biotope in about 1 meter of water off Tavenier Key of the Florida reef tract. *Thalassia* blades are 10-15 cm. high.

D. Small knobs of *Montastrea annularis* surrounded by many fragmented *Porites porites* sticks (locality L12, Barbados).

E. Several large *Strombus* shells among numerous *Porites porites* fragments (locality B25).

FRINGING-REEF FACIES

F. Road cut exhibiting a typical *Acropora palmata* development with large but relatively few scattered *Acropora palmata* branches (locality B14).



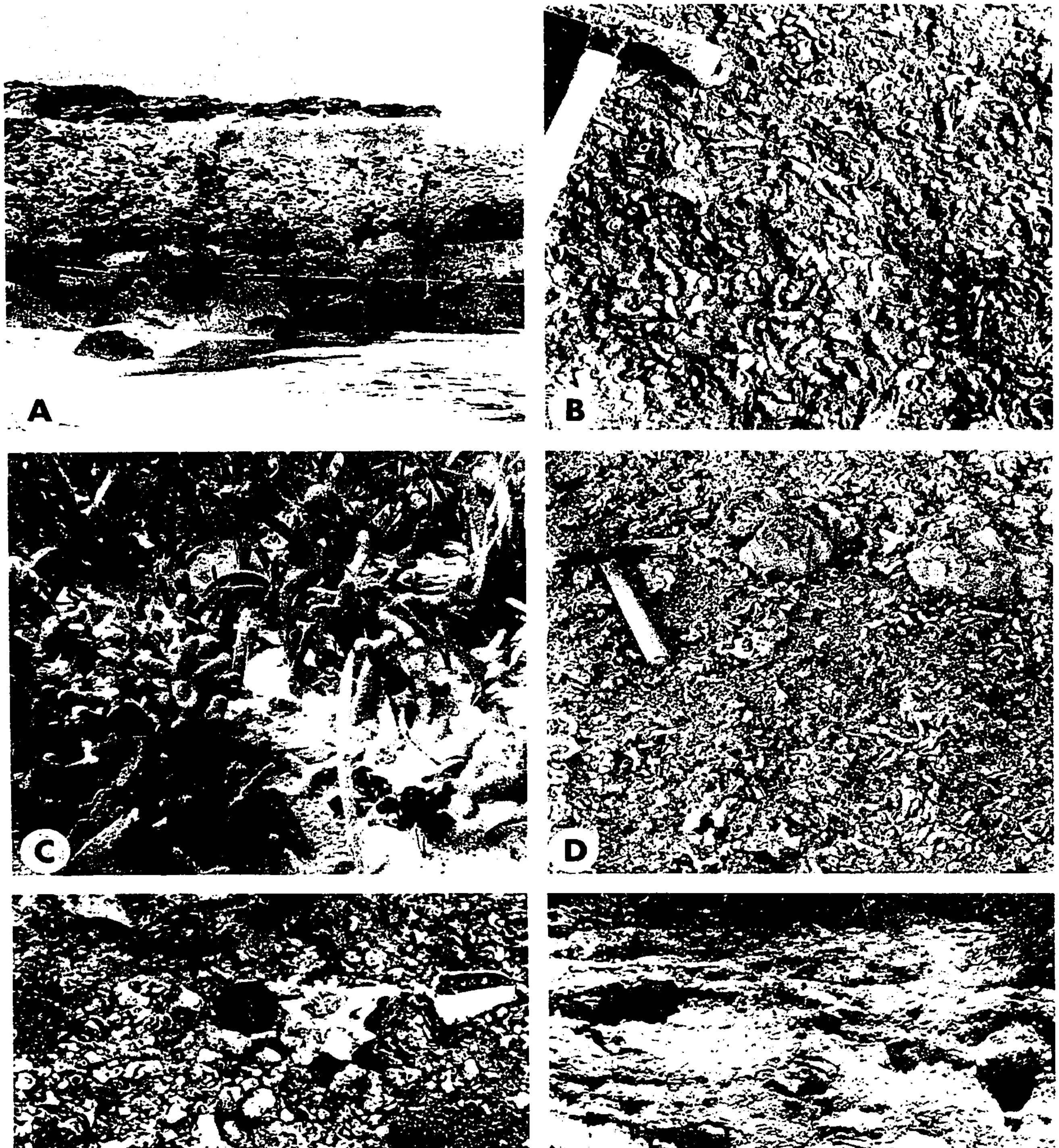

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PLATE 15

83,000 YEAR OLD REEF COMPLEX

SEDIMENTS OF THE PORITES-THALASSIA ZONE

Photomicrographs - Plane Polarized Light

A. Scattered, fine grained, skeletal fragments in a pelmicrosparite typical of the fine grained sediments in the lower portion of the zone. (Sample RB1 A2).

B. Calcite coral grains in a micrite matrix. (Sample RB1 B2).

C. Coarse grained calcarenite composed of articulate coralline red algae and whole valves of the pelecypod *Chione cancellata*. (Sample LC 5).

D. Coral calcarenite composed mostly of aragonite coral fragments. (Sample RB C6).

104,000 YEAR OLD REEF COMPLEX

BACK-REEF FACIES SEDIMENTS

Photomicrographs - Plane Polarized Light

E. Well cemented coral calcarenite with numerous micrite envelopes which originally enclosed coral grains but have since been dissolved and the voids filled with calcite. Small intraclasts are made up of mud, planktonic foraminifera and the encrusting foraminifer *Homotrema*. (Sample FW 7A).

F. Coarse whole skeletal grains typical of back-reef sands adjacent to the reef facies. These grains are *Homotrema* (left), pelecypod valve (centre) and *Amphiroa* (right). (Sample M52).


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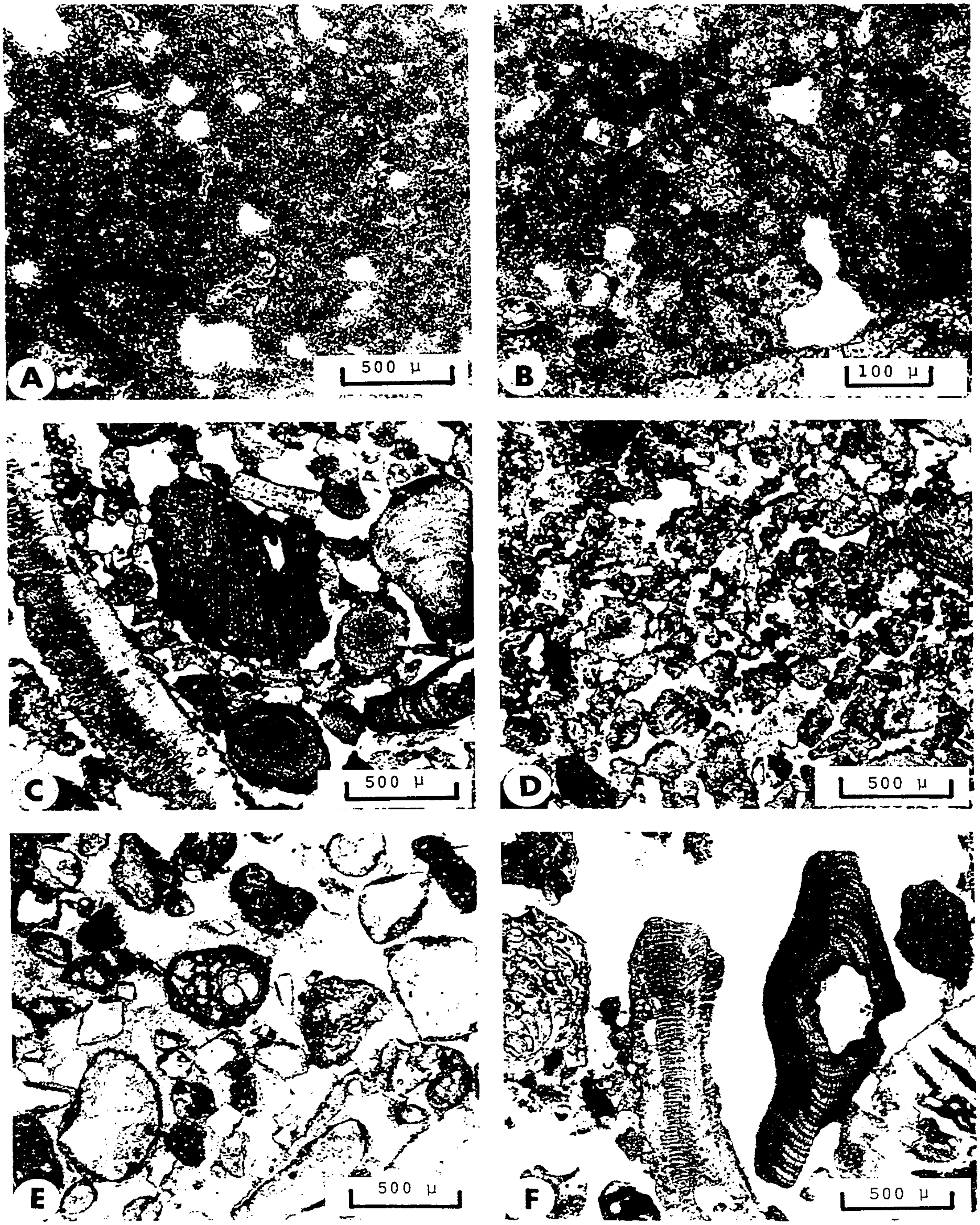
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PLATE 16

104,000 YEAR OLD REEF COMPLEX

BACK-REEF FACIES - SEDIMENTS

A. Calcarenite adjacent to the _palmata_ zone with differentially cemented tubes.

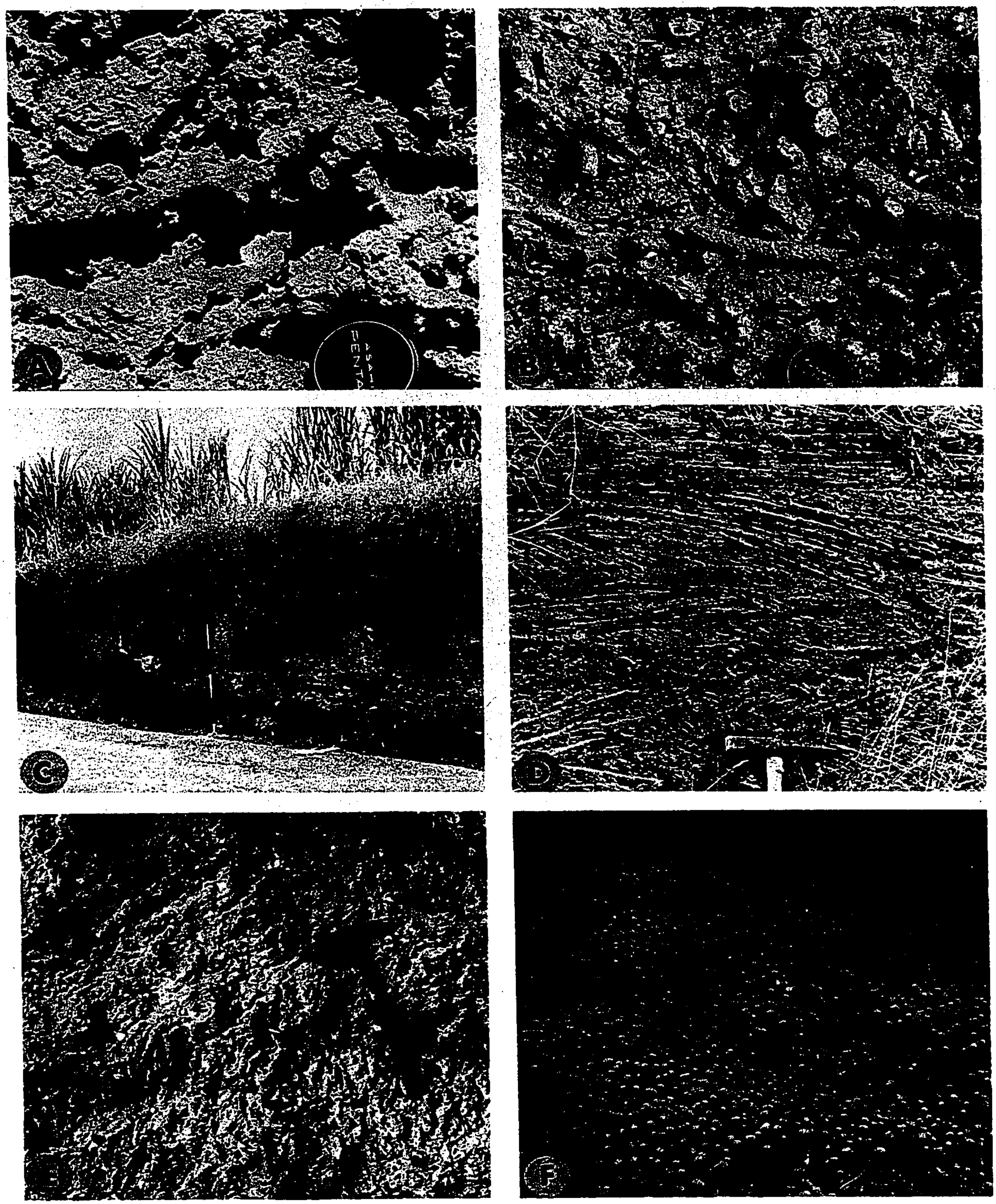
B. _Acropora cervicornis_ sticks in the stick-coral zone of the back-reef facies surrounded by fine grained calcarenite to calcilutite matrix.

C. Contact between 125,000? year old reef complex and 104,000 year old reef complex in a road cut east of Fryer's Well Bay (locality FW 12). Exposure of the underlying older reef complex to subaerial weathering prior to burial created a crumbly limestone similar to that seen on the northeast coast today. The overlying younger limestones are well-laminated calcarenites similar to modern beach sands.

D. Cross bedding in the Pleistocene beach calcarenites illustrated in Plate 16C (locality A3A).

E. _Porites_ bank zone (locality M29), with numerous vertical _Porites porites_ sticks, all in growth position. Contrast with Plate 14D.

F. _Porites porites_ bank in about 5 meters of water off the west coast of Barbados. Compare with Plate 16E.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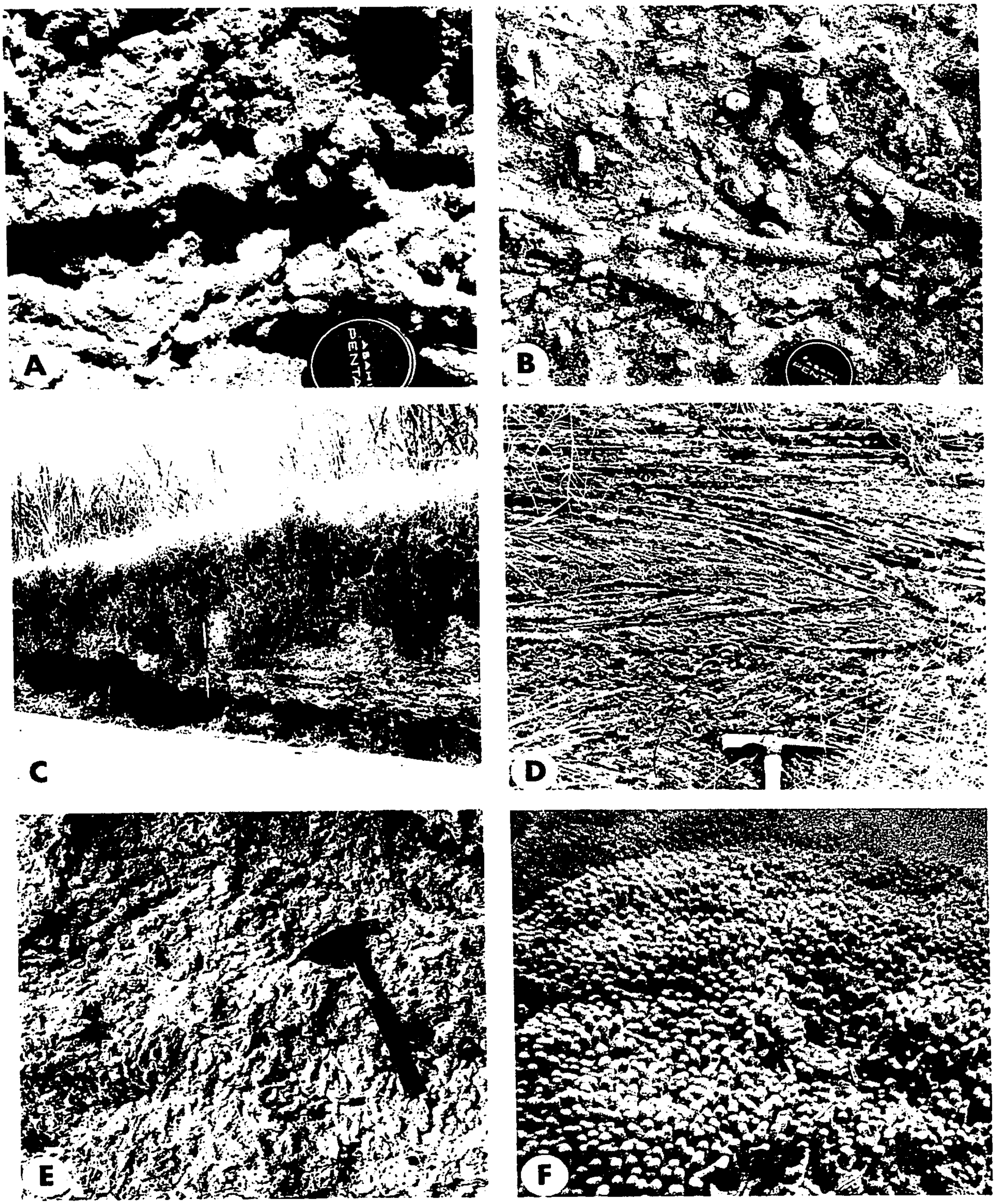
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PLATE 17

104,000 YEAR OLD REEF COMPLEX

BACK-REEF SEDIMENTS

Photomicrographs - Plane Polarized Light

A. Coral calcarenite with accessory red algae and mollusc fragments. Although most clear coral grains are calcite, several aragonite ones remain unaltered (a). (Sample M52).

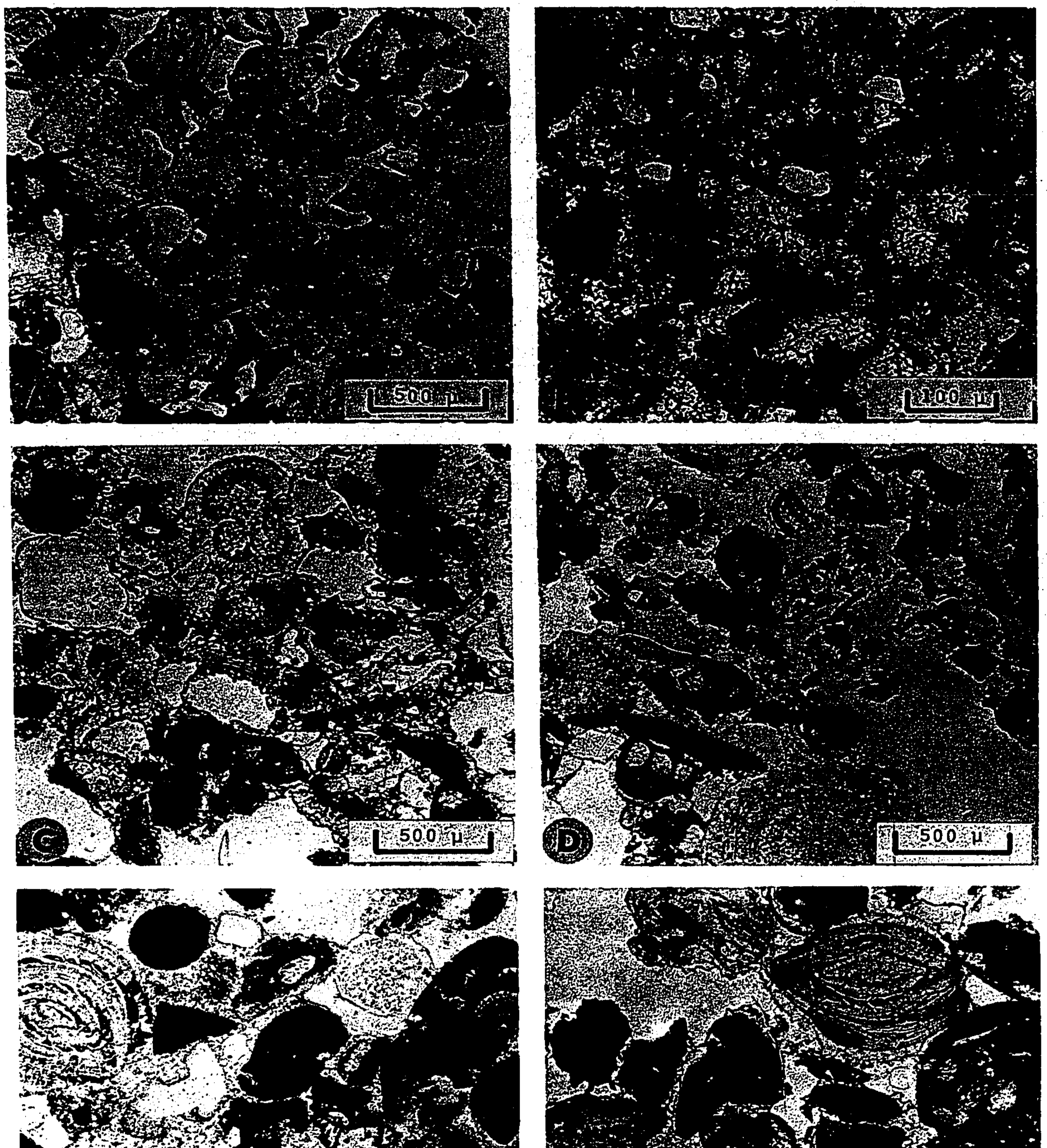
B. Biomicrite from stick-coral zone of the central back-reef illustrated in Plate 16B. Areas of clear, blocky calcite result from the precipitation of calcite into voids created by solution of fine aragonite allochems (mainly corals). Accessory grains are planktonic foraminifera and micritized peloids. (Sample FW33).

C. Fine grained foraminiferal calcarenite adjacent to cross-laminated beach calcarenites. (Sample FW34).

D. Medium grained calcarenite similar to (C) but from fine laminae in cross-laminated beach sediment illustrated in Plate 16D. (Sample A3A-a).

E. Coarse grained calcarenite dominated by the foraminifer *Amphistegina* and well-rounded fragments of red algae and intraclasts. (Sample FW12).

F. Sediment from the coarse laminae in the same cross-bedded beach sand sample as (D). (Sample A3A-b).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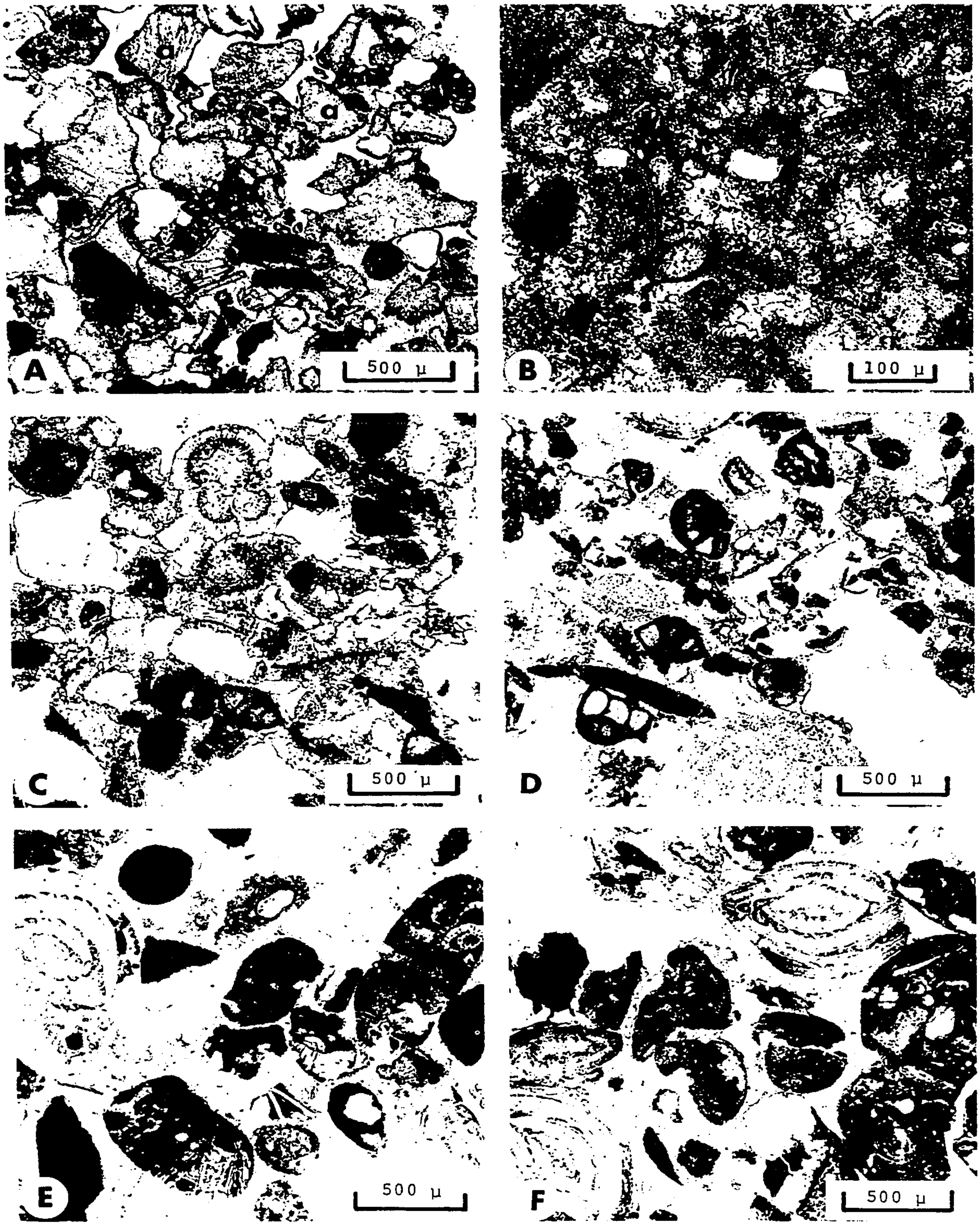
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PLATE 18

SYNSEDIMENTARY SUBMARINE LITHIFICATION

A. Sticks of *Acropora cervicornis* (a) surrounded and cemented by a lumpy crust of pelsparite (b). Sample from reef facies of living reef off the north coast of Jamaica (courtesy L.S. Land). The pelleted crust is composed of Mg-calcite.

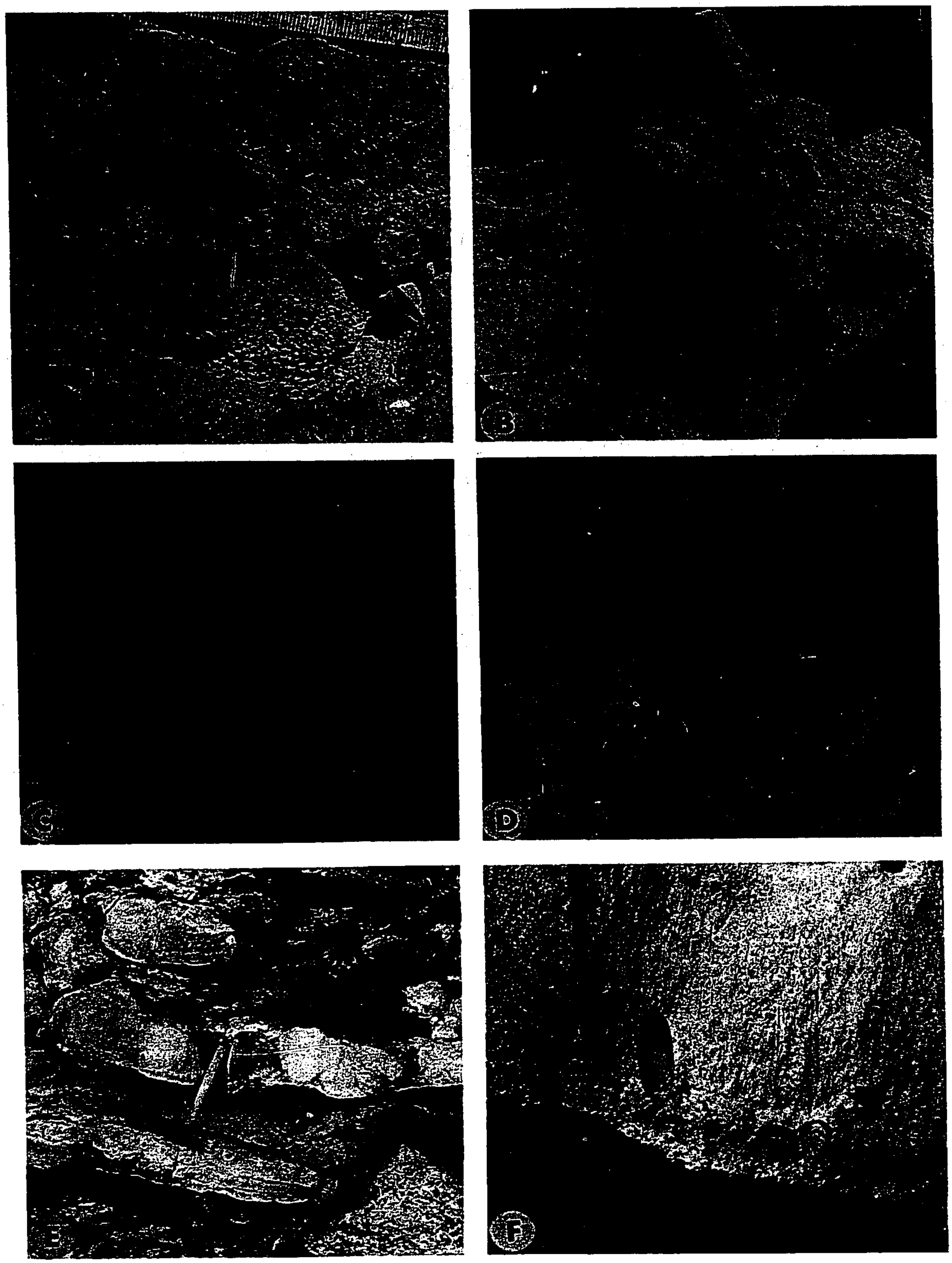
B. Sticks of *Acropora cervicornis* surrounded by a lumpy crust of grey pelsparite (compare with A). Sample from the reef facies of the Pleistocene, 83,000 year old, reef complex on the northeast coast of Barbados. The crust in this sample is composed of calcite. Penny scale is 18 mm diameter. (Sample RBD).

C. Cut slab of the Jamaican crust illustrated in (A) with irregular laminae in the pelsparite surrounding white *Acropora cervicornis* sticks. Photo is 2 cm wide.

D. Cut slab of a brown, lumpy crust with irregular laminae surrounding an *Acropora cervicornis* stick from the reef facies of the Pleistocene, 83,000 year old, reef complex on Barbados. The pelsparite in this crust is Mg-calcite. Photo is 2 cm. wide. (Sample RB C4).

E. *Palmata* zone, 83,000 year old reef complex, northeast coast, Barbados (locality AF D). The lower surface of each coral frond is coated with a pelsparite crust.

F. Enlargement of central coral frond in (E). Arrows indicate the base of the coral, the sediment below this is a well-lithified calcite pelsparite crust. The elliptical boring of the date mussel *Lithophaga* cuts both the coral and cemented crust, suggesting pelsparite lithification occurred early in the coral's history.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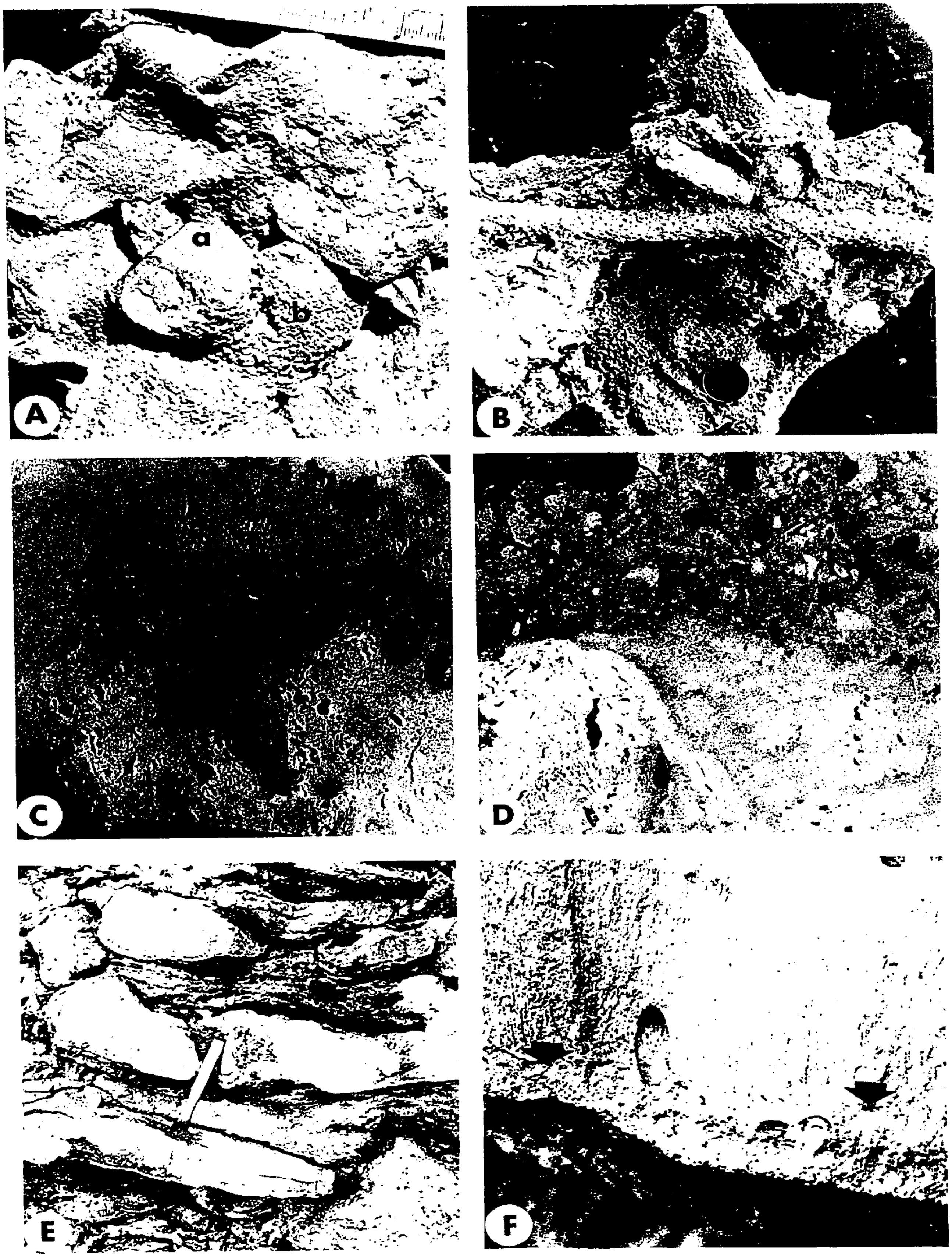
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PLATE 19

SYNSEDIMENTARY SUBMARINE LITHIFICATION

Photomicrographs - Plane Polarized Light

A. Mg-calcite pelsparite. Lithified crust cementing *Acropora cervicornis* sticks in the living reef facies off Discovery Bay, Jamaica. Thin section from sample illustrated in Plate 18A.

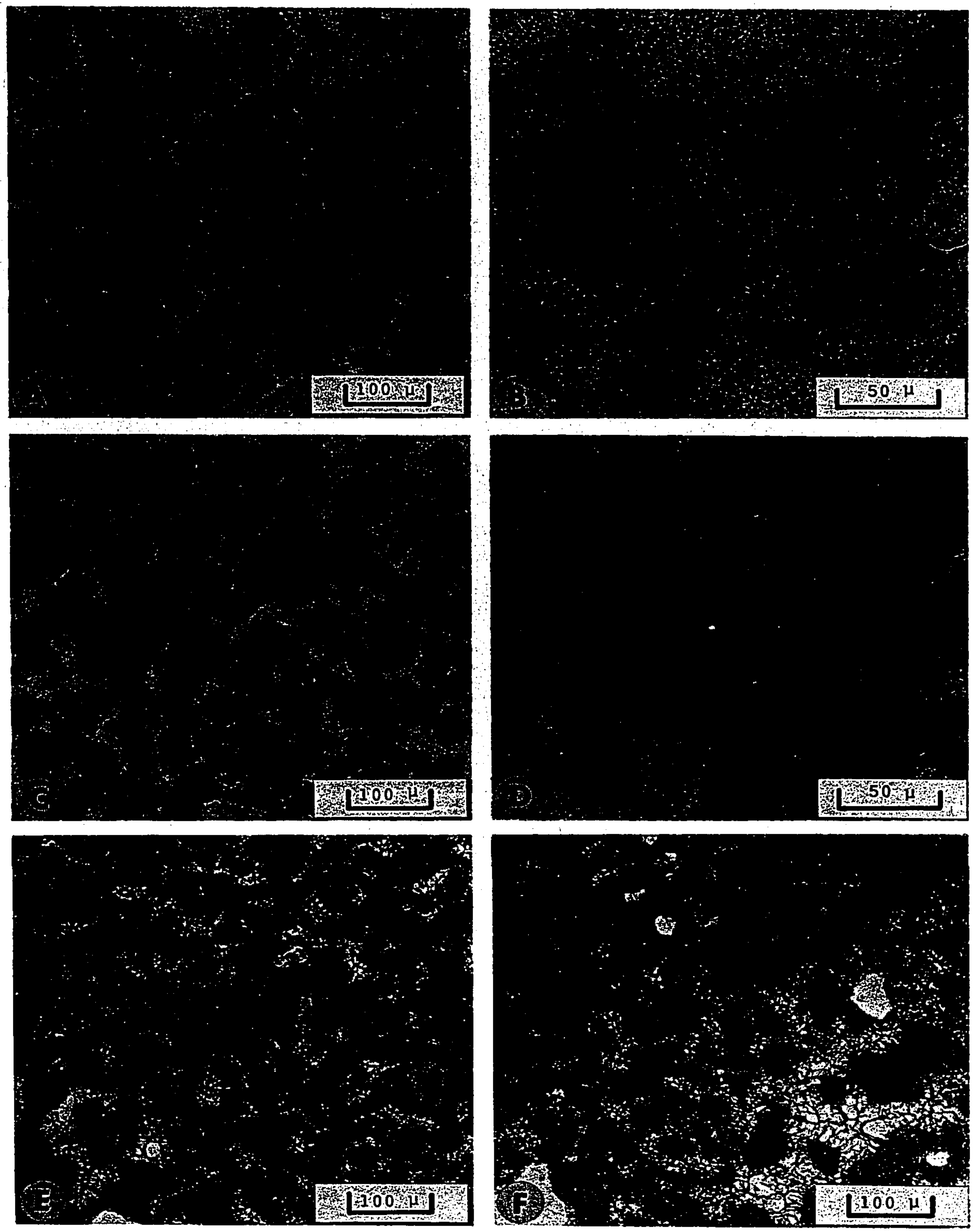
B. Enlargement of the thin section illustrated in (A). Each irregular micrite pellet is surrounded by an isopachous fringe of dentate Mg-calcite.

C. Mg-calcite pelsparite. Brown, well-lithified crust surrounding *Acropora cervicornis* sticks in the reef facies of the Pleistocene, 83,000 year old complex on Barbados' northeast coast. Thin section from sample illustrated in Plate 18D.

D. Enlargement of thin section illustrated in (C). Each micrite pellet is surrounded by an isopachous fringe of dentate Mg-calcite similar to that in (B).

E. Pelsparite. Well-lithified grey crusts surrounding *Acropora cervicornis* sticks in the reef facies of the Pleistocene, 83,000 year old complex on the northeast coast of Barbados. Both pellets and cement in this sample are calcite. The calcite spar is coarser than in (B) and (D) and all voids between pellets are completely filled with spar. (Sample AF D2 B3).

F. Pelsparite. Thin, well-lithified crust at the base of the *Acropora palmata* frond illustrated in Plate 18E. The pellets are similar in size and distribution to those around *Acropora cervicornis* sticks illustrated in (E). The voids are also filled with clear calcite, suggesting that these crusts may be lithified early as well.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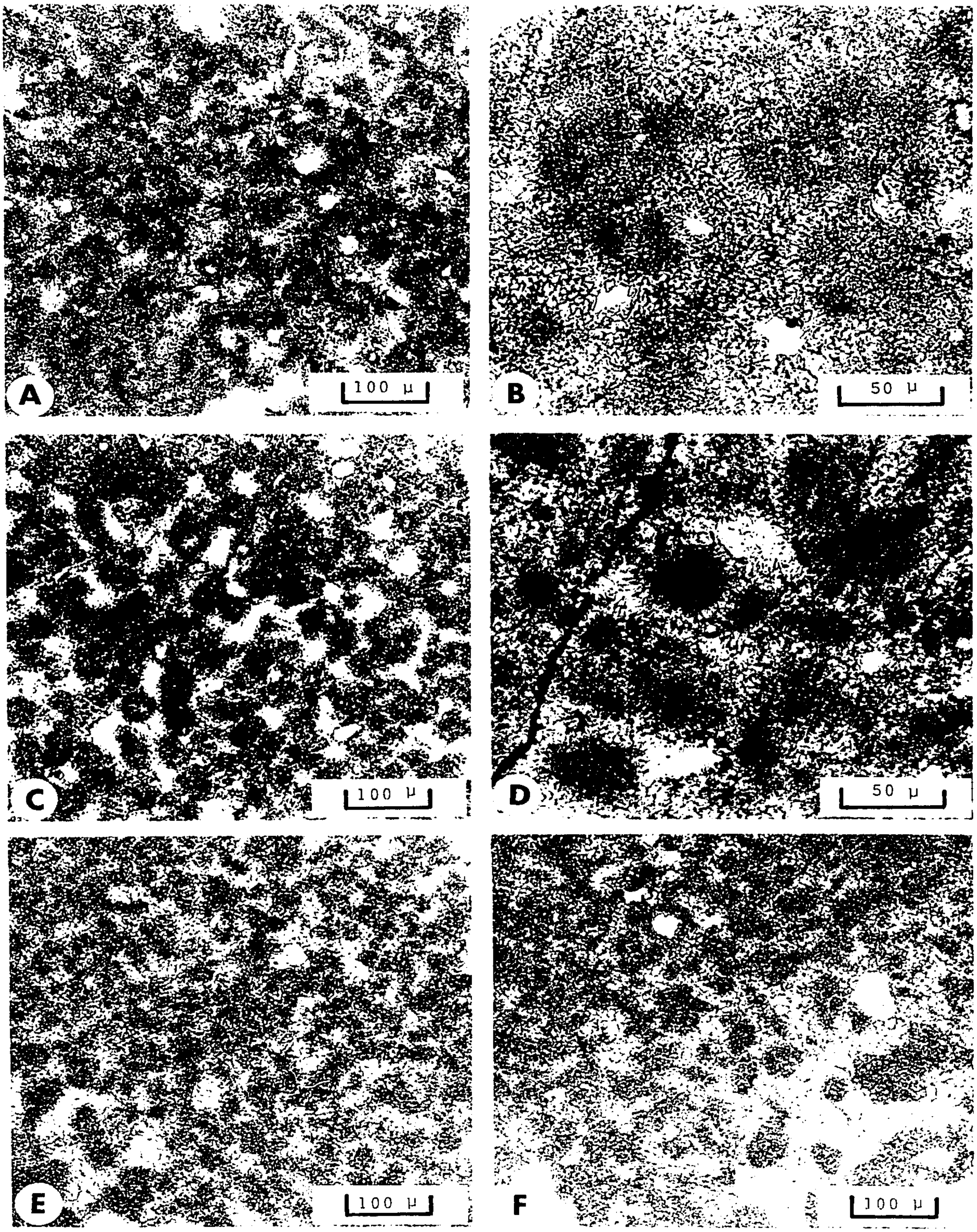
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PLATE 20

INTERTIDAL LITHIFICATION

A. Norse's Bay. 60,000 year old reef terrace just above sea level at the foot of older, Pleistocene limestone cliffs, obscured by trees. The vertical rod (arrow) on the terrace is 1.5 meters high. The partially lithified, Pleistocene sediments which form the terrace are continuously bathed in salt spray.

Photomicrographs - Plane Polarized Light

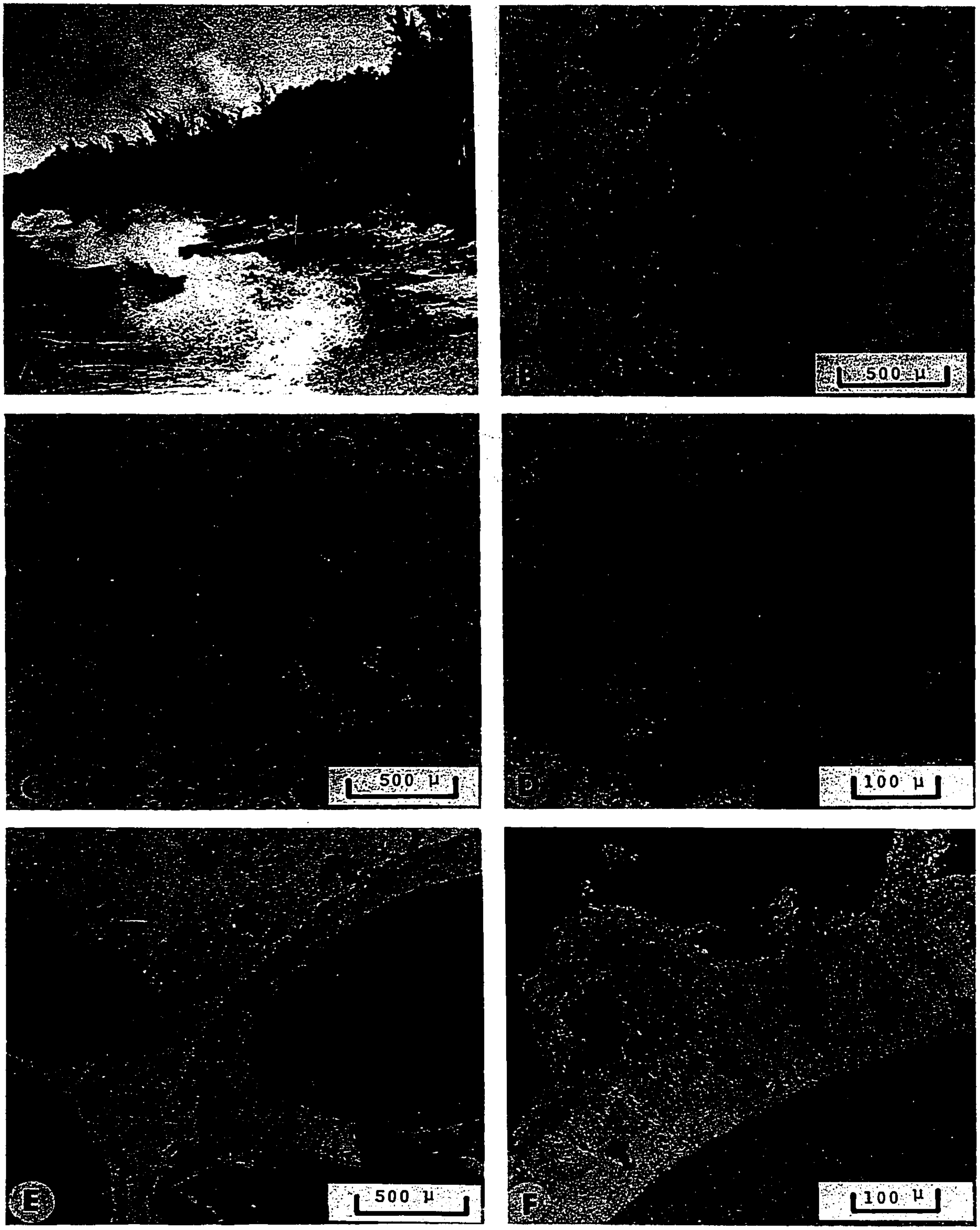
B. Fine grained calcarenite between numerous sticks of *Acropora cervicornis* directly underlying the 60,000 year old reef terrace (see Fig. 18). Large voids are lined with an isopachous crust of clear calcite up to 30 micra thick. The remainder of the void is filled with calcilutite which stains red with Clayton yellow, indicating the presence of Mg-calcite. This suggests that the void was filled during deposition of the overlying 60,000 year old reef sediments, which are still Mg-calcite-rich. (Sample SB 1A).

C. Fine grained calcarenite from the same lithology as above. Grains are mostly fragments of the articulated coralline algae *Amphiroa* and *Jania*. Each grain is surrounded by an isopachous rim of clear calcite about 30 micra thick. (Sample N 6A).

D. Enlargement of the thin section illustrated in (C). The clear calcite rim cement is succeeded by a second stage of slightly darker cement. This second stage cement stains bright red with Clayton yellow indicating Mg-calcite.

E. Coarse calcarenite of well-rounded crustose red algal fragments, typical of the sediments in the 60,000 year old, fringing reef terrace. This sample is from the upper part of the terrace, in the spray zone, and exhibits two stages of carbonate cement. The grains are cemented together by clear drusy calcite, the outer half of which exhibits a dark rim. When stained with Clayton yellow, the outer dark rim turns red and the inner clear calcite is unaffected, indicating the former is Mg-calcite. (Sample N 4B).

F. Enlargement of the thin section illustrated in (E), viewed under cross-polarized light. The two cement stages can easily be differentiated. The dark, second stage has precipitated in optical continuity with the first stage even though made up of smaller crystallites.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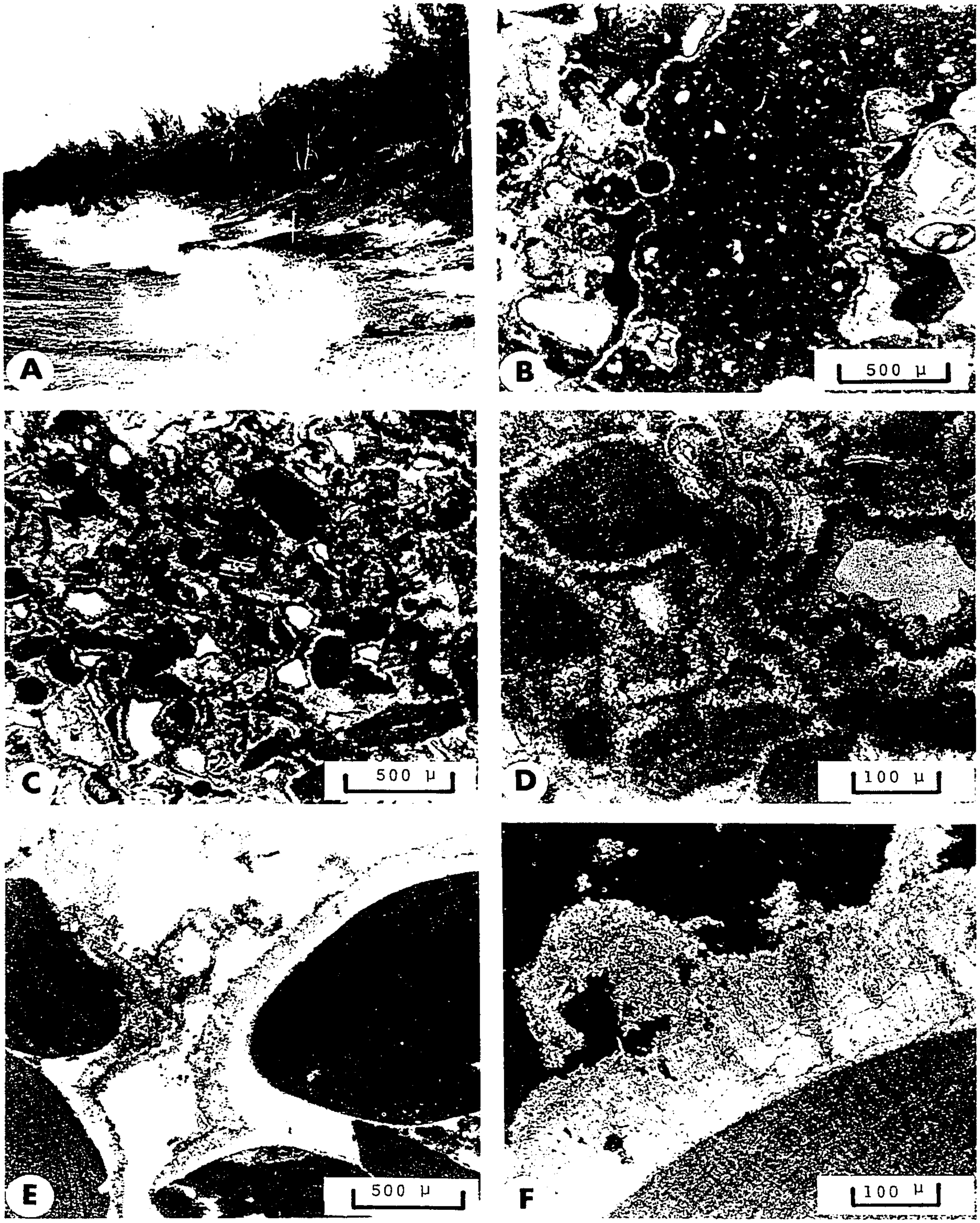
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PLATE 21

SALT SPRAY ARAGONITE

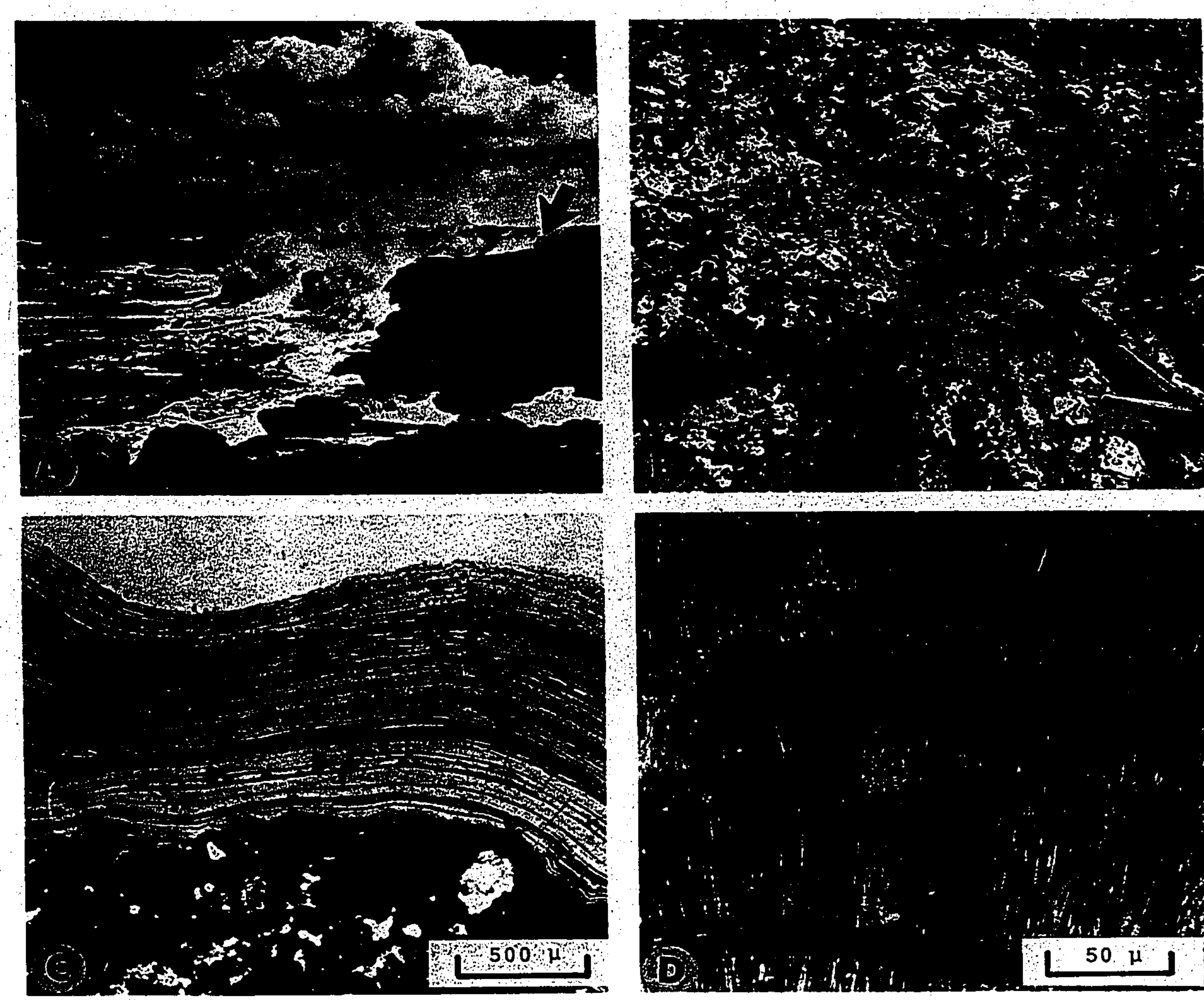
A. Northeast coast of Barbados near Animal Flower Bay. Waves breaking against cliffs throw large amounts of salt spray into the air. Cliffs about 12 meters high. Person on cliff top provides scale (arrow).

B. Surface of cliff top along the northeast coast with patchy white coating of aragonite on dark limestone.

Photomicrographs

C. Cross section of limestone (dark lower third) and laminated aragonite crust from area pictured in (B). Plane polarized light.

D. Enlarged area of aragonite crust viewed under cross polarized light. Long aragonite needles are oriented at right angles to the horizontal laminae.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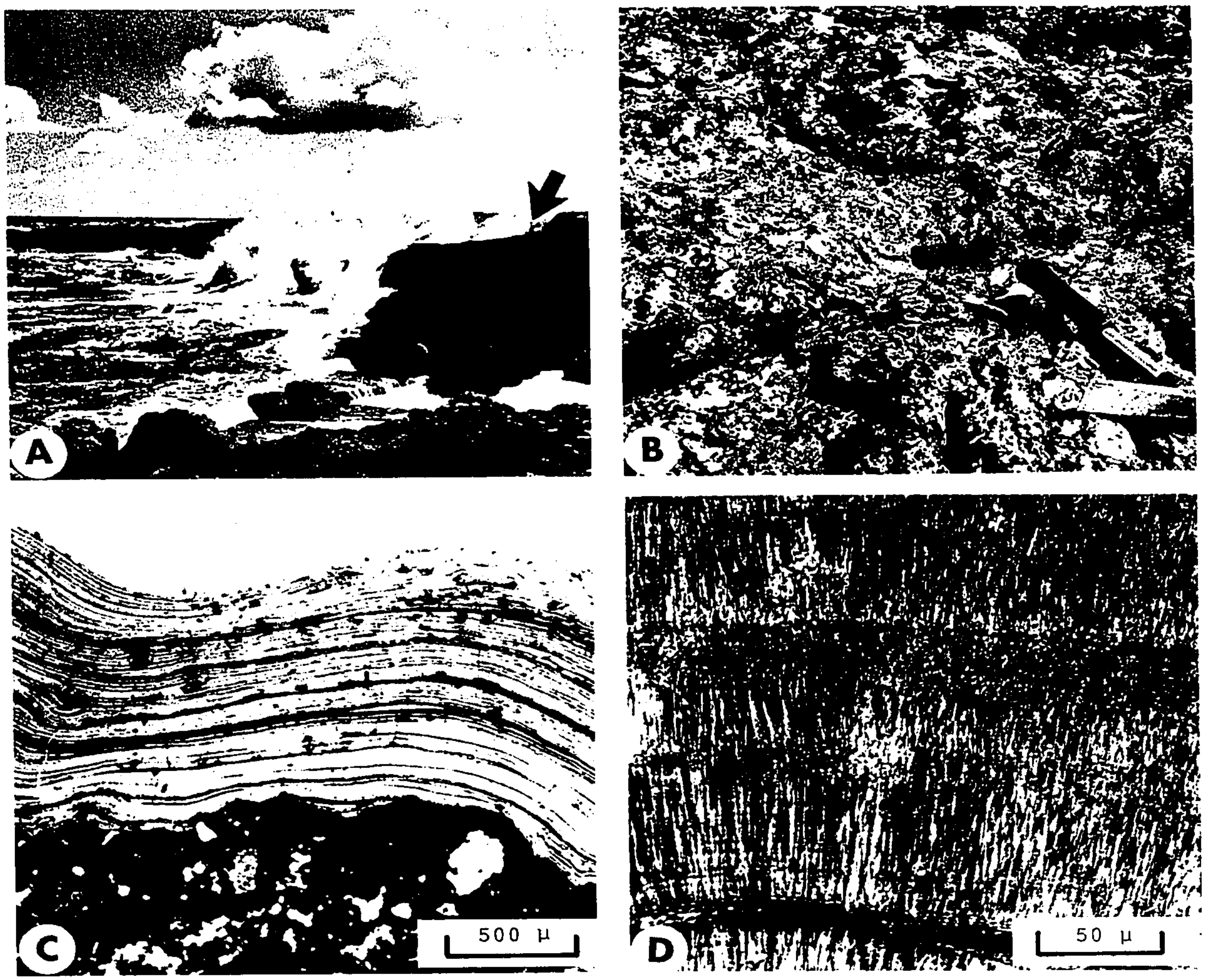
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PLATE 22

SURFICIAL CALCAREOUS CRUST PROFILES

FIELD EXPOSURES

A. Sea cliffs, about 10 meters high, along the northeast coast of Barbados, near The Landlock. The development of hard, calcareous crusts occurs in the upper few feet of the section. These hard crusts are more resistant to erosion than the underlying poorly lithified, 83,000 year old, Pleistocene, reef limestones.

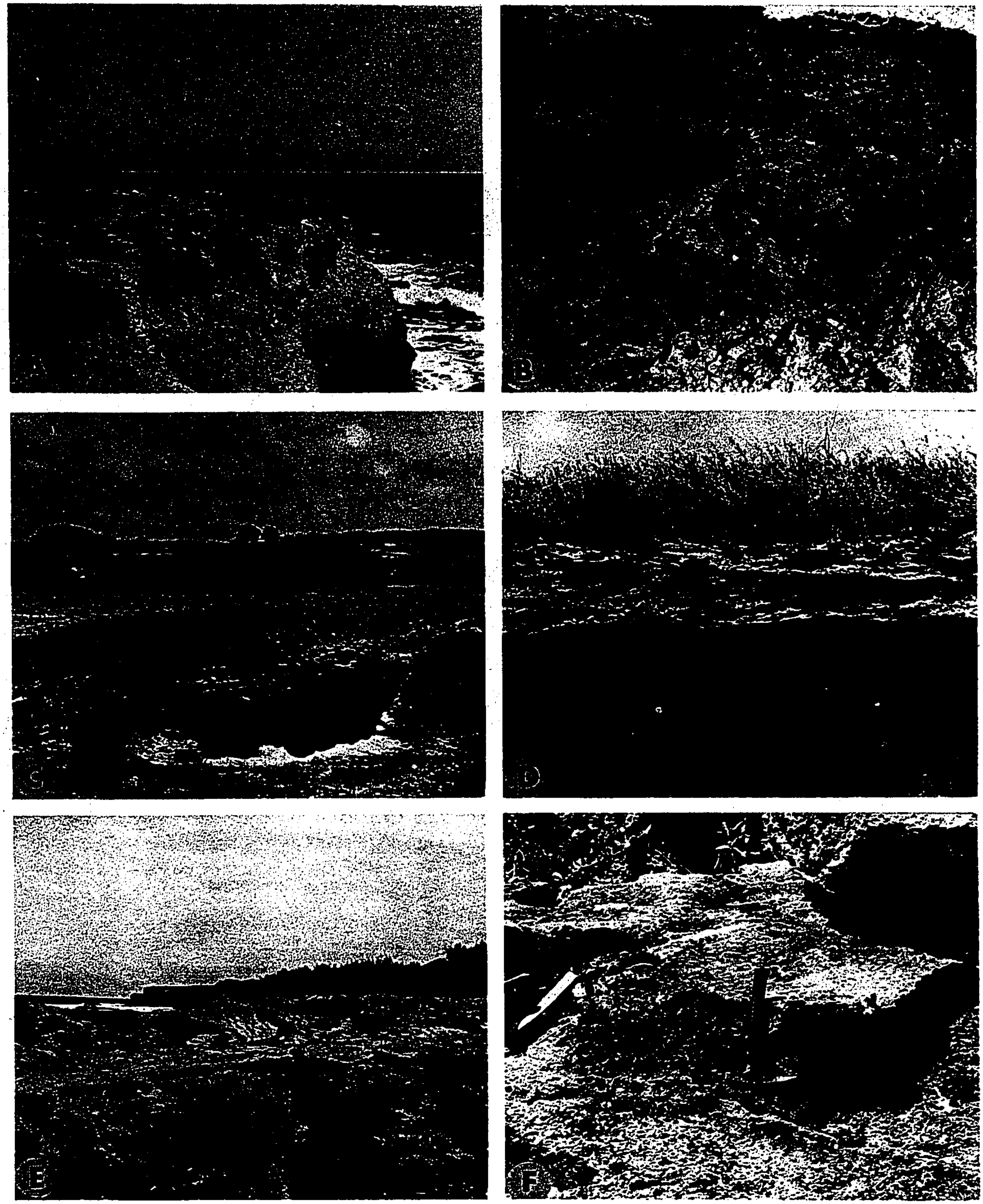
B. Surface of the crusts illustrated in (A) with numerous fractures.

C. Surficial calcareous crusts developed in the upper part of late Pleistocene (83,000 year old) calcarenites some 1-1/2 kilometers from the northeast coast (locality SG 7, looking east).

D. Closer view of crusts pictured in (C) with numerous thin resistant crusts which, although more or less parallel to the ground surface, are highly irregular and branch and merge in several places. The poorly developed horizontal crusts also occur below the extensive upper zone. Dark vertical lines are organic stain on the rock surface. Hammer in lower left is scale.

E. Surficial calcareous crust development on the 60,000 year old reef limestones at Goulding's Green. A cross section of this crust is illustrated in Plate 30C.

F. A single, thin, calcareous crust developed on well-lithified, older Pleistocene calcarenites (locality C51).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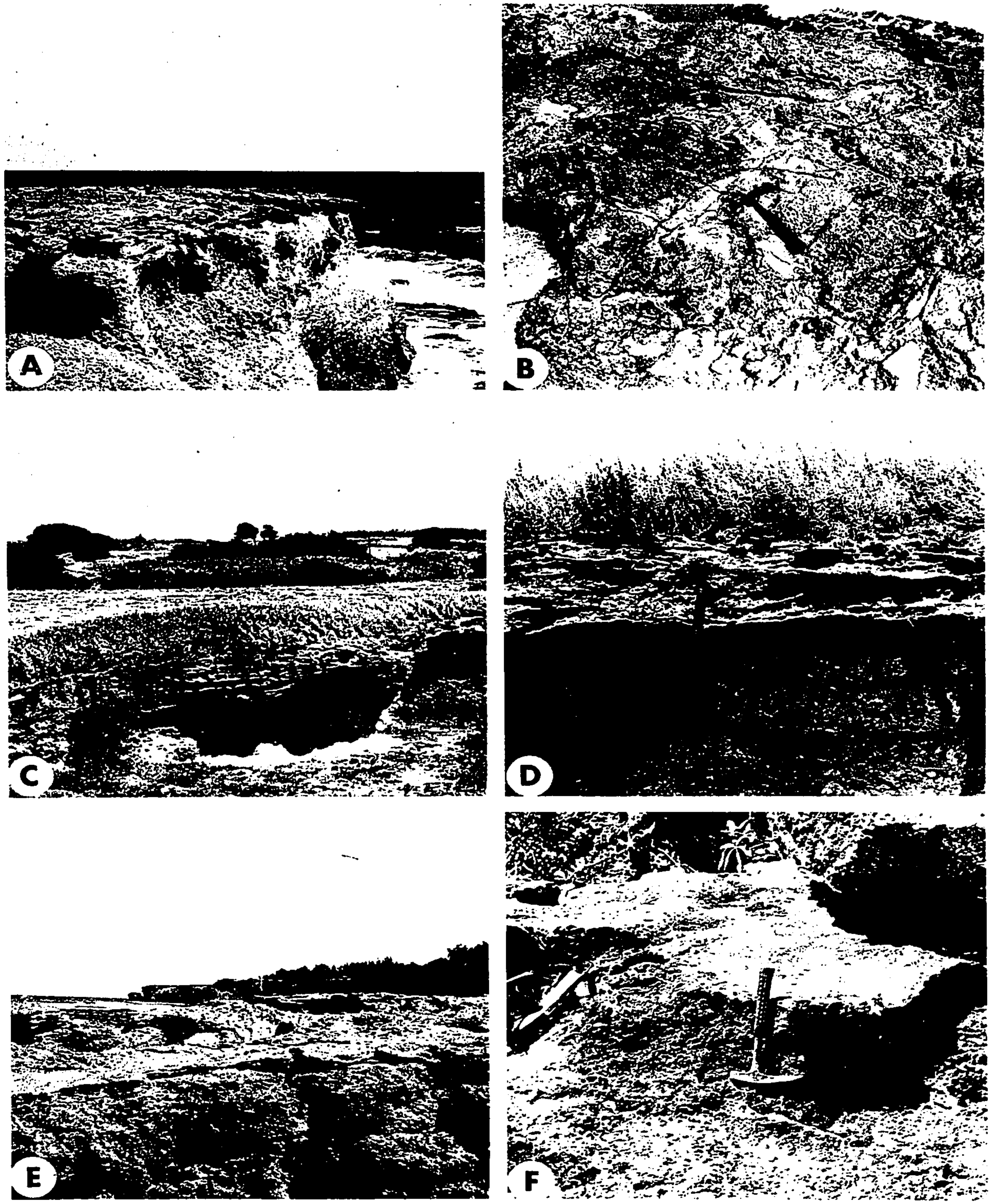
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PLATE 23

SURFICIAL CALCAREOUS CRUST PROFILES

Rock Slabs

Arrow indicates up; square is 2 cm on a side

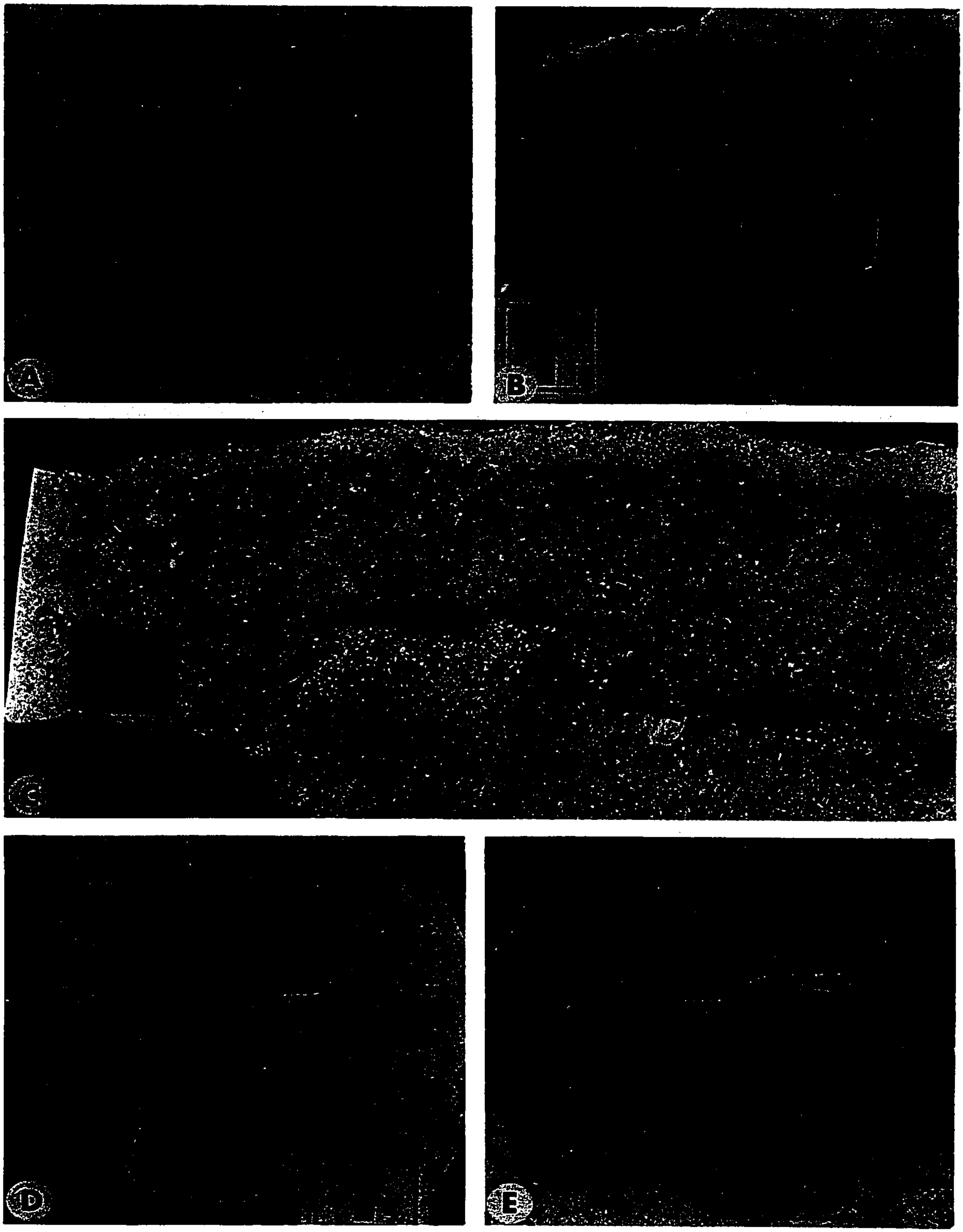
A. Crust profile typical of development along the northeast coast. A series of hard, irregular, calcareous crusts (c), underlain by original brecciated limestone fragments (b), and separated by carbonate with abundant coated particles (p). (Sample RB1 B5).

B. Well-lithified, Pleistocene calcilutite (83,000 year old) brecciated in the caliche profile with fractures filled with brown carbonate and crust developed in upper part of sample. (Sample RB CR).

C. Crust developed on 60,000 year old calcarenites along the northwest coast (see Plate 29E). The calcarenite at the base, composed of grains of unstable mineralogy, is directly overlain by a thin laminated crust of tangential needles and pelletoids, similar to the "laminated microcrystalline rind" of Multer and Hoffmeister (1968). Material above the crust is calcarenite grains, of unstable mineralogy and similar in composition to those below, coated with concentric laminae of brown calcite and numerous micrite pelletoids. Pelletoids become dominant towards the top of the crust. (Sample SB 1G).

D. Highly fractured limestone between the calcareous crusts on the northeast coast. This material is easily broken by hand and often crumbles upon touching. (Sample LCR 1).

E. A thin, single, surficial brown crust developed on well-lithified older Pleistocene calcarenites. (Sample C51).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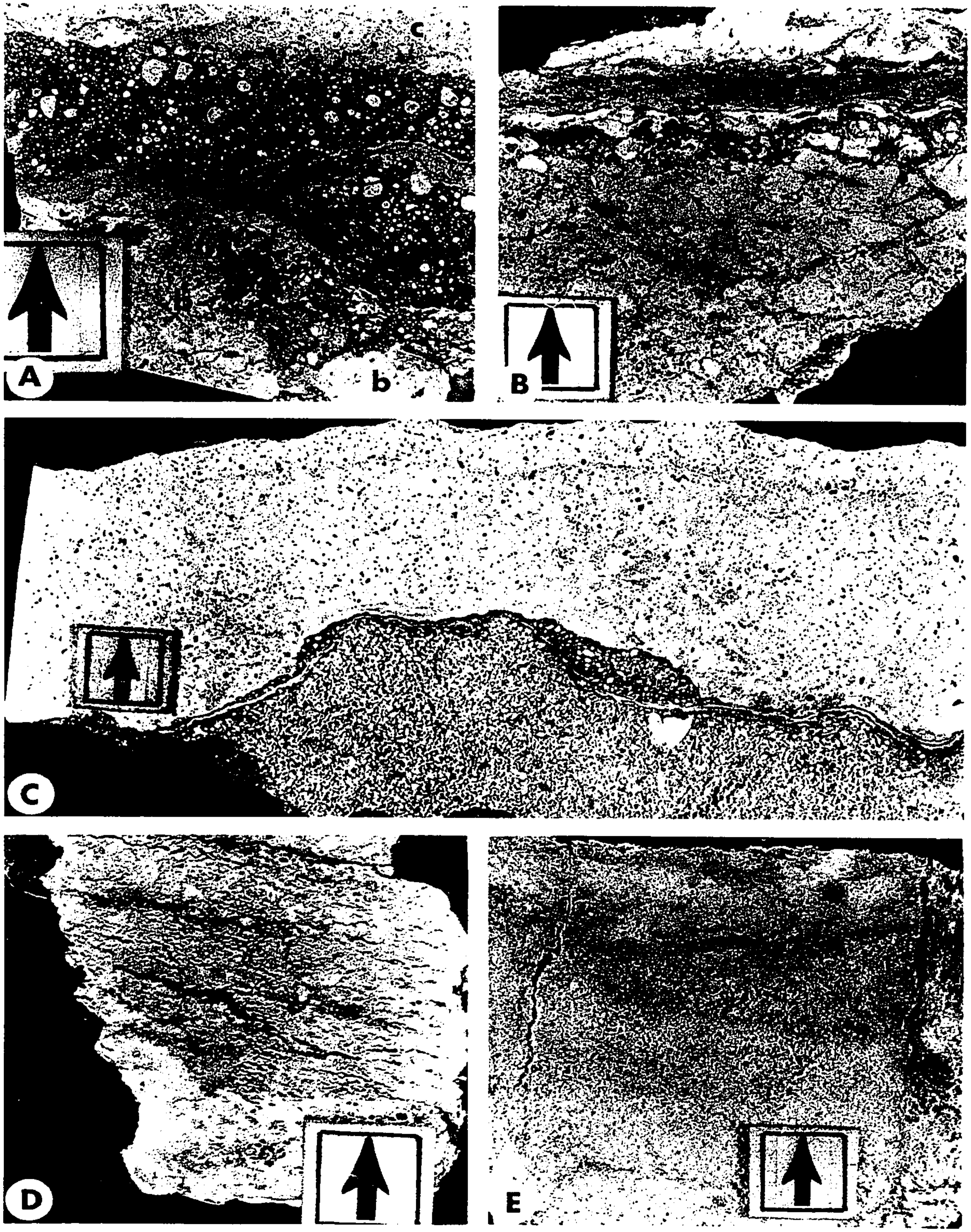

c
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PLATE 24

SURFICIAL CALCAREOUS CRUST PROFILES

ALTERATION OF ORIGINAL LIMESTONE

Photomicrographs - Plane Polarized Light

A. Limestone brecciation. Fracturing takes place both around the periphery of the Amphiroa fragment, separating it from the matrix, and across the grain itself, breaking it into several separate pieces. (Sample RB CR3).

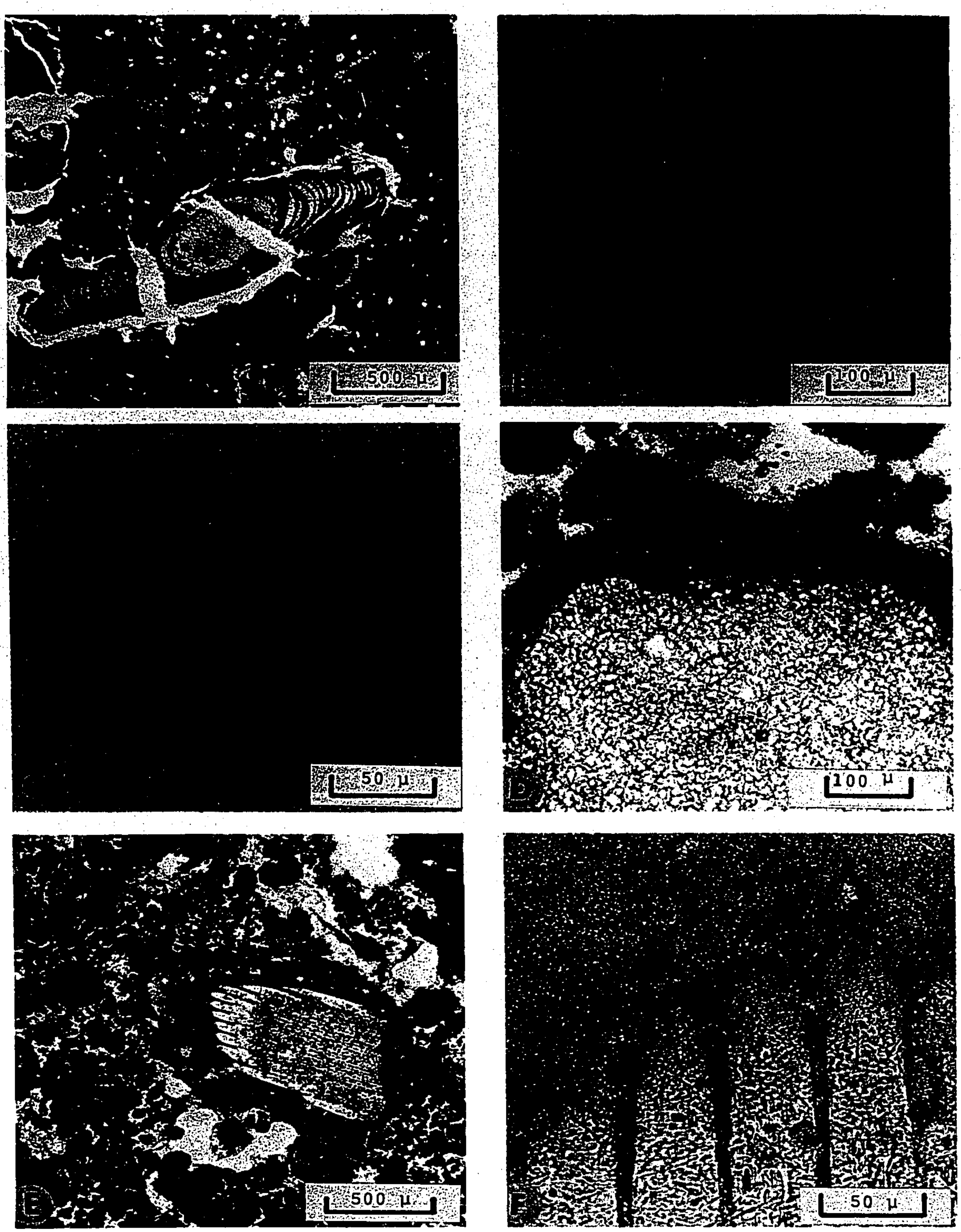
B. Microspar brecciation. (Sample LCR 1).

C. Microspar, a common component of many profiles, results from the recrystallization of Pleistocene micrite rich limestones. (Sample LCR 3).

D. Fragments of brecciated microspar, such as those illustrated in (B), are often coated with a layer of fine brown calcite, composed of brown micrite and tangential needle fibres. Small microspar crystals can often be seen in the coating, suggesting it may be, in part, an alteration rim of degrading recrystallization. (Sample WB 7G).

E. Echinoid fragment, surrounded by brown micrite. The boundary between grain and micrite is irregular and diffuse. (Sample N4 H).

F. Enlarged view of contact described in (E). Note the gradual alteration of the single large calcite crystal to fine micrite size crystallites. The ordginal structure of the allochem can be traced into the micrite for some distance.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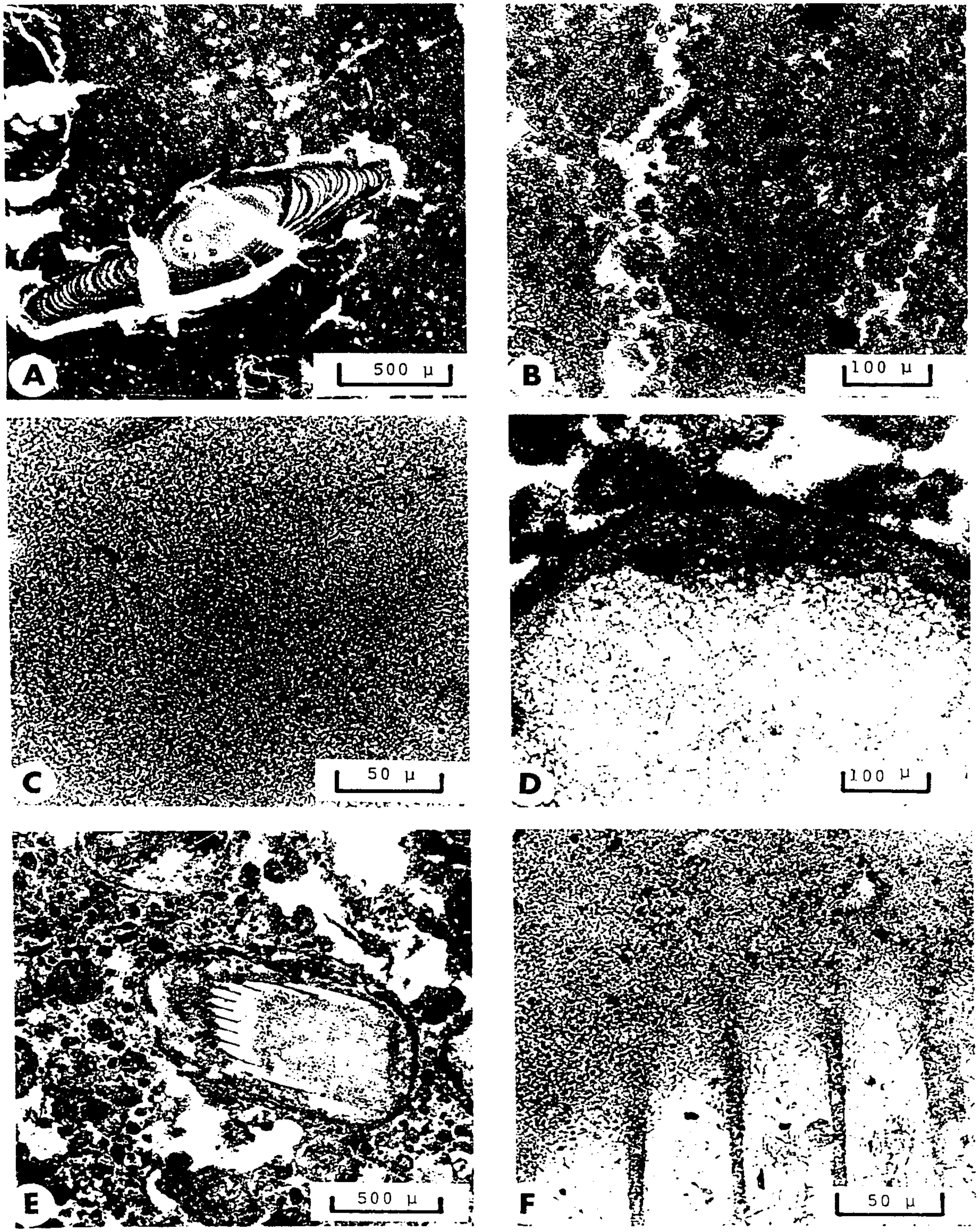
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PLATE 25

SURFICIAL CALCAREOUS CRUST PROFILES

ALTERATION OF THE ORIGINAL LIMESTONE

Photomicrographs - Plane Polarized Light

A. The lentiform foram Amphistegina with an irregular incomplete outline surrounded by a thick coat of brown micritic calcite. The coating can be divided into two areas, a dark inner zone, and a lighter outer zone. (Sample N4 H).

B. Enlargement of the Amphistegina test illustrated in (A), showing the irregular fuzzy nature of the contact between the brown micrite and clear calcite of the test. The clear patches of calcite indicated by the arrows are in optical continuity with the rest of the test and mark unaltered remnants of the skeleton. It appears the skeleton is partially micritized and that the darker micrite may mark the original outline of the test.

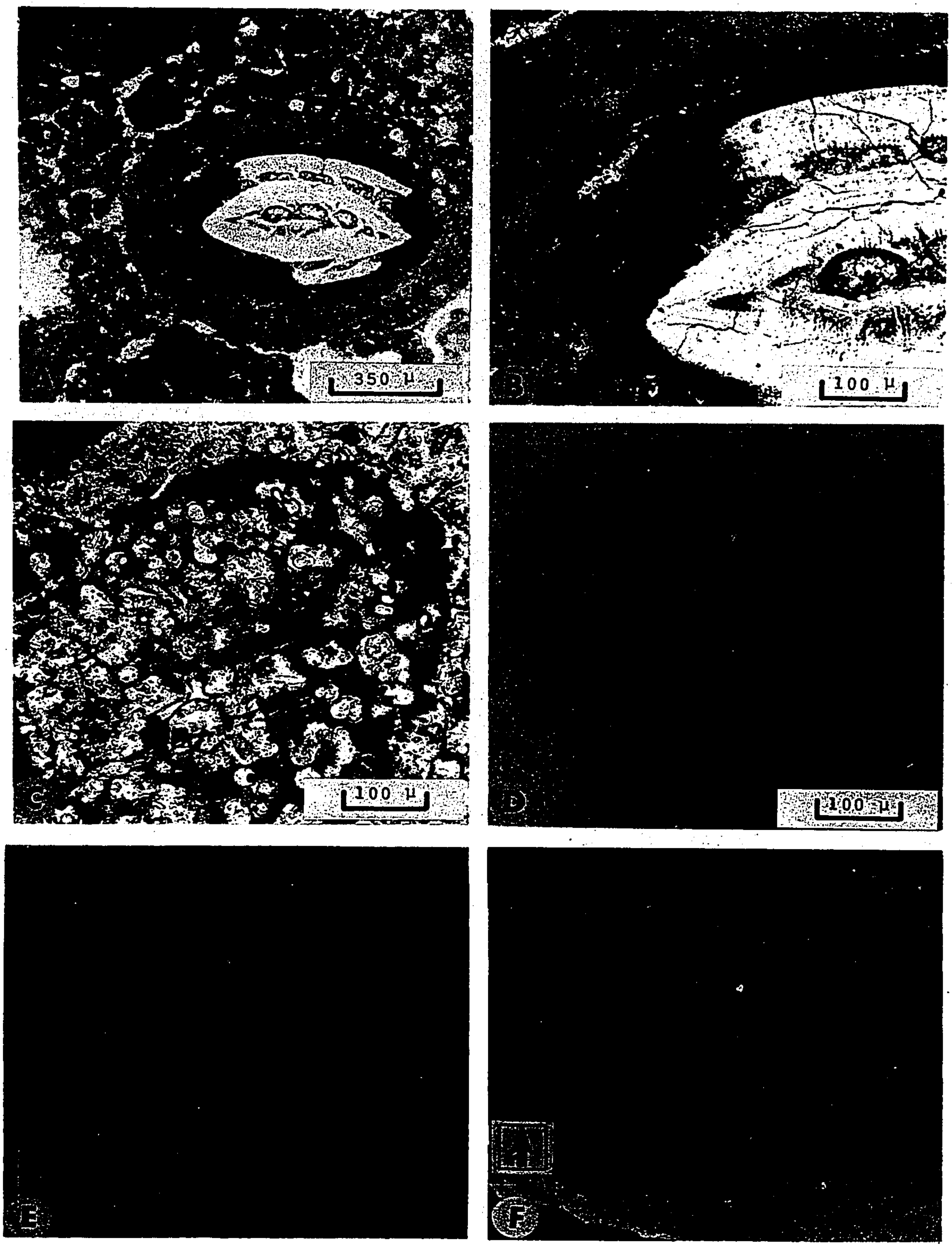
C. A fragment of the articulated coralline red algae Amphiroa that has been extensively bored. The remnant reticulate algal texture in the centre is the only remaining clue to the original nature of the grain. (Sample WB 2E).

D. Borings of the blue-green alga Schizothrix in the intertidal zone along the northeast coast showing the slightly smaller nature of the holes in both calcite cement and Amphiroa. (Sample N4 G).

Rock slabs

E. Fine grained calcarenite in the upper part of the Porites-Thalassia zone in the 83,000 year old reef complex with a small dark vertical root tube in the centre. (Sample LCR Z).

F. Same zone as in (E) showing numerous small brown root tubes, many of which are nearly horizontal. (Sample RB CR1).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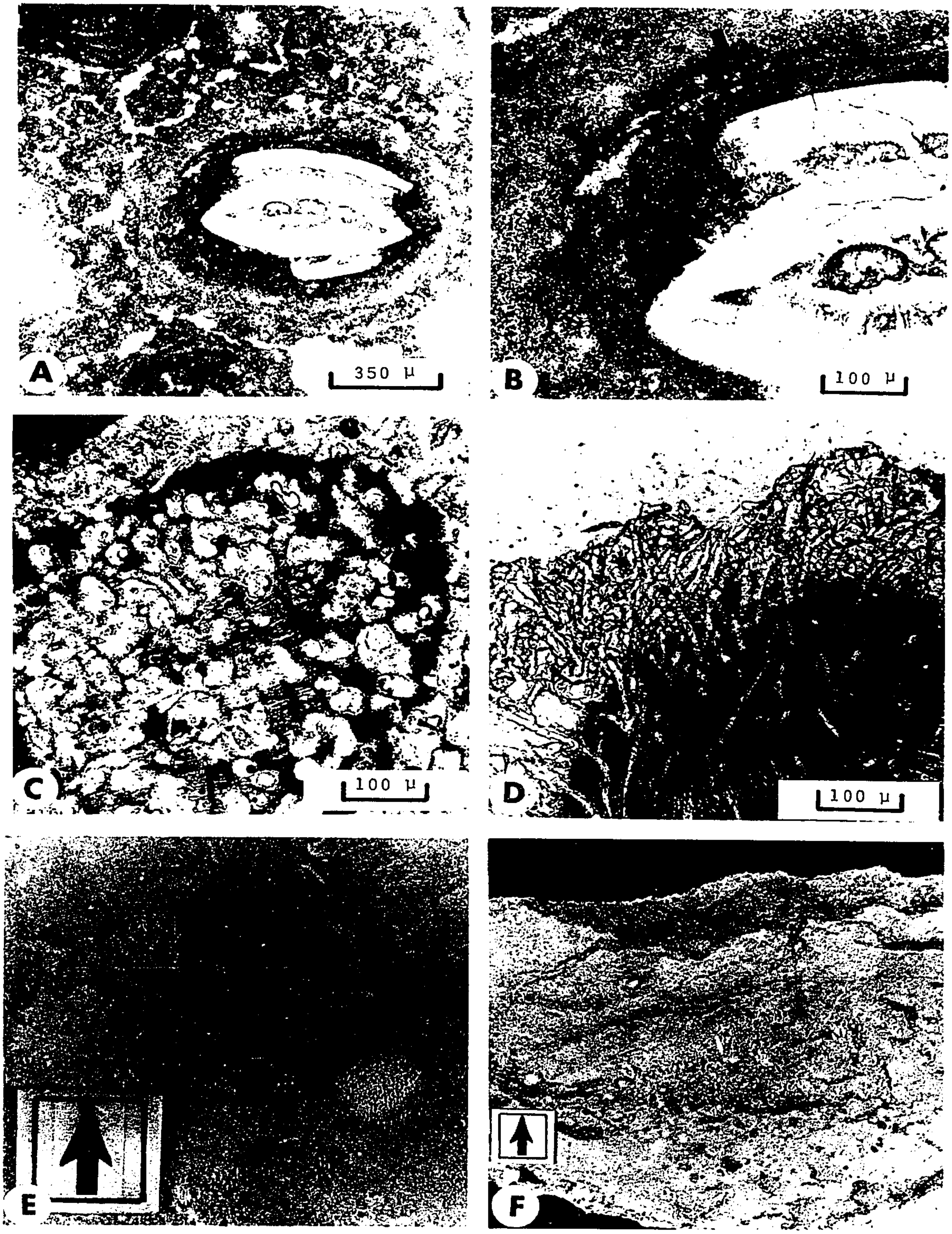
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PLATE 26

SURFICIAL CALCAREOUS CRUSTS

MICRITE, RANDOM NEEDLE FIBRES

Photomicrographs

A. Clotted micrite, plane polarized light, from crusts developed on Pleistocene Key Largo limestone, Windley Key, Florida.

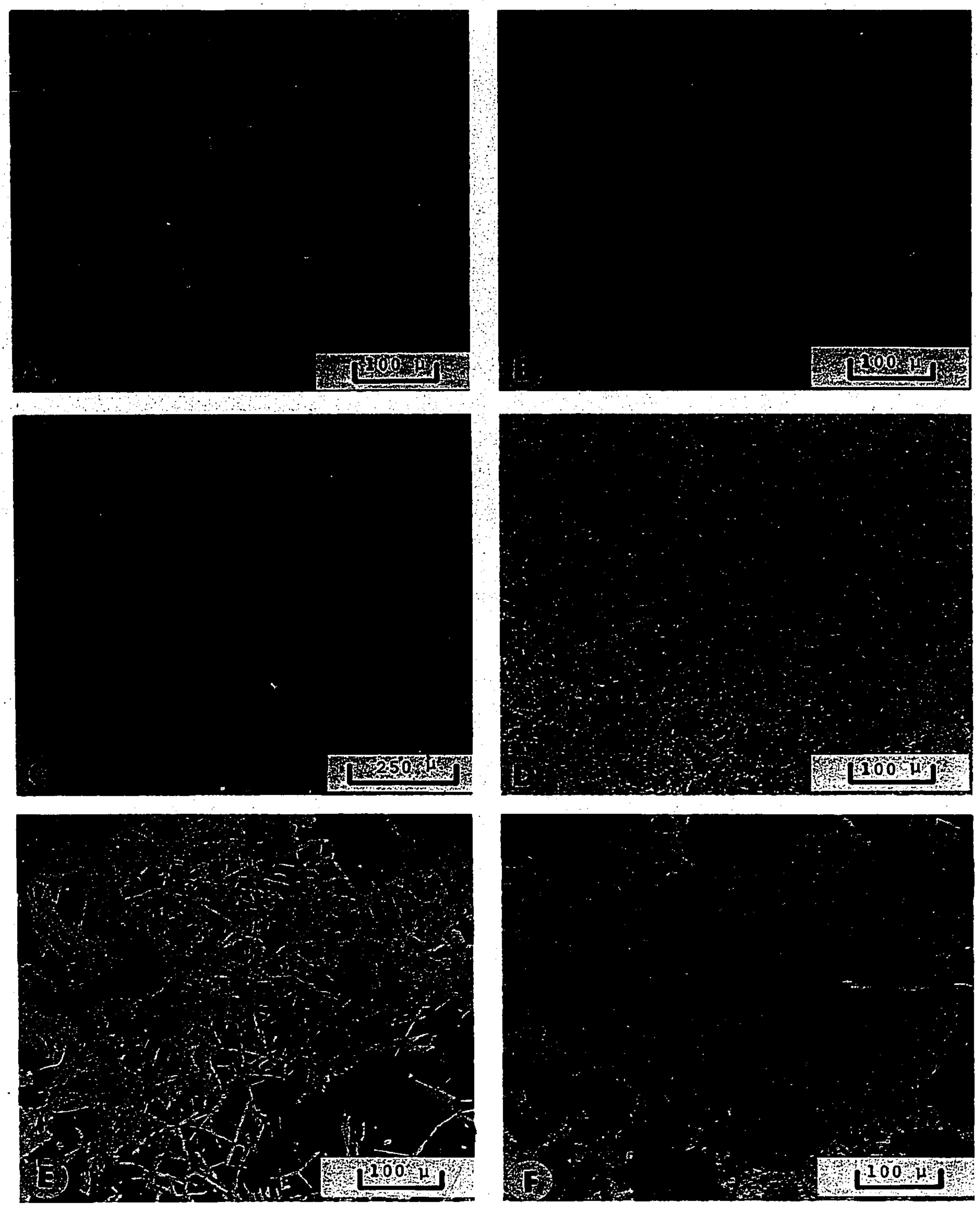
B. Dense micritic crust limestone composed of numerous close packed pelletoids, each of which has a thin coating of tangential calcite needles. Plane polarized light. Goulding's Green, Barbados. (Sample C33C).

C. Micrite pelletoids with a relatively thick coating of tangential calcite needles (between arrows). Plane polarized light. Waites Bay, Barbados. (Sample WB2 J).

D. Random needle fibres, cross polarized light, showing complete lack of preferred orientation. Waites Bay, Barbados. (Sample WB2 E).

E. Random needle fibres, cross polarized light. River Bay, Barbados. (Sample RB C7).

F. Random needle fibres, plane polarized light, from calcareous crust profiles developed on Pleistocene Key Largo limestone, Key Largo, Florida.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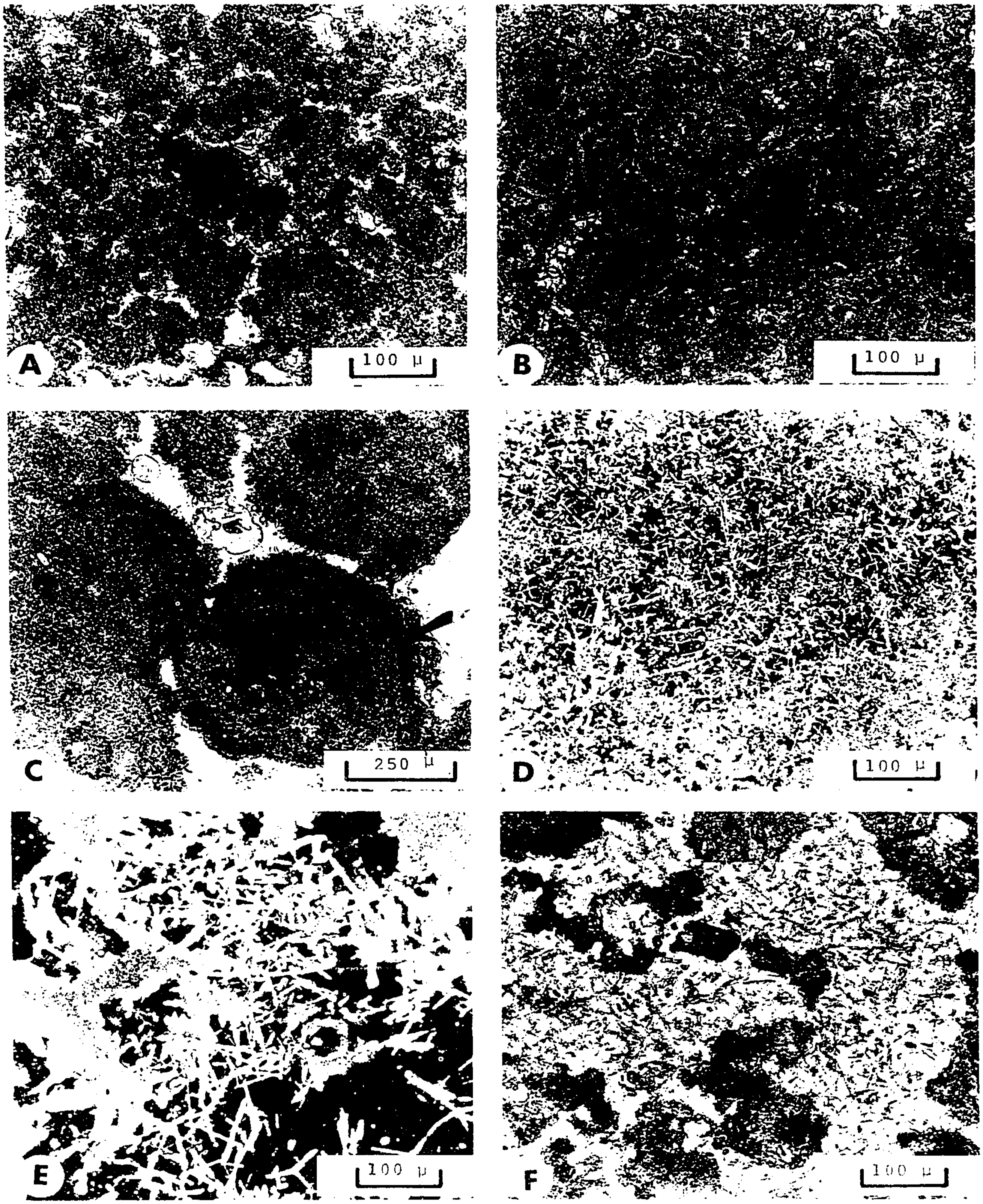
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PLATE 27

SURFICIAL CALCAREOUS CRUST PROFILES

TANGENTIAL NEEDLE FIBRES, FLOWER SPAR

Photomicrographs

A. Tangential needle fibres, cross-polarized light, showing a general alignment compared to the random fibres in Plate 26. Waites Bay, Barbados. (Sample WB 2J).

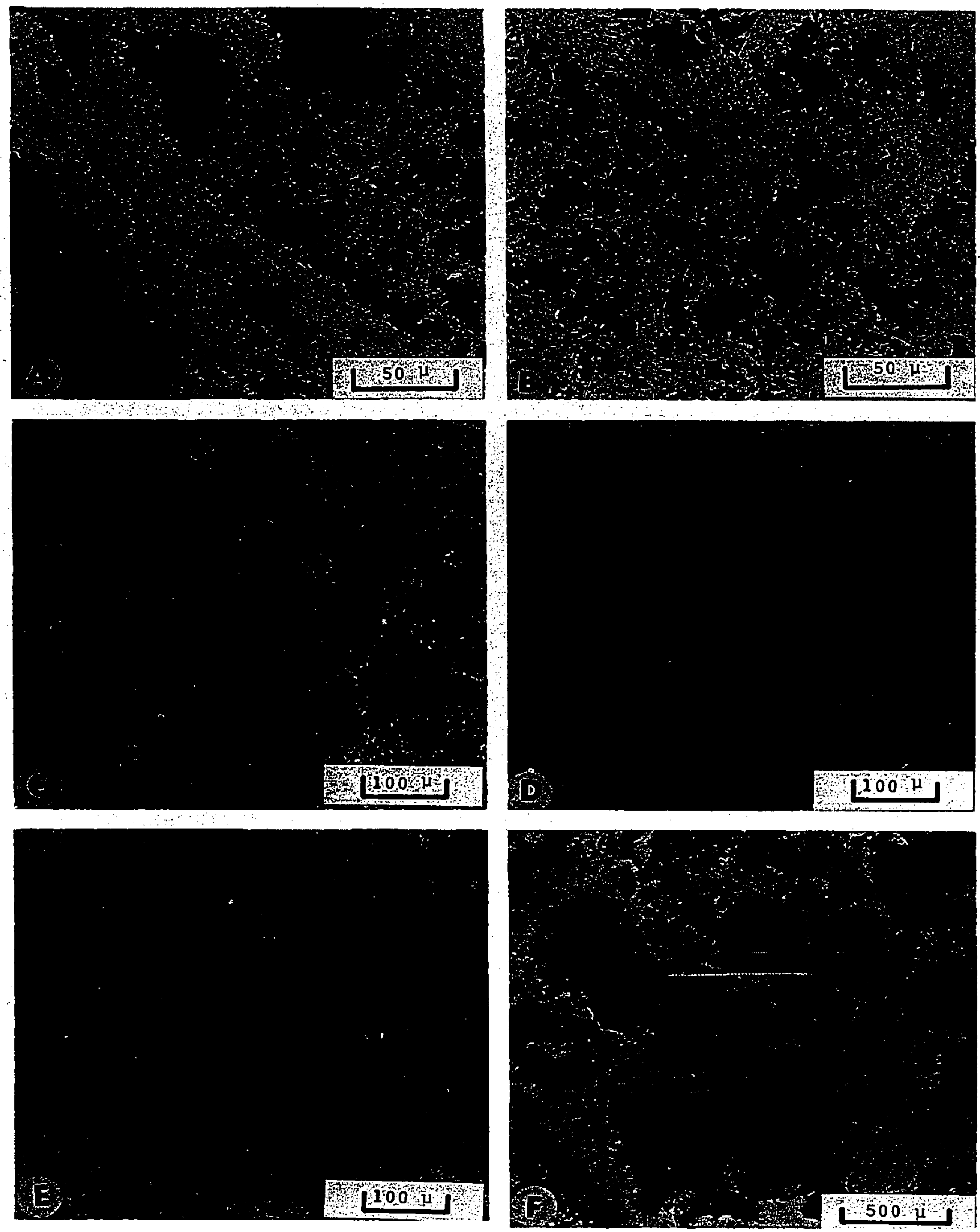
B. Tangential needle fibres, cross polarized light. River Bay, Barbados. (Sample RB C3).

C. Contact between Pleistocene calcilutite (left) and a fracture filling of brown calcite spar (right) (see Plate 23B). The tangential needle fibres are aligned parallel to the fracture wall (centre).

D. Flower spar. Each calcarenite allochem is rimmed with elongate crystals of calcite. This calcite cement occurs as distinct groups of crystals which radiate out from separate points on the grain boundary. Cluff's Bay, Barbados. (Sample C51).

E. Flower spar. Composed in this case of elongate crystals of calcite, growing from a preexisting epitaxial cement rim precipitated on an echinoid fragment (left). Cluff's Bay, Barbados. (Sample C51).

F. Flower spar. Cementing allochems in the upper part of the Pleistocene Key Largo limestone, Key Largo, Florida.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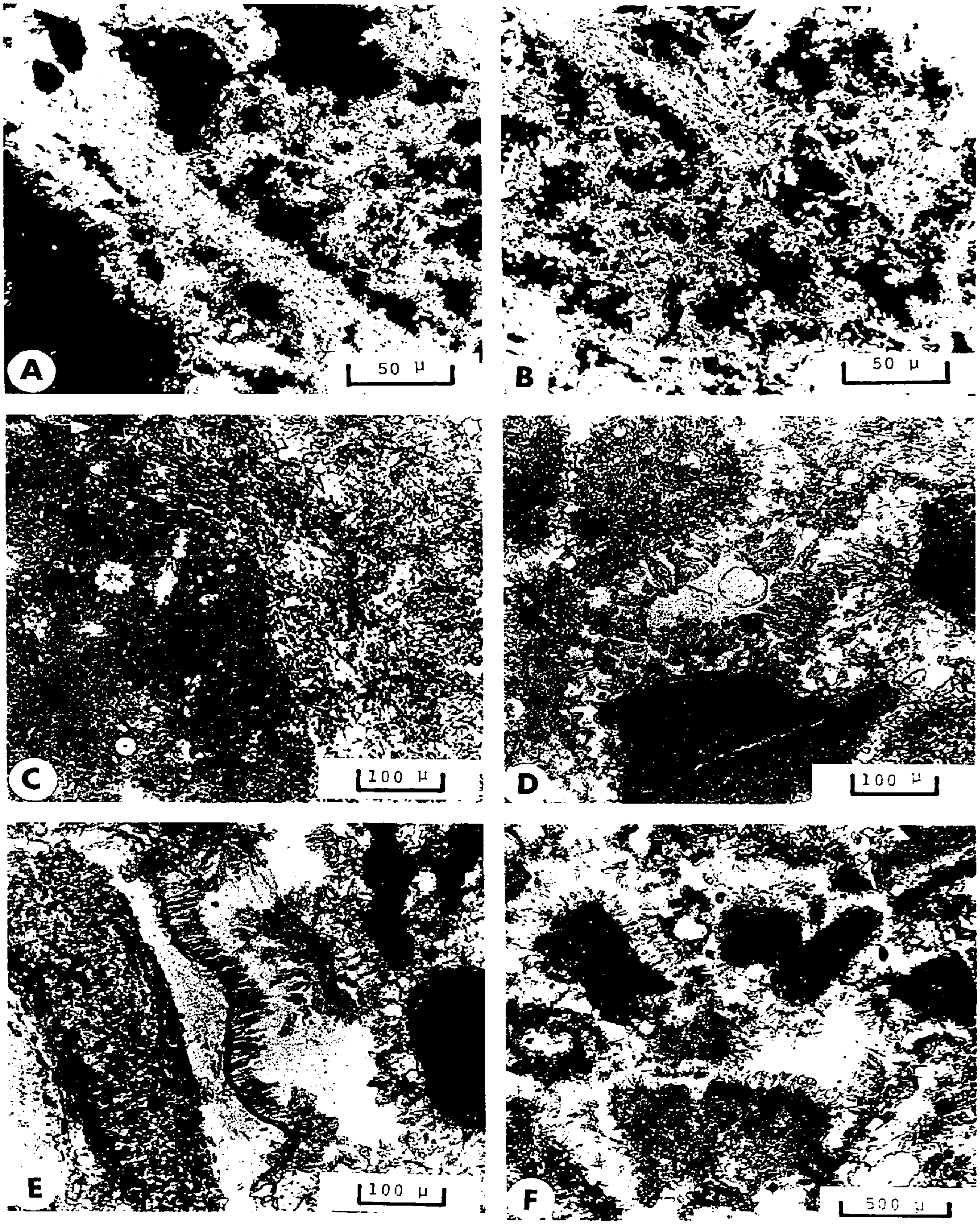
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PLATE 28

SURFICIAL CALCAREOUS CRUST PROFILES

COATED PARTICLES

Photomicrographs - Plane Polarized Light

A. Unlithified calcarenite. Each allochem, still retaining its original mineralogy, is coated with brown calcite micrite. Stroud Bay, Barbados. (Sample SB 1M).

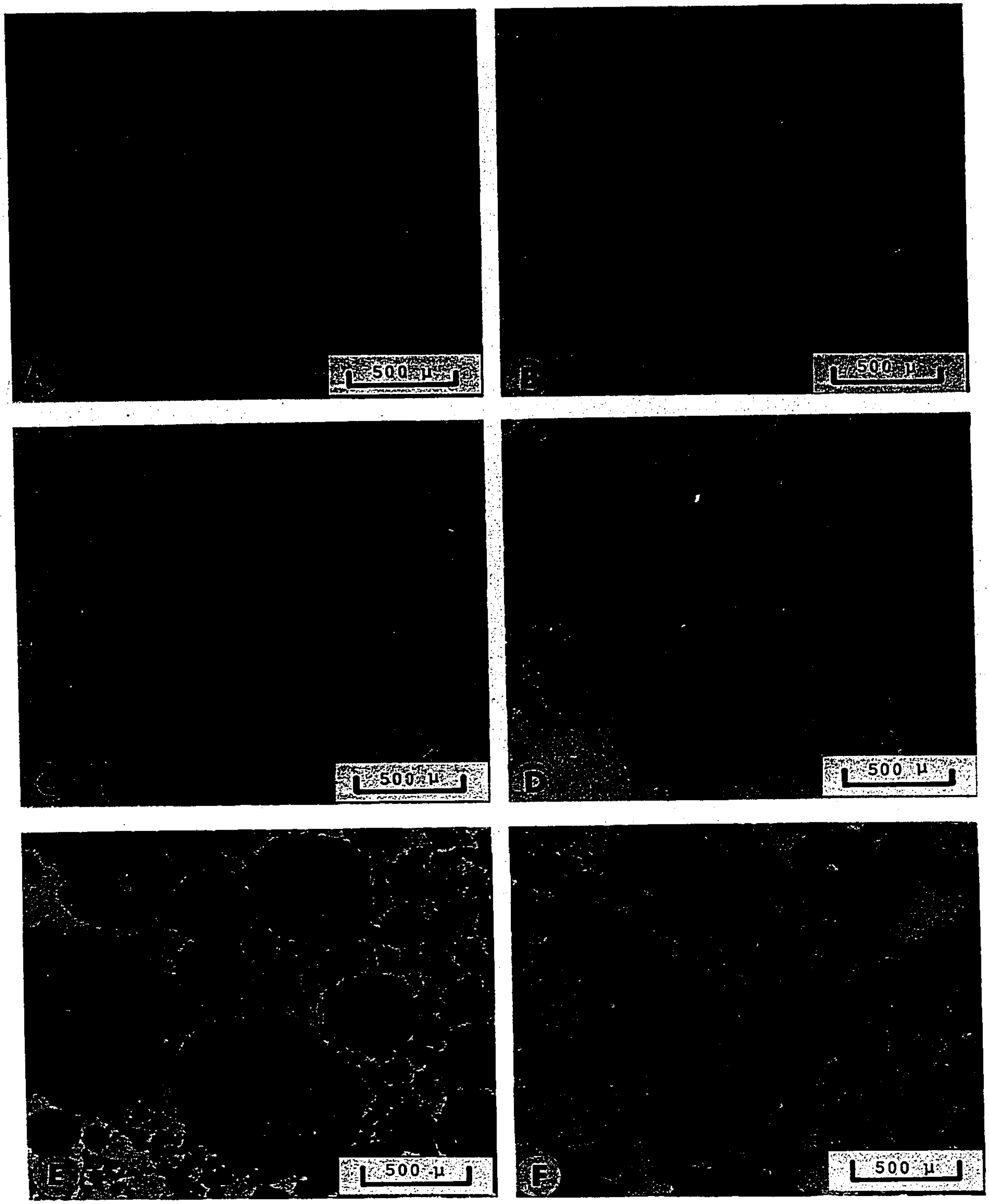
B. Compound coated particle. Each allochem, still retaining its original unstable mineralogy is coated with a thin series of laminae made up of micrite and tangential needle fibres. A second, thicker, coat of identical composition surrounds and joins both coated particles. Stroud Bay, Barbados. (Sample SB 1C).

C. Coated micrite pelletoids, from the slab illustrated in Plate 23A, The dark centre of each pelletoid may be a micritized skeletal particle (see Plate 24E,F, 25A,B). The micrite between the larger pelletoids has a clotted texture. River Bay, Barbados. (Sample RB1 B5).

D. Coated particles exhibiting many laminae (bottom centre). Stroud Bay, Barbados. (Sample SB 1F).

E. Coated microspar fragment. The irregular nature of the coating suggests partial micritization. Waites Bay, Barbados. (Sample WB 2J).

F. Interrelationship between crust and coated particles. The two grains in the centre left and extreme centre right are both coated with laminated micrite and needles. The outer coatings, however, are continuous with the crust that joins both particles. Stroud Bay, Barbados. (Sample SB 1C).



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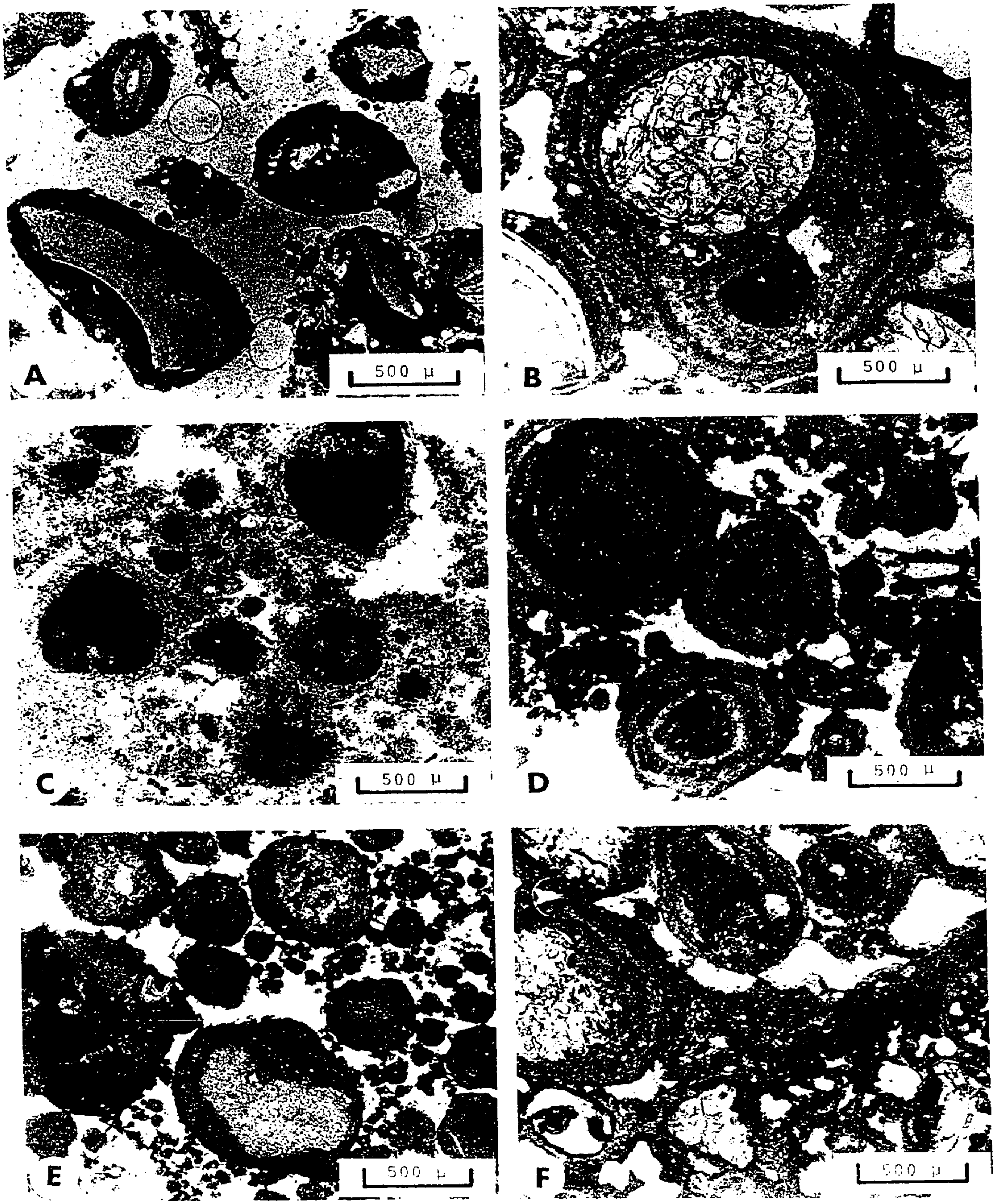
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PLATE 29

SURFICIAL CALCAREOUS CRUST PROFILES

TUBULES

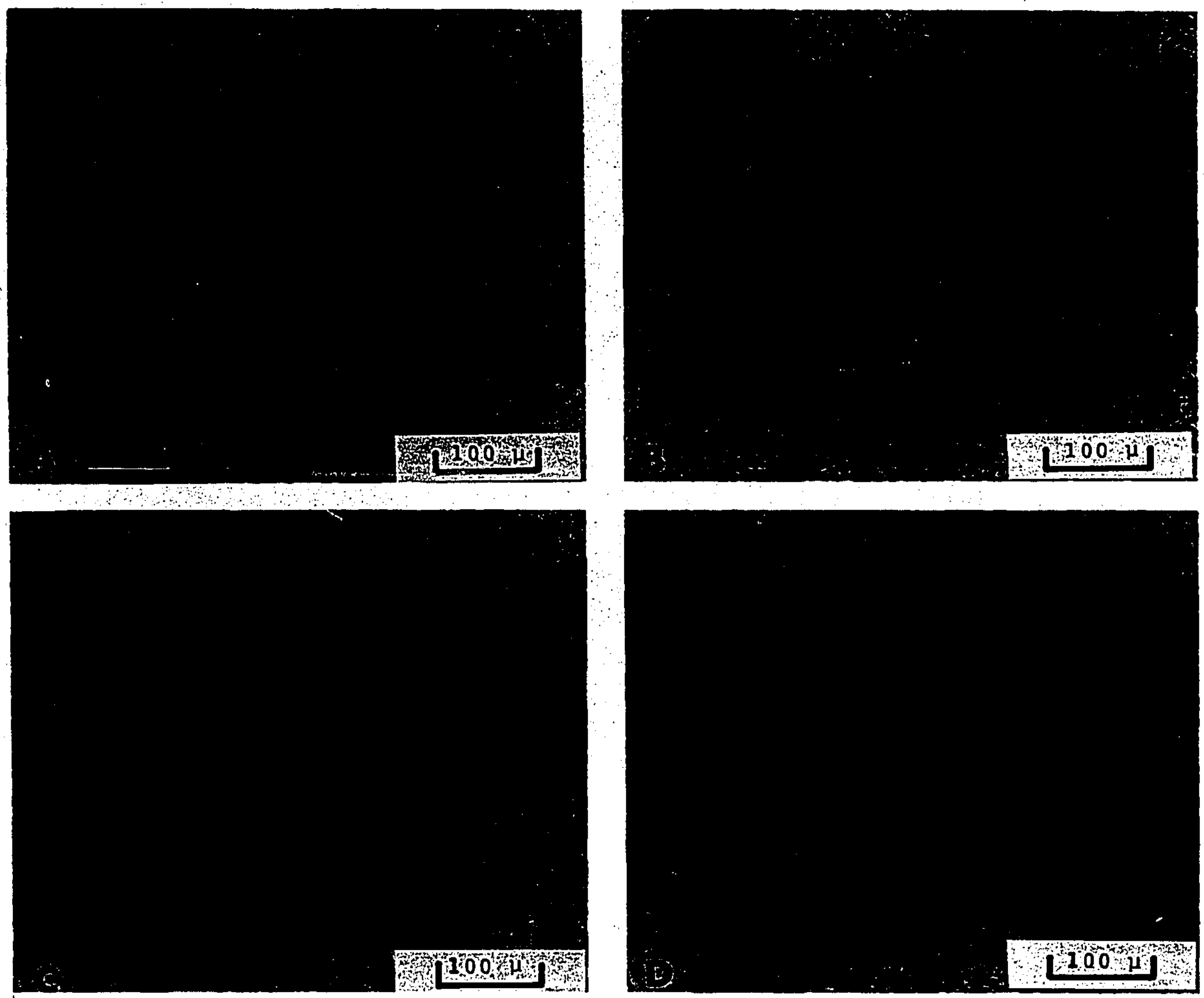
Photomicrographs - Plane Polarized Light

A. Ramifying network of tubules. The walls of each tubule are composed of micrite and microspar. North Point Shelf, Barbados. (Sample C15).

B. Network of interlocking tubules. Northeast coast, Barbados. (Sample WB 2E). The tubules are continuous with the borings illustrated in Plate 25C.

C. Tubules, developed in upper meter or so of Pleistocene Key Largo limestone, Windley Key Quarry, Florida.

D. Tubules, developed in upper meter or so of Pleistocene Key Largo limestone, Cross Key Canal, Key Largo, Florida.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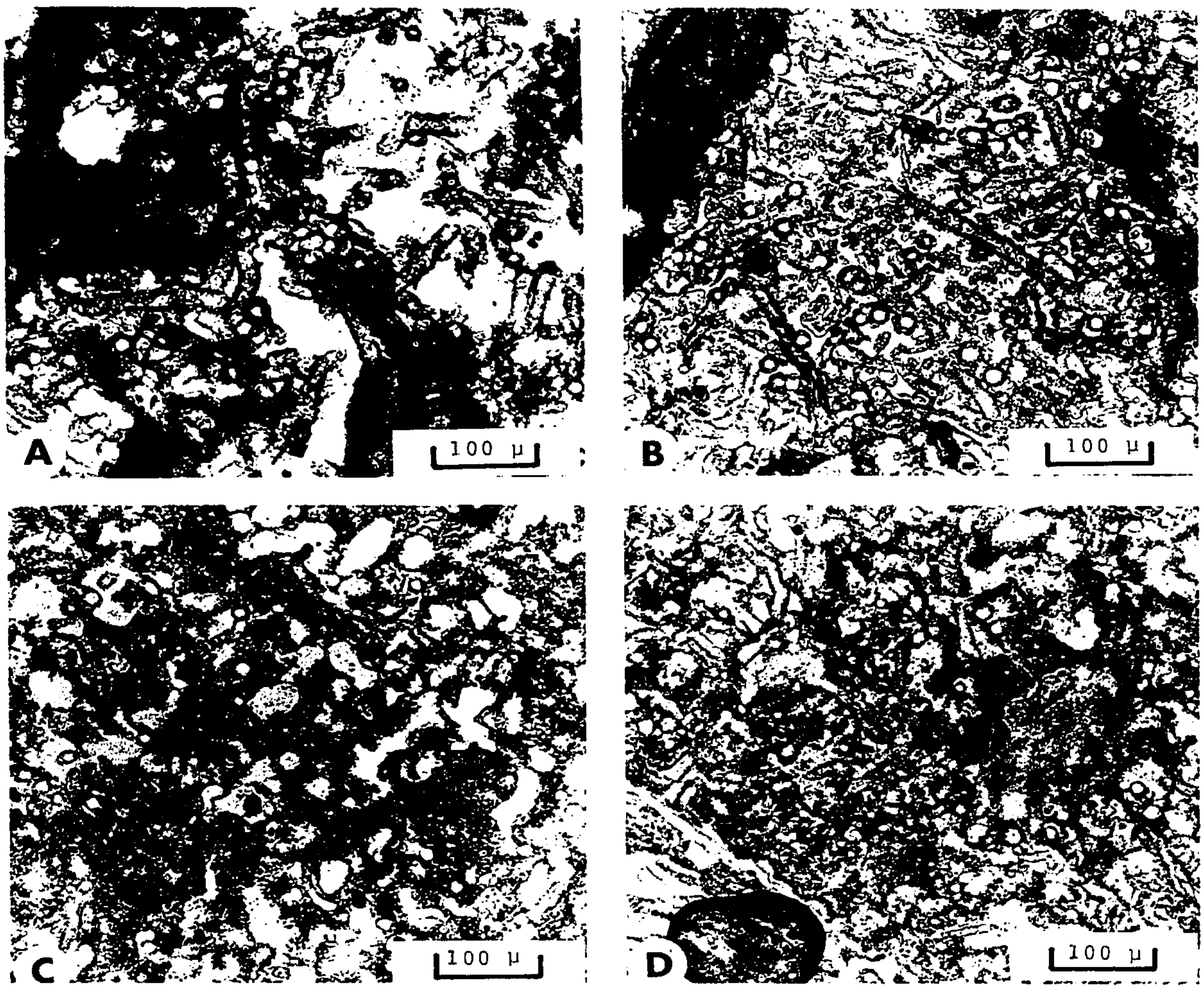
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PLATE 30

BURIED CALCAREOUS CRUST PROFILES

A. Contact between 104,000 year old Pleistocene reef complex (upper unit) and 125,000? year old Pleistocene reef complex (lower recessive unit). (See also Plate 16C). (Locality FW).

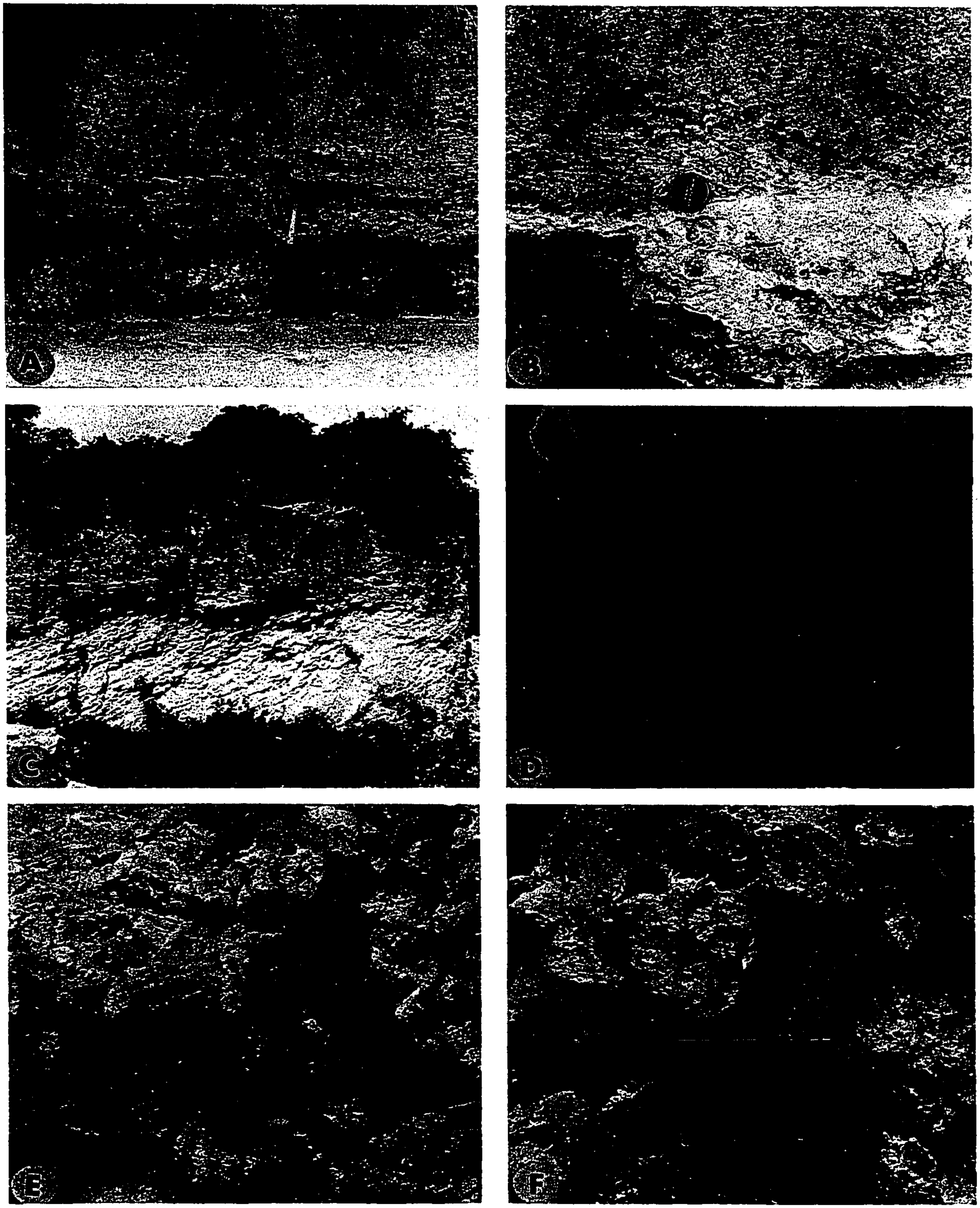
B. Hard, well-lithified, calcareous crust profile developed at the contact between the two reef complexes pictured in (A). These buried crusts and associated features indicate subaerial exposure of the underlying 125,000? year old complex to conditions similar to those on the northeast coast today,prior to burial by the 104,000 year old complex.

C. Contact between flat lying limestones of the 104,000 year old reef complex and dipping calcarenite beds of an older complex. Arrow indicates location of slab pictured in (D) (locality M18). Outcrop is 5.8 meters high.

D. Rock slab illustrating dark irregular bands developed in the upper few feet of the steeply dipping calcarenite pictured in (C). In outcrop these dark bands cut across bedding and are parallel to the upper surface. (Sample M18).

E. Contact between palmata zone of the 104,000 year old reef complex and underlying older cervicornis zone of the 125,000? year old reef complex. Large vugs developed in the upper few feet of the underlying cervicornis zone pictured here also attest to the subaerial exposure of the limestone prior to burial. The vugs are lined with brown calcareous crusts and floored with coated grains. Lens cover is 5 cm. in diameter (locality US).

F. Enlarged area of (E) illustrating the irregularities (arrows) of the vug linings. Photograph covers an area 16 cm wide.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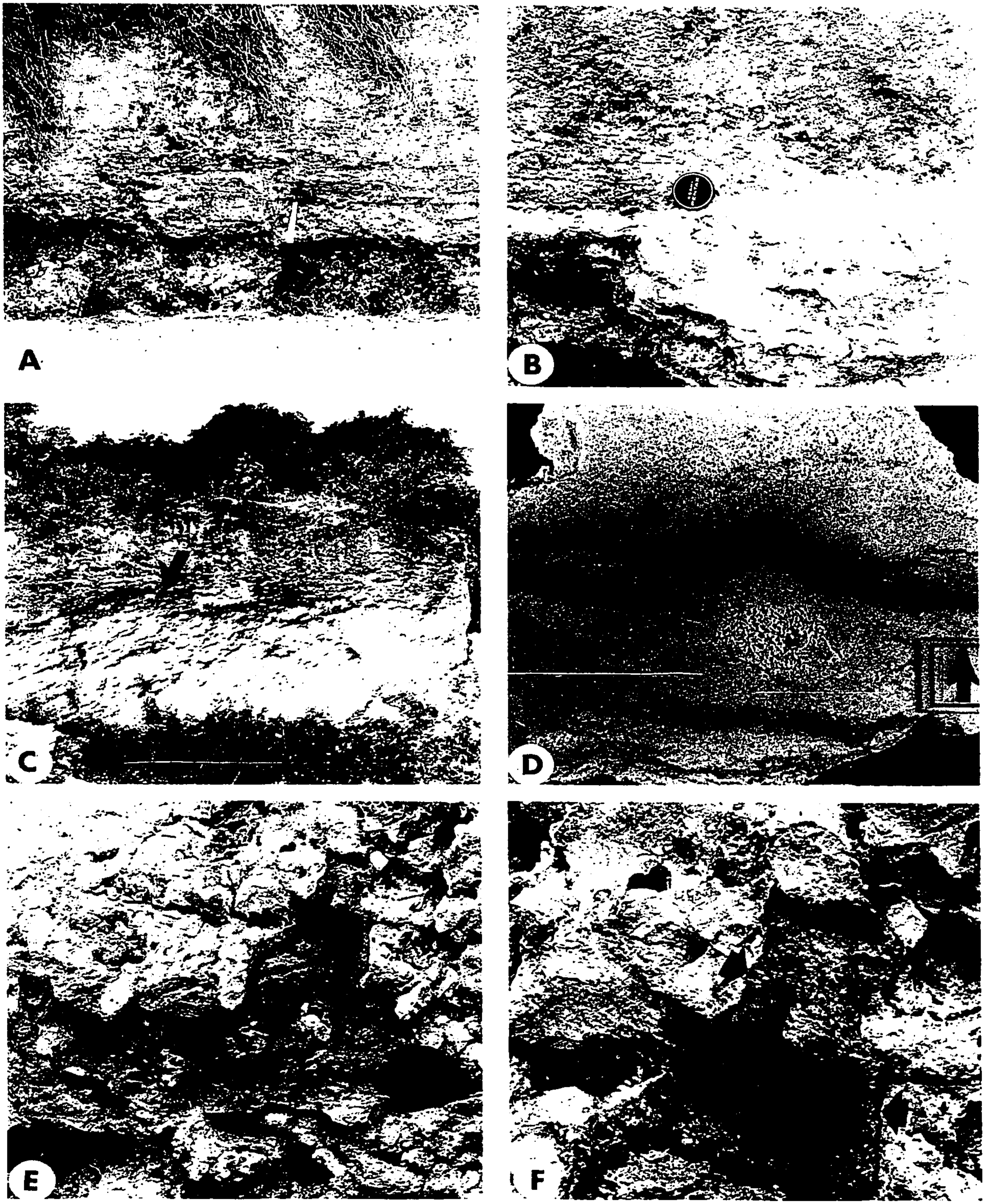
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PLATE 31

BURIED CALCAREOUS CRUST PROFILES

Photomicrographs -- Plane Polarized Light

A. Coated skeletal grains. Coatings composed of alternating laminae of tangential needle fibres and micrite. The curved mollusc fragment is coated with successive layers to form a circular particle. (Sample M18).

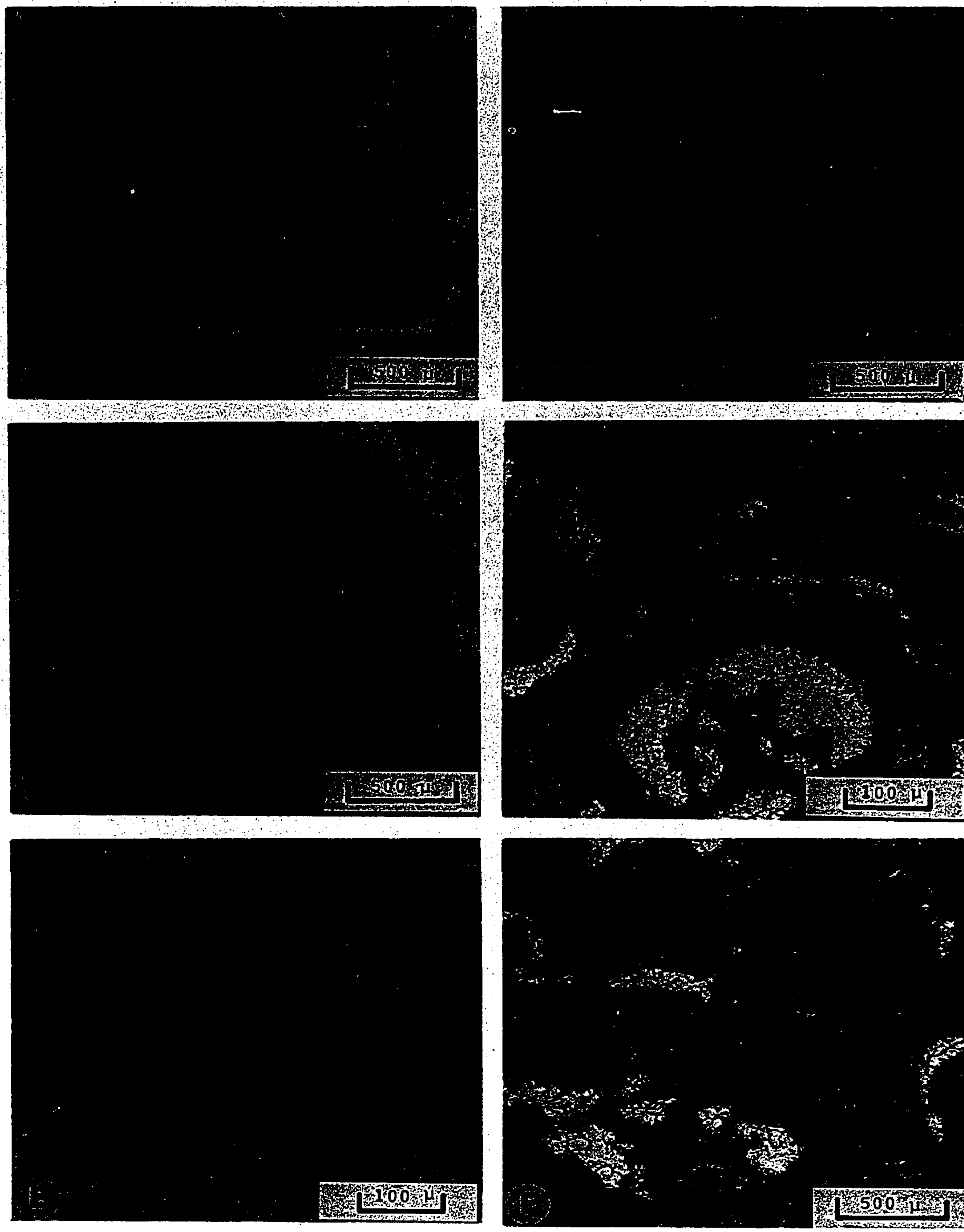
B. Coated micrite pelletoids, well cemented with clear calcite spar. (Sample M18).

C. Coated pelletoid, enlarged with alternating laminae of tangential needles (dark) and micrite (light). (Sample M18).

D. Coated allochem. The original allochem has dissolved subsequent to being coated and the resulting void has been filled with clear calcite. The calcite coating has, however, remained unaffected. (Sample M18).

E. Calcareous crust. Irregular laminae of clear calcite spar. (Sample FW 12).

F. Calcareous crust. Horizontal laminae of tangential needle fibres. (Sample M18).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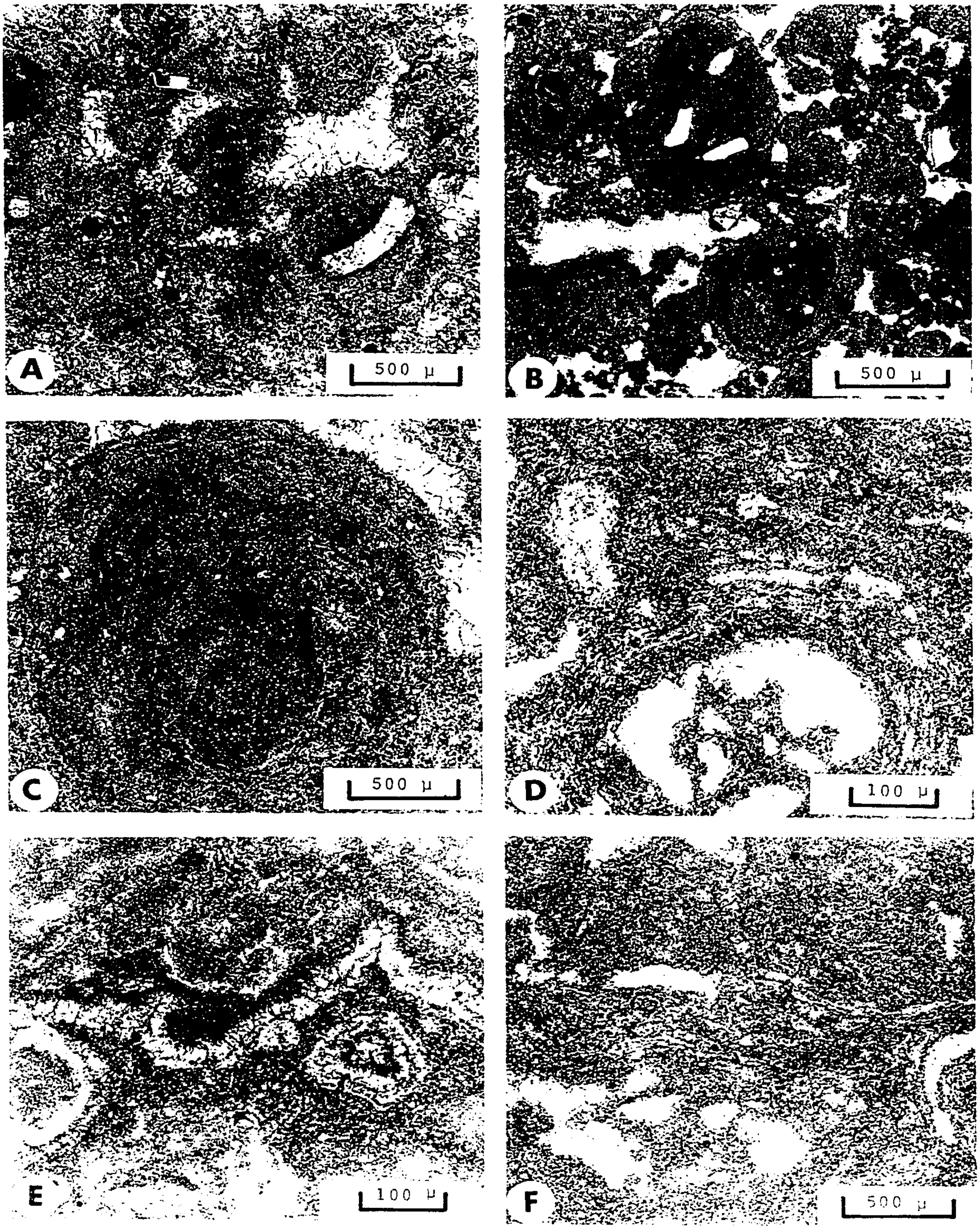
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PLATE 32

CORAL DIAGENESIS

A. *Acropora palmata*, cross-section of frond. Long, vertical corallites (c) are joined together by a series of horizontal bars and vertical rods, collectively called the coenosteum. Photo is 1 cm wide.

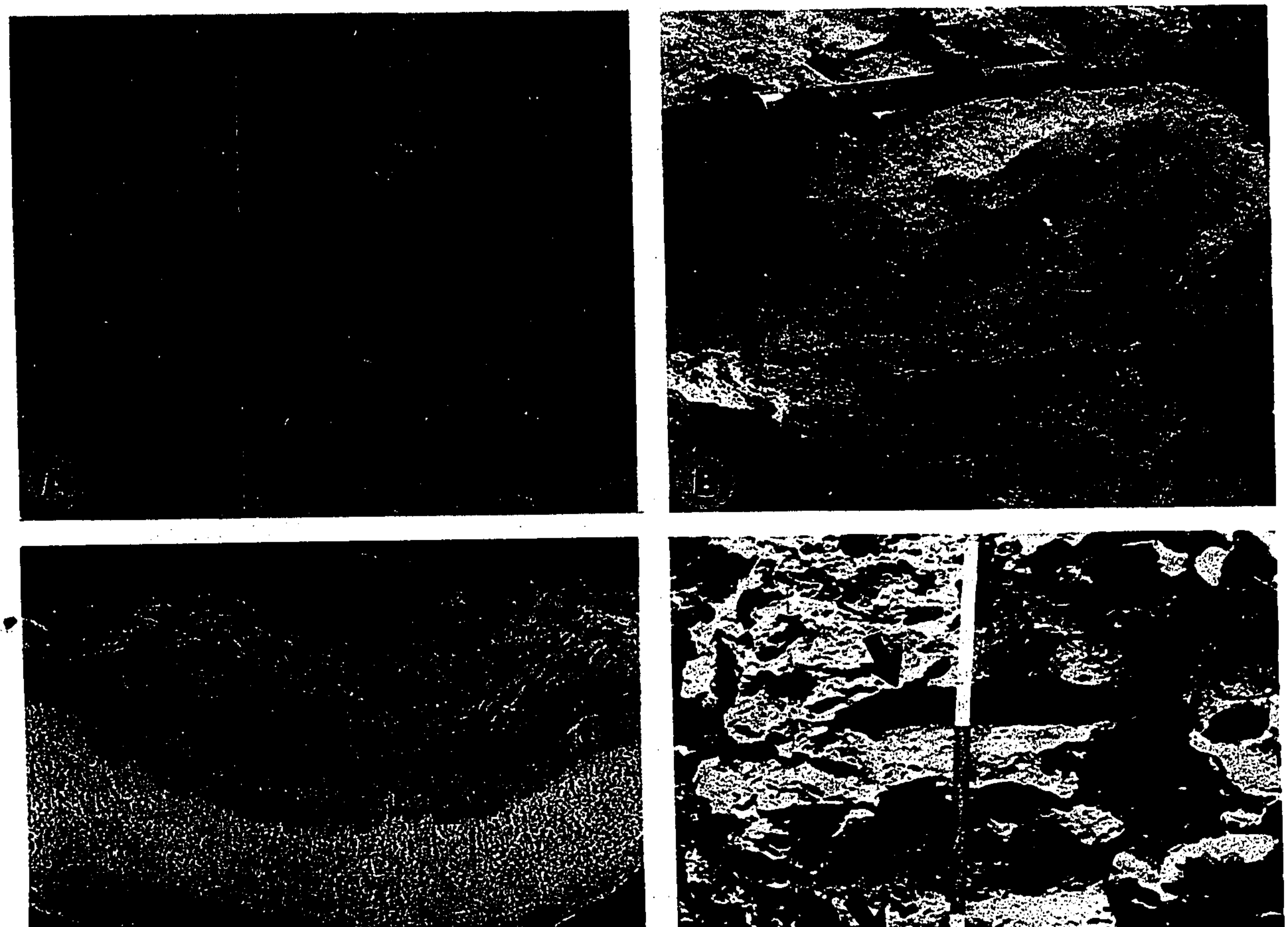
B. *Acropora palmata*, 104,000 year old reef complex, illustrating axial alteration. Note the calcite (c) concentrated at the centre of the coral branch while the aragonite remains at the periphery (locality P25).

C. *Acropora palmata*, 83,000 year old reef complex, illustrating dorsal alteration. Note the crustose red algae on the upper surface of the coral which is directly underlain by calcite. The basal part of the coral is chalky aragonite. Scale in cm. (locality RB).

D. *Acropora palmata* zone, 125,000 year old reef complex. The coral fronds have been completely dissolved, resulting in a series of curved vugs (arrows) in well-lithified calcilutite (locality River Bay).

E. *Cervicornis* zone, 104,000 year old reef complex. Note the numerous coral sticks that are being dissolved by solution around the periphery of each stick (locality FW3).

F. *Cervicornis* zone, 104,000 year old reef complex. The coral sticks have been completely dissolved resulting in a series of holes in a well-lithified calcilutite, yielding an exposure resembling Swiss cheese (locality FW1).



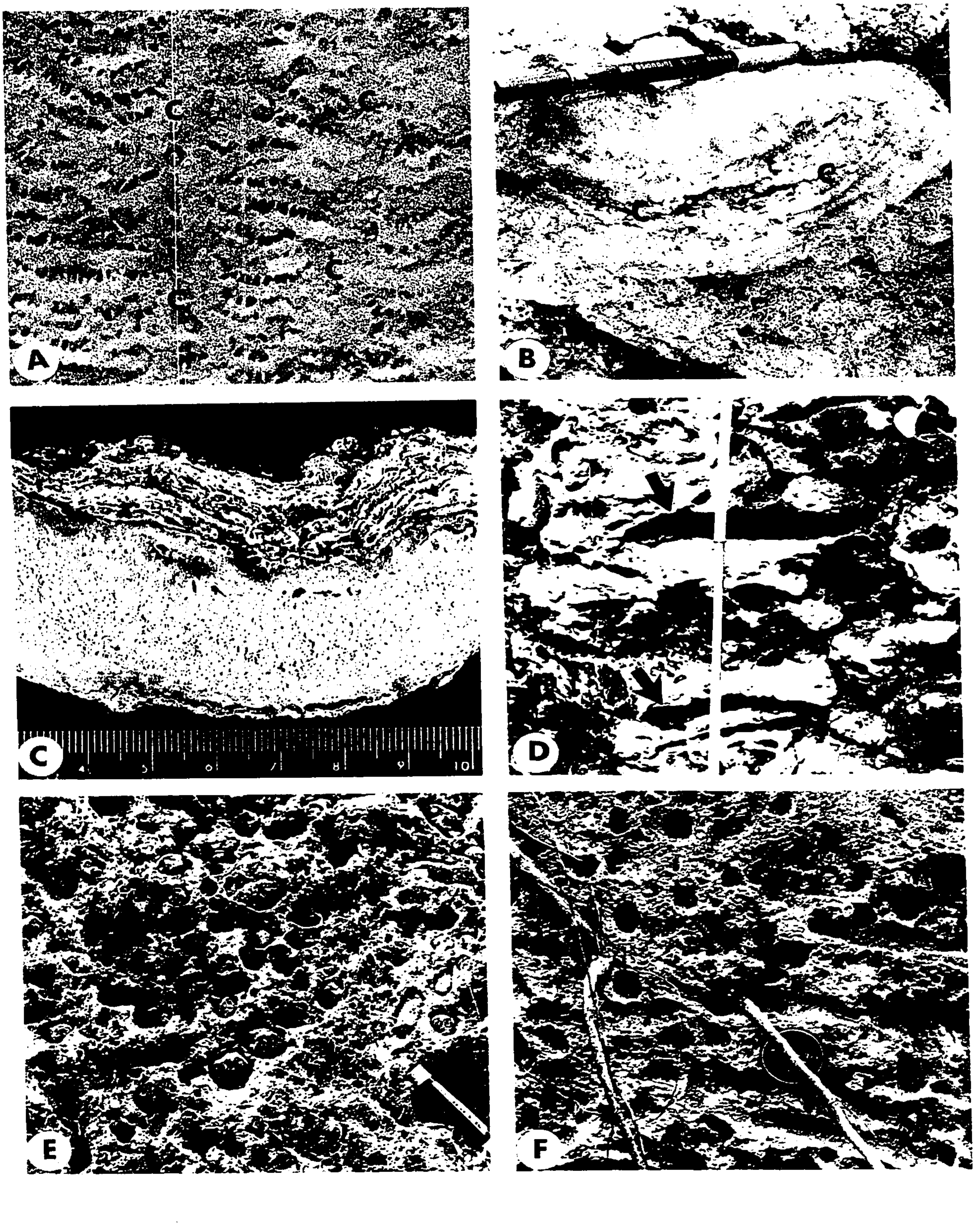

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PLATE 33

ACROPORA PALMATA

Photomicrographs

A. Recent, aragonite, offshore western Barbados, plane polarized light. Note the numerous irregular pores. Dark horizontal lines are the centre of calcification of separate horizontal trabecula.

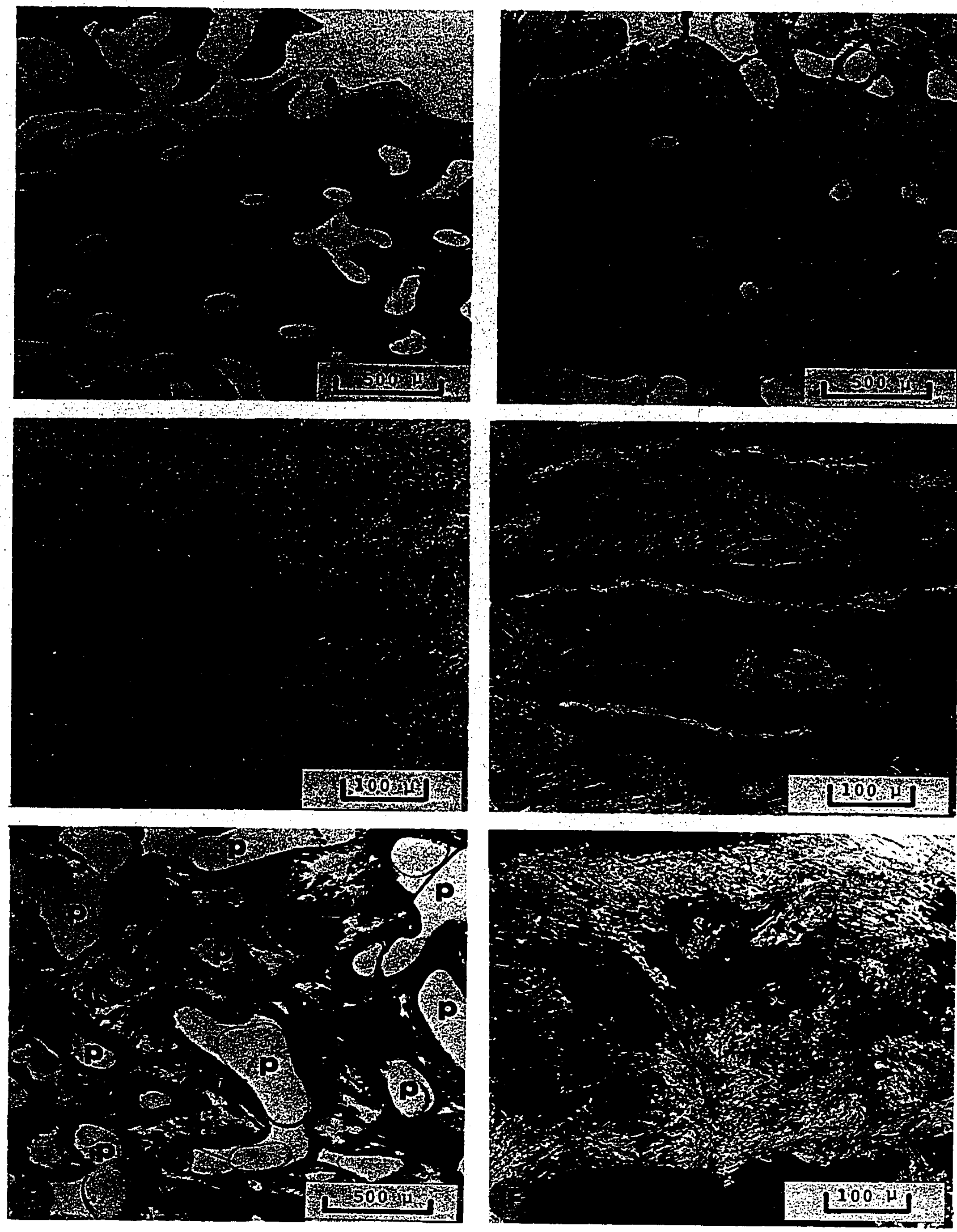
B. Pleistocene, aragonite, reef facies, 83,000 year old reef complex, plane polarized light. The original texture has been retained and there is a complete lack of alteration. Dark horizontal lines are the centres of calcification of separate parallel trabecula. (Sample AFD, A).

C. Pleistocene, aragonite, reef facies, 83,000 year old reef complex, plane polarized light. Enlargement of Plate 33B showing relatively dark centres of calcification (arrows) and aragonite needles radiating from these lines. (Sample AFD, A).

D. Pleistocene, chalky aragonite, reef facies, 83,000 year old reef complex, plane polarized light. Initial solution of the coral skeleton. Each centre of calcification has been dissolved and is now a linear white void and the chalky aragonite is darker compared to the unaltered aragonite in (C). The darker colour is due to internal reflection of the light in the minute pore space created by solution between the aragonite needles (see S.E.M. plate 36). (Sample L17).

E. Pleistocene, chalky aragonite, reef facies, 83,000 year old reef complex, plane polarized light. Extensive solution of the coral skeleton without reprecipitation of calcite. Solution is restricted to the inner parts of the trabecula (clear irregular white patches, not labelled) and in some cases almost all of the original aragonite has been dissolved. The pore walls, on the other hand, retain their sharp outline indicating little or no solution. (Sample L17).

F. Pleistocene, chalky aragonite, reef facies, 83,000 year old reef complex. Enlarged area of coral pictured in (E) viewed under cross polarized light. The central part of this trabecula is almost completely dissolved and the aragonite surrounding the void is ragged and irregular indicating solution is proceeding outward from the centre. (Sample AFD, A).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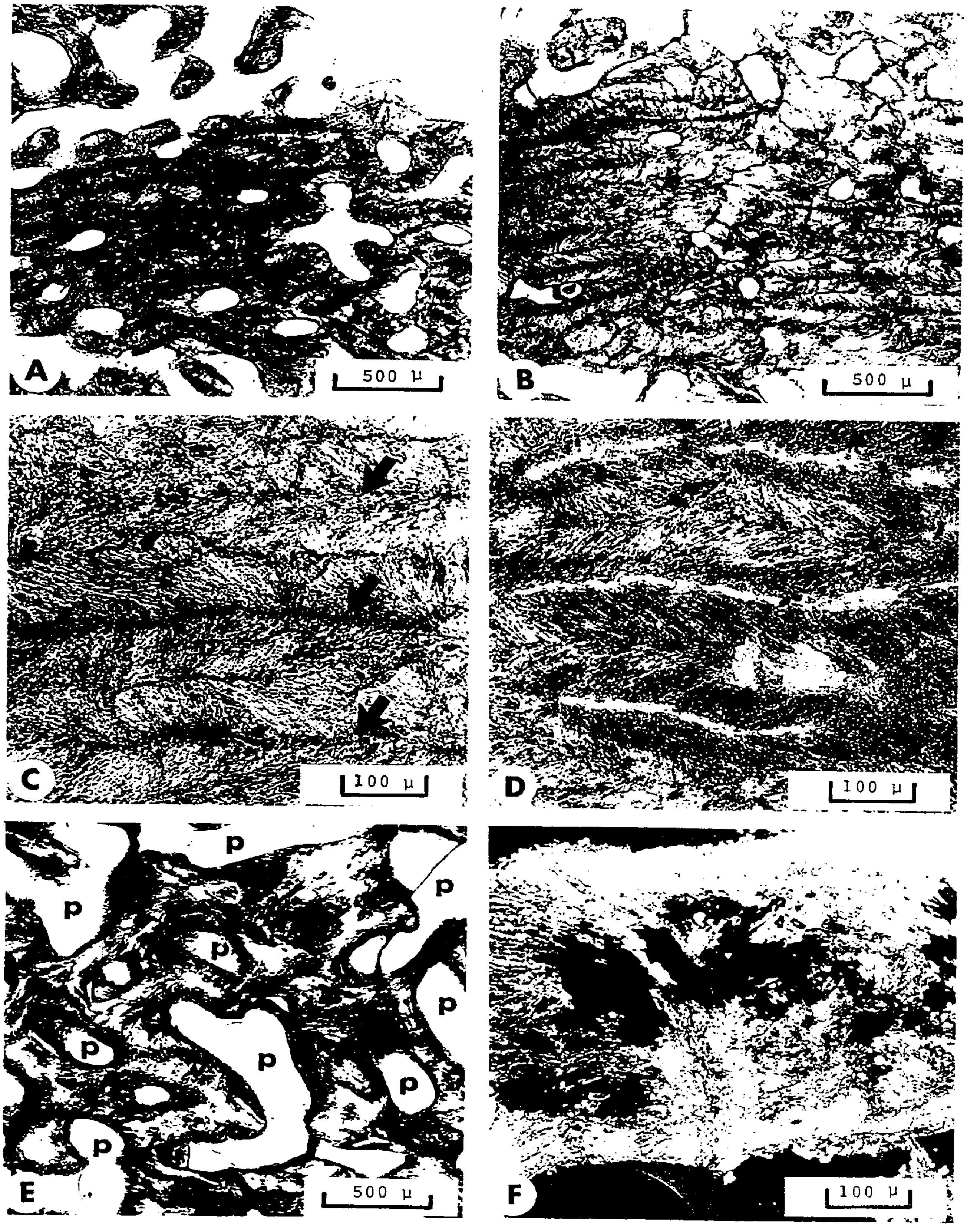
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PLATE 34

ACROPORA PALMATA

Photomicrographs - Plane Polarized Light

A. Pleistocene, chalky aragonite, reef facies, 83,000 year old reef complex. Light material in upper part of thin section is calcite; dark material in lower part is aragonite. In the calcite area, the original pore outlines are still retained. Chalky aragonite still fringes many pore walls, indicating that replacement took place from the centre of the trabecula out towards the pore wall. Aragonite-calcite contact at the upper right (arrow) is similar to that illustrated in S.E.M. Plate 38B. (Sample L15).

B. Pleistocene, chalky aragonite and calcite, reef facies, 104,000 year old reef complex. Light material in upper part of thin section is calcite; dark material is aragonite and the pores are indicated by (p). Clear calcite is restricted to the interior of the trabecula and never occurs first adjacent to the pore walls. In the centre of the plate, the long, thin ribbon of calcite follows the original centre of calcification. (Sample SD 2).

C. Pleistocene, calcite, reef facies, 104,000 year old reef complex. Completely replaced portion of sample illustrated in (b). The original form and sharp boundaries of the pores are retained, but the original dark centre of calcification in aragonite corals is now a canal of clear calcite.

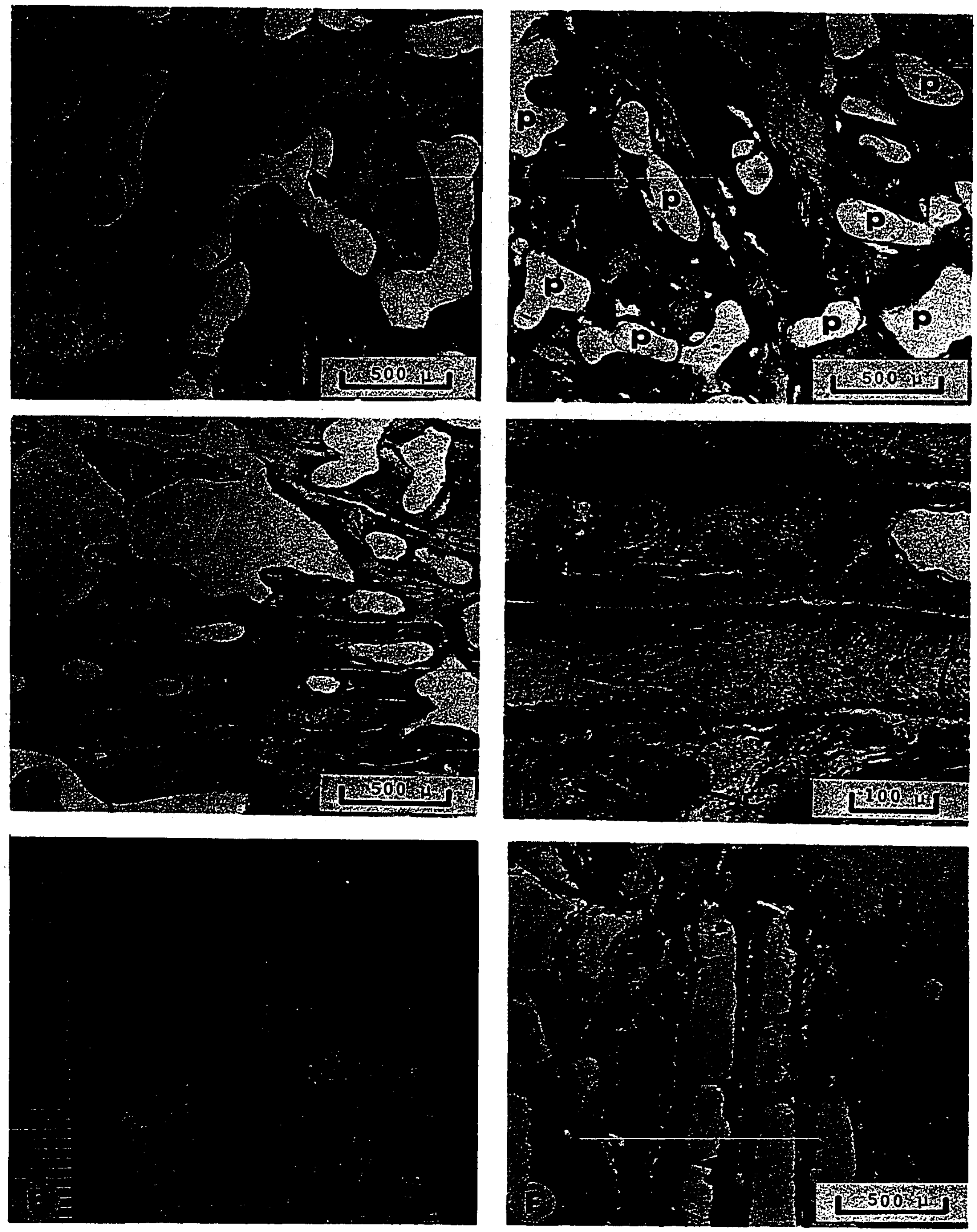
D. Pleistocene, calcite, reef facies, 104,000 year old reef complex. Enlargement of sample illustrated in (C). A clear band of calcite is now in the position occupied by centre of calcification in aragonite forms. Compare to Plates 33C and 33D. The new calcite cleavage cuts across the original trabecular texture. (Sample SD 2).

MONTASTREA ANNULARIS

E. Rock slab illustrating a partially altered form. Dark material at top is calcite; light material at bottom is aragonite. Photomicrograph in (F) is taken at contact. Scale in mm. (Sample B25).

Photomicrograph - Plane Polarized Light

F. Pleistocene, calcite and chalky aragonite, 83,000 year old reef complex. Clear material is calcite and dark material is chalky aragonite. The clear bands of calcite follow the original centres of calcification.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100 µ
500 µ

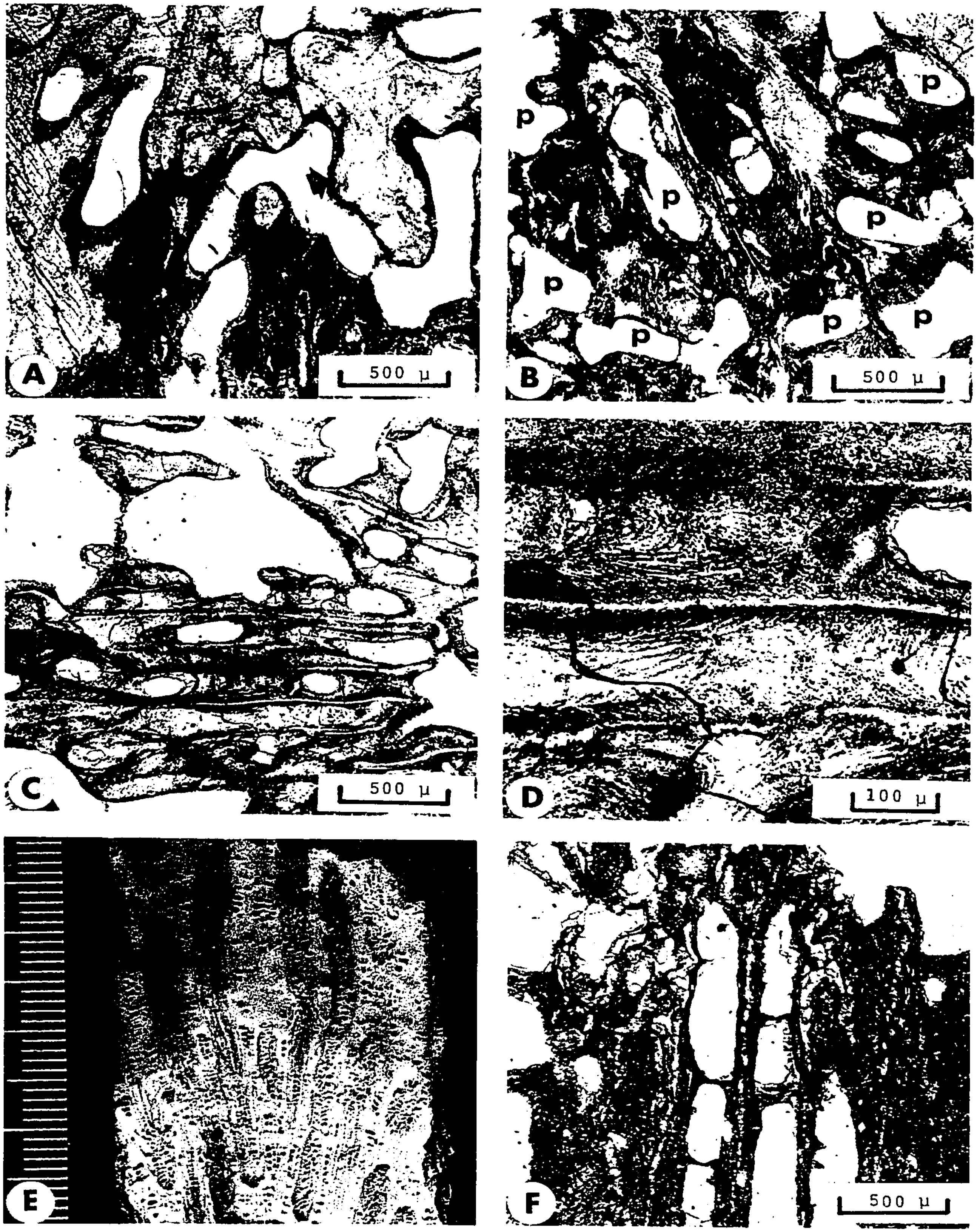

A
500 µ
B
p
p
p
p
p
p
p
p
500 µ
C
500 µ
D
100 µ
E
F
500 µ

PLATE 35

SCLERACTINIAN CORAL, ACROPORA CERVICORNIS

Photomicrographs - Plane Polarized Light

A. Recent, aragonite, axial cross-section, offshore, western Barbados. The numerous trabecula are well illustrated, each with a dark centre of calcification surrounded by light, fibrous aragonite.

B. Pleistocene, chalky aragonite, axial cross-section, reef facies, 83,000 year old reef complex, northern Barbados. Dark material is chalky aragonite. The long, linear clear voids were once occupied by individual centres of calcification (compare with A). (Sample B21A 1A).

C. Pleistocene, calcite, axial cross-section, reef facies, 104,000 year old reef complex, northern Barbados. The canals of clear calcite were once occupied by the dark centre of calcification (compare with A and B). Original pores are now rimmed with calcite spar cement. (Sample FW2 C).

TABULATE CORAL, THAMNOPORA

Upper Devonian, Perdrix and Mount Hawk Formations
Mount Haultain, Jasper National Park, Alberta

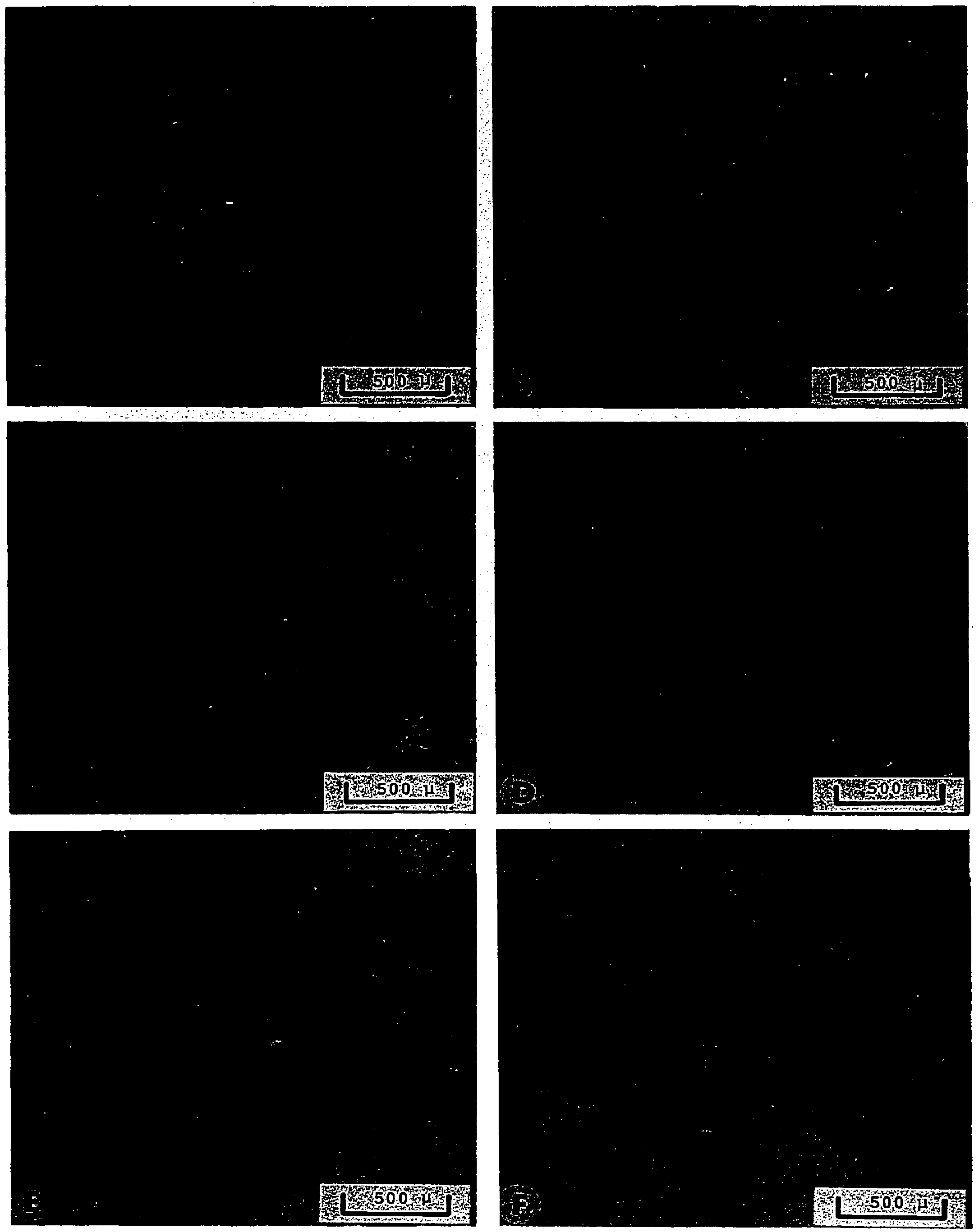
(samples courtesy J.C. Hopkins)

Photomicrographs - Plane Polarized Light

D. Calcite, axial cross-section. A canal of clear calcite occupies the centre of each trabecula and the original pores are now filled with a light, late stage, calcite cement. Location - Section 2, Perdrix Formation, 44 meters (Hopkins, 1972).

E. Calcite, tangential section. A clear calcite canal occupies the centre of each trabecula and the main part of the skeleton is composed of radaxial calcite. Pores are filled with pelsparite (bottom). Location - Section 1, Mount Hawk Formation, 2 meters from base of Arcs Member (Hopkins, 1972).

F. Calcite, tangential section. A canal of clear calcite occupies the centre of each trabecula and the main part of the skeleton is composed of radaxial calcite. The original coral pores are filled with microspar and late stage, clear calcite cement. Location - Section 1, Mount Hawk Formation, 1 meter from base of Arcs Member (Hopkins, 1972).


500 µ
500 µ
500 µ
D
500 µ
500 µ
F
500 µ

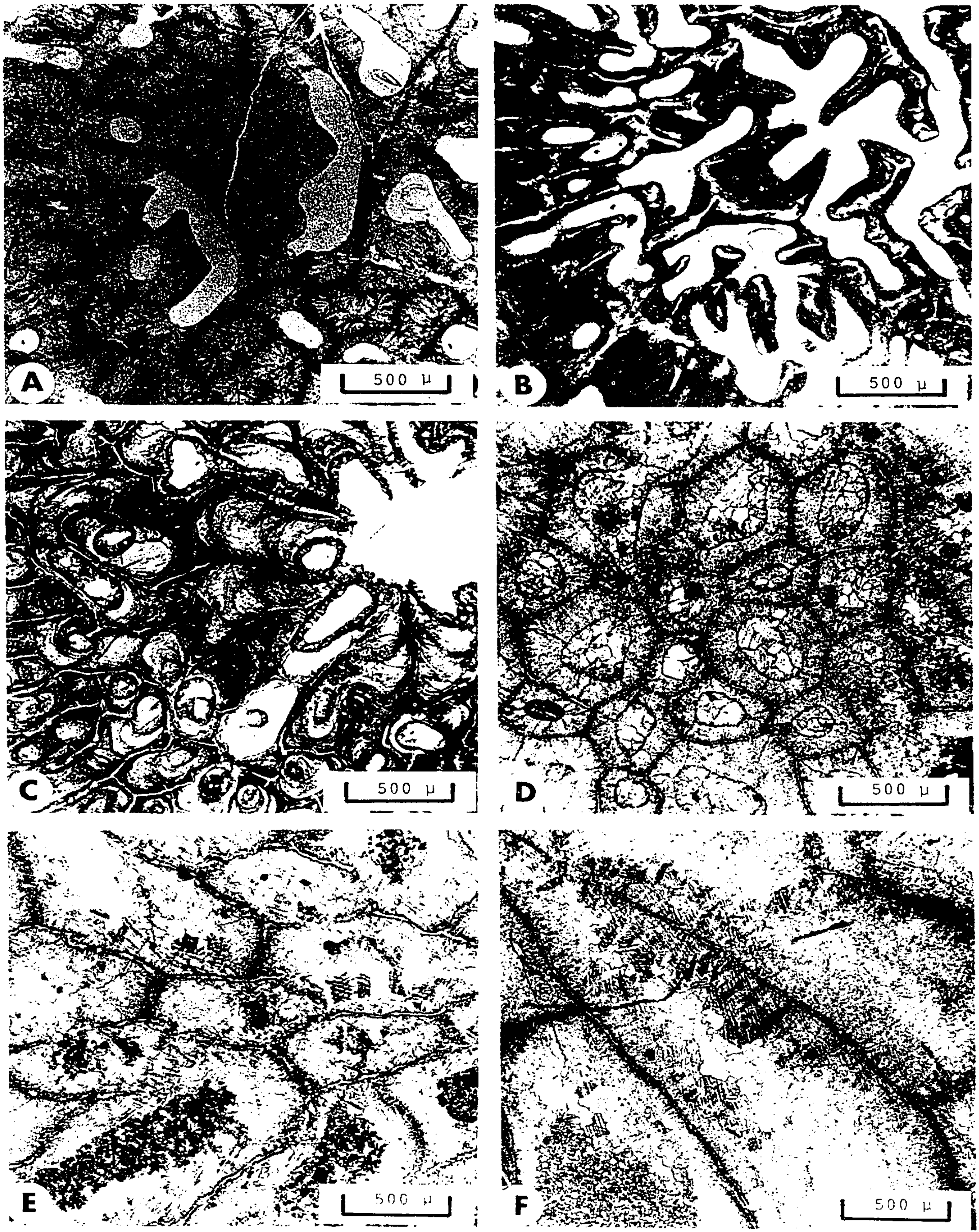

A
500 μ
B
500 μ
C
500 μ
D
500 μ
E
500 μ
F
500 μ

PLATE 36

ACROPORA PALMATA - RECENT

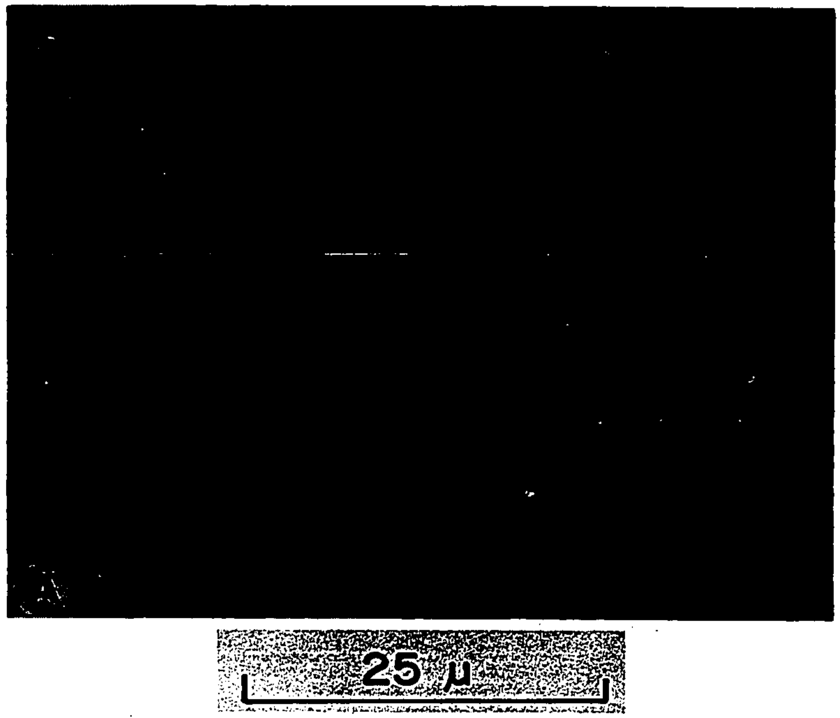
Unaltered coral

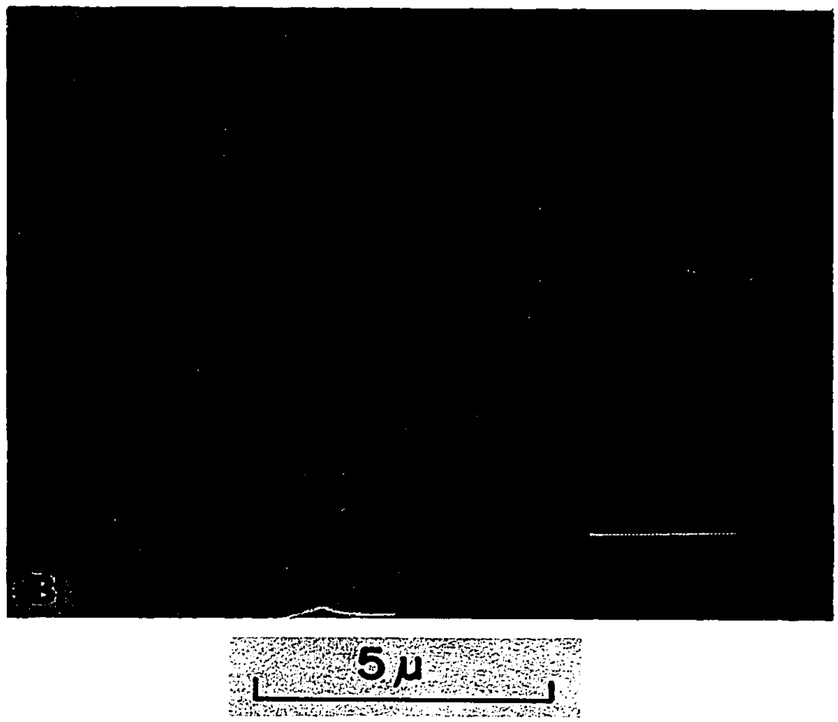
(Living specimen, off west coast of Barbados, depth 5 meters)

Scanning electron micrograph of broken surface

A. Centre of trabecula. The fine irregular crystallites of aragonite in the centre of calcification, running from lower left to upper right, are surrounded by closely packed bundles of aragonite needles. The fine crystallites in the centre of calcification are the first to be dissolved or recrystallize to calcite during alteration. The small intercrystalline pore spaces between these crystallites (Wainwright, 1964) may act as minute conduits for percolating vadose water.

B. An enlarged view of the junction between two bundles of aragonite needles, or sclerodermites, in the outer part of the trabecula. In this coral skeleton these needles are tightly packed and give the exoskeleton its dense, rigid structure. Initial solution, however, acting along the long linear intercrystalline contacts (see Plate 37), destroys this dense structure.


A
25 µ


B
5 µ

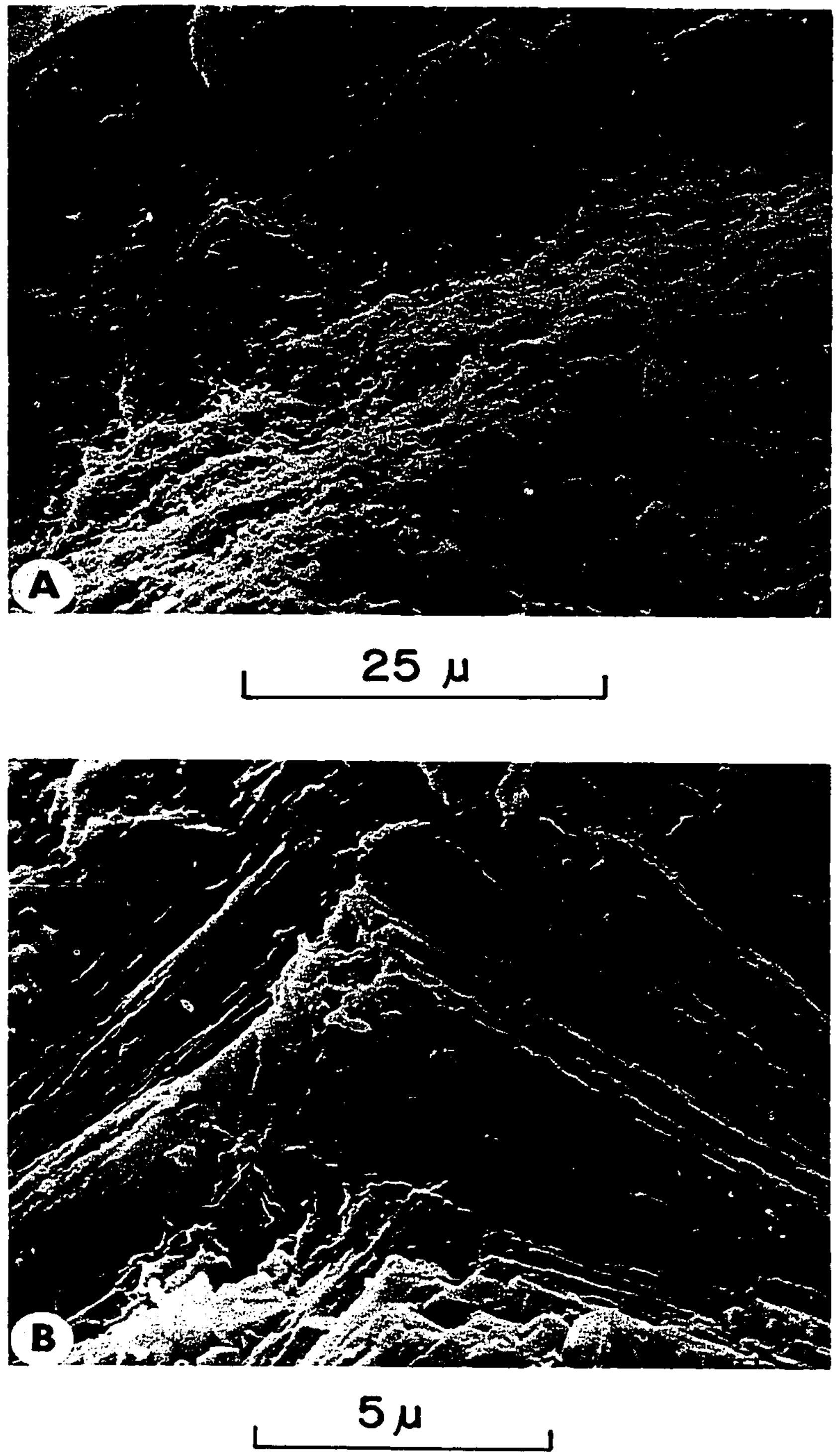

A
25 μ
B
5 μ

PLATE 37

ACROPORA PALMATA - PLEISTOCENE

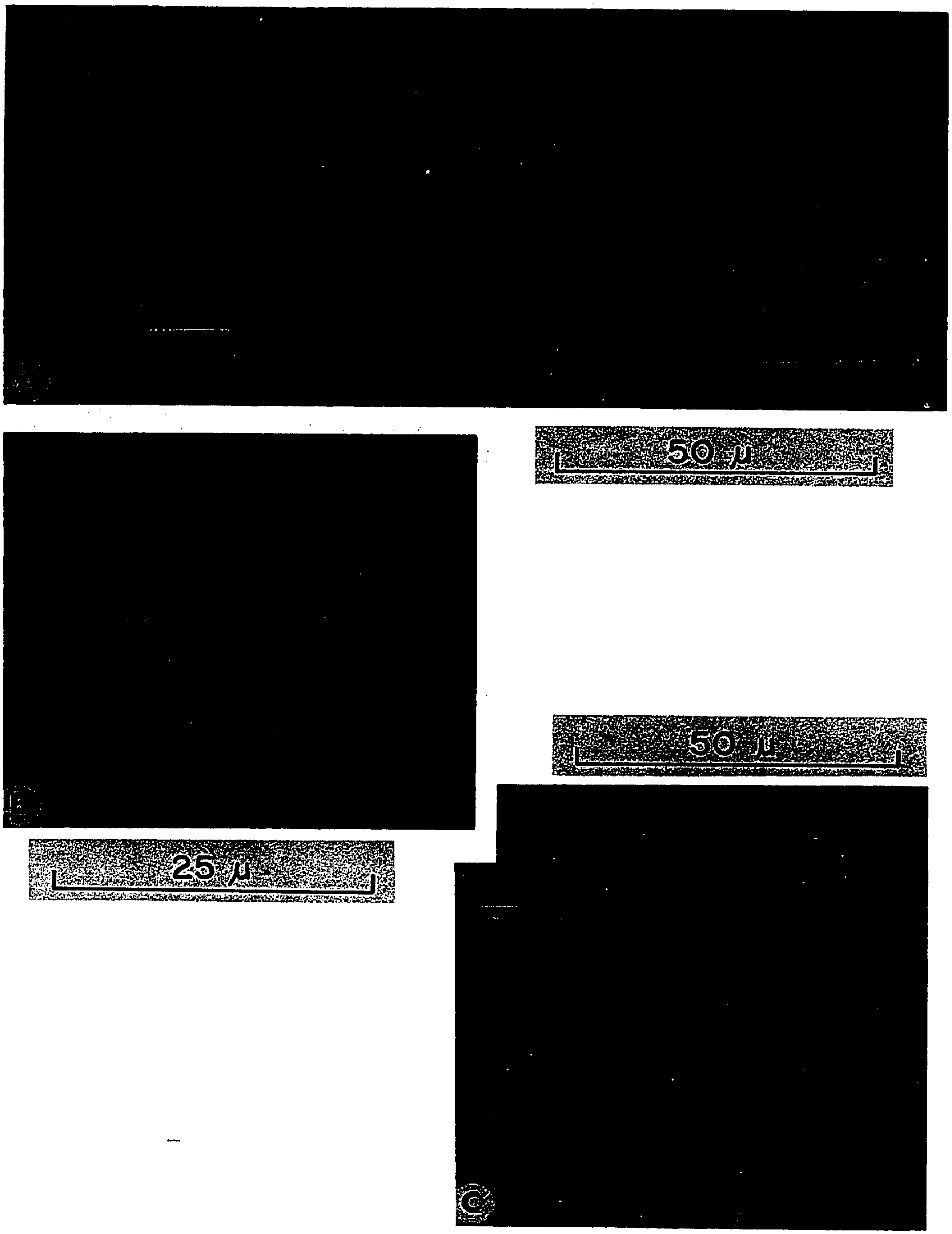
(Reef facies, 83,000 year old reef complex)

Scanning electron micrograph of broken surface

A. Composite micrograph illustrating partial solution of a small trabecula in *Acropora palmata*. The trabecula is being dissolved from left to right. Aragonite needles on the far right are unaffected and retain the original smooth, shiny, well packed texture. The partially dissolved needles in the centre and to the left, however, are ragged, dull, and separated from one another. These partially dissolved needles can easily be broken and on a macroscale give the coral a soft "chalky" appearance. (Sample L22 A).

B. An enlargement of the central part of Plate A. Although partially dissolved, the aragonite needles still retain their original spatial arrangement. Solution does not appear to have cut across needles but occurred parallel to them, along the linear intercrystalline contacts.

C. Aragonite from a partially dissolved *Acropora palmata* frond. Solution along the intercrystalline boundaries has separated the aragonite needles, creating a porous, weak, coral structure. (Sample L17).


A
50 µ
B
25 µ
50 µ
C

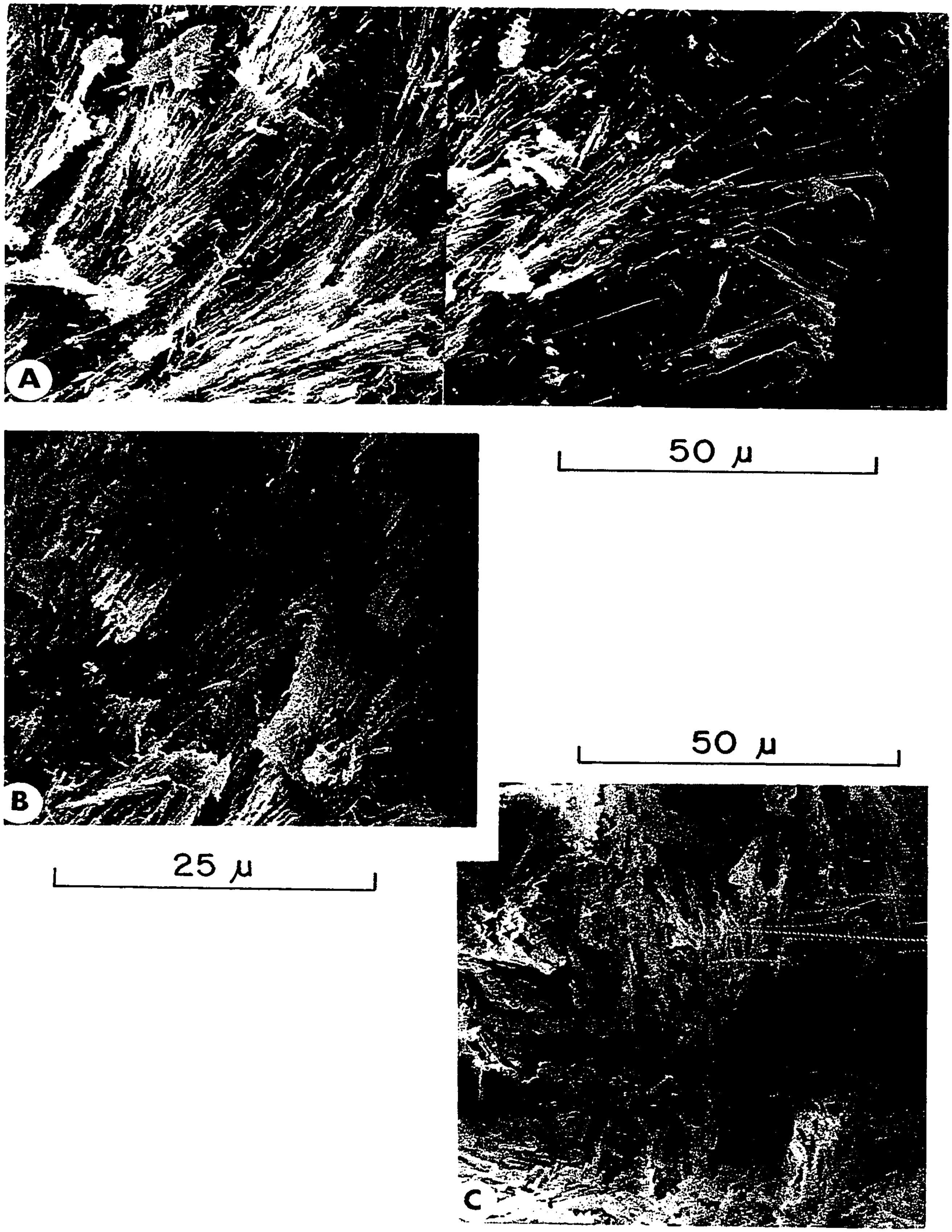

A
50 µ
B
25 µ
50 µ
C

PLATE 38

ACROPORA PALMATA – PLEISTOCENE

SAMPLE L15, 83,000 YEAR OLD REEF COMPLEX

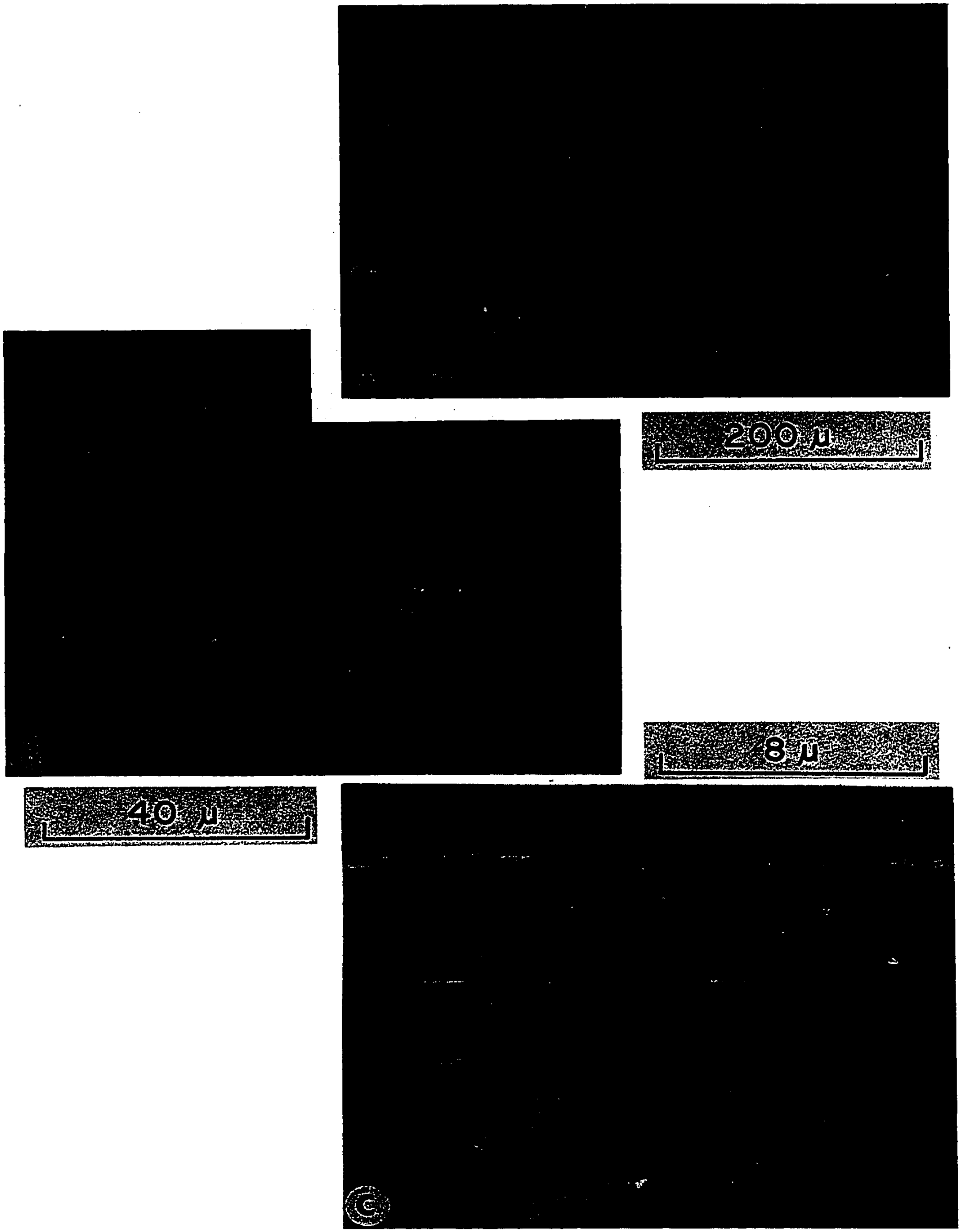
Calcite and aragonite

Scanning electron micrograph of broken surface

A. Contact between calcite, flat blocky crystals, and chalky aragonite fibrous crystals. Centre of photograph is a trabecula between two pores (centre left and upper right) almost completely altered to calcite.

B. Enlargement of area adjacent to pore wall with only a rim of aragonite needles bordering the pore wall left. The position of this photograph is similar to that illustrated in photomicrograph 34A.

C. Enlargement of contact between aragonite (left) and calcite (right). Partial solution has separated some of the bundles of aragonite needles. There is, however, no evidence of a solution stage between aragonite and calcite. The spaces between the needles are still preserved a short way into the new crystal.


200 μ
40 μ
8 μ

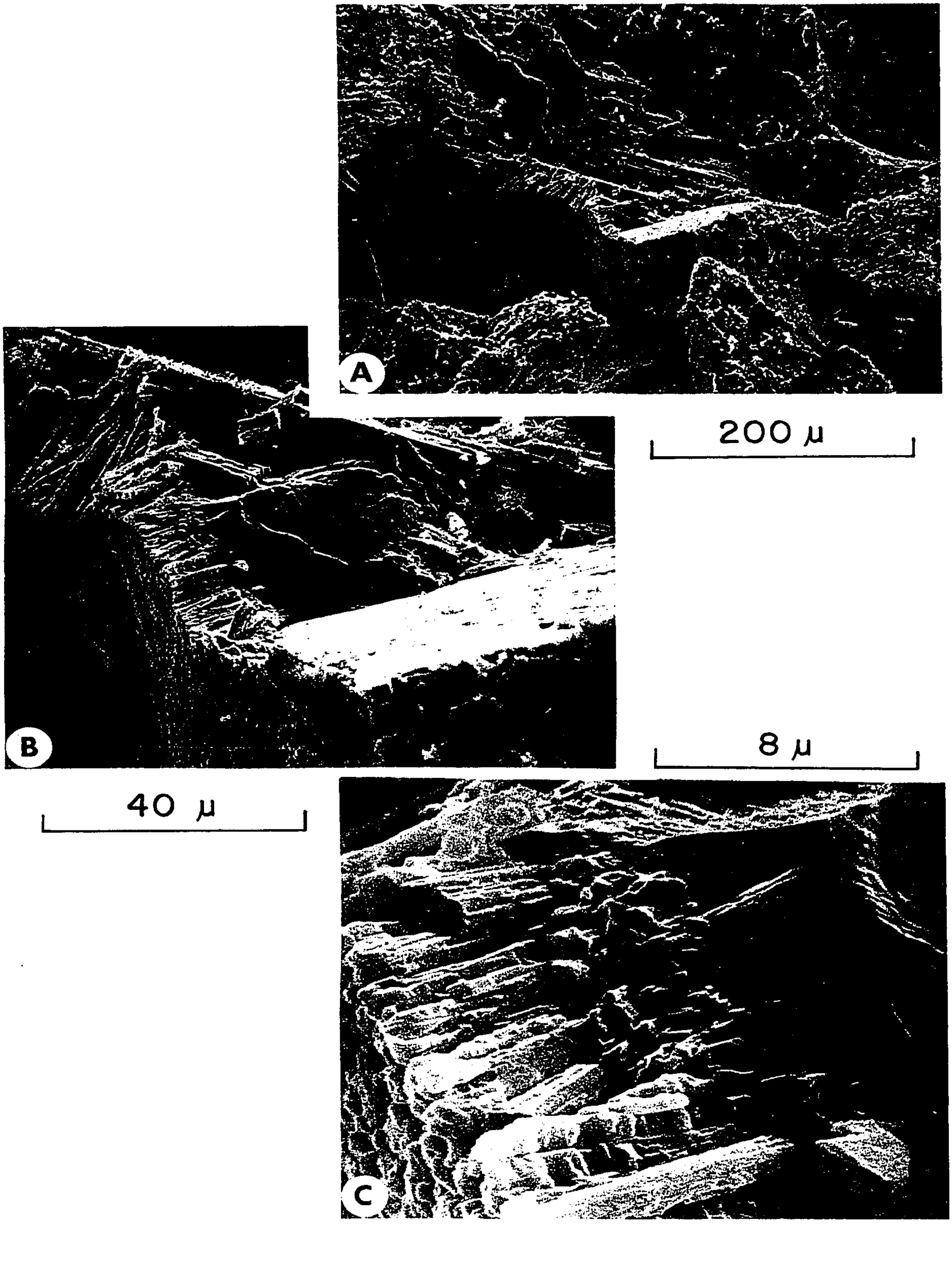

A
200 µ
B
8 µ
40 µ
C

PLATE 39

ACROPORA PALMATA - PLEISTOCENE

SAMPLE L17, 83,000 YEAR OLD REEF COMPLEX

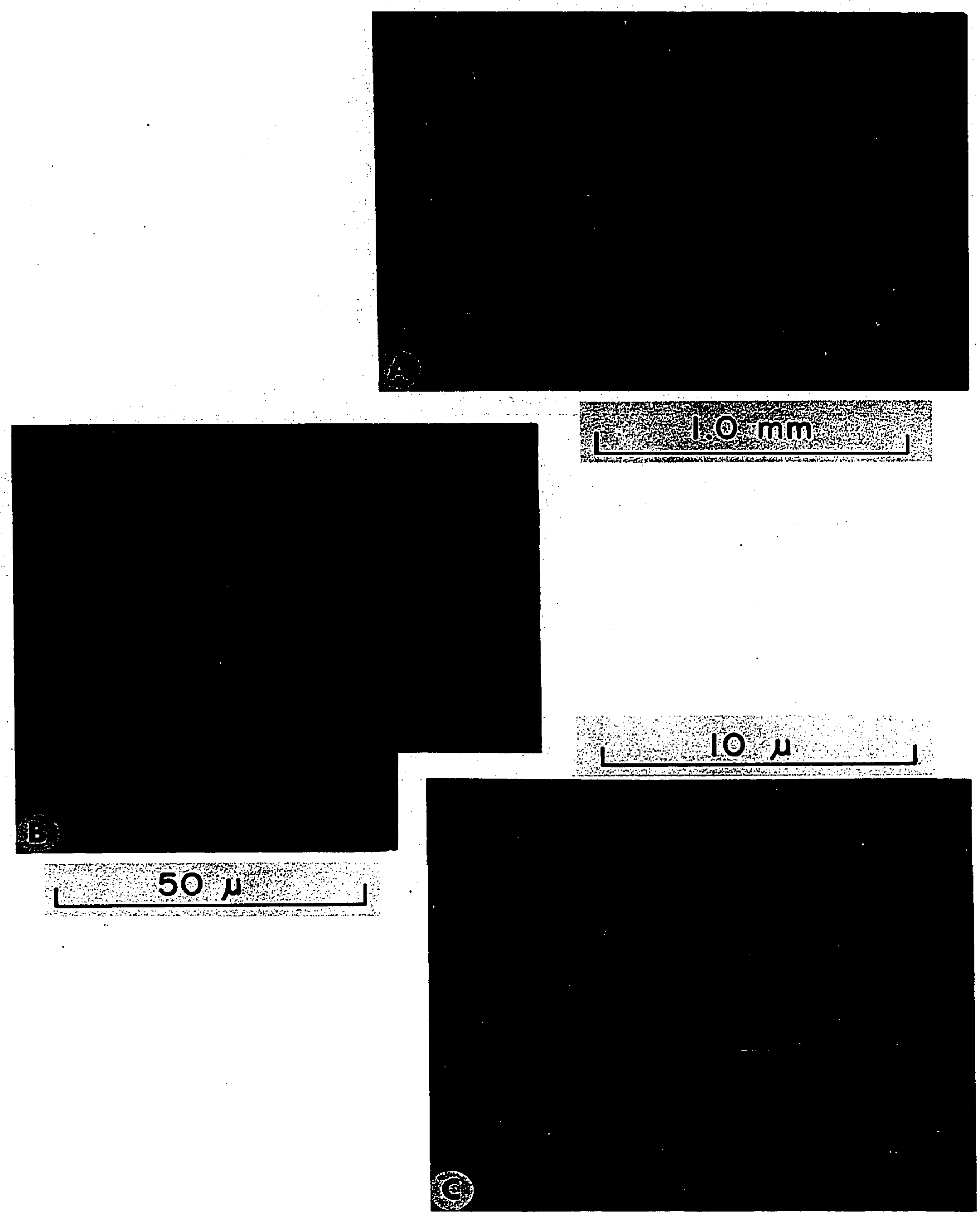
Calcite and aragonite

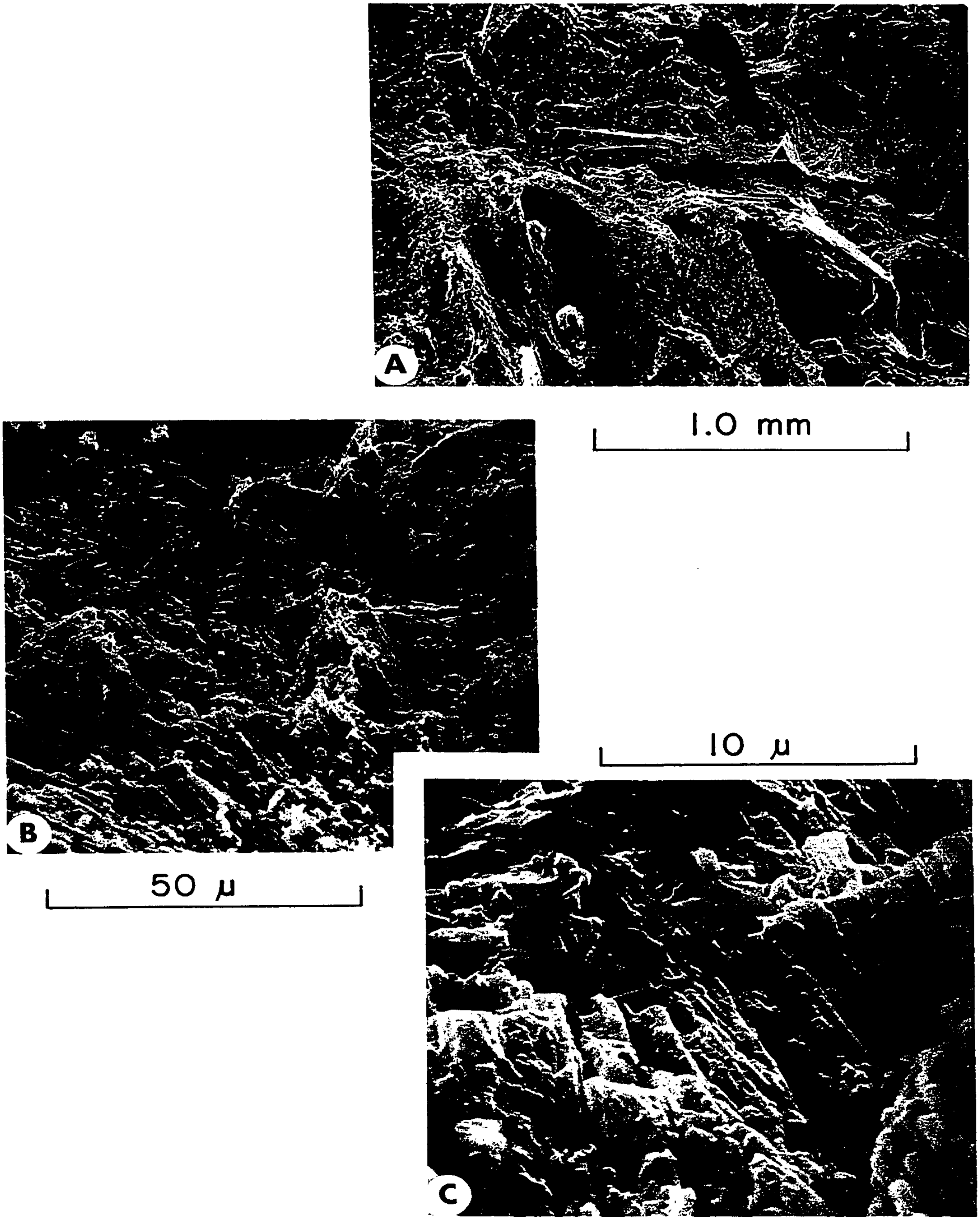
Scanning electron micrograph of broken surface

A. Contact between calcite, flat blocky crystals (top), and chalky fibrous aragonite (bottom). The following photographs are from the centre of the trabecula indicated by arrow.

B. Enlargement of calcite (upper left) and chalky aragonite (lower left and right) contact,

C. Enlargement of contact at centre of (B). Calcite at upper left and aragonite at lower right. Aragonite needles are enclosed by blocky calcite and a void, indicative of partial solution, does not occur between them.


A
1.0 mm
B
50 µ
10 µ
C


A
1.0 mm
B
50 μ
10 μ
C

APPENDIX A

PROCEDURE

Field studies on northern Barbados were facilitated by a series of detailed topographic maps. All road cuts, quarries, and, where possible, river valleys and sea cliffs, in the area were visited, mapped and sampled. A brief description of the lithology and dominant corals found at each of these localities is tabulated in Appendix B. Each outcrop or section was numbered and its location can be found on the map enclosed at the back of the text. Complete areal photographic coverage enabled less obvious outcrops to be discerned and subtle trends to be followed laterally.

A total of 300 Pleistocene limestone samples were routinely analysed by X-Ray diffraction to determine which carbonate minerals were present (Appendix C). On the basis of field studies and X-Ray diffraction analysis, a total of 140 samples, representing the spectrum of carbonate lithologies encountered, were impregnated with epoxy resin, and thin sectioned. The composition of these sediments was visually estimated by comparison with grain estimation charts. Each sample is classified according to the spectral subdivision of limestone types proposed by Folk (1959, 1963, 1968) (Appendix D).

Specific petrographic problems were resolved by additional X-Ray diffraction analysis, thin section staining (Friedman, 1959; Windland, 1969), electron microprobe analysis and viewing broken surfaces under a scanning electron microscope.

Electron microprobe samples were analysed semi-quantitatively. Standard carbonate samples, selected to span the range of elemental composition expected, were analysed for the desired elements by atomic absorption. These results were checked with values from other studies on similar material. Polished thin sections of these standard carbonates were then analysed on the electron microprobe and the relationship between counts/background and p.p.m. obtained. For magnesium content a series of samples with known $MgCO_3$ content was run and a working curve obtained.

A Cambridge model scanning electron microscope at the Pulp and Paper Research Association, Pointe Claire, Quebec, was used to view broken surfaces of carbonates up to a magnification of 8000x.

APPENDIX B

OUTCROP DESCRIPTIONS

Each locality described and section measured is assigned a combination letter and number code and can be located on the large map in the pocket at the back of the text.

If the first letter of the location is B, then the locality was investigated during the initial reconnaissance phase of this study. In most cases, however, the first letter or letters refer to the general area in which the locality or section occurs and are as follows:

SG	Spring Garden	FW	Fryer's Well Bay
SH	Spring Hall Factory	A	Alleyndale
AF	Animal Flower Bay	S	Speightstown
C	Cluff's Bay	P	North of Porter's Factory
M	Maycock's Bay		

The first number refers to the exact locality described. The letter following this number, if included, designates a particular sample or line of samples.

For example: SH23 B1

SH	Spring Hall Factory area
23	locality 23
B	section B
1	sample 1

On the broad, relatively flat, North Point Shelf, most exposures are in the form of small, shallow, road cuts and occasional quarries. The steep cliffs bordering most of the platform yield more extensive vertical exposure. Along the north and northwest coast the face of these cliffs is often obscured by heavy vegetation and so visual correlation between measured stratigraphic sections is not possible. Along the barren northeast coast, however, the entire sequence is exposed and units can be traced laterally with ease.

This appendix is subdivided into four separate sections, representing different geographic areas and type of outcrop:

Table 4A	Small scattered outcrops on the North Point Shelf and inland from the northwest coast.
Table 4B	Cliff sections along the north and northwest coast.
Table 4C	Intertidal and supratidal sections of the narrow 60,000 yr. old fringing reef terrace.
Table 4D	Continuous exposure of the 83,000 yr. old reef complex along the northeast coast. The exposure between Gay's Cove and River Bay is varied and reveals both the reef and back-reef facies. North of River Bay, however, the sea cliffs are almost exclusively massive Acropora palmata and so have not been plotted.

TABLE 4A

North Point Shelf Samples

Locality	Description
B 1	Scattered *M. annularis* and *Diploria* in calcarenite.
B 3	Well lithified calcarenite with numerous *M. annularis* and *M. cavernosa*.
B 4	Calcarenite with numerous Rhodolites.
B 5	Cross-laminated calcarenite (also M 51).
B 6	Scattered *A. palmata* in calcarenite.
B 7	Scattered *A. palmata* in calcarenite grading eastward into *P. porites* in calcarenite.
B 10	Conglomerate composed of well lithified calcarenite clasts in poorly lithified calcarenite.
B 13	Second High Cliff. Well lithified calcarenite.
B 14	Scattered *A. palmata* in calcarenite.
B 15	*P. porites* in calcarenite.
B 16	*A. cervicornis* in calcarenite.
B 17	*A. cervicornis* in calcilutite.
B 18	Calcarenite with widely scattered *A. palmata*.
B 19	*P. porites* in calcarenite.
B 20	*A. cervicornis* in calcarenite.
B 22	*A. palmata* in calcarenite.
B 24	Calcarenite with numerous *Strombus*.
B 27	Rhodolite calcarenite.
RB CR	Massive *P. porites* in calcarenite grading eastward into *A. cervicornis* in calcilutite.
L CR	Massive *P. porites* in calcarenite.

Locality	Description
AF 25	Interbedded *P. porites* and *A. cervicornis* in calcarenite.
AF 26	Interbedded *P. porites* and *A. cervicornis* with scattered *Diploria* and *M. annularis* in calcarenite.
AF 27	*A. cervicornis* in calcilutite.
AF 28	Scattered *A. palmata* and *A. cervicornis* in calcarenite.
AF 29	*P. porites* in calcarenite.
AF 30	*A. cervicornis* in calcilutite.
AF 31	*P. porites* grading seaward to *A. palmata*. Interbedded with *P. porites* are numerous *Siderastrea*, *Solenastrea*, small *Montastrea*, bivalves and numerous *Strombus*.
AF 33	Scattered *A. palmata* in calcarenite.
AF 34	Large area of *P. porites* in calcilutite with scattered *M. annularis* that grades seaward to *A. palmata*.
AF 35	*M. annularis* in pipe growth form and scattered *A. palmata* in calcarenite.
AF 36	*P. porites* in calcarenite.
AF 37	*P. porites* with scattered *M. annularis* in pipe growth form in calcarenite.
AF 38	Scattered *A. palmata* in calcarenite. Occasional lenses of *P. porites* in calcarenite.
AF 39	*P. porites* in calcilutite.
AF 40	*P. porites* in calcilutite.
AF 41	*Amphistegina* calcarenite.
AF 42	*Amphistegina* calcarenite.
AF 43	*Diploria* and *M. annularis* in very well lithified calcarenite.
AF 44	Scattered *A. palmata* in calcarenite.
SG 1	Crustose red algal limestone overlying conglomerate at the top of poorly lithified Scotland Formation sandstones.
SG 2	*Diploria* and *M. annularis* in very well lithified calcarenite.
SG 3	Very well lithified calcarenite.
SG 4	*Amphistegina* calcarenite.

Locality	Description
SG 5	*Amphistegina* calcarenite.
SG 6	Small rounded heads of *P. astreoides* and *Siderastrea* with scattered large *Strombus* in mottled calcarenite.
SG 7	Scattered *A. palmata* grading eastward to calcilutite similar to that described in SG 6.
SG 8	Scattered *Strombus* and small *Siderastrea* in mottled calcarenite.
SG 9	*Amphistegina* calcarenite.
SG 10	Very well lithified calcarenite.
SG 11	Conglomerate. Clasts dominated by *Amphistegina* calcarenite and very well lithified calcarenite. Matrix unlithified calcarenite.
SG 12	Identical to SG 11.
SG 13	*M. annularis* and *Diploria* in very well lithified calcarenite.
SG 14	Conglomerate. Matrix unlithified calcarenite. Clasts very well lithified calcarenite.
SG 15	*P. porites* in calcarenite.
SG 16	*P. porites* grading westward to scattered *A. palmata* in calcarenite.
SG 17	Scattered *A. palmata* in calcarenite.
SG 18	Perched boulder of well lithified calcarenite.
SG 19	Conglomerate with clasts of well lithified calcarenite in unlithified calcarenite matrix.
SG 20	Cave in Second High Cliff with floor 20 feet above the surrounding plain.
SG 21	Scattered *A. palmata* in calcarenite.
SG 22	Well lithified calcarenite.
SG 23	Scattered *A. palmata* in calcarenite.
SG 24	Well lithified calcarenite.
SG 25	Cross laminated calcarenite (beach facies?).
SG 26	*M. annularis* and *Diploria* in calcarenite.
SG 27	Well lithified calcarenite.

Locality	Description
SH 1	*M. annularis* and *M. cavernosa* in very well lithified calcarenite.
SH 2	*M. annularis* and *M. cavernosa* in very well lithified calcarenite.
SH 3	*M. annularis* and *M. cavernosa* in very well lithified, mollusc-rich, calcarenite.
SH 4	*M. annularis* and *M. cavernosa* in very well lithified calcarenite.
SH 5	Well lithified calcilutite.
SH 6	Very well lithified crustose red algal limestone overlying unlithified Scotland Formation sandstones.
SH 7	Very well lithified crustose red algal limestone.
SH 8	Very well lithified crustose red algal limestone.
SH 9	Very well lithified crustose red algal limestone overlain by conglomerate made up of well lithified calcarenite clasts in unlithified sandy calcarenite matrix.
SH 10	Very well lithified crustose red algal limestone overlying unlithified Scotland Formation sandstones.
SH 11	Second High Cliff. *M. annularis* in well lithified calcarenite.
SH 12	Second High Cliff. *M. annularis* and *Diploria* thickly encrusted with crustose red algae in a very well lithified calcarenite.
SH 13	*M. annularis* and *Diploria* in well lithified calcarenite.
SH 14	*M. annularis* and *Diploria* and *M. cavernosa* in well lithified calcarenite.
SH 15	Very well lithified crustose red algal limestone overlying Scotland Formation sandstones containing several large boulders.
SH 16	Widespread very well lithified crustose red algal limestone.
SH 17	*Amphistegina* calcarenite.
SH 18	Very well lithified crustose red algal limestone containing numerous *Amphistegina*.
SH 19	*Amphistegina* calcarenite.
SH 20	Very well lithified crustose red algal limestone overlying Scotland Formation sandstones.
SH 21	*Amphistegina* calcarenite.

Locality	Description
SH 22	Well lithified calcarenite, rich in *Amphistegina*.
SH 23	Unlithified Scotland Formation sandstone.
SH 24	Well lithified calcarenite with numerous *M. annularis* and *M. cavernosa*.
SH 26	Scotland Formation sandstones overlain by a conglomerate made up of sandstone clasts in calcilutite matrix, capped by very well lithified crustose red algal limestone.
SH 27	*Amphistegina* calcarenite rich in crustose red algae.
SH 28	Well lithified calcarenite.
SH 29	Crustose red algal limestone overlying unlithified Scotland Formation sandstones.
SH 30	Crustose red algal limestone overlying unlithified Scotland Formation sandstones.
SH 31	Scotland Formation sandstones overlain by conglomerate of clasts made up of Scotland Formation sandstones. Conglomerate overlain by very well lithified crustose red algal limestone.
SH 32	Scotland Formation sandstones.
SH 33	Scotland Formation sandstones overlain by very well lithified crustose red algal limestone.
M 15	Scattered *A. palmata* in calcarenite.
M 16	*M. annularis* and *Diploria* in calcarenite. Coral heads disappear northward.
M 17	Rhodolite calcarenite.
M 18	Well laminated calcarenite dipping 30° west, overlain by flat-lying calcarenites rich in small coral heads. Upper part of steeply dipping calcarenite contains numerous horizontal fossil calcareous crusts.
M 19	Rhodolite calcarenite.
M 19a	Rhodolite calcarenite.
M 20	*Amphistegina* calcarenite.
M 20a	Very well lithified calcarenite with numerous *Amphistegina*.

Locality	Description
M 21	Rhodolite calcarenite.
M 22	Very well lithified *A. cervicornis* calcilutite, corals dissolved.
M 23	Poorly lithified calcarenite rich in Rhodolites overlying the *A. cervicornis* lithology described in M 22.
M 24	Numerous *M. annularis* in pipe growth form in calcarenite.
M 25	Very well lithified *A. cervicornis* calcilutite, corals dissolved.
M 27	*M. annularis* and *Diploria* in well lithified calcarenite overlain by Rhodolite calcarenite.
M 28	Scattered *A. palmata* interbedded and overlain by banks of *P. porites* in growth position.
M 29	Massive banks of *P. porites* in growth position.
M 30	Scattered *A. palmata* and banks of *P. porites*.
M 31	Fine grained calcarenite.
M 32	Rhodolite calcarenite.
M 33	*M. annularis* in very well lithified calcarenite overlain by Rhodolite calcarenite.
M 35	Scotland Formation mudstones and siltstones overlain by very well lithified crustose red algal limestone.
M 36	*Amphistegina* calcarenite.
M 37	Scotland Formation mudstones and siltstones.
M 38	Scotland Formation mudstones and siltstones overlain by very well lithified crustose red algal limestone. Contact between the two dips eastward.
M 39	*M. annularis* in very well lithified calcarenite.
M 41	*Amphistegina* calcarenite.
M 42	*M. annularis* and *M. cavernosa* in well lithified calcarenite.
M 43	*M. annularis* and *M. cavernosa* in well lithified calcarenite.
M 45	Scotland Formation sandstones overlain by well lithified crustose red algal limestone in turn overlain by well lithified calcarenite. Contacts dip northwest.

Locality	Description
M 46	_M_. _annularis_ and _M_. _cavernosa_ in well lithified calcarenite.
M 47a	_Amphistegina_ calcarenite.
M 47b	_Amphistegina_ calcarenite with numerous mollusc fragments.
M 48	_Amphistegina_ calcarenite.
M 50	_Amphistegina_ calcarenite.
C 28	Very well lithified crustose red algal limestone.
C 50	_Amphistegina_ calcarenite.
C 51	_Amphistegina_ calcarenite.
C 56	_P_. _porites_ bank and scattered _A_. _palmata_ in calcarenite.
FW 1	_A_. _cervicornis_ in very well lithified calcilutite. Corals mostly dissolved.
FW 2	_A_. _cervicornis_ in very well lithified calcilutite. Corals mostly dissolved.
FW 3	_A_. _cervicornis_ and scattered _M_. _annularis_ in calcarenite.
FW 4	_A_. _cervicornis_ and scattered _A_. _palmata_ in calcarenite.
FW 5	_A_. _palmata_ in calcarenite.
FW 6	Numerous overturned heads of _M_. _annularis_ and _Diploria_ in calcarenite.
FW 7	Calcarenite.
FW 8	Calcarenite.
FW 9	Calcarenite with scattered _P_. _porites_ and _A_. _cervicornis_.
FW 10	Calcarenite.
FW 11	Cross laminated calcarenite.
FW 12	Cross laminated calcarenite overlying highly weathered, recessive unit of _Diploria_ and scattered _M_. _annularis_ in calcarenite. The upper part of the lower unit exhibits fossil calcareous crusts.
FW 20	Cross laminated calcarenite.

Locality	Description
FW 21	_M. annularis_ and _Diploria_ in well lithified calcarenite.
FW 22	_M. annularis_, _M. cavernosa_ and _Diploria_ in well lithified calcarenite.
FW 23	_M. annularis_, _M. cavernosa_ and _Diploria_ in calcarenite (very weathered outcrop).
FW 24	_M. annularis_, _M. cavernosa_ and _Diploria_ in well lithified calcarenite.
FW 25	Well lithified calcarenite with occasional coral heads and _A. cervicornis_ sticks.
FW 26	_A. cervicornis_ in well lithified calcilutite. Coral sticks often weathered out.
FW 27	_A. cervicornis_ in well lithified calcilutite, coral sticks often dissolved.
FW 28	Calcarenite.
FW 29	Calcarenite.
FW 31	Calcarenite.
FW 32	Calcarenite.
FW 33	_A. cervicornis_ and scattered _P. porites_ in calcilutite.
FW 34	Calcarenite.
A 1	_M. annularis_ in pipe growth form in calcarenite (well lithified).
A 2	Scattered _A. palmata_ in calcarenite.
A 3	Cross laminated calcarenite.
A 4	Well lithified calcarenite.
A 5	Well lithified calcarenite.
MA 1	_M. annularis_ in pipe growth form surrounded by well lithified calcarenite.
MA 2	Calcarenite with occasional coral heads and _A. cervicornis_.
MA 3	Cross laminated calcarenite.

Locality	Description
MA 4	Calcarenite.
MA 5	Calcarenite.
MA 6	_A. palmata_ in calcarenite grading westward into _A. cervicornis_ in calcilutite and calcarenite.
S 1a	Calcarenite with occasional _P. porites_, _M. annularis_, _Diploria_ and numerous bivalves.
S 1c	_A. palmata_ in calcarenite.
SD 2	_A. palmata_ in calcarenite.
S 1d	_A. cervicornis_ in calcilutite.
SD 1	_A. cervicornis_ in calcilutite.
S 2	Cross laminated calcarenite overlying _A. cervicornis_ in calcilutite. _A. cervicornis_ grades westward to _A. palmata_.
S 3	_A. cervicornis_ in calcilutite overlying _A. palmata_ in calcarenite.
S 4	_M. annularis_ in pipe growth form surrounded by calcarenite.
S 5	Rounded _M. annularis_ in calcarenite.
P 1	Scattered _A. cervicornis_ and occasional small coral heads in calcarenite.
P 2	Scattered _A. cervicornis_, small coral heads and several _Strombus_ in calcarenite.
P 3	Scattered _A. cervicornis_ in cross laminated calcarenite.
P 4	_M. annularis_ in pipe and encrusting growth forms surrounded by well lithified calcarenite.
P 5	_A. palmata_ in well lithified calcarenite. Corals dissolved.
P 6	Scattered _M. annularis_ and _A. palmata_ in well lithified calcarenite.
P 7	_A. palmata_ in calcarenite that grades westward to _A. cervicornis_ in calcilutite.
P 8	_M. annularis_ and _M. cavernosa_ in well lithified calcarenite.

Locality	Description
P 9	Scattered A. cervicornis in calcarenite overlying A. palmata and M. annularis in calcarenite.
P 10	Massive M. annularis in pipe and encrusting growth forms and scattered A. palmata in calcarenite.
P 11	Rhodolite calcarenite with scattered encrusting M. annularis.
P 12	A. cervicornis in calcarenite.
P 13	Scattered A. palmata in calcarenite grading westward into extensive A. cervicornis in calcarenite. Large overturned M. annularis and Diploria at westernmost portion of exposure.
P 14	A. palmata in calcarenite grading westward into A. cervicornis in calcarenite.
P 15	M. annularis and Diploria in calcarenite with numerous bivalves.
P 16	Calcarenite with occasional A. palmata and A. cervicornis.
P 17	M. annularis in both pipe and encrusting growth forms grading westward into Rhodolite calcarenite.
P 18	A. palmata in very well lithified calcarenite. Coral dissolved.
P 19	Rhodolite calcarenite overlain and interbedded with massive encrusting M. annularis.
P 20	Conglomerate of very well lithified calcarenite clasts in unlithified calcarenite matrix.
P 21	A. palmata in calcarenite grading westward into A. cervicornis in calcarenite.
P 22	A. palmata in calcarenite grading westward into A. cervicornis.
P 23	Conglomerate of very well lithified calcarenite clasts and A. cervicornis sticks in poorly lithified calcarenite.
P 24	Coral heads in calcarenite (very poor outcrop).
P 25	A. palmata in calcarenite grading westward into A. cervicornis in calcilutite.
P 26	Conglomerate composed of coral heads and well lithified pieces of calcarenite in a poorly lithified matrix.
P 27	Scattered A. cervicornis, small M. annularis and P. astreoides in calcarenite.
P 28	A. palmata in calcarenite grading westward into A. cervicornis in calcarenite.

TABLE 4B

Cliff Sections Along Northwest Coast

Section	Location	Elevation (m)	Description	Thickness (m)
M 53	Maycock's Bay	0- 6	Covered	6
		6-34	_A._ _palmata_ in calcarenite	28
M 51	Maycock's Bay	0- 6	Covered	6
		6-34	_A._ _palmata_ in calcarenite	28
M 50	Mother's Day Bay	0- 4	Covered	4
		4-12	_A._ _cervicornis_ in calcilutite	8
		12-13	Covered	1
		13-17	_A._ _palmata_ in calcarenite and terrigenous sand	4
		17-25	_A._ _palmata_ in calcilutite and terrigenous sand	8
		25-34	_A._ _palmata_ in calcilutite	9
US 1	Greshie Bay	0- 9	Covered	9
		9-15	_A._ _cervicornis_ in calcilutite	6
		15-17	_A._ _cervicornis_ in calcilutite. Weathered with numerous vadose cavities and calcareous crusts	2
		17-20	_M._ _annularis_ in terrigenous sand	3
		20-34	_A._ _palmata_ in terrigenous sand	14
B 26	Harrison Point	0- 4	_M._ _annularis_, _M._ _cavernosa_ and _Diploria_ in calcarenite	4
		4-4.5	_A._ _cervicornis_ in calcarenite	0.5
		4.5- 9	Calcarenite with scattered _Diploria_	4.5
		9-18	_M._ _annularis_, _Diploria_ and _A._ _cervicornis_ in calcarenite	9

Section	Location	Elevation (m)	Description	Thickness (m)
C 54	Norse's Bay	0- 7	Covered	7
		7-18	Cross laminated terrigenous sand with abundant P. porites	11
		18-23	Terrigenous sand with abundant P. porites and Strombus	5
		23-34	P. porites in calcarenite	11
C 53	Norse's Bay	0- 4	A. palmata, M. annularis and Diploria in calcilutite	4
		4-23	Calcarenite	19
		23-29	A. palmata in calcarenite	6
		29-35	P. porites and Strombus in calcarenite	6
C 51	Norse's Bay	0-17	A. cervicornis with minor A. palmata, M. annularis and Diploria in calcilutite	17
		17-20	M. annularis in calcarenite	3
		20-35	Partially covered, P. porites in calcarenite	15
C 49	Stroud Bay	0- 4	M. annularis in calcarenite	4
		4-11	M. annularis and Diploria with minor A. palmata and A. cervicornis in calcarenite	7
		11-14	Covered	3
		14-17	M. annularis in calcarenite	3
		17-18	Covered	1
		18-20	M. annularis and Diploria in calcarenite	2
		20-26	P. porites in calcilutite	6

Section	Location	Elevation (m)	Description	Thickness (m)
C 48	Taylor Bay	0- 6	A. cervicornis in calcilutite	6
		6-12	A. palmata in calcilutite	6
		12-13	M. annularis in calcarenite	1
		13-17	Covered (M. annularis)	4
		17-23	A. palmata in calcarenite	6
		23-26	P. porites in calcarenite	3
C 46	Lambert Point	0- 4	A. cervicornis in calcilutite	4
		4- 7	M. annularis and Diploria in calcarenite	3
		7-12	A. palmata in calcilutite	5
		12-15	M. annularis and A. palmata in calcarenite	3
		15-20	Covered	5
		20-23	M. annularis in calcarenite	3
		23-24	A. cervicornis in calcarenite	1
		24-29	P. porites in calcarenite	5
C 45	East of Lambert Point	0- 7	A. cervicornis in calcilutite	7
		7-10	Covered	3
		10-15	A. palmata in calcilutite	5
		15-18	Covered	3
		18-22	M. annularis in calcarenite	4
		22-25	Covered	3
		25-29	A. palmata in calcarenite	4

Section	Location	Elevation (m)	Description	Thickness (m)
B 23	Stroud Point	0– 4	M. annularis, M. cavernosa and Diploria in calcarenite	4
		4– 6	Well laminated calcarenite	2
		6– 8	M. annularis and Diploria in cross laminated calcarenite	2
		8– 9	Cross laminated calcarenite	1
		9–12	M. annularis, M. cavernosa and Diploria in calcarenite	3
		12–18	A. palmata in calcarenite	6
C 43	Archer's Bay	0– 4	A. cervicornis in calcilutite	4
		4–10	M. annularis in calcarenite	6
		10–13	A. palmata in calcarenite	3
C 42	Archer's Bay	0– 4	A. cervicornis in calcilutite	4
		4– 9	Cross laminated calcarenite	5
		9–12	A. palmata in calcarenite	3
C 33	Cluff's Bay	0– 3	Crustose red algal limestone	3
		3–10	Amphistegina calcarenite	7
		10–12	Covered	2
		12–26	Calcarenite	14
		26–28	M. annularis and Diploria in calcarenite	2
C 36	Cluff's Bay	0–27	Oceanic Formation, partially covered	27
		27–28	Crustose red algal limestone	1
		28–30	Amphistegina calcarenite	2

Section	Location	Elevation (m)	Description	Thickness (m)
C 23	Gents Bay	0-11	Oceanic Formation	11
		11-12	Conglomerate	1
		12-13	Crustose red algal limestone	1
		13-23	Well bedded Amphistegina calcarenite	10
AF 21	Touce's Point	0-13	Calcarenite with scattered _M. annularis_ and _Diploria_	13
		13-14	_M. annularis_ in calcarenite	1
		14-21	_A. palmata_ in calcarenite	7
AF 20	Jordan's Cowpen	0-10	_M. annularis_ and _Diploria_ in calcarenite	10
		10-10.5	Calcarenite	0.5
		10.5-12	_M. annularis_ and _A. palmata_ in calcarenite	1.5
		12-23	_A. palmata_ in calcarenite and calcilutite	11

TABLE 4C

Sediments From 60,000 Yr. Old Terrace

(See Fig. 18)

Sample	Zone	Description
N3 A	Lapei	Poorly lithified calcarenite
N3 B	Lapei	Well lithified calcarenite
N3 C1	Crust	Well lithified calcarenite
N3 C2	Crust	Brown micrite beneath calcareous crust
N3 D	Crust	Calcareous crust
N4 A	Lapei	Cemented calcarenite
N4 B	Lapei	Cemented calcarenite
N4 C	Lapei	Small _M._ _annularis_
N4 E	Lapei	Cemented calcarenite
N4F	Lapei	Cemented calcarenite
N4 G	Lapei	Calcarenite overlain by calcareous crust
N4 H	Crust	Calcareous crust
N4 J	Crust	Well cemented calcarenite
N4 K	Crust	Well cemented calcarenite and calcareous crust
N4 L		Older Pleistocene, well lithified calcarenite
N6 A1	Lapei	Small _M._ _annularis_
N6 A2	Lapei	Calcareous red algae
N6 A3	Lapei	Calcarenite
N6 B1	Lapei	Lithified calcarenite
N6 B2	Lapei	_A._ _cervicornis_ and calcarenite
N6 C	Lapei	Calcarenite
N6 D	Crust	Calcarenite overlain by calcareous crust
N6 E	Crust	Calcareous crust

Sample	Zone	Description
N6 F	Crust	Calcareous crust and underlying calcarenite
N6 G	Crust	Calcarenite with many coated grains overlain by calcareous crust
SB1 A	Lapei	Calcarenite
SB1 B	Lapei	Calcarenite with occasional corals
SB1 C	Lapei	Calcarenite containing many coated grains
SB1 D	Lapei	Well lithified calcarenite with many coated grains
SB1 E	Lapei	Calcarenite with many coated grains
SB1 F	Crust	Calcareous crust
SB1 G	Crust	Calcareous crust and underlying calcarenite
SB1 H	Crust	Calcareous crust
SB1 J	Crust	Calcareous crust
SB1 K	Crust	Calcareous crust
SB1 L	Crust	Unlithified calcarenite
SB1 M	Crust	Unlithified calcarenite
SB2 A	Lapei	Calcarenite
SB2 B	Lapei	Calcarenite with many coated grains
SB2 C	Lapei	Calcarenite with many coated grains
SB2 D	Crust	Calcareous crust
SB2 E	Crust	Calcareous crust plus underlying calcarenite
SB2 F	Crust	Calcareous crust plus underlying calcarenite
SB4 A	Lapei	Calcarenite
SB4 B	Lapei	Calcarenite
SB4 C	Crust	Calcareous crust
SB4 D	Crust	Calcareous crust

Sample	Zone	Description
C17 A	Lapei	Well lithified calcarenite
C17 B	Lapei	Poorly lithified calcarenite
C17 C	Lapei	Poorly lithified calcarenite
C17 D	Crust	Calcareous crust and underlying calcarenite
C17 E	Crust	Calcareous crust and underlying calcarenite
C17 G	Crust	Calcareous crust
C17 J	Crust	Calcareous crust
B33	Lapei	Calcarenite
GG 3	Crust	Unlithified calcarenite

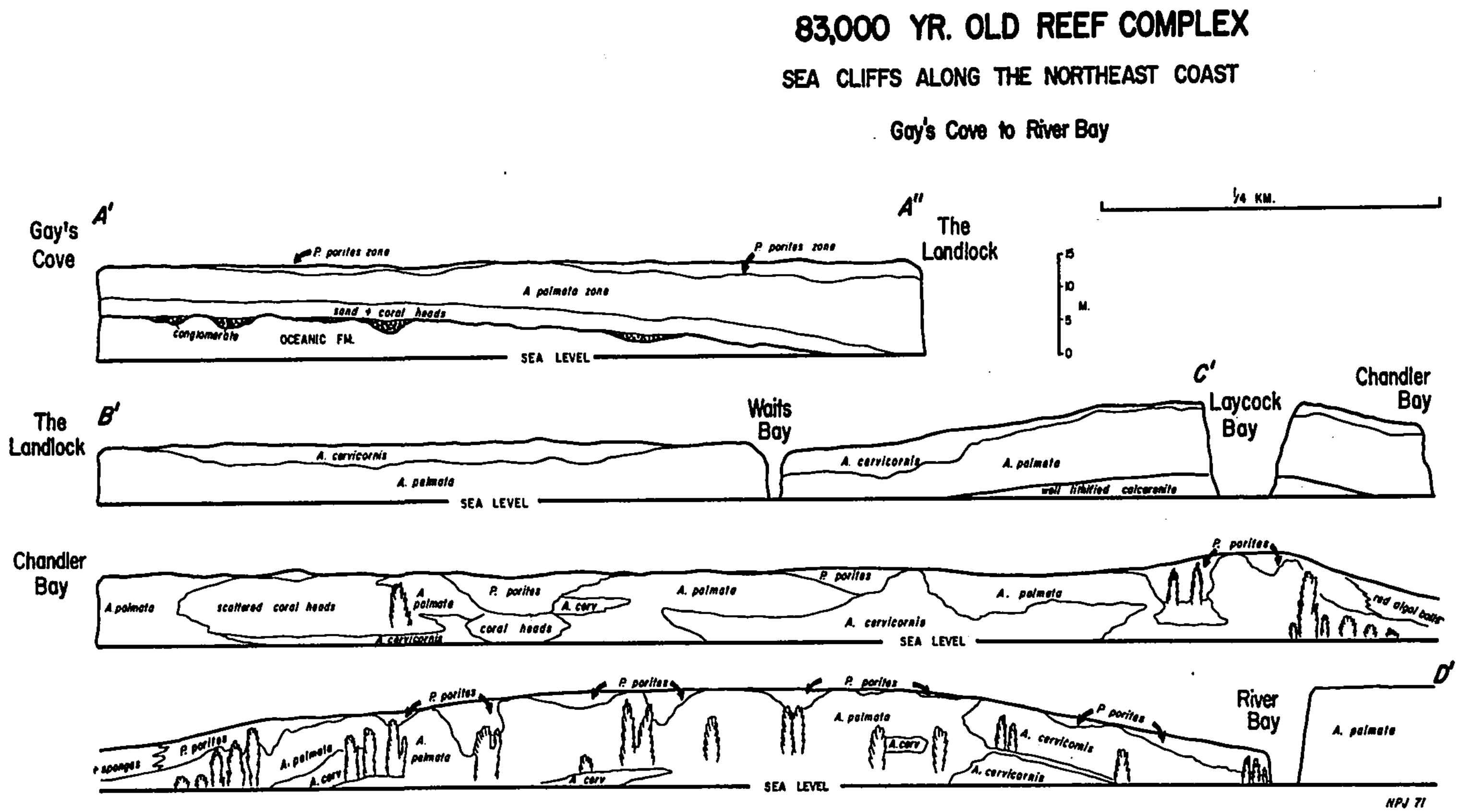


Figure 31. Sea cliff exposure of the 83,000 year old reef complex along the northeast coast.

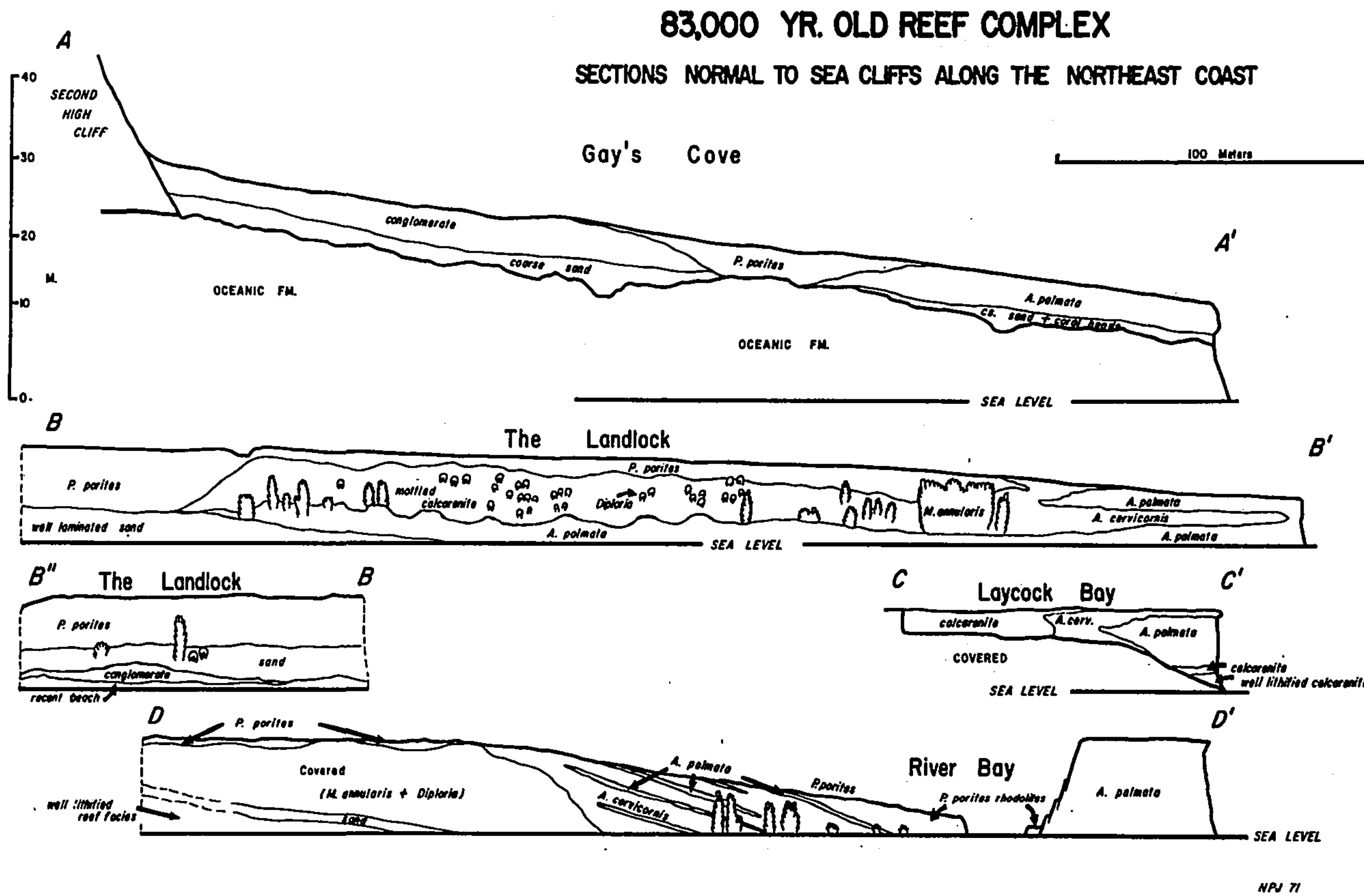


Figure 32. Exposures of the 83,000 year old reef complex in bays and river valleys along the northeast coast.

APPENDIX C

SAMPLE MINERALOGY

Samples were analysed on a Philips-Norelco X-Ray diffractometer. Mounts were prepared by placing a finely ground powder (less than 125 micra) in a shallow aluminum holder and tamping slightly following the procedure suggested by McCreery (1949). In general, the goniometer was run between 25° and 40° 2θ, the region in which the main peaks for carbonate minerals under discussion are found, at a rate of ½° per minute.

Mineralogy of all samples is recorded, opposite the sample number and brief description, in Table 5. Minerals abundant enough to yield a good diffraction peak, well above background, are recorded and denoted by a "+" sign. Those minerals whose main diffraction peaks are barely discernable from background are also recorded, but differentiated by "tr".

TABLE 5

MINERALOGY OF SAMPLES STUDIED

60,000 Yr. Old Fringing Reef Terrace

Sample No.	Description	Arag	Mg-Cal	Cal	Qtz	Other
N2 A	calcareous crust			+	+	
N2 B	soft caliche carbonate			+		
N2 C	calcareous crust			+	tr	
N3 A	calcarenite	tr		+		
N3 B	calcarenite		+	+		
N3 C	pelleted calcareous crust			+		
N3 D	calcareous crust			+		
N4 A	calcarenite	+	+	+		
N4 B	calcarenite	+	+	+		
N4 E	calcarenite		+	+		
N4 F	calcarenite	+	+	+		
N4 G	calcarenite	tr		+	tr	
N4 J	calcareous crust			+		
N6 A	*Montastrea annularis*			+		
N6 A	crustose red algae		+	+		
N6 B	calcarenite	tr	+	+	tr	
N6 C	calcarenite	tr		+		
N6 D	calcareous crust			+		
N6 E	pelleted calcareous crust			+		
N6 F	soft caliche carbonate	tr		+	tr	
N6 G	soft caliche carbonate			+	tr	
SB1 A	calcarenite	+	+	+	tr	
SB1 B	calcarenite	tr	+	+	tr	
SB1 C	calcarenite with coated allochems			+	tr	
SB1 E	crumbly calcarenite			+	tr	
SB1 F	pelleted calcareous crust			+	tr	
SB1 Gu	calcareous crust	tr		+	tr	
SB1 Gl	calcarenite	+	+	+	tr	
SB1 J	pelleted calcareous crust	tr		+	tr	
SB1 L	calcarenite			+	+	
SB1 M	unlithified calcarenite	+	+	+	tr	
SB1 M	brown carbonate coating allochems			+		
C17 A	calcarenite	+	+	+		
C17 B	calcarenite	tr		+	tr	
C17 C	*M. annularis*	+				
C17 C	calcareous crust	tr		+		
C17 D	calcarenite	tr	+	+		
C17 E	calcareous crust			+		
C17 G	calcareous crust			+		
C32 C	unlithified calcarenite	+		+	tr	
C32 E	unlithified calcarenite		+	+		
C32 E	brown carbonate coating allochems			+		
GG 3	unlithified calcarenite	+		+		

83,000 Yr. Old Reef Complex

Sample	No.	Description	Arag	Mg-Cal	Cal	Qtz	Other
AF20	A	calcarenite			+		
AF20	F	calcarenite	tr		+	+	
AF20	H	calcarenite			+	+	
AF20	L	grey pelleted crust below *A. palmata*			+	+	
AFD2	B2	calcarenite	+		+		
AFD2	B3	grey pelleted crust below *A. palmata*	tr		+	+	
AFD2	B4	pelleted (submarine) crust			+		
AFD2	B5	crustose red algae & calcilutite	tr		+	+	
AFD2	B6	crustose red algae & calcilutite			+	+	
AFD2	B7	calcarenite	tr		+		
AFD2	B8	calcilutite	tr	+	+	+	
B21A1	A	*A. palmata*	+		+		
B21A1	B	crustose red algae			+	tr	
B21A1	C	calcilutite	tr		+	tr	
B21A2	A	*A. palmata*	+		+		
B21A2	C	very fine calcarenite			+	tr	
B21A3	A	*A. palmata*	+	tr	+		
B21A3	B	very fine calcarenite	+		+		
B21A3	D	crustose red algae			+		
B21B1	A	*A. palmata*	tr		+		
B21B1	B	calcarenite			+		
B21B1	C	calcilutite			+	tr	
B21B2	C	calcilutite			+	tr	
B21D1	A	*A. palmata*	+		tr		
B21D1	B	Crustose red algae			+		
B21D1	C	Calcilutite	tr		+	tr	
B21AB1		Calcilutite	tr		+	tr	
B21AB2		Calcilutite			+	+	
B21AB3		Calcilutite			+	+	
B21AB4		Calcilutite			+		
B21AB5		Calcilutite			+		
B21D	4	Calcilutite			+		
B21D	5	Calcilutite			+		
RB1	A1	*M. annularis*	+		+		
RB1	A2	Very fine calcarenite			+		
RB1	A4	Chalky calcareous crust	+		+		
RB1	B1	Calcarenite	+		+		
RB1	B1(2)	Calcarenite	tr		+		
RB1	B3	Calcarenite	tr		+		
RB1	D1	Calcilutite			+	tr	
RB1	D2	*A. palmata*	+		tr		
RB1	D3	*P. porites* & calcareous crust	+		+		
RB1	D5	Pelleted calcareous crust			+		
RB1	A3	Calcarenite	tr		+		
RB3	A1	Calcarenite			+	+	
RB3	A2	Calcarenite			+	tr	
RB3	A3	Calcilutite	+		+		
RB3	B1	Calcilutite			+	+	
RB3	B4	Calcarenite			+	tr	

Sample No.	Description	Arag	Mg-Cal	Cal	Qtz	Other
RB3 C1	calcarenite	+		+		
RB3 C2	calcareous crust	tr		+	tr	
RB3 B3	calcarenite	+				
RBD 1A	calcilutite			+	+	
RBD 1B	calcilutite			+	+	
RBD 1C	pelleted crust on *A. cervicornis*			+	tr	
RBD 2	calcilutite			+	+	
RBD 3	calcarenite			+	+	
RBD 3	pelleted crust (submarine)			+	+	
RBD 3(1)	pelleted crust below *A. palmata*		+	+	+	
RBCR 1	brecciated calcilutite & caliche carbonate	tr		+		
RBCR 3	brecciated calcilutite & caliche carbonate	tr		+		
RBCR 4	pelleted submarine crust around *A. cervicornis*		+			
RBCR 5	calcarenite	+		+		
RBCR 7	calcarenite	+	tr	+		
B25 A	*M. annularis*			+		
B25 B	calcilutite			+	+	
B25 C	*P. porites* and calcilutite			+		
B25 D	calcarenite			+	tr	
B25 E1	calcarenite			+	tr	
B25 E2	*Diploria strigosa*	tr		+	tr	
B25 G	calcilutite			+	tr	
B25 H1	*M. annularis*	+		+		
B25 H2	crustose red algae & calcarenite			+	tr	
B25 K	calcarenite			+	tr	
B25 N	*A. palmata*	tr		+	+	
B25 O1	calcilutite			+	tr	
B25 O2	calcilutite			+	tr	
B25 P	calcarenite	tr	tr	+	tr	
B25 Q	*P. porites*	+		+	tr	
B25 R	crustose red algae			+	tr	
B25 T	calcilutite			+	tr	
WB5 D1	*A. palmata*	+		tr		
WB5 D2	calcarenite			+		
WB5 D3	crustose red algae & calcarenite			+	+	
WB5 D4	calcarenite			+		
WB5 E1	*A. palmata*	+		tr		
WB5 E2	calcarenite			+	+	
WB5 F1	calcarenite			+	+	
WB5 F2	*M. annularis*	+				
WB5 G1	*A. palmata*	+		tr		
WB5 G2	calcarenite			+	+	
WB5 H1A	*A. cervicornis*	+				
WB5 H1B	calcarenite	+		+	tr	
WB5 H2	*A. palmata*	+		tr		
WB5 J	calcareous crust	tr		+	tr	
WB5 K1	*Strombus* & calcarenite			+	tr	

Sample No.	Description	Arag	Mg-Cal	Cal	Qtz	Other
WB5 K2	calcareous crust			+		
WB5 K3	calcareous crust	tr		+	tr	
WB5 K4	calcareous crust	tr		+	tr	
WB5 K5	calcareous crust			+		
WB7 A1	calcarenite			+	tr	
WB7 A2	*A. palmata*	+				
WB7 A3	*Diploria*	+		tr		
WB7 B1	*A. cervicornis*	+		tr		
WB7 B2	Calcarenite	+		+		
WB7 C2	Calcarenite			+	tr	
WB7 D1	Calcarenite			+	tr	
WB7 D2	*A. palmata*	+		tr		
WB7 D4	Calcarenite			+	+	
WB7 E1	Calcarenite			+	+	
WB7 E2	*A. palmata*	+		tr		
WB7 E3	*M. annularis*	+		tr		
WB7 K3	Calcareous crust	tr		+		
L3	Calcilutite (clast)			+		
L6	Sand			+	+	
L7	Sand			tr	+	Feld.
L8	Sand			+	+	Feld.
L15	Calcarenite			+	+	
L16	Calcilutite			+	+	Feld.
L16 C	Calcarenite			+	+	
L19	Calcilutite (white mottle)			+	+	
L19	Calcilutite (white mottle)			+	+	
L19	Calcilutite (white mottle)			+	+	
L19	*P. porites* & calcilutite	tr		+	tr	
L19	Brown sand			tr	+	
L20	Calcarenite			+	tr	
L20	Calcilutite			+	+	
L22 A	Calcarenite			+	+	
L22 B	Calcilutite			+	tr	
LCR 1	Crumbly caliche carbonate			+		
LCR 2	Crumbly caliche carbonate			+		
LCR 5	Calcarenite	+		+	tr	
LCR 7	calcarenite & calcareous crust			+		
GC A1	calcarenite			+		
GC A2	calcarenite – matrix of conglomerate	tr		+	tr	
GC B3A	calcarenite			+	tr	
GC B3B	calcilutite			+	tr	
SG7 A	*Goniolithon*			+	tr	
SG7 B	calcarenite			+	+	
SG7 C	calcarenite	+		+	+	
SG7 D	calcilutite	tr		+	+	

Sample No.	Description	Arag	Mg-Cal	Cal	Qtz	Other
B6	calcarenite			+	+	
B8	calcarenite	tr		+	+	
B14 A	*A. palmata*	+		tr		
B14 B	calcareous crust			+		
B14 C	calcarenite			+	tr	
B15 A	*P. porites* & calcareous crust			+	tr	
B15 C	caliche carbonate	tr		+	tr	
B16 A	*A. palmata*	+	tr	tr		
B14 D	calcarenite	+		+	tr	
B16 B	calcarenite			+		
B17 C	calcarenite	tr		+	tr	
B17 D	*A. cervicornis*	+				

104,000 Yr. Old Reef Complex

Sample No.	Description	Arag	Mg-Cal	Cal	Qtz	Other
P25 A	calcarenite			+		
P25 B	calcarenite	tr		+		
P25 C	calcilutite			+		
P25 D	calcilutite			+		
P25 E	calcilutite			+		
P25 F	calcilutite			+		
P13	calcarenite	tr		+		
SD 1	calcilutite			+		
SD 1	calcilutite			+		
SD 2	calcarenite	tr		+		
SD 2	calcarenite			+		
S1 A	calcarenite			+		
S1 B	calcilutite			+		
S1 C	calcarenite	tr		+		
S1 D	calcilutite			+		
FW1 A	very fine calcarenite			+	tr	
FW1 B	*A. cervicornis*			+		
FW2 A	very fine calcarenite			+		
FW2 B	very fine calcarenite			+		
FW2 C	*A. cervicornis*	tr		+		
FW3 A	very fine calcarenite			+		
FW3 B	*A. cervicornis*	tr		+		
FW4 B	*A. palmata*	+		+		
FW4 D	very fine calcarenite	+		+		
FW7 A	calcarenite			+	+	
FW7 B	calcarenite	tr		+	+	
FW8	calcarenite	tr		+	+	
FW9	calcarenite			+	+	
FW10 A	calcarenite			+		
FW10 B	calcarenite			+	+	
FW11	calcarenite			+	+	
FW12	calcarenite			+	+	
FW33	calcilutite			+	+	

Sample No.	Description	Arag	Mg-Cal	Cal	Qtz	Other
US1 A	sandy calcarenite			+	+	Feld.
US1 B	sandy calcarenite			+	+	
FHD 1	sandy calcarenite			+	+	Feld.
FHD 2	sandy calcilutite			+	+	Feld.
FHD 3	calcilutite			+	tr	
B26 A	calcarenite			+	tr	
B26 B	calcarenite			+		
B26 C	<u>M. annularis</u>	+		tr		
B26 C	<u>Diploria</u>	+		+		
B26 C	<u>M. cavernosa</u>	tr		+		
B26 D	<u>A. cervicornis</u>			+		
B26 E	calcarenite			+	+	
B26 F	calcarenite			+	tr	
B26 G	calcarenite			+	tr	
B26 K	<u>M. annularis</u>	+		+		
B26 N	calcarenite	+	+	+		
B23 A	<u>A. palmata</u>	+		tr		
B23 B	calcarenite	tr		+	tr	
B23 C	<u>P. astreoides</u>			+		
B23 C	calcarenite			+		
B23 D	calcarenite			+	+	
B23 E	calcarenite			+	+	
B23 F	<u>M. cavernosa</u>	+		tr		
B23 G	<u>M. annularis</u>	tr		+		
B23 H	calcarenite	tr		+	tr	
B23 J	<u>A. palmata</u>	+		tr		
B4 C	calcarenite	+		+		
B27	calcarenite			+		
B28 A	calcarenite			+	+	
B28 B	calcarenite			+	+	
B30 A	calcarenite			+	tr	
B30 B	calcarenite			+	tr	
B32	calcarenite	tr		+	tr	
M17	calcarenite			+	tr	
M30	calcarenite			+	+	
M31	calcarenite			+	tr	
M19	calcarenite			+		

Sample No.	Description	Arag	Mg-Cal	Cal	Qtz	Other
	Undated (Older?) Pleistocene Carbonates					
B2 A	calcarenite			+		
B3 A	calcarenite			+		
B3 B	calcarenite			+		
M22	calcarenite			+		
SH12	calcilutite			+		
SG22	calcarenite			+		
	Plio-Pleistocene					
B10 A	_Amphistegina_ limestone			+		
C32 A	Phylloid-algal limestone			+		
M45 B	Phylloid-algal limestone			+		
SH26	Calcilutite			+	+	
SG9	_Amphistegina_ limestone			+		
C24 B	_Amphistegina_ limestone			+		
M41 C	_Amphistegina_ limestone			+		
M34	_Amphistegina_ limestone			+		
SH10	Phylloid-algal limestone			+		
M47	_Amphistegina_ limestone			+		
AF42	_Amphistegina_ limestone			+		
	Scotland Formation					
SH10	Sand			tr	+	(feldspar
SH23	Sandstone				+	(sericite
M45 C	Sandstone				+	(illite

APPENDIX D (TABLE 6)

SAMPLE DESCRIPTION

Sample No.	Porosity	Grain Size	Classification
			60,000 Yr. Old Reef Terrace
N3 B	Porous	cs.	Amphiroa, coral (a)*, peneropolid, rounded, intrabiosparite
N4 F	Porous	cs.	coral (v), peneropolid, mollusc (v), rounded, intrabiosparite
C17 A	Porous	cs.	Homotrema (mc), peneropolid (mc), rounded, intrabiosparite
N4 G		m-cs.	peneropolid, coral, Amphiroa, mollusc (a), rounded, intrabiosparite
SB1 B	Porous	cs.	peneropolid, coral (a), mollusc (a), Amphiroa (mc), rounded, intrabiosparite
SB1 G	Porous	m-cs.	peneropolid (mc), mollusc (a), Amphiroa (mc), rounded, intrabiosparite
C17 B	Porous	cs.	Homotrema, mollusc (v), Amphiroa, rounded, intrabiosparite
N4 B	Porous	vf-cs.	Lithothamnion, Amphiroa, rounded, intrabiosparite
SB1 C	Porous	cs.	coated grain, rounded, intrabiosparite
			Sediment Underlying 60,000 Yr. Old Reef Terrace
SB1 A	Porous	m-f.	Homotrema, miliolid, Lithothamnion, sorted, biosparite
N6 A	Porous	m-f.	Homotrema, Lithothamnion, sorted, biosparite
			83,000 Yr. Old Reef Complex – Palmata Zone
AFD2 B3	Porous	bimodal	cs. Homotrema & f. coral (a), unsorted, intrabiosparite
AFD2 B4	Porous	m.	Homotrema, Lithothamnion, coral (v), sorted, biosparite
AF20 L	Porous	cs-m.	Homotrema, Lithothamnion, Amphiroa, unsorted, biomicrite
AFD2 B7a	Porous	f.	coral (v), sorted biosparite

* all constituents are calcite except when denoted as (a) aragonite, (mc) Mg-calcite, or (v) void.

Sample No.	Porosity	Grain Size	Classification
AFD2 B7b	Porous	cs.	Amphiroa, mollusc, unsorted biomicrite
AFD2 B9	Porous	f.	coral (v) & (a), sorted biosparite
B21D 4	Porous	bimodal	cs. Amphiroa, mollusc, Homotrema & f. coral, unsorted, biomicrite
B21B 1C	Porous	cs.	Amphiroa, Homotrema, mollusc, unsorted, biomicrite
B25 T	Porous	cs-f.	Amphiroa, mollusc, coral (a), unsorted, intrabiosparite
WB5 G2	Porous	f.	coral (a), sorted biomicrite
RBD3 C	Porous	cs.	Homotrema, Amphiroa, unsorted, biomicrite
RB2 A2(2)	Porous	m.	Amphiroa, Lithothamnion, Homotrema, unsorted biomicrite
B21A 2C	Porous	cs.	Amphiroa, Lithothamnion, Homotrema, unsorted, biomicrite
RB3 C1	Porous	m-f.	coral (a), Amphiroa, mollusc, unsorted biomicrite
B21D 1C	Porous	cs.	Amphiroa, coral (a), Homotrema, unsorted biomicrite
RB3 B4A	Porous		pelsparite
B21B 2C	Porous	vf.	Amphiroa, unsorted biomicrite
B21AB	Porous	vf.	Homotrema, Lithothamnion, Amphiroa, unsorted,biomicrite.
RB3 D	Porous	m.	Homotrema, Amphiroa, unsorted biomicrite
RB3 C3	Porous		microsparite
B21D AB	Porous		micrite & pelsparite

Cervicornis Zone

Sample No.	Porosity	Grain Size	Classification
RB3 B1	Porous		micrite
B25 B	Porous	cs.	Amphiroa, mollusc, unsorted, biomicrite
RBD 2(3)	Porous	f.	coral (a), sorted, biosparite
RBD 1A	Porous	cs.	Amphiroa, Homotrema, unsorted micrite & pelsparite
RBD 2	Porous		sandy micrite

Sample No.	Porosity	Grain Size	Classification
B21 D	Porous	cs.	Amphiroa, Homotrema, unsorted, biomicrite
RB1 D1(b)	Porous	m.	sandy Amphiroa, sorted, intrabiosparite
RBC 4	Porous	cs-f.	Homotrema, coral (a), unsorted, biosparite
			Porites-Thalassia Zone
LCR 5	Porous	m.	Amphiroa, peneropolid, unsorted, biosparite
RBCR 6	Porous	bimodal	cs. mollusc & f. coral (a), unsorted biosparite
B25 D	Porous	bimodal	cs. mollusc, Amphiroa & f. coral (a), unsorted, biomicrite
B25 C	Porous	m.	Homotrema, coral (a), mollusc, unsorted, biomicrite
B25 E	Porous	bimodal	cs. mollusc, Amphiroa & f. coral (a), unsorted, biomicrite
RBCR 5	Porous	bimodal	cs. mollusc & f. coral (a), unsorted, biomicrite
L19	Porous	vf.	sandy, biomicrite
B17 C	Porous	f.	coral (a), unsorted, biomicrite
L13 B	Porous	cs-vf.	mollusc, coral (a), unsorted, biomicrite
B25 0	Porous	m.	coral (v), mollusc (v), unsorted, biomicrite
RB1 B2	Porous	cs-vf.	coral (a), mollusc (a), unsorted, biomicrite
RB1 B1	Porous	bimodal	cs. coral (a), mollusc (a), unsorted biomicrite
RB1 A1	Porous	bimodal	cs. Amphiroa, coral (a), mollusc (a) & f. unsorted biomicrite
RB1 A2	Porous	cs-f.	coral (a), mollusc (a), Homotrema, unsorted biomicrite
RB1 B3	Porous	cs-f.	coral (a), mollusc (a), unsorted, biomicrite
RB3 E5	Porous	cs.	mollusc (v) & (a), unsorted, biomicrite
RB1 A3	Porous	cs.	Homotrema, unsorted, biomicrite
RB1 A4	Porous	cs.	Homotrema, Amphiroa, coral (a), unsorted, biomicrite

Sample No.	Porosity	Grain Size	Classification
			Coral-Knob Zone
L19	Porous	f.	sandy, mollusc (a), unsorted, microsparite
L20	Porous	m.	Amphiroa, unsorted, biosparite
WB7 B2	Porous	v-cs.	algal ball, Homotrema, mollusc (v), unsorted, biosparite
WB7 E1	Porous		microsparite
WB7 B7	Porous		microsparite
WB7 B2	Porous		microsparite
WB7 C2	Porous		microsparite
L19 (2)	Porous	f.	sandy, mollusc (a), unsorted, microsparite
L7	Porous	vf.	sandstone
L8	Porous	vf.	sandstone
L16	Porous	cs-vf.	unsorted, biosparite
			Fringing-reef Facies
SG7 1	Porous	cs.	Homotrema, Lithothamnion, unsorted, biomicrite
SG7 2	Porous	cs.	Homotrema, mollusc (v), unsorted, biomicrite
SG7 4	Porous	cs.	Homotrema, Lithothamnion, unsorted, biomicrite
			Basal Lithologies
GC A2	Porous	cs.	unsorted biosparite (conglomerate clast)
AF20 F	Porous	f.	sandy, Amphiroa, unsorted, intrabiosparite
GC B4	Porous	m-f.	sandy, coral (v), mollusc (v), Lithothamnion, unsorted, intrabiosparite
GC B3	Porous	cs-m.	sandy, Lithothamnion, unsorted, biosparite
AF20 H	Porous	m-f.	Amphiroa, unsorted, biosparite

Sample No.	Porosity	Grain Size	Classification
AF20 G	Porous	m-f.	sandy, Amphiroa, unsorted, intrabiosparite
RB3 E2	Porous	cs.	sandy, Amphiroa, unsorted, biosparite
WB5 D	Porous	f.	sandy, Homotrema, Amphiroa, unsorted, biosparite
WB5 E2	Porous	bimodal	cs. Amphiroa, Homotrema & vf. unsorted, intrabiosparite
L15 A	Porous		sandstone
L15 B	Porous	cs.	Amphiroa, unsorted, biosparite
			104,000 Yr. Old Reef Complex - Palmata Zone
S1 C	Porous	m.	Amphiroa, sorted, intrasparite
SD 2	Porous	m.	coral, Amphiroa, Homotrema, sorted, biosparite
SD 2	Porous	cs.	Homotrema, mollusc, unsorted, biomicrite
FHD 1	Porous		sandstone
FHD 2	Porous	f.	sandy, Homotrema, Amphiroa, coral, unsorted, biosparite
FHD 3	Porous	f-vf.	coral (a), packed, intrabiomicrite
US 1	Porous		sandstone
US 2	Porous	bimodal	sandy, cs. coral (a) & f. quartz, unsorted, biosparite
			Cervicornis Zone
P25 C	Porous	bimodal	cs. Amphiroa & f. coral, sparse, biomicrite
P25 E	Porous	bimodal	cs. Amphiroa & f. coral, sparse, biomicrite
P 25 F	Porous	bimodal	cs. Amphiroa & f. coral, packed, intrabiomicrite
P13 C	Porous	bimodal	cs. Amphiroa & f. coral, packed, biomicrite
P13 D	Porous	bimodal	cs. Amphiroa & f. coral, unsorted, biosparite
SD 1	Porous	cs.	coral, Amphiroa, packed, biomicrite

Sample No.	Porosity	Grain Size	Classification
FW1 A	Porous	cs.	Amphiroa, mollusc (v), sparse, biomicrite
FW2 A	Porous	m-f.	mollusc, coral, packed, biomicrite
			Back-reef Facies
FW7 A	Porous	m.	sandy, coral (v), mollusc (v), peneropolid, sorted, intrabiosparite
P15	Porous	cs.	coral, mollusc, Lithothamnion, unsorted, intrabiosparite
M52	Porous	m.	Lithothamnion, coral, sorted, intrabiosparite
M52	Porous	cs.	coral (a) & (c), Homotrema, Amphiroa, unsorted, intrabiosparite
M31	Porous	m.	coral, Homotrema, mollusc, Lithothamnion, sorted, biosparite
FW8	Porous	f.	Lithothamnion, echinoid, sorted, intrabiosparite
FW9	Porous	f.	sandy, coral (v), peneropolid, Lithothamnion, unsorted, biosparite
FW30	Porous	f.	sandy, coral, Lithothamnion, sorted, biosparite
FW31	Porous	f.	sandy, Lithothamnion, sorted, intrabiosparite
FW32	Porous	f.	sandy, Lithothamnion, sorted, biosparite
S1 B	Porous	m-vf.	coral, Amphiroa, unsorted, biosparite
S2 B	Porous	cs-m.	coral, unsorted, intrabiosparite
FW10 A	Porous	cs-f.	Lithothamnion, mollusc, echinoid, unsorted, biomicrite
FW33	Porous	m-f.	coral, unsorted, biomicrite
S2 A	Porous	f.	sandy, foraminifera, sorted, intrabiosparite
FW10 B	Porous	m.	Lithothamnion, Amphistegina, rounded, biosparite
FW28	Porous	m.	sandy, foraminifera, Lithothamnion, sorted, biosparite
FW20 B	Porous	m.	sandy, foraminifera, sorted, biosparite
FW20 A	Porous	m.	sandy, foraminifera, sorted, biosparite
FW34	Porous	m.	sandy, foraminifera, sorted, intrabiosparite

Sample No.	Porosity	Grain Size	Classification
FW11	Porous	cs.	sandy, Amphistegina, rounded, intrabiosparite
FW12	Porous	cs.	Lithothamnion, rounded, intrabiosparite
FW12 A	Porous	cs.	Lithothamnion, rounded, intrabiosparite
A3A A	Porous	f.	sandy, foraminifera, Lithothamnion, sorted, biosparite
A3A B	Porous	cs.	sandy, Amphistegina, Lithothamnion, sorted, intrabiosparite
B32	Porous	cs-f.	Amphistegina, unsorted, biosparite
B32 A	Porous	cs-f.	Amphistegina, Lithothamnion, unsorted, biosparite
M23	Porous	cs.	Amphistegina, mollusc, Lithothamnion, sorted, intrabiosparite
M19 A	Porous	cs-f.	Amphistegina, Lithothamnion, unsorted, biomicrite
			Plio-Pleistocene Limestone - Phylloid Algal Unit
SH26	Porous		sandy, planktonic foraminifera, sparse, biomicrite
SH22 A	Porous		crustose red algal, intrabiolithite
SH22 B	Porous	cs-f.	crustose red algal, unsorted, intrapelsparite
C33 A	Porous	cs-f.	crustose red algal, Amphistegina, unsorted, intrapelsparite
C32 H	-	cs-f.	crustose red algal, planktonic foraminifera, packed, intrapelmicrite
M35 B	-		crustose red algal, intrabiolithite
M45 B	-	cs-f.	crustose red algal, packed, intrapelmicrite
			Amphistegina Calcarenite Unit
C25 E	-	cs-vf.	Amphistegina, unsorted, pelbiomicrosparite
SG9	-	cs-vf.	Amphistegina, packed, pelbiomicrite
C24 B	-	cs-m.	Amphistegina, Lithothamnion, unsorted, pelbiomicrite
C37	-	cs-vf.	Amphistegina, unsorted, pelbiointramicrosparite
M41 C	-	cs.	Amphistegina, planktonic foraminifera, unsorted, microsparite
M34	-	f.	sorted, intrapelmicrosparite

APPENDIX E TABLE 7

FORAMINIFERA FROM OCEANIC FORMATION

AT CLUFF'S BAY, NORTHERN BARBADOS

(identified by K. Laborde)

	SAMPLE NO. C36-1	C36-2	C36-3	C36-4	C20-10 FT.	C20-20 FT.	C20-30 FT.	C20-50 FT.	C20-95 FT.
Globigerina senni (Beckmann)	x		x	x	x	x			
Globigerina boweri Bolli					x	x	x	x	
Globorotalia aragonensis Nuttall		x	x		x	x	x	x	x
Globorotalia bullbrooki Bolli		x			x	x	x		
Globorotalia spinulosa Cushman	x		x						
Globorotalia lehneri Cushman & Jarvis		x						x	x
Globorotalia centralis Cushman & Bermudez	x		x						
Globorotalia bolivariana (Petters)					x			x	
Globigerapsis kugleri Bolli, Loeblich & Tappan	x		x		x		x	x	
Globigerapsis index (Findlay)			x					x	x
Globigerapsis semiinvoluta Keijzer									x
Globigerinoides higginsi Bolli					x	x	x	x	x
Globorotaloides suteri Bolli							x		
Globigerinatheka barri Bronniman	x								
Truncorotaloides topilensis (Cushman)	x								
Truncorotaloides rohri Bronniman & Bermudez	x	x	x			x	x	x	x
Catapsydrax cf. dissimilis Cushman & Bermudez	x	x			x		x	x	x
Hantkenina aragonensis Nuttall						x	x	x	

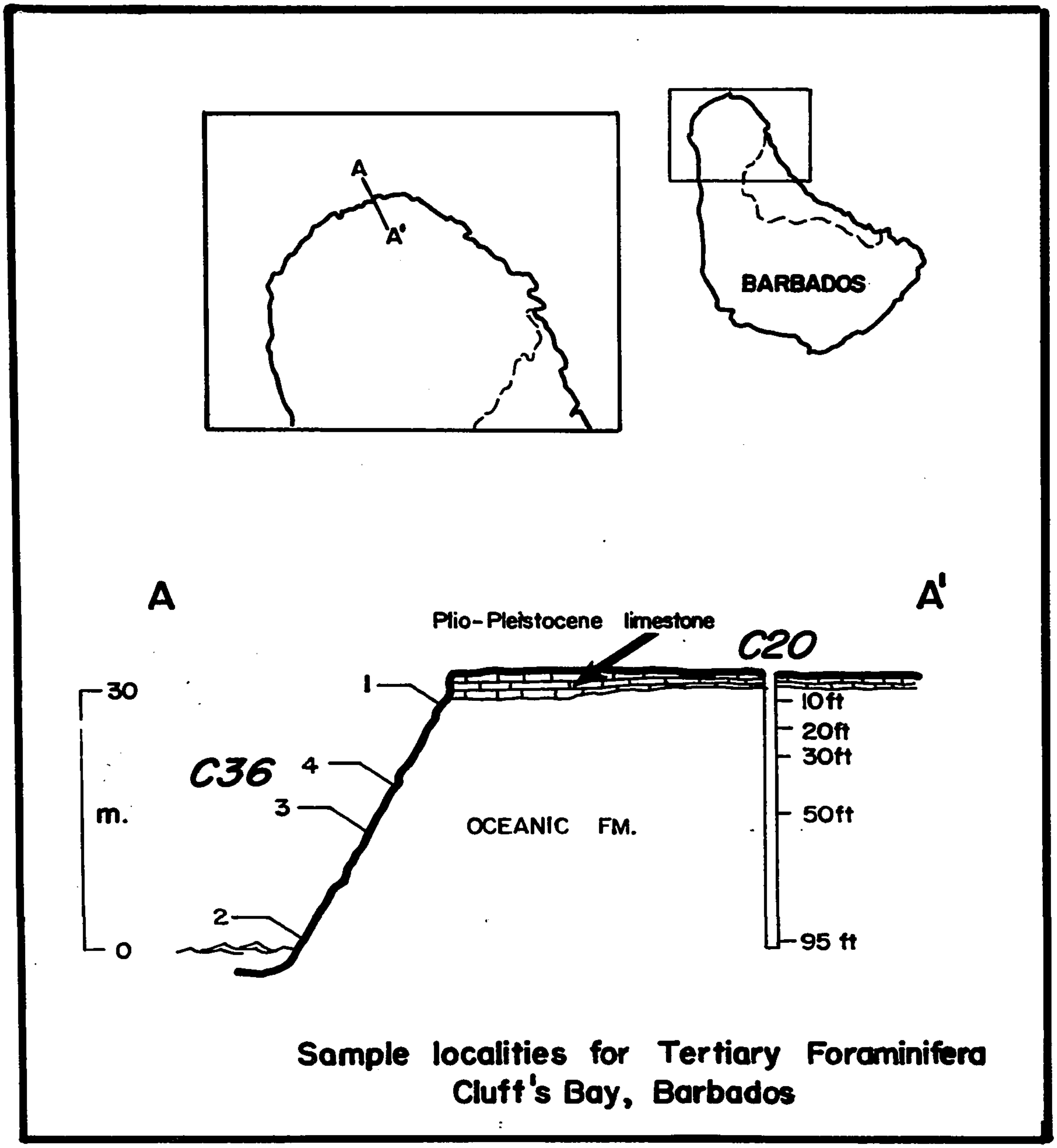


Figure 33. Sample localities of Eocene foraminifera in the Oceanic Formation, Cluff's Bay, Barbados.

APPENDIX F

RADIOMETRIC AGE DETERMINATIONS

All radiometric age dating was carried out at Kanazawa University, Department of Earth Sciences, under the direction of Akio Omura. In all cases, both Th^{230}/U^{234} and Pa^{231}/U^{235} ratios were determined on the material supplied.

Samples of coral were used for age determination in all cases except two, when gastropods were analysed. Each sample was first checked by X-Ray diffraction to confirm that aragonite was the only carbonate mineral phase present. Thin sections were cut to discern whether epitaxial aragonite was present in the pores and if solution of the skeleton had commenced. Age determinations were only carried out on those skeletons that were exclusively aragonite with no secondary cement precipitation.

Samples were collected from some of the outcrops already dated by Mesolella and others (1969) and these samples were analysed along with the samples of unknown age (Table 8). The close agreement between age determinations on similar samples by Mesolella and others (1969) and Omura (this study) suggests that the remaining recently determined radiometric ages from northern Barbados can be added to those obtained by Mesolella and others (1969) to yield an almost complete chronology of the late Pleistocene limestones on the island. Radiometric ages of the undated material from northern Barbados are listed in Table 9 and each sample is located on the accompanying map.

TABLE 8

Radiometric Ages of Late Pleistocene Corals From Dated Outcrops on Southern Barbados*

Sample	Material **	U^{238} (ppm)	$U^{234}:U^{238}$	$Th^{230}:U^{234}$	$Pa^{231}:U^{235}$	Th^{230} Age ($x10^3$ yr)	Pa^{231} Age ($x10^3$ yr)
B-OC	Ma	2.94 ± 0.05	1.13 ± 0.01	0.530 ± 0.010		82 ± 2	
J-OC	Ma	3.02 ± 0.06	1.04 ± 0.03	0.540 ± 0.015	0.817 ± 0.031	84 ± 2	80 ± 2
B-FS	Ac	4.12 ± 0.08	1.13 ± 0.02	0.540 ± 0.020		84 + 4	
J-FS	Ap	3.18 ± 0.07	1.08 ± 0.03	0.524 ± 0.015	0.790 ± 0.030	81 ± 2	73 ± 3
B-FT	Ma	2.72 ± 0.05	1.11 ± 0.02	0.620 ± 0.020		104 ± 4	
J-FT	Ap	3.68 ± 0.13	1.12 ± 0.05	0.628 ± 0.009	0.892 ± 0.026	107 ± 4	105 ± 5
B-AFZ	Ap	3.34 ± 0.05	1.10 ± 0.01	0.620 ± 0.020		104 ± 4	
J-AFZ	Ap	3.26 ± 0.10	1.08 ± 0.05	0.611 ± 0.020	0.888 ± 0.037	103 ± 3	103 ± 3
B-ADR	Ap	3.74 ± 0.05	1.11 ± 0.02	0.700 ± 0.020		127 ± 6	
J-ADR	Ap	3.31 ± 0.06	1.08 ± 0.03	0.684 ± 0.017	0.927 ± 0.032	125 ± 3	123 ± 4

* Samples with prefix "B" are from Mesolella and others (1969;Table 1, p. 257);samples with prefix "J" were collected from the same outcrop by James and dated by Omura (this study).

** Coral species Ma=<u>Montastrea annularis</u>, Ac=<u>Aeropora cervicornis</u>, Ap=<u>Aeropora palmata</u>

TABLE 9

Radiometric Ages of Previously Undated Samples From Northern Barbados*

Sample	Material **	U^{238} (ppm)	$U^{234}:U^{238}$	$Th^{230}:U^{234}$	$Pa^{231}:U^{235}$	Th^{230} Age ($x10^3$ yr)	Pa^{231} Age ($x10^3$ yr)
GG1-A	Pa	3.06 ± 0.06	1.09 ± 0.03	0.442 ± 0.012	0.742 ± 0.024	63 ± 2	63 ± 2
GG1-B	Pa	3.01 ± 0.03	1.13 ± 0.03	0.436 ± 0.012	0.723 ± 0.025	63 ± 2	60 ± 2
GG-2	Cp	0.245 ± 0.010	1.15 ± 0.06	0.420 ± 0.018	0.699 ± 0.036	59 ± 3	56 ± 3
SB4-B	Cp	0.720 ± 0.018	1.09 ± 0.03	0.419 ± 0.016	0.692 ± 0.030	59 ± 2	55 ± 2
B6-A	Ap	3.79 ± 0.08	1.08 ± 0.03	0.516 ± 0.015	0.831 ± 0.030	79 ± 2	83 ± 3
B21A-3A	Ap	3.76 ± 0.09	1.13 ± 0.04	0.533 ± 0.016	0.836 ± 0.028	83 ± 2	83 ± 3
WB7-E3	Sr	3.14 ± 0.05	1.13 ± 0.02	0.534 ± 0.011	0.823 ± 0.020	83 ± 2	81 ± 2
FW	Ap	3.43 ± 0.01	1.08 ± 0.05	0.621 ± 0.020	0.888 ± 0.040	105 ± 3	103 ± 3
US-1	Ap	3.83 ± 0.08	1.10 ± 0.03	0.605 ± 0.016	0.862 ± 0.029	100 ± 3	93 ± 3
C-44	Ap	3.96 ± 0.06	1.06 ± 0.02	0.589 ± 0.012	0.877 ± 0.026	97 ± 2	98 ± 3
B26-C	Ap	2.66 ± 0.07	1.14 ± 0.04	0.633 ± 0.020	0.882 ± 0.038	110 ± 3	100 ± 4
B22	Ap	4.11 ± 0.09	1.09 ± 0.03	0.630 ± 0.018	0.901 ± 0.032	108 ± 3	108 ± 4
AF-50	Ma	3.54 ± 0.08	1.04 ± 0.02	0.690 ± 0.014	0.929 ± 0.036	127 ± 3	124 ± 5

* See Fig. 34 for sample locations.

** Coral species Pa=<u>Porites astreoides</u>, Ap=<u>Acropora palmata</u>, Sr=<u>Siderastrea radiens</u>, Ma=<u>Montastrea annularis</u>

Gastropod Cp=<u>Cittarium pica</u>

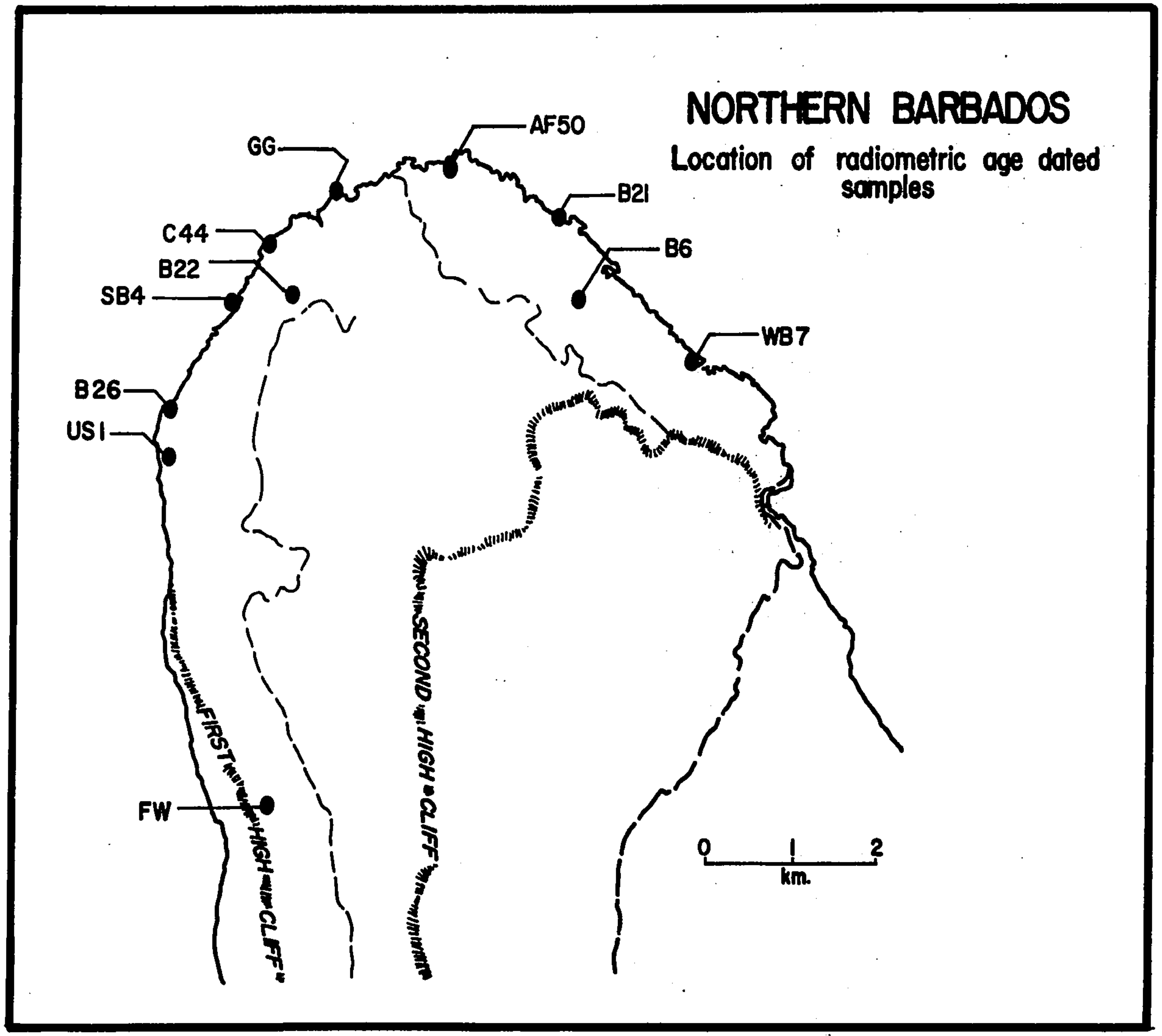


Figure 34. Localities of radiometrically dated Pleistocene samples from northern Barbados.

APPENDIX G

TABLE 10

MINERALOGY OF *ACROPORA PALMATA* COLONIES

IN REPRESENTATIVE LATE PLEISTOCENE REEF SECTIONS

ON NORTHERN BARBADOS*

Section	Age ($x10^3$yr)	Number	Aragonite %	"Chalk" %	Transition %	Calcite %
P28	104	48	0	0	26	73
SD 2	104	44	2	0	34	64
FH 1	104	49	0	10	63	27
FH 2	104	35	3	15	69	14
FH 3	104	24	21	10	67	4
AFD 1A	83	50	28	10	62	0
AFD 1B	83	15	53	0	47	0
B21	83	38	13	0	87	0
RBD 3	83	74	7	50	43	0
RBD 4A	83	20	25	50	25	0
L15	83	20	0	10	90	0
L22 A	83	24	0	75	25	0
L22 B	83	26	8	15	77	0
Total		467	10%	19%	54%	18%

* See Fig. 35 for location.

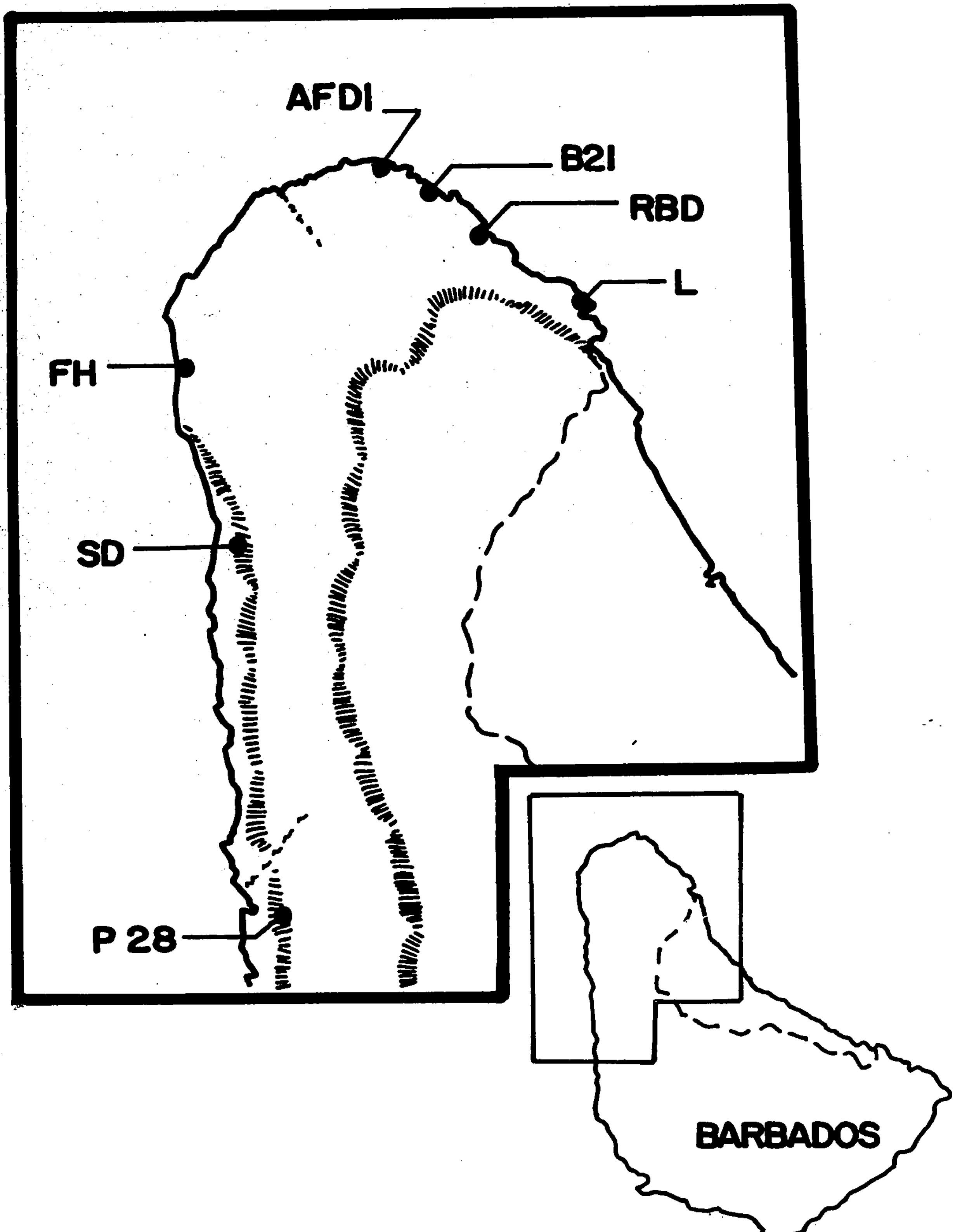


Figure 35. Localities where the mineralogy of Pleistocene *Acropora palmata* was investigated in detail.

TABLE 11

POSITION OF "CHALKY" ARAGONITE OR CALCITE

IN PARTIALLY-ALTERED PLEISTOCENE *ACROPORA PALMATA* FRONDS

Section	Number of Samples	Axial Alteration*		Dorsal Alteration**	
		algal encrustation	no algal encrustation	algal encrustation	no algal encrustation
P28	13	9	0	4	0
SD 2	15	7	8	0	0
FH 1	31	0	25	6	0
FH 2	24	4	14	3	3
FH 3	16	0	16	0	0
AFD 1A	31	1	26	0	4
AFD 1B	7	0	4	3	0
B21	33	0	14	19	0
RBD 3	32	9	1	22	0
RBD 4A	5	0	5	0	0
L15	18	0	18	0	0
L22 A	6	1	5	0	0
L22 B	20	0	16	4	0
Total	251	31	152	61	7
%	100	12	61	24	3

* axial alteration – "chalky" aragonite or calcite located at centre of frond.

** dorsal alteration – "chalky" aragonite or calcite located at upper surface of coral frond.