A STUDY OF THE BIOEROSION OF COASTAL LIMESTONES: A PHOTOGRAMMETRIC APPROACH

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by

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A Thesis submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy

Department of Biology
and
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Memorial University of Newfoundland

June, 1977

St. John's Newfoundland

ABSTRACT

The present study investigates the importance of bio-erosion in the destruction of coastal limestones of the tropical island of Barbados. A stereophotogrammetric system capable of obtaining yearly photographs of the rock surface and of providing quantitative data on rock surface data points from which erosional values can be obtained is described. Results of photogrammetric analysis of five study localities show a range of erosion rates (for inter-tidal and supratidal localities) which vary from 1.2 mm./year to 2.4 mm./year. Following establishment of erosion rates for the localities studied, calculations have been carried out to determine the erosional capabilities of the epilithophagic organisms present on the rock surfaces. These calculations show that in no case do epilithophagic organisms account for more than 40 per cent of the total erosion. Other factors which may account for the remaining erosion include physical and chemical weathering as well as non-epilithophagic biological erosion. The author suggests that of the latter category the erosional effects of boring microphytes (chasmolithic and endolithic algae and fungi) are extremely important in explaining the non-epilithophagic erosion. These microphytes act directly on the substrate by

biochemical boring activity and indirectly by attracting the epilithophagic organisms which rasp the rock to gain nourishment provided by the thalli of the microphytes.

PREFACE

This thesis deals with the establishment of a photogrammetric system capable of monitoring small-scale geomorphic and ecologic changes in the environment. Further, the implementation of such a system in order to study organism-rock interactions at selected localities in the coastal limestones of Barbados is described. The relative importance of such factors as lithology, biota and geomorphology on erosion rates of the rock substrates are discussed.

Parts of this thesis have been presented at the Symposium of Commission V, International Society of Photogrammetry, Washington, D.C., September, 1974. The section on lithophytic algae is in manuscript form for publication.

ACKNOWLEDGMENTS

Due to the interdisciplinary nature of this project, it is virtually impossible to acknowledge individually all those whose advice and expertise in their fields of specialization contributed to the completion of the work. Their aid is nevertheless greatly appreciated.

The author is especially grateful to J.W. Evans, M.M. Anderson and L.E. Fahraeus for their support and guidance during the study. Their comments and constructive criticism are greatly appreciated. The author also wishes to thank Dr. Walter Adey and Dr. Richard Buggeln for aid in identification of algal material and Dr. R. Robertson for identification of certain of the gastropods. The patience of Dr. S.E. Masry and Mr. Nicola Nur during design and implementation of the photogrammetric system is appreciated. Dr. Dan Stewart aided in establishing proper statistical tests. The expertise of Roy MacLellan of the Technical Service staff of Memorial University was instrumental in the fabrication of the photogrammetric apparatus. Newfoundland-Labrador Computer Services provided important advice concerning the SYMAP program. The photographic expertise of Roy Ficken of the Biology Department of Memorial University greatly facilitated final processing of the plates. Any merit in the appearance of the text is due entirely to the typing of Ms. Dallas Strange. The research facilities of the Bellairs Research Institute of McGill University, the Marine Sciences Research Laboratory of Memorial University and the Discovery Bay Marine Lab of the University of the West Indies are gratefully acknowledged.

Financial support for this project was provided by the Office of Graduate Studies of Memorial University and by a National Research Council of Canada grant to Dr. J.W. Evans. Ancillary funds were received from the Department of Geology and the Marine Sciences Research Laboratory of Memorial University.

The author gratefully acknowledges the encouragement, patience and understanding of Dr. F.A. Aldrich, Dean of Graduate Studies, especially during the final stages of manuscript preparation. Special thanks are also due Dr. and Mrs. J.W. Evans for their personal interest in the project and for invaluable support during field work. Finally, the author is indebted to his wife, Marie, who gave constant help and encouragement in all phases of this work.

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CHAPTER I

INTRODUCTION

The dynamics of the coastal zone have for many years been a focus of attention for earth and life scientists. Biologists have given considerable attention to the ecology of this zone where the terrestrial environment meeting the marine produces an area of varying physiological stress for the organisms inhabiting it. Studies of the natural history of these organisms have revealed the existence of complex interrelationships between the organisms and their substrates. Geologists and geomorphologists have studied the coastal zone to gain an understanding of processes of marine erosion.

The purpose of the present study is to shed light on the complex interplay between intertidal and supratidal erosional and accretional agents and the rock substrates. This is accomplished by correlating precise measurements of erosion and accretion with the topographic, lithologic, and biologic characteristics of the substrate. Erosional and accretional data were collected by means of stereophotogrammetric analysis and computer mapping of the intertidal and supratidal study areas. This was augmented by standard biologic and geologic procedures. These analyses were then used in conjunction with published information on erosional factors to evaluate the relative importance of erosive agents.

Literature Review of Coastal Erosion

Early theories of coastal erosion dealt mainly with physical or chemical potential for degradation of coastal rocks. Physical agents were at first considered by many workers to be singularly important in the erosional process. Ramsay (1846) established a mechanical theory of marine erosion of rocky coasts in which wave energy coupled with the abrasive properties of suspended sediment causes a planation of coastal rocks. The term "abrasion" was proposed for this mechanical process by Richthofen (1886, in Fairbridge, 1952). Lyell (1865) argued that the slow but extensive actions of waves upon the land was the only conceivable cause for coastal planation. The overriding belief of these researchers and others of this mechanical school (Johnson, 1938) was that the vertical limit of marine erosion must be considered as a depth below which no wave action is present.

In contrast to the theories of the mechanical school, workers such as Whitaker (1867), Reade (1877), Green (1882) and Geikie (1903) argued that the actual agent of erosion was subaerial chemical weathering of the inter- and supratidal rocks and that wave action only served to remove the already broken-down materials.

These early theories placed little emphasis on the role of organisms in modifying the substrate, although a number of workers pointed out the erosive capabilities of organisms inhabiting the coastal zone. Borley (1907) compiled a list of British marine boring organisms and described the hatitats and probable method of boring. Agassiz (1895) and Verrill (1907) both commented on the presence of boring fauna in the intertidal to subtidal zones of tropical limestone coastlines. Duerden's (1902) classic work pointed out the potential role of marine algae as erosional agents.

Later studies of coastal limestone erosion describe a complex situation in which all three major erosional agents--physical, chemical, biological--may be active. Sediments, often reef-derived, may act as an abrasive in physico-mechanical erosion of the coastal rocks. Complex physico-chemical and/or biochemical situations arise to cause dissolution of the substrate. Finally, a large and varied biotic community may be active in the modification of the substrate. These processes may act singly or in conjunction with each other to sculpt the coastal rocks.

A number of studies have examined the parameters which modify the shore profile of limestone coasts (MacFayden, 1930; Fairbridge, 1948, 1952; Hills, 1949; Edwards, 1951; Newell, 1960; Jennings, 1962; King, 1963; Russell, 1963; Wellman and Wilson, 1965; Abbott and Pottratz, 1969). These studies have pointed out that the earlier abrasional theories of limestone erosion attached far too much importance to the erosional ability of waves and sediment. While abrasional scour may occur along limestone coasts, erosion is generally brought about by chemical and biological factors. One exception to this rule would appear to be the localized phenomenon of pothole formation (Abbott and Pottratz, 1969). Physico-chemical salt weathering has also been considered (Wellman and Wilson, 1965; Brückner, 1966; Coleman, Gagliano and Smith, 1966; Beaumont, 1968) as a potentially important erosional agent in the salt-spray zones of limestone coasts.

The chemical forces involved in limestone erosion have been investigated by MacFayden (1930); Kuenen (1933); Wentworth (1938); Emery (1946); Revelle and Emery (1957); Kaye (1959); Hodgkin (1964); Coleman, Gagliano and Smith (1966). Kuenen (1933) commented that the solvent action of sea-water was limited to the tidal range. In his review of marine erosion, Fairbridge (1952, p. 8) stated that "chemical erosion of limestone is accomplished by physico-chemical and/or biochemical processes of sea-water in its surface few inches near the shore." Revelle and Emery (1957) discussed the importance of diurnal fluctuations of alkalinity and chlorinity on the solubility of limestone in isolated intertidal pools. Changes in alkalinity were linked to changes in the CO_2 concentration due to organism respiration and photosynthesis. In a paper on rates of intertidal erosion, Hodgkin (1964) briefly described similar corrosional effects on the shores of Norfolk Island and Point Peron, Australia, as did Coleman, Gagliano and Smith (1966) for high tidal flats of Northern Queensland. MacFayden (1930, p. 31) did not specify the term "biochemical" with reference to the mode of boring, but observed that there were "algae, molluscs, sea urchins, barnacles and particularly polychaete worms and small sponges" found as "boring organisms" on the shoreline.

Detailed work emphasizing the importance of biological erosion was carried out by Ginsburg (1953) on the Flordia Keys. His work suggested that physico-chemical solution of limestone was of minimal importance in intertidal erosion and that the activities of boring and grazing organisms were by far the most important factors in intertidal erosion of the Florida Keys. North (1954) described intertidal bioerosive activities and drew conclusions as to the rates at which intertidal gastropods were capable of eroding floors and walls of intertidal pools. Yonge (1955) and Hodgkin (1962) both discussed the role of the pholad <u>Lithophaga</u> in limestone boring. The indirect role of the organism on solution of limestone of Bikini Atoll in the Marshall Islands was discussed by Revelle and Emery (1957). They suggested that changes in pH and corresponding changes in CO_2 of the sea-water in intertidal pools were at least partially due to the respiratory and photosynthetic functions of organisms inhabiting them. Purdy and Kornicker (1958) investigated algal disintegration of Bahamian limestone coasts. In his work on shoreline features of Puerto Rico, Kaye (1959) described the echinoid, Echinometra lucunter (Linné), as an important boring organism and also mentioned the ability of chitons to form shallow pits in the rock. Goreau and Hartman (1963) described the erosive capabilities of boring sponges of the genus Cliona in producing very fine-grained calcareous detritus from their boring activities on Jamaican reefs. McLean (1964), studying physical and biological erosion of beachrock in Barbados, calculated erosion rates for a number of intertidal species. The boring sponge, Cliona lampa, was determined by Neumann (1966) to be of major importance in the undercutting of limestone cliffs in Bermuda. In this same paper, Neumann was the first to propose the term "bioerosion" defined as the "destruction and removal of consolidated mineral or lithic substrate by the direct action of organisms" (p. 92). Healy (1968) emphasized the importance of bioerosion as a process active in shore platform development and established a classification of bioerosive organisms based on their mechanism of erosion. Hodgkin (1970) concluded that boring organisms were mainly responsible for erosion of the limestone coasts of Malaysia.

In a number of studies, including several of the above, quantitative aspects of the problem of limestone erosion have been considered, i.e., how much rock can be destroyed by the erosional agents and how fast does the destruction occur. Numerous methods have been used to obtain the answers to these questions. Evans (1970) reviewed the various methods that have been used to obtain erosion data. These methods have included measurement of rock surface differences as measured in photographs (Verrill, 1907), wear of inscription carved in intertidal rock (Emery, 1941), erosion of blocks placed in the intertidal zone at a known date (Kaye, 1959), lowering of heights of steps cut in limestone cliffs at a known date (Hodgkin, 1964), and depths of notches cut in boulders thrown into the intertidal at the date of the Krakatoa eruption (Russell, 1963). In addition to direct measurement of the rock surfaces, a number of studies have employed survey-engineering techniques in analysis of coastal erosion. Hodgkin (1964) placed stainless steel reference rods in the rock surface and made plaster casts of the surface with the rods as references. Patrikeyev and Aybulatov (1965) drilled holes in the rock and probed for changing depth of the holes to determine erosion rates. Hanna (1966) and High and Hanna (1969) designed an apparatus based on "principles of kinematic motion" for measuring microerosion in cave passages and on limestone surfaces. Evans (1970) designed a drawing board which was bolted to a surface in order to trace yearly rock profiles on acetate film. Trudgill (1972) designed a "microerosion meter" to study localized (0.5 to 1.0 $mm.^2$ area) erosion of intertidal, subaerial, and subsoil environments.

Biological investigations of intertidal organisms have also contributed to knowledge of erosion (Evans, 1967, 1968a, 1968b, 1968c, 1968d, 1968e, 1970; Emery, 1946; North, 1954; McLean, 1964; Neumann, 1966). These studies have been based on either direct measurement of burrow and/or boring dimensions or on rapidity of gut content renewal, hence, rock processing, by selected individuals of the intertidal organisms.

While the studies cited above have all contributed valuable information in the study of coastal erosion, several questions remain unresolved. The most important of these are:

1. How much variation in erosion rate can one expect to obtain at the same locality, that is, is it possible to characterize a particular location/substrate/zone as having a specific erosion rate?
2. If precise erosion values can be obtained, can variations be attributed to specific characteristics of the immediate environment, such as substrate type, biotic assemblages or physical or chemical environmental conditions?

Resolution of these questions and their ramifications will require more precise and detailed analysis of coastal rock environments than has been carried out hitherto.

Purpose of the Present Study

The present study employs photogrammetric techniques to obtain erosion and accretion values at a number of limestone localities along the coast of Barbados. An advantage in the use of stereophotogrammetry is that a permanent, three-dimensional record of the surface conditions and configurations is available for later consideration. Standard biologic and geologic procedures have been used to analyse the respective biota and substrates which include both Pleistocene calcarenites and recent intertidal beachrocks. In addition to determining overall locality erosion values, an attempt has been made to analyse intra- and interlocality variance in zonal erosion values. These are considered in terms of the erosional parameters such as substrate, biota, and chemical and physical factors acting in the particular zone. The techniques used in this study allow a three-dimensional representation of the limestone surface, which is requisite before a complete understanding of coastal limestone erosion is possible.

General Setting of Study

The island of Barbados is located at 18°10' N by 59°30' W and is ninety miles east of the Lesser Antilles chain of the West Indies (Figure 1). The island is roughly triangular with dimensions of approximately 21 miles north to south and 14 miles east to west at its widest extent. It covers approximately 167 square miles. Barbados exhibits a

Figure 1. Barbados and its location in the Lesser Antilles. Arrow (in inset) indicates position of Barbados in the Lesser Antilles chain. Scotland District represents the only non-carbonate terrain on the island. The Scotland District rocks are folded and faulted Eocene to Miocene sediments. Surrounding this early Tertiary core are Pleistocene reef terraces. Spot heights (in meters) are also shown on this map.

LESSER ANTILLES
SOUTH AMERICA
Coral cap
Scotland Fm.
SPEIGHTSTOWN
SCOTLAND
DISTRICT
340
338
44
64
HOLETOWN
BRIDGETOWN
121
97
0
6
KM
0
4
MI
59°35′W
59°30′W

tropical maritime climate. Rainfall averages approximately 152 cm. per year, three-quarters of which falls in the period from June to December. According to Rouse (unpublished M.Sc. thesis, 1962), rainfall is relatively uniform over the island. The annual average shade temperature in the lowland/coastal area is 26°C, while the interior areas average approximately 5°C cooler (Rouse, 1962; Barbados Tourist Board, personal communication). The island is situated in the path of the northeast trade winds causing the east coast to experience higher wave energy conditions than the leeward west coast and also causing a higher salt content in the air of the east coast due to spray evaporation.

Geological Background

Barbados is of non-volcanic origin, the emergent portion of a submarine ridge, the Barbados ridge, consisting of contorted flysch-like sediments as well as deep sea oozes and marls (Ewing et al., 1957). About 85 per cent of the island's surface is covered by carbonate rock of coral and associated sedimentary origin. The oldest rocks, those of the Scotland Formation, are found in the east-central part of the island (Figure 1) where they form a resistant core of rugged highland relief (hence the Scotland District). These rocks are thickly-bedded, Tertiary (Eocene to Oligocene), geosynclinal sediments which were highly deformed in the late Tertiary.

Overlying the Scotland formation is a series of Miocene to Pleistocene rocks, the upper part forming a "coral cap" (Matthews, 1967, page 1147) of Pleistocene reef terraces. Beneath this cap are Pliocene Globigerinal marls which are in turn underlain by Miocene deep water radiolarian earth, grey felspathic and pumiceous sands and dusts as well as deep water calcareous oozes. Poor exposure of these Miocene and Pliocene rocks is thought to be due to subaerial erosion prior to formation of the Pleistocene reef terraces.

The youngest rocks are the recently-formed/presently-forming beachrocks which are found discontinuously around the beaches of the island, between high subtidal and low supratidal zones. The present study deals with both these present beachrocks and the Pleistocene rocks of the Coral Rock Formation exposed along the Barbadian coast.

CHAPTER II

METHODS AND PROCEDURES

Thirteen sections were initially established at six localities along the Barbados coast (Table 1). They were chosen in an attempt to represent both exposed and protected coastal rock environments as well as to be representative of varying biota, lithology, and microtopography in the intertidal/supratidal coastal zone. Sections were established from low intertidal to high intertidal and supratidal zones. Decreasing duration of subaerial exposure of low intertidal rock surfaces imposed a practical limit upon study of these areas. As it was not found possible in the time available to analyse all thirteen sections photogrammetrically, six sections displaying the greatest diversity in surface characteristics were chosen for detailed analysis (Figure 2).

A close-range photogrammetric system was employed in order to permanently record changes in microtopography of the coastal rock surfaces. Photogrammetric data obtained was used in conjunction with standard geologic and biologic procedures to evaluate erosional dynamics.

TABLE 1

TABULATION OF DATA ON COASTAL SECTIONS STUDIED

Section	Location	Locality	Photogrammetric Analysis Yes/No	Rock Type*	Age and References**
4	NE coast	Wait's Bay	Yes	BR	[2]82,000 BP
6	NE coast	Wait's Bay	Yes	BR	[2]82,000 BP
18	W coast	Heywood's Beach	Yes	BR	[1]< 4000 BP
20	W coast	Heywood's Beach	No	BR	[1]< 4000 BP
22	W coast	Heywood's Beach	No	BR	[1]< 4000 BP
30	SE coast	Long Bay	Yes	BR	N.D.
33	W coast	Six Men's Bay	No	BR	[1]< 4000 BP
43	W coast	Six Men's Bay	No	BR	[1]< 4000 BP
44	W coast	Six Men's Bay	No	BR	[1]< 4000 BP
45	W coast	Six Men's Bay	No	BR	[1]< 4000 BP
47	W coast	Six Men's Bay	Yes	BR	[1]< 4000 BP
48	N coast	Stroud's Bay	Yes	PC	[2]60,000 BP
49	NE coast	Little Bay	No	PC	[2]82,000 BP

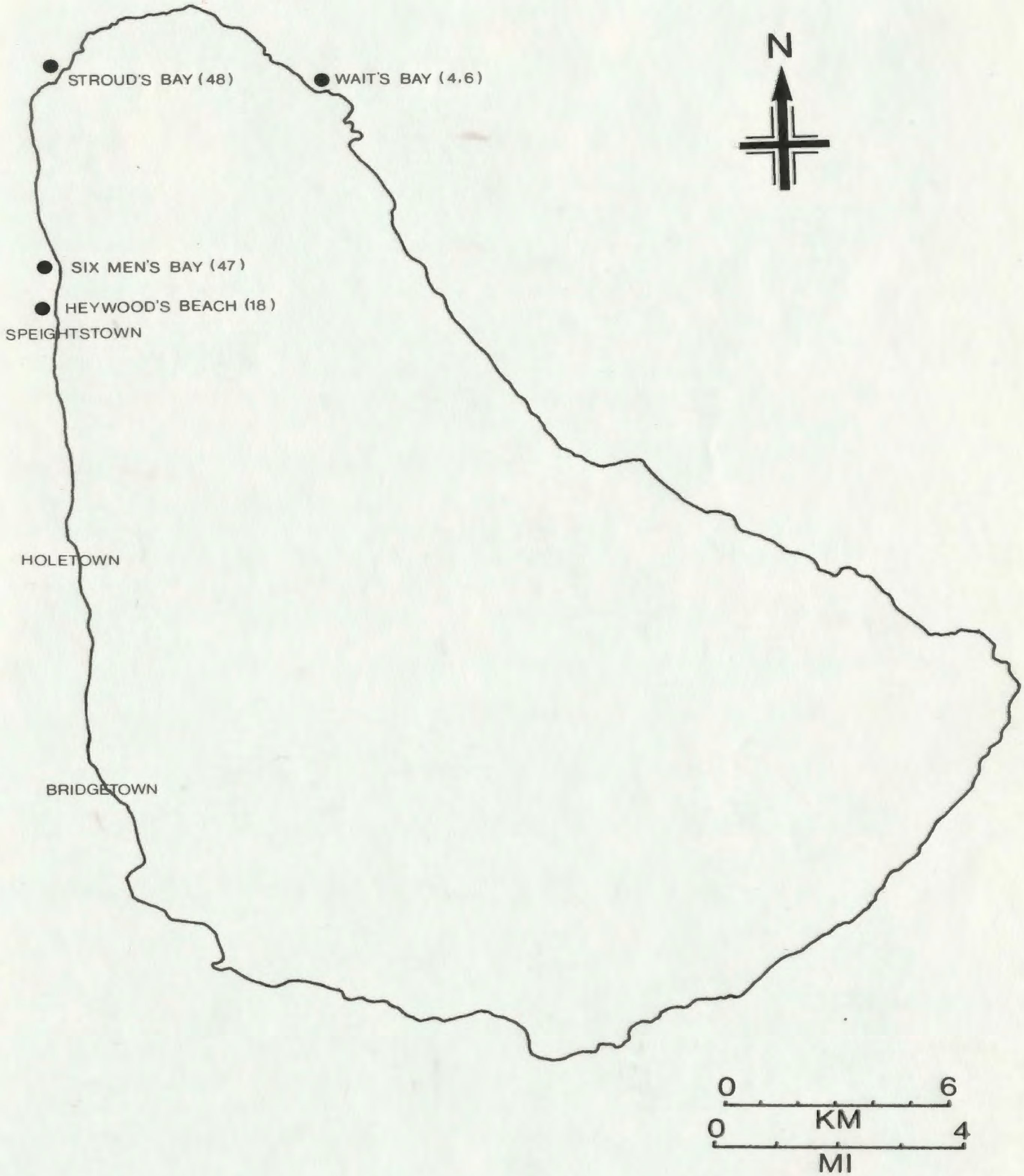
*BR = beachrock
PC = Pleistocene calcarenite
**N.D. = no date
1 = Matthews, R.K., personal communication
2 = James, N.P., 1972a

Photogrammetric Procedures

Photogrammetry has been defined as the science or art of interpreting photographs and obtaining reliable measurements from photographs (Manual of Photogrammetry, V. 1, p. 1). More specifically, stereophotogrammetry implies the use of paired photographs, which when viewed through a stereoscope, create the illusion of a three-dimensional model of the object or terrain photographed. With the appropriate controls, measurements can be carried out using stereoscopic parallax principles to establish heights, depths and distances on the model terrain. These characteristics of stereophotogrammetry, i.e., the fact that a permanent photographic record of a locality is obtained and that various measurements can be carried out on an accurate model of the terrain suggest that stereophotogrammetry would be an ideal tool for use in the close-range study of micro-ecologic or geomorphic processes which must be monitored for extended time periods.

In the past the use of photogrammetry has been restricted almost exclusively to military and government operations due to the expensive equipment and critical calibration requirements imposed on the equipment. More recently, however, close range stereometric systems have been used extensively in biomedical research where they serve as biostereometric instruments to measure, in a non-contact fashion, the form, shape, and geometry of components of the human body.

Figure 2. Study site locations. Section numbers are indicated in parentheses after locality name. Predominant wind and wave action are from the east.



N
STROUD'S BAY (48)
WAIT'S BAY (4.6)
SIX MEN'S BAY (47)
HEYWOOD'S BEACH (18)
SPEIGHTSTOWN
HOLETOWN
BRIDGETOWN
0
6
KM
0
4
MI

The principles of this biostereometric usage can be extended to the field of ecology and geomorphology where a short range (<2 meter) non-contact means of recording change is desired.

The camera system described in the following pages is a compromise system. Although by no means the best system in a technical sense, it is sufficiently accurate for medium to long-term close-range studies in biogeodynamics and has the advantage of being orders of magnitude less expensive than the camera systems available commercially.* The flexibility of the system and its applicability to almost any long-term ecological or geological monitoring problem will readily become apparent.

To establish permanent, three-dimensional records of a study area, techniques involving a short-range, non-convergent, stereophotogrammetric camera system were developed. The system itself is lightweight, portable and capable of producing precise, controlled stereopairs of the terrain under investigation. The camera, a modified (4" x 5" negative format) Graphlex with a highly corrected Zeiss Voightlaender Apo-Skopar 160 mm. lens, is bolted onto a

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*Commercial stereometric, high-precision cameras available for close-range work include the Zeiss SMK-40, the Zeiss/Jena SMK 5.5/0808, the Wild C-40, and the Galileo-Santoni Stereometric camera. All are extremely expensive. This, and the fact that they would all require considerable modification, eliminated them from consideration for the purposes of this study.

horizontal bar which is approximately 1½ m. from zero datum. This allows a coverage of roughly 100 cm. by 125 cm. on the ground. Photographs are taken from three positions on this bar with a base distance between the three camera positions of 48 cm. This results in an overlap of approximately 60 per cent for each stereopair (see Figures 3A and 3B). A reference cross capable of being replaced in precisely the same position each year is an integral part of the mounting system and appears in all photographs. Five bezels on this cross are finely levelled with reference to each other to define a zero datum plane. A minimum of six ground reference points are permanently fixed in the rock (see Appendix I). These provide a method of levelling in later photogrammetric analysis as well as providing a corroborative check on yearly positioning.

Field Assembly of System

Plates 1 to 12 graphically explain the components and procedures involved in preparing the apparatus for stereophotography in the field. An end bolt of known length is firmly secured into a benchmark which has been drilled and countersunk in such a manner as to become a permanent fixture in the rock (Plate 1). The length of the end bolt is chosen so as to place the reference cross (hence the zero datum plane) as close to the rock surface as possible. The right-hand (fixed) socket of the reference cross is slipped

Figure 3. A. Schematic representation of photographic system employed in this study. Numbers refer to the three camera positions used to obtain a 60 per cent overlap necessary for stereographic imagery. (fp = film plane, pc = perspective centre of lens system, g = ground/zero datum plane, 0 = overlap area produced by camera positions 1 and 2, 0' = overlap area produced by camera positions 2 and 3).

B. Schematic representation of ground surface viewed from camera positions. Cross represents the reference bar with zero datum reference bezels (open circles). Idealized ground control point array is represented by closed circles. Due to ground irregularities, ground controls are seldom distributed in this manner.

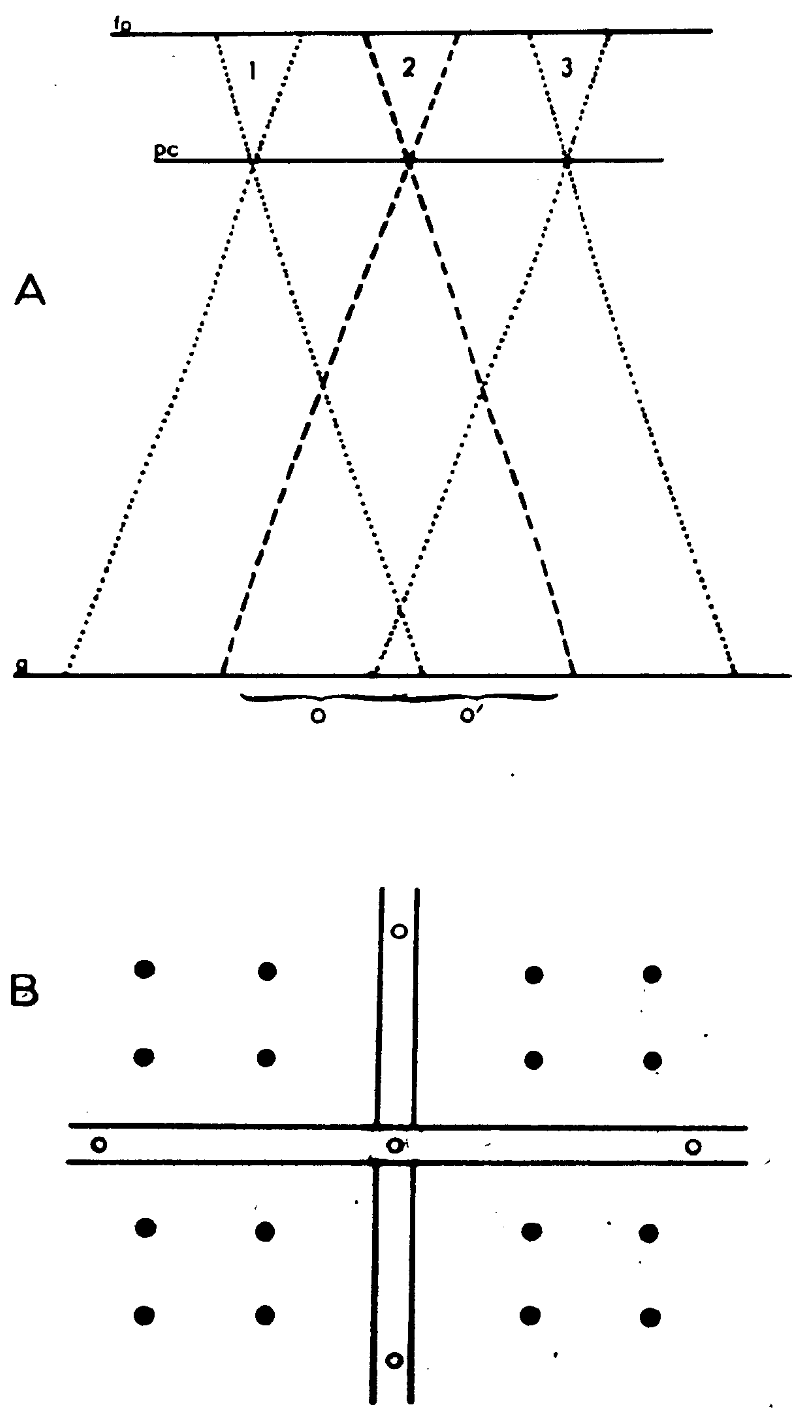

fo
1
2
3
pc
A
a
o
o′
B

Plate 1. Fixed endbolt (a) of known length is secured to the rock surface by tightening into bench-mark (b) which has been permanently embedded into the rock.

Plate 2. Fixed socket (a) on right of reference bar is fitted over the fixed endbolt. Adjustable sliding collar (b) will be placed over the endbolt (c) and locked into position when the long axis of the bar is level.


a
b

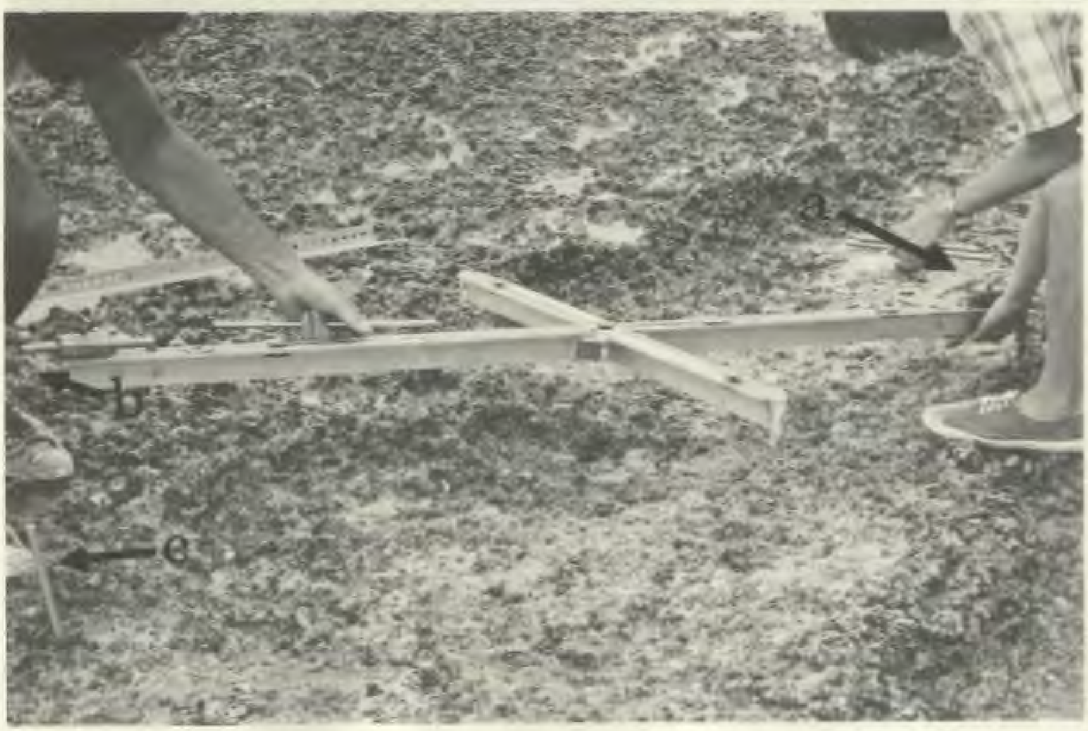

a
b
e

Plate 3. Rough levelling of the short axis of the bar is accomplished by locking the bar in position on the support pins (a) which slide into locking collars on the end of each short bar axis.

Plate 4. Larger pins (arrow) are placed in collars at either end of the long cross bar axis. These serve as attachment columns upon which the vertical uprights are placed (see next plate).

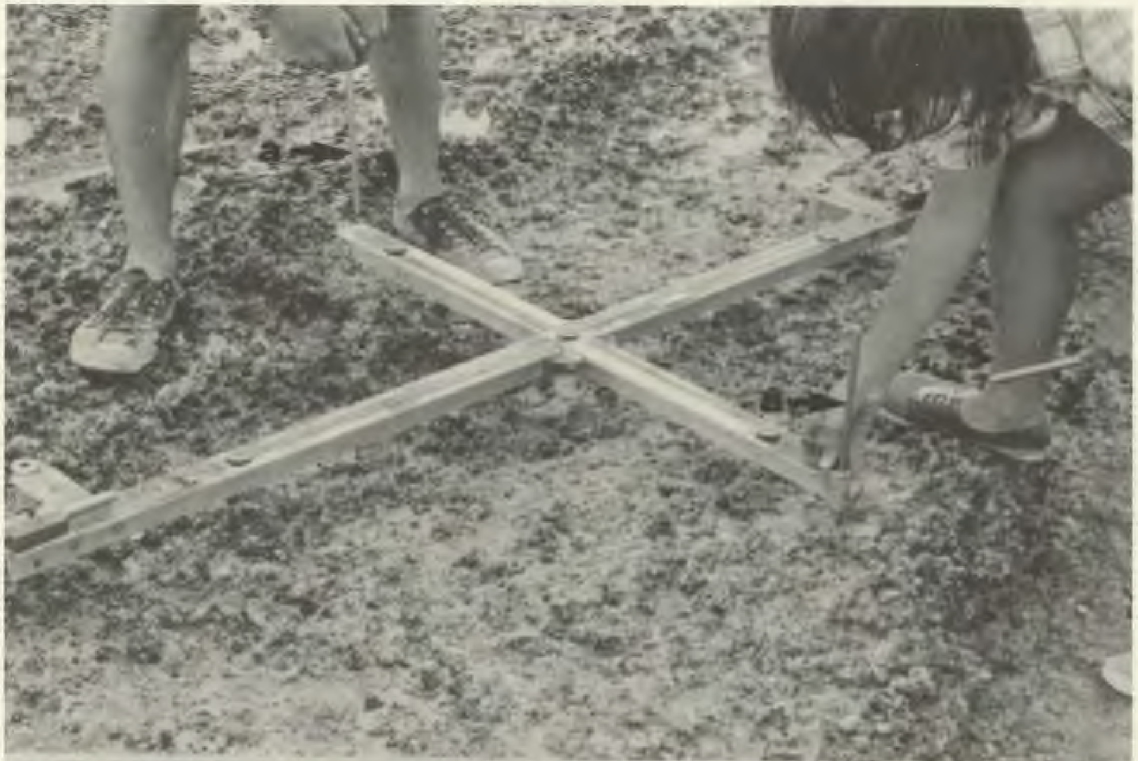



Plate 5. Upright dexion bars (a) are placed over the large pins and angle braces (b) are attached.

Plate 6. Angle braces are used in conjunction with the machinist spirit level (arrow) to insure that the uprights are vertical.


a
b

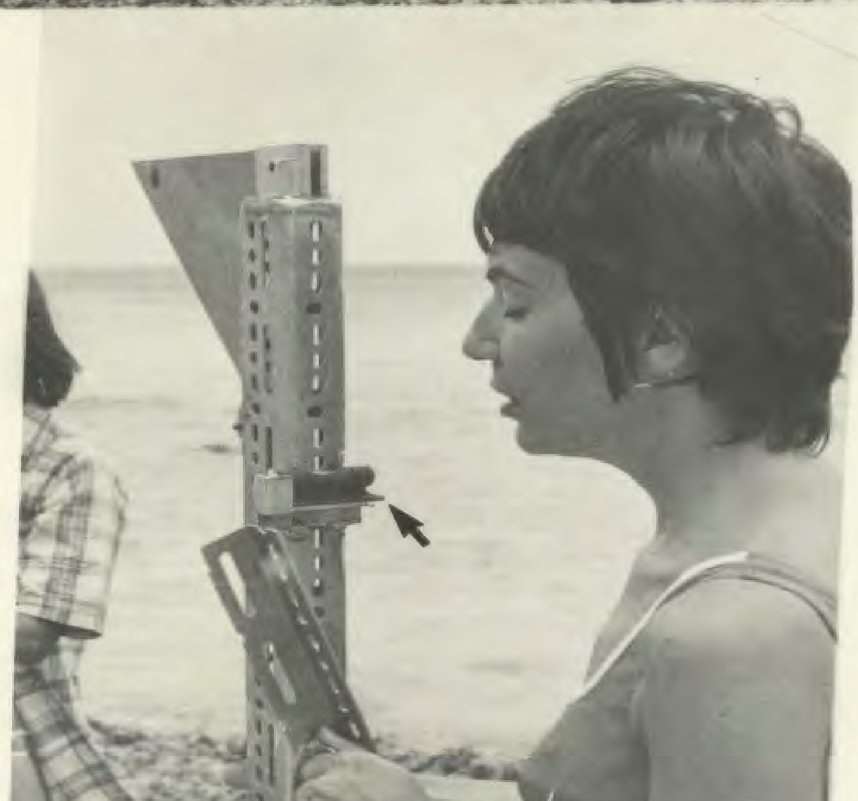
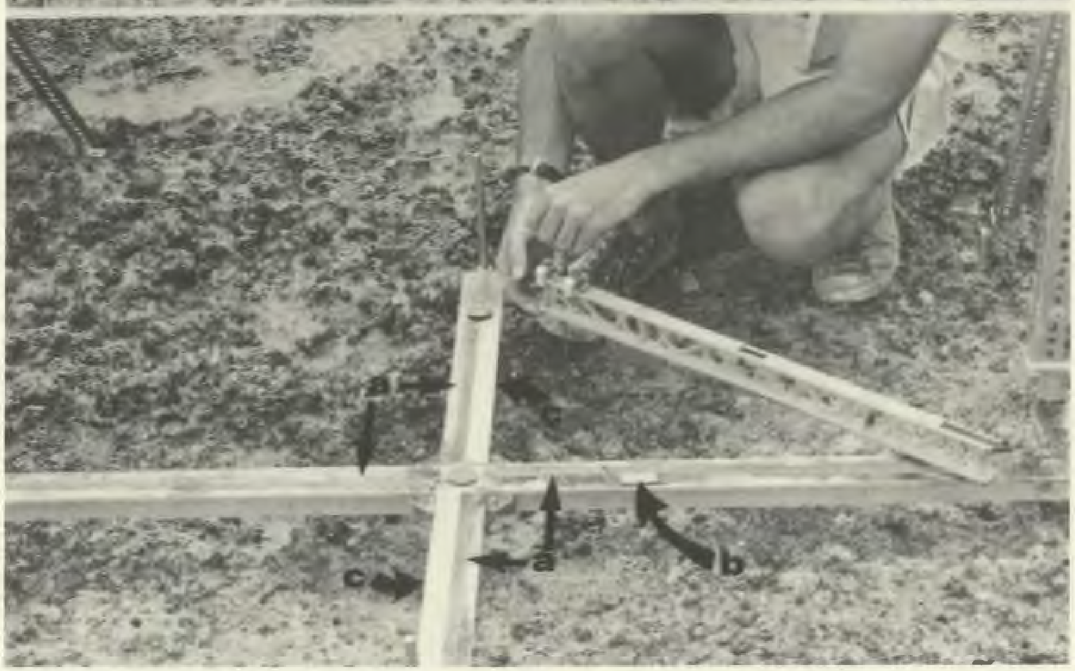


Plate 7. The horizontal camera bar is mounted on the uprights and bolted to the aluminum fins at the top of the uprights.

Plate 8. Camera and strobe light are mounted on the bar. The power source (arrow) for the strobe light serves as a counterweight for the camera.

Plate 9. Five brass bezels (arrows) serve to define the zero datum reference plane from which all ground surface values are measured. These are precisely levelled with respect to one another using a machinist's level.

Plate 10. From the zero datum plane, defined by the bar bezels, readings are taken with a micrometer depth gauge and machinist's level to establish values for each ground control point (described in text and illustrated in next plate). In addition to zero datum bezels, the reference bar carries metric scales (a), resolution target (b) and white plexiglass strips (c) for recording locality information, date, section number and film/exposure information.



a
c
a
c
b

Plate 11. Ground control point (arrow) is used in field levelling and in later photogrammetric procedures. Monel bolts cemented into the rock surface with underwater setting epoxy serve as ground control points.

Plate 12. The apparatus in use. The strobe is held in position to offset deep sun shadows. Exposures, film types, frame numbers and ancillary information are logged in the field notebook.

over the end bolt until it bottoms at the top of the bolt. The left end of the reference cross consists of a sleeve which fits over a long end bolt (fixed into the rock in the same manner as the previous bolt) and is locked into place when the long axis is roughly level (Plate 2). The short axis is then roughly levelled by adjusting two pins which slide in sleeves at the ends of the short arms of the cross (Plate 3). Larger pins, 5/8 inch in diameter, are then placed in sleeves at the ends of the long axis of the reference bar (Plate 4). The lower ends of these pins rest on the rock surface. Uprights used to support the horizontal camera bar, slip over these pins. These uprights are braced by two aluminum angle braces which are anchored to bench marks as before (Plate 5). Spirit levels are used to ensure that they are precisely vertical (Plate 6). The horizontal camera bar is then placed on top of the uprights and the camera is bolted into position (Plates 7 and 8).

Final critical levelling of the zero datum points is accomplished with the aid of a precision machinist's bench level used on the reference bezels (Plate 9). These bezels are broad-headed, brass bolts tapped into the reference cross. The bezel on the right side of the reference cross serves as a control/reference bezel, fixed immovably to the bar. There are two more bezels located to the left of the control bezel, spaced 50 cm. apart, and two more above and below the centre bezel, at a distance of 35 cm.

All but the control bezel are capable of being raised or lowered (approximately 2.5 mm.) and locked into position when they have been precisely levelled with reference to the control bezel. These five bezels then define the zero datum plane from which depth readings on ground control points are measured (Plates 10 and 11). Metal rules indicating distance from the centre bezel, a resolution target, and space for logging station data are also provided on the reference cross.

Photography

Following completion of the assembly procedures, the rock surfaces are photographed (Plate 12). Experimentation showed that the black and white emulsion which offered optimum results (with reference to availability, resolution, development characteristics, etc.) was Kodak Plus-X, while optimum results for colour were achieved using Kodak High-Speed Ektachrome Daylight, 1115 emulsion. Kodak High-Speed Infrared emulsion was tested in 1970 and 1971, but it was decided that the minimal advantages it offered with reference to interpretation were outweighed by the disadvantages. Development of the Plus-X was done at the Bellairs Lab, while processing of the colour film was done commercially by Winnipeg Photo Ltd., Winnipeg, Manitoba.

Stereocompilation

In order to obtain data contained on the stereopairs of photographs, several stereocompilation techniques were attempted. It was found that in order to obtain reliable data from the photographs, an accurate stereoplotting machine was necessary. In its simplest form, a stereoplotter measures parallax on the stereopairs. This parallax difference can then be converted to height or depth measurements.

Prior to analysis of the photographs, it was necessary to determine the exact focal length of the camera system (N.B. --the rated focal length of a lens system is only valid if the lens is focused at ∞). Using an iterative procedure in a space resection programme on an analytical stereoplotter AP-2C, combined with an OMI Bendix computer (courtesy of Dr. S.E. Masry, Survey Engineering, University of New Brunswick), it was possible to establish the working focal distance as 171.5 mm.

Once principal distance information was obtained, the stereopairs were introduced into a Wild A-10 Stereoplotter (Aero Technical Service, St. John's, Newfoundland) for analysis. Spot depth values were read at 2 cm. intervals for each position on a grid over selected portions of each study area. Time and operational cost of the A-10 limited coverage. The grid system method proved feasible for all sections with the exception of Section 47, an area of extreme relief. Section 47 was randomly spot-heighted, since grid contouring on this surface would have been meaningless. Between 200 and 400 readings per study area were collected for each set of annual photos.

Computer Techniques

Upon completion of photogrammetric work, the surface depth data were computer processed by running them against the programme SYMAP (Dudnik, 1971). This programme produces maps, histograms, and frequency distribution information when supplied with spot depth data as input. The data from each section for each of three years, i.e., 1971, 1972, 1973, were run separately against SYMAP to produce sixty-seven sets of information (maps and frequency distribution histograms). The maps generated took the form of contour maps, residual contour maps and residual printout maps. Contour maps were produced from spot depth control readings on the 2 cm. interval grid described above. Five contour levels were used, whose interval size was based upon the minimum and maximum depth values found in the section under study. Residual contour maps were generated from data which were obtained by subtracting one year's depth values from another year's values at corresponding points, thus obtaining yearly (1973-72, 1972-71) or bi-yearly (1973-71) erosion values for each point. These data were then run against SYMAP and residual contour maps were produced. Five residual contour levels were established for these maps: -5.00 mm. to

-3.00 mm.; -3.00 mm. to -1.00 mm.; -1.00 mm. to +1.00 mm.; +1.00 mm. to +3.00 mm.; +3.00 mm. to +5.00 mm. (+ = erosion; - = accretion). Any absolute residual values greater than 5.00 mm. were considered invalid for computer mapping. This was necessary to avoid spurious results. All such invalidated points were, however, investigated in order to determine the reason for such a reading. The points were investigated using residual printout maps, again generated from the residual values. These maps were designed to numerically display on the printout sheets the actual residual value at its appropriate grid position. The coordinates of any unusual depth residual value could then be investigated on the photopairs.

In addition to computer mappings, SYMAP produced histograms which graphically showed the frequency distribution of data point values in each level. These were useful in determining changes in depth value classes and in residual value classes for each locality for each year.

Analysis of Error

In the development and use of the present system, a number of error sources were considered. These fell into two categories--accidental (random) and systematic.

Accidental errors, that is, errors on the part of the investigator or observer were characterized by disorder in incidence and variability in magnitude with both positive and negative values occurring in repeated measurements and in no ascertainable sequence. The type of error included: (1) errors caused by inaccuracies in field set-up procedures; (2) errors in reading machinist's levels and micrometer gauge in field; (3) errors in recording ground control point values; (4) errors due to non-standardized film storage and development procedures; (5) errors imposed by observer during photogrammetric processing on the restitution instrument. (These latter errors included improper positioning of negatives on carriers, failure or inability of observer to completely eliminate parallax from the model, inaccurate readings of ground height by the observer, improper interpretation of terrain (misidentification of organisms, confusion of encrusting organism with rock surface)).

Systematic errors, resulting from lack of precision or uniformity in the system, included: (1) errors imposed on the field apparatus by environmental conditions, that is, slight expansion and/or warpage of the aluminum frame due to fluctuating temperature; (2) errors imposed by the measuring devices, such as machinist's levels and micrometer gauges; (3) errors inherent in the camera system, which included such factors as imprecision in principal distance determination and imprecise location of fiducial marks; (4) errors inherent in the photogrammetric restitution instrument; and (5) errors in computer analysis.

Treatment of Error

Personal errors of observation occurred during measuring precedures and could be detected and eliminated using repetitive methods. These included field errors arising from incorrect reading of the control point values on the micrometer depth gauge, as well as later laboratory errors arising from incorrect reading of spot depths in the restitution instrument. Random error in control readings could be detected by comparison with previous year's values or by non-uniformity with other control point values. Errors in restitution instrument reading were minimized by taking repetitive readings on all points. This detected gross errors in human readings as well as human bias and provided a basis for evaluation of precision in readings.

The source of systematic error was in some cases difficult to locate and evaluate. For example, it was not possible to evaluate or eliminate environmental influences from the field system. The result of this source of error would be a rotation of the camera proper about any or all of its three rotational axes, κ, ϕ, and/or ω. Errors in the camera system were for the most part due to the indeterminate nature of the principal distance of the camera-lens system. It was ultimately necessary to have this determined by iterative procedures. Several pairs of stereophotographs were measured on an analytical stereoplotter linked to a computer (OMI-Bendix AP-2C analytical stereoplotter, courtesy of Dr. S.E. Masry, University of New Brunswick, Survey Engineering Department). Through computer comparison of the known coordinates in the photographs, it was possible to reconstruct the lens system theoretically, especially the principal distance datum, through a space resectioning programme (Resection, University of New Brunswick Survey Engineering Department, Computer Programme, courtesy Dr. S.E. Masry). Following this procedure, it was found that there was still error in readings using this principal distance due to affine deformation.* It was found empirically that this error could be removed by carrying out a regression analysis on the ground control point values and bar bezel values and correcting all other values accordingly.

Following determination of the working principal distance, it was possible to evaluate other camera system errors, such as film flatness, film distortion characteristics and fiducial placement. These were examined and found to give isolated non-resolvable parallax at several points that could not be eliminated. However, the parallax was readily apparent to the restitution instrument operator and could be eliminated from the readings.

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*In this particular context, affine deformation leads to a linear scale deformation of the photo model along the Z-direction of the analysing instrument. This may be caused by indeterminate principal distance or tilting of one or both of the negatives during photography.

Another source of error was encountered in the restitution instrument. The instrument chosen for analysis was the Wild A-10 Autograph stereoplotting instrument (Aero Technical Services Ltd., St. John's, Newfoundland). This instrument had an accuracy of 0.07 per cent of Z in height (in a stereo grid test), thus making the expected maximum error in the present case approximately ∓ 0.1 mm.

Theoretically, no errors should be expected during computer analysis, since only simple mathematical manipulations were carried out with the data (that is, regression correction for affine deformation).

Table 2 presents the mean error values ($\bar{X}$) in the repetitive readings for each section and year analysed. (N.B. Section 47 does not appear due to the fact that the values were not based on a grid system and were more difficult to reposition for subsequent readings). As can be seen, mean error for the section varies from -0.3 mm. to +0.3 mm. with a maximum variance of 0.16. The fact that the average or mean error is not zero in all cases (which would be expected with a normal unbiased distribution of error for repetitive readings) reflects a personal reading bias on the part of the machine operators, i.e., repetitive sets of readings were taken by different operators. Hence, personal bias is to be expected and explains the shift in the mean error away from the theoretical value (zero). In the present analysis, this is of little consequence in Sections 4, 6, 18,

TABLE 2

MEAN ERROR IN PHOTOGRAMMETRIC READINGS

Section /Year	$\bar{X}$ (mm)	S (mm)	S^2	n
4/1971	+0.1	±0.4	0.16	325
4/1972	-0.3	±0.3	0.09	314
4/1973	+0.1	±0.3	0.09	324
6/1971	0.0	±0.3	0.09	315
6/1972	+0.1	±0.3	0.09	309
6/1973	0.0	±0.2	0.04	318
18/1971	+0.2	±0.3	0.09	372
18/1972	+0.2	±0.3	0.09	368
18/1973	+0.2	±0.3	0.09	370
30/1971	+0.3	±0.4	0.16	338
30/1972	-0.2	±0.3	0.09	336
30/1973	-0.1	±0.4	0.16	337
48/1972	0.0	±0.3	0.09	340
48/1973	0.0	±0.3	0.09	339

This table tabulates the mean error ($\bar{X}$), the standard deviation of this error (S) and the variance (S^2) on the error for n, the total number of data points for each section/year.

and 48 since the bias is of the same sign and magnitude for both 1971 and 1973 (the years used to calculate erosion rates). Unfortunately, Section 30 is less reliable as the values of the mean error do not offset each other. The importance of this error must then be considered.

The above described errors affect residual value determinations in a manner shown in the following equation:

$$\text{r.v.} = \frac{X_2 - X_1}{A_2 - A_1} + \frac{e_2 - e_1}{A_2 - A_1}$$

where r.v. = mean residual value, X_2 = mean value of spot heights for a particular section and year, X_1 = mean value of preceding year's spot heights, e_2 = mean error for X_2 readings, e_1 = mean error for X_1 readings, A_2 = year for which X_2 values were obtained and A_1 = year for which X_1 values were obtained. From this equation, it can be seen that effect of the error on residual values varies inversely with the absolute difference in years, that is, the larger the number of years between readings, the smaller will be the relative importance of the error. The present study was limited to obtaining three consecutive annual sets of readings for each section which allowed an $A_2 - A_1$ difference of only 2 (that is 1973-1971). The exception to this was Section 48 for which only two consecutive year's readings were available.

In considering erosion values for the sections analysed, single values were avoided as a basis for interpretation. Instead, average values were used to characterize a section or part thereof, thus minimizing the possibility of working with values from extreme ends of the error curve. In addition, statistical analysis of each section was carried out using three t-tests:

a) to ensure that the mean annual erosion value was statistically significant, that is to determine whether the mean of the values for one year was significantly different from the mean of the values for another year;

b) to determine whether interlocality differences in mean erosion rate were statistically significant;

c) to determine whether particular subsamples of non-matched (independent) variables were from distinctly different populations.

These statistical steps are presented and summarized in the Appendix and are used as basis for later discussion.

Geologic Procedures

A sampling programme was carried out to obtain rock specimens representative of each study area. Samples approximately 10 cm. x 10 cm. x 10 cm. or larger were collected from each section under study. In addition to these hand samples, a 3½ hp. portable rock corer (courtesy of Dr. E.

Deutsch, Physics Department, Memorial University of Newfoundland) facilitated collection of rock cores (2.5 cm. diameter) up to 40 cm. in length from each area. Surveying techniques were used to obtain elevation data along a transect line perpendicular to the strike of the rock surface.

Hand samples were initially examined for surface texture while the cores were inspected for any variation in gross lithologic characteristics with depth. Thin sections were then ground, examined and photographed under bright field, crossed nicols and interference-contrast (Nomarski) light conditions using a Zeiss Standard Universal microscope. The thin sections were studied specifically to determine petrographic parameters such as grain-matrix-cement ratios, type and degree of cementation, percentage pore space, and grain size distribution. Also noted was any evidence of deterioration of the grains or cement and the presence and morphology of microborers.

Concurrent with the microscope study, staining procedures were carried out to determine the mineralogy of the components in the rock. The staining techniques were those suggested by Friedman (1959), using Feigl's Solution, Alizarin Red, and Alizarin Red/10% NaOH (boiling) to discriminate between aragonite and high- and low-magnesium calcite.

A Cambridge Stereoscan scanning electron microscope proved useful in investigating the habits of various cements. It also served admirably in demonstrating the ability of endolithic algae to penetrate the calcarenite grains.

Biologic Procedures

In the first year, representative collections of organisms were made on all study sites. Thereafter, annual surveys of species and numbers of organisms present on the surface under investigation were made. These surveys were accomplished by using a portable grid of known areal coverage (1 meter^2). Grid orientation was strictly controlled by reference points fixed permanently to the rock surface. An array of fixed reference points were positioned such that they defined a transect line roughly perpendicular to the shoreline. It was then possible to record organism abundance and diversity along an intertidal/supratidal study transect.

A photographic record was produced from which biologic/ecologic information was obtained.

Organisms collected in the field were identified. This work was facilitated by previous taxonomic and ecologic work on the areas under investigation (Lewis, 1960; McLean, 1964; Conde, 1966; Doran, 1968; Axelsen, 1968).

From grid transect data, abundance and diversity information was obtained for organisms at each locality.

Based on this and on the photographic information, fluctuation in organism abundance and diversity was investigated.

CHAPTER III

OBSERVATIONS

In the following pages, general lithology, micro-topography, biology and photogrammetric data are described. Following this, a section-by-section analysis is carried out in order to describe in detail the lithology, the micro-topography and the biology of each section and to correlate erosion values with these characteristics.

Lithology of Study Sites

Analysis of rock samples collected from the study sites indicated that a similar lithology existed in all sections even though the ages of the rocks differed (Table 3). (With the exception of Section 48 (Stroud's Bay), all sections are located on beachrock* surfaces). Petrographic analysis revealed that all rocks are reef derived biocal-carenites. The framework material consists of essentially pure, fairly well-sorted skeletal lime sands whose major components are coralline algal fragments, mollusc and coral fragments and foraminiferans. Grain sizes for these frame-work components varies from 0.4 mm. to 0.7 mm. (Table 3),

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*The term "beachrock" is here used in its geologic sense, meaning "sediments lithified in the intertidal plus sea spray zones, whether on high- or low-energy beaches or even on broad tidal flats and tidal channels" (Bricker, 1971, p. 1).

TABLE 3

GRAIN SIZE AND STANDARD DEVIATION, PER CENT COMPOSITION AND INSOLUBLE RESIDUE (WGT. %) OF ROCKS FROM STUDY SITES[1]

Section	Average Grain Size (mm)	Std. Dev. (mm)	Grain %	Matrix %	Cement %	Pore Space %	Insoluble Residue (Wgt. %)
4	0.65	0.23	65	1	9	25	6.3
6	0.68	0.26	61	4	6	28	4.5
18	0.38	0.12	71	0	4	25	3.3
30	0.58	0.27	76	1	7	16	1.0
47	0.43	0.24	71	5	12	12	0.2
48c*	0.63	0.32	50	22	3	25	0.2
48	0.63	0.32	62	3	12	22	0.2

*c indicates caliche horizon.

[1]These data reflect the characteristics of the rock from the surface to a depth of 1 to 2 cm. The condition of the rock at depth may vary from that at the surface. (See text).

indicating a medium to coarse sand. A very small percentage (<6%) of the sand is noncarbonate and appears in insoluble residue analysis as fine to medium-grained quartz sand.

This framework material is bound together by $CaCO_3$ cements (Table 4). All three of the common carbonate cements: Mg-calcite, calcite, and aragonite are represented in the samples analysed. In some cases, more than one cement type is observed at a single locality. Three common beachrock cement morphologies are encountered in this study: (1) an aragonitic or micritic Mg-calcite coating, on the grains, similar to that described by Bricker (1971, p. 1) as "consisting of crypto- to microcrystalline carbonate in the crystal size range of less than 1 to about 3 or 4μ, appearing as semi-opaque mud"; (2) fibrous or bladed crusts, composed of elongate crystals aligned perpendicular to the grain surface; (3) equant crusts of Mg-calcite. In considering point count estimates of relative percentages of grain, matrix, cement, and pore space, all rocks are similar with the exception of sample 48c which comes from a caliche horizon and hence displays an unusually high percentage of matrix material. The values in Table 3 are representative of lithology at each study site and do not reflect the dissolution effects that are noted at depth in some samples, notably those from Sections 4 and 6 (both Wait's Bay) and Section 48 (Stroud's Bay). The dissolution was reflected in the coring procedures by grossly differing degrees of

TABLE 4

CEMENTS: MINERALOGY* AND HABITS

Section	Sample or Core #	Depth in Core	Mineralogy	Habit
4	Core #4	Surface	Calcite	Blades (20μ long) (perpendicular to grain surface) forming halos
	Core #5	Surface	Calcite	Same as Core #4
6	Core #1	Surface	Calcite	Micrite "halos" (4-8μ)
	Core #1	7.25 cm.	Calcite-Aragonite	Micritic calcite overgrown by aragonite needles perpendicular to grain (~10μ long axis)
18	Core #2	Surface	Calcite	Thin (1-2μ) discontinuous halo around some grains
	Core #2	4.5 cm.	Calcite-Aragonite	Micritic infill
30	Core #3	Surface	Aragonite	Long, thin, aragonite needles (<20μ)
	Sample #9	Surface	Aragonite	Same as Core #3
47	Core #4	Surface	Calcite Mg-calcite	Dogtooth and blocky crystals up to 20-30μ
	Core #4	10.0 cm.	Calcite Mg-calcite	Same as Core #4 - surface
48	Core #3	Surface	Calcite	Caliche
	Core #3	1.75 cm.	Calcite Aragonite Mg-calcite	Blocky (10-20μ) calcite and infilling of aragonite-thin aragonite halos (5-10μ)

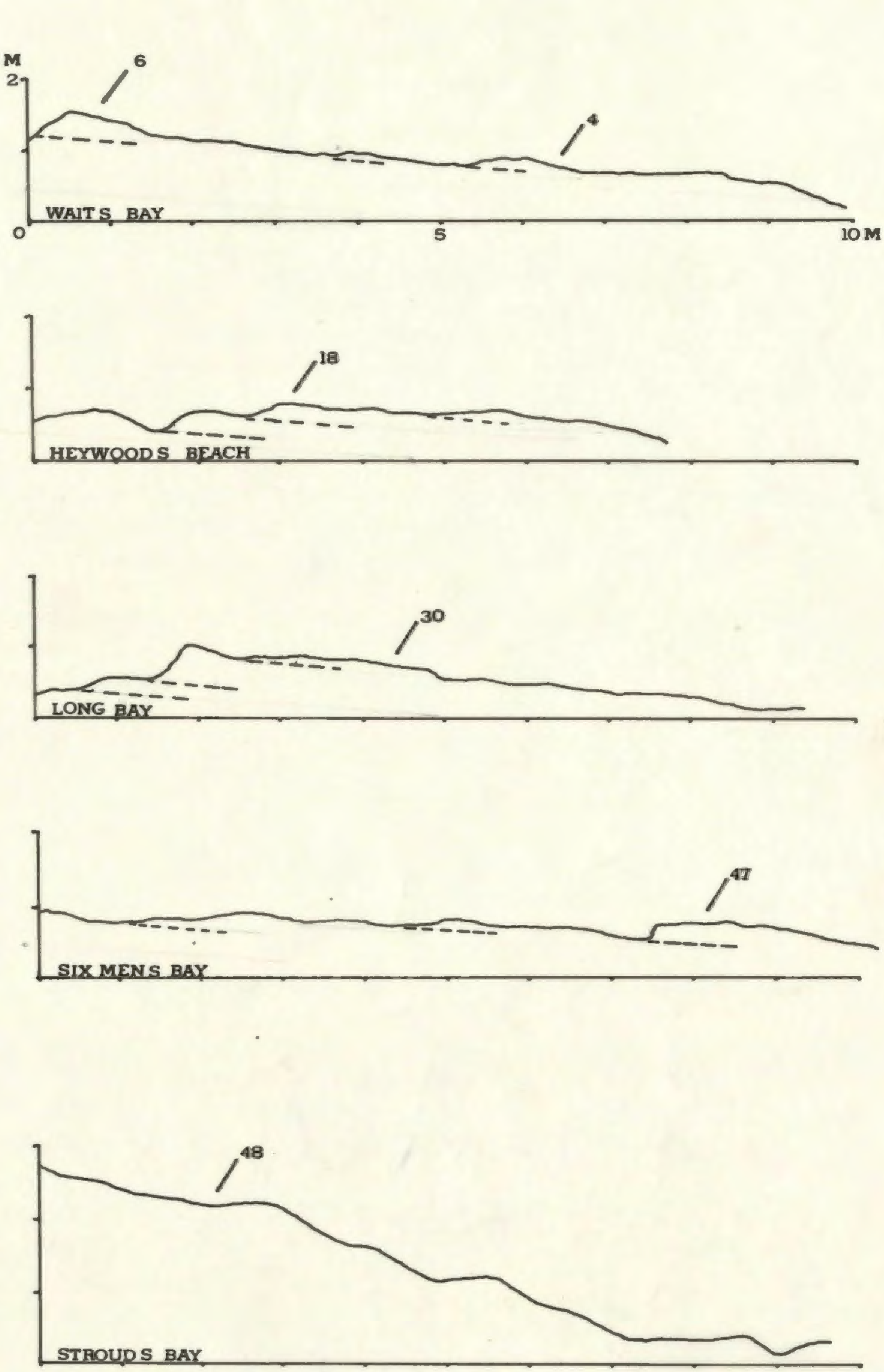
*Mineralogy was established by staining techniques (Friedman, 1959).

induration. This induration did not appear to be homogeneous with depth. Also, the presence of hard discontinuous crusts at Stroud's Bay, similar to the caliche crusts described by James (1972), suggests that rain water dissolution at depth in the rock may be followed by upward capillary migration and precipitation of $CaCO_3$ on or near the surface of the rock.

Geomorphology and Microtopography of Study Sites

All beachrock outcrops in the present study exhibit a characteristic shallow (3^{o} to 5^{o}), seaward dip in their stratification (Figure 4). The Stroud's Bay calcarenite exhibits no obvious stratification or dip, but instead displays a topography of sharp, jagged ridges surrounding deep, rounded depressions. This topography is also displayed, although to a less marked extent, at Section 6 (Wait's Bay). A probable remnant topography is suggested at Section 4 (Wait's Bay). Section 30 (Long Bay) displays a finely pitted microlapies surface. The remaining two sections give evidence of biologic control of topography. Section 18 (Heywood's Beach) appears as a rough, irregular surface when examined closely. This is due to the presence of encrusting barnacles which create a peak and depression terrain. Finally, Section 47 (Six Men's Bay) consists of a rock surface dissected by sinuous channels that are separated from one another by rounded ridges. The channels are attributed to the boring

Figure 4. Cross-sectional profiles of rock surfaces at each study locality. Relative position of the sections at each locality are shown. In the first four localities, a sand beach is found shoreward (left) of the outcrop. At Stroud's Bay, however, the upward incline continues and no beach is present. Zero datum on vertical scale represents mean low tide level. Dashed lines indicate approximate dip of strata.


M
2
6
4
WAIT S BAY
0
5
10 M
18
HEYWOOD S BEACH
30
LONG BAY
47
SIX MEN S BAY
48
STROUD S BAY

LAND SEA

activities of sea urchins which inhabit the section. The rounded ridges are covered by clumps of articulated coralline algae together with encrusting coralline algal nodules and crusts.

Environmental Factors

Physical factors affecting zonation of the Barbadian intertidal communities have been described and discussed by Lewis (1960). These factors include tides, temperature and wave action. Surface wave curves for the east and west coasts show significant differences in energy impinging upon the coastal environment. The east coast of Barbados is exposed to the onslaught of waves generated by the predominant easterly winds, while the west coast is characterized by much lower wave energy. Sea surface temperatures vary by only $3^{o}C$ ($25^{o}C$ to $28^{o}C$) between the coldest (February) and the warmest (August) months of the year (Lewis, 1960). Tides are of a mixed, semi-diurnal variety with mean tidal range of slightly over 0.6 meters and a maximum diurnal range of 1.1 meters (Lewis, 1960). In addition, local dessication or floodings of rocky surfaces, also influence zonation.

Biota of Study Sites*

Interlocality variation in flora and fauna is considerable and appears to be dependent upon a number of environmental factors, such as wave intensity, tidal range, daily rock temperature extremes, and period of exposure. Lewis

*Complete taxonomic list of all organisms cited in this thesis appears in Appendix III.

(1960) has discussed this dependence in detail.

In the high intertidal zone and in the supratidal spray zone, represented in Section 6 (Wait's Bay) and Section 48 (Stroud's Bay), the grazing gastropods, *Nodilittorina tuberculata*, *Littorina ziczac* and *Littorina meleagris* are abundant. These gastropods are capable of existing on the dry and very hot rock surfaces of these upper intertidal/supratidal areas. On the damp bottom of the basinal depressions in this zone, *Nerita peloronta* and *Nerita versicolor* are sometimes present. The grey colour of these rocks is due to the presence of blue-green lithophytic algae. These are often found in a state of considerable dessication in interstitial spaces (chasmoliths) or actually penetrating carbonate material (endoliths).

The mid-intertidal zone represented in Section 4 (Wait's Bay), Section 18 (Heywood's Beach) and Section 30 (Long Bay) is the most diversified of the zones with respect to flora and fauna. In general, this area is inhabited by the sessile barnacle, *Tetraclita squamosa*, and the vermetid gastropods, *Petaloconchus* sp. and *Spiroglyphus irregularis*. Wandering over this area are grazers such as the limpet *Acmaea jamaicensis*, the keyhole limpet *Fissurella barbadensis*, and the chiton *Acanthopleura granulata*. Ephemeral covering of this surface by non-calcareous macroalgae (*Bostrychia* sp., *Cladophora* sp., *Valonia* sp., *Polysiphonia* sp.) is occasionally observed. Thin, discontinuous, surficial coatings of crustose coralline algae (Porolithon sp., Neogoniolithon sp. and Lithophyllum sp.) are present in places.

The lower intertidal zone is represented in only one section in the present study (Section 47, Six Men's Bay). At this locality, the zone is characterized by a relatively steep, seaward-sloping surface that is much dissected by burrows of the sea urchin Echinometra lucunter, and surficially covered by crustose coralline algae (Lithophyllum congestum, Neogoniolithon sp.), cushions of articulated corallines (Amphiroa sp., Jania sp., Galaxaura sp.), or leaves of foliaceous phaeophytes (Padina sp., Sargassum sp.). Small patches of the vermetid gastropod Petaloconchus cf. p. varians also occur in this area. At one place a conspicuous blanket of Zooanthus pulchellus appears to be overgrowing the Echinometra burrows. Gastropods of the species Heliacus cylindricus, Nitidella nitida, and Coralliophila caribea (Robertson, personal communication) were noted intimately associated with, and preying upon, the zooanthid blanket. Small numbers of the grazing keyhole limpet Fissurella barbadensis were found on the rock surface in this area. The large carnivorous gastropods Thais deltoidea and Purpura patula were occasionally observed.

Throughout the supratidal/intertidal range, boring infaunal organisms include microboring algae (Entophysalis sp., Mastigocoleus sp.), sipunculids (Phascolosoma antillarum) and barnacles (Lithotrya dorsalis).

Ecological Observations

Of necessity, any observations at this time of the ecological dynamics of the surfaces investigated are of limited scope. The temporal aspect of the ecologic interactions, especially with respect to competition and succession, requires longer periods of observation. However, a number of observations on the natural history of the organisms have been made which have a bearing on their erosive capabilities.

Bioaccretion (biologically-induced accretion of $CaCO_3$ substrate) is of limited importance in the present study. Only three kinds of organisms were recognized which exhibited bioaccretional potential. These included encrusting coralline algae, vermetid gastropods and thoracic barnacles.

The most conspicuous coralline alga forms a smooth, pink to purple crust in patches up to 4 cm. across with a thickness of 2 to 3 mm. These crusts commonly appear white and are presumed to be dead plants. Identification based on colour, appearance and microstructure (absence of multi-pored conceptacles and presence of many heterocyst fields) indicate that this alga is Porolithon pachydermum.[1] Less important and also less conspicuous on the rock surfaces are coralline algae of the genera Neogoniolithon and Lithophyllum. These algae are not found as high in the intertidal zone as Porolithon pachydermum and only became abundant in the very low intertidal areas.

[1] W. Adey, personal communication, 1974.

Vermetid gastropods, Petaloconchus cf. p. varians and Spiroglyphus sp., are found in several areas (notably Sections 4, 18 and 30) encrusting the rock surface. The shells of these sessile organisms are densely grouped and sometimes completely cover limited areas of the lower and damper rock surfaces. In some cases, the vermetids are encrusted with coralline algae which may help to strengthen the rather weak, open structure of the colonies. These organisms appear to be important in bioaccretion only where cementing and infilling agents are capable of infiltrating dead or empty shells to help consolidate the structure. (This phenomenon was observed to be operating at one location, i.e., Little Bay, along the Barbados coastline. This was not, however, a beachrock locality). Occasionally, dense black mats of filamentous blue-green algae are found covering the vermetid encrustations. (The effect of these on the well-being of the vermetids is unknown but may be detrimental in that circulation is reduced and hence smothering of the gastropods could occur).

The encrusting thoracic barnacle, Tetraclita squamosa, is found in large numbers at one locality (Section 18, Heywood's Beach). This organism protects the underlying rock surface from vertical attack by erosional agents but does not prevent lateral undermining of its base by keyhole limpets and endolithic algal borers. With sufficient undermining, the barnacle is isolated on a rock pedestal.

Continued undermining eventually leads to the pinnacle breaking off.

Bioerosion of the rock surfaces is a much more pervasive phenomenon than bioaccretion in the present study. A number of epilithic grazers, such as limpets, keyhole limpets, chitons and sea urchins are present at the study sites. However, endolithic and chasmolithic microphytes may well prove to play an equally important role in bioerosive processes.

In the upper intertidal areas (Sections 6 and 48), grazing molluscs are common. The most impressive displays, in a numerical sense, are those of the littorinid gastropods. Three species of littorines are present in large numbers (*Littorina ziczac*, *L. meleagris* and *Nodilittorina tuberculata*). *L. ziczac* and *N. tuberculata* are found on walls of depressions and slopes of rock pinnacles and on ridges between depressions. Two neritid gastropods, *Nerita peloronta* and *N. versicolor*, appear to prefer the lower walls and damp basins in the upper intertidal. They occur in smaller numbers than the littorines.

Both littorine gastropods and neritids are grazers which wander over the rock surface ingesting epilithic and endolithic microphytes by rasping away the rock with their hard radulae. In the process of obtaining food, they dislodge grains and/or file away rock particles, thus contributing to the overall erosion of the rock surface.

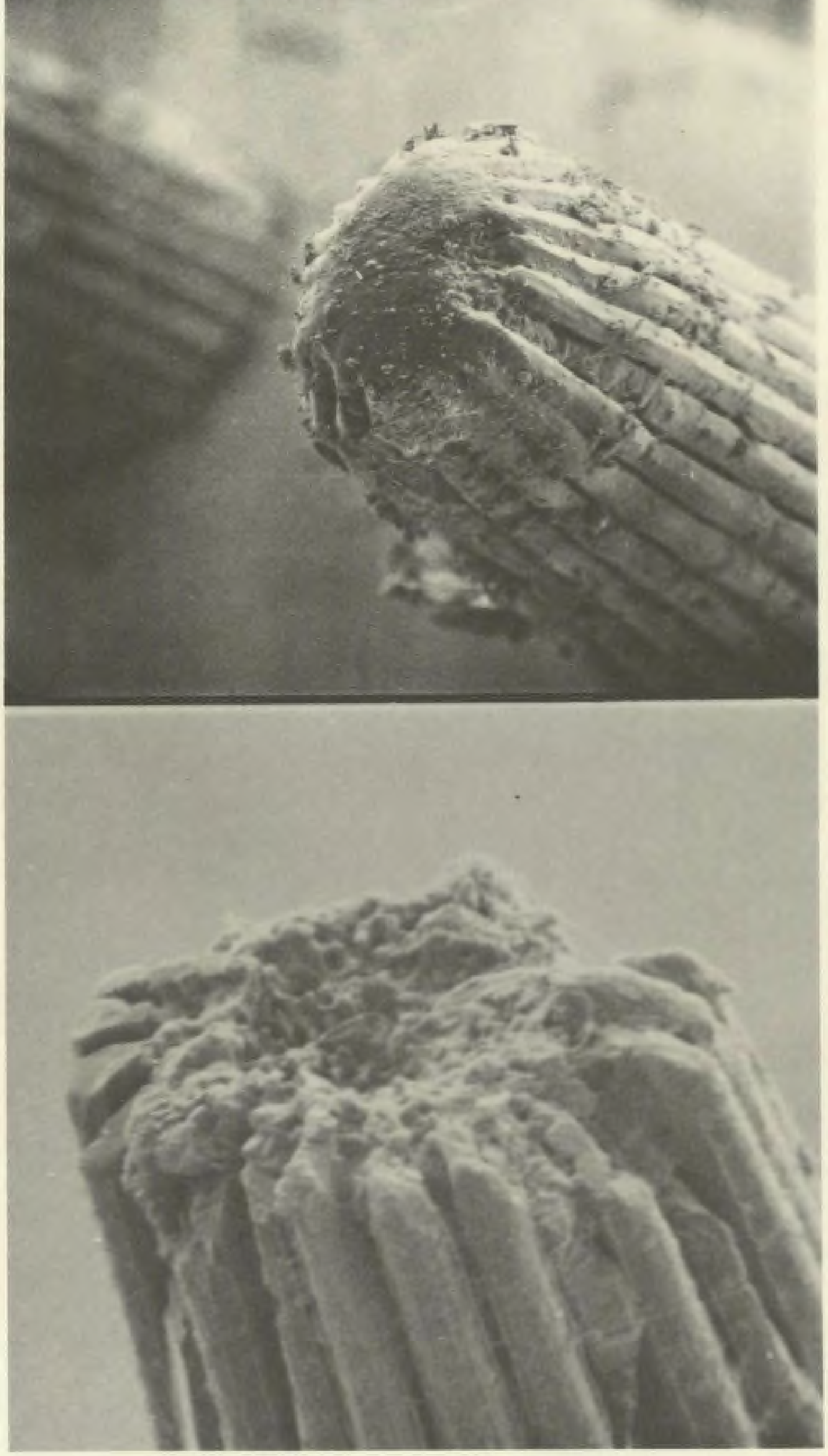
Limpets of the species *Acmaea jamaicensis* and key-hole limpets of the species *Fissurella barbadensis* are common in several localities (Sections 4, 18, 30, 47). Like the littorine and neritid gastropods, they are grazers which ingest epi- and endolithic plants, hence contributing to erosion. However, in addition to erosion caused by their mode of feeding, they may also cause erosion by a second process. During periods of high light intensities, the limpets firmly attach themselves to the rock surface and do not move until more favourable conditions occur (Morton, 1963). While in this state, erosion in the form of substrate etching by means of a biochemical secretion or biochemically-induced acid condition under the foot of the organism occurs. (Mucous secretions are necessary in order to obtain and maintain a firm attachment to the substrate). That this type of erosion occurs is evidenced by distinctive pits which are often observed on the rock surface when the limpet is removed. As the mucous secreted by the foot is only a weak acid and since the limpet does not continually occupy this position, a considerable period of occupancy must elapse before well-developed rock scars can develop. This supports the concept of limpet home sites as described by Frank (1964) in which a limpet returns to the same position during each inactive period.

Chitons (*Acanthopleura granulata* and *Chiton marmoratus*) are present in small numbers at several localities. These organisms act in much the same manner as the limpets with respect to erosive behaviour. They are grazers which rasp the rock surface with their radulae, thus abrading or plucking grains from the surface. They are active only when light intensities are low, i.e., during high tide conditions or at night. At other times, they firmly attach themselves to the substrate by means of a muscular foot. Again, acid mucous secretions around the foot are probably active in breaking down the underlying rock.

The boring sea urchin Echinometra lucunter is present at one locality (Six Men's Bay) in the low intertidal zone. McLean (1964) investigated the mode of boring and stated that bioerosion occurs when the urchins "chew" into the burrow walls and floors to obtain endolithic algal material. He also suggested that there is a certain amount of erosion caused by movement of the spines. Present evidence (Plate 13) indicates that E. lucunter spine tips are capped by a protective carbonate deposit. This was not found in non-boring representatives of the same species (Plate 14). This cap may be a healing response to injury of the spine during plucking of the surrounding rock. The cap shows no signs of being scratched or scraped as would be expected if the spine had been used as an abrasive tool. The urchins are inactive during the periods of low tide and remain for the most part in the available shade of the burrows to avoid dessication.

Plate 13. Scanning electron micrograph of an aboral spine tip from a boring Echinometra lucunter from the Six Men's Bay locality. Note the protective (?) disc formed on the end of the spine. 99x.

Plate 14. Scanning electron micrograph of an aboral spine tip from a non-boring E. lucunter from Discovery Bay, Jamaica. Note the sharp crystal surfaces and the lack of a protective disc. 210x.



In the low intertidal Echinometra zone described above, a thick zooanthid blanket is found. This blanket is composed of the zooanthid, Zooanthus pulchellus, and is seen to be slowly overgrowing the E. lucunter burrowed areas. Three species of gastropods are found inhabiting the surface of this zooanthid blanket. These are identified as Heliacus cylindricus, Nitidella nitida and Coralliophila caribea (Robertson, personal communication). Although they are predators on the zooanthids, there is no obvious evidence of detrimental effects on the colony.

The role of lithophytic microphytes in the ecology and microtopography of the intertidal and supratidal zones has been a relatively lightly investigated field. The following section presents detailed information which will describe some of the more important roles of these organisms in coastal morphologic processes.

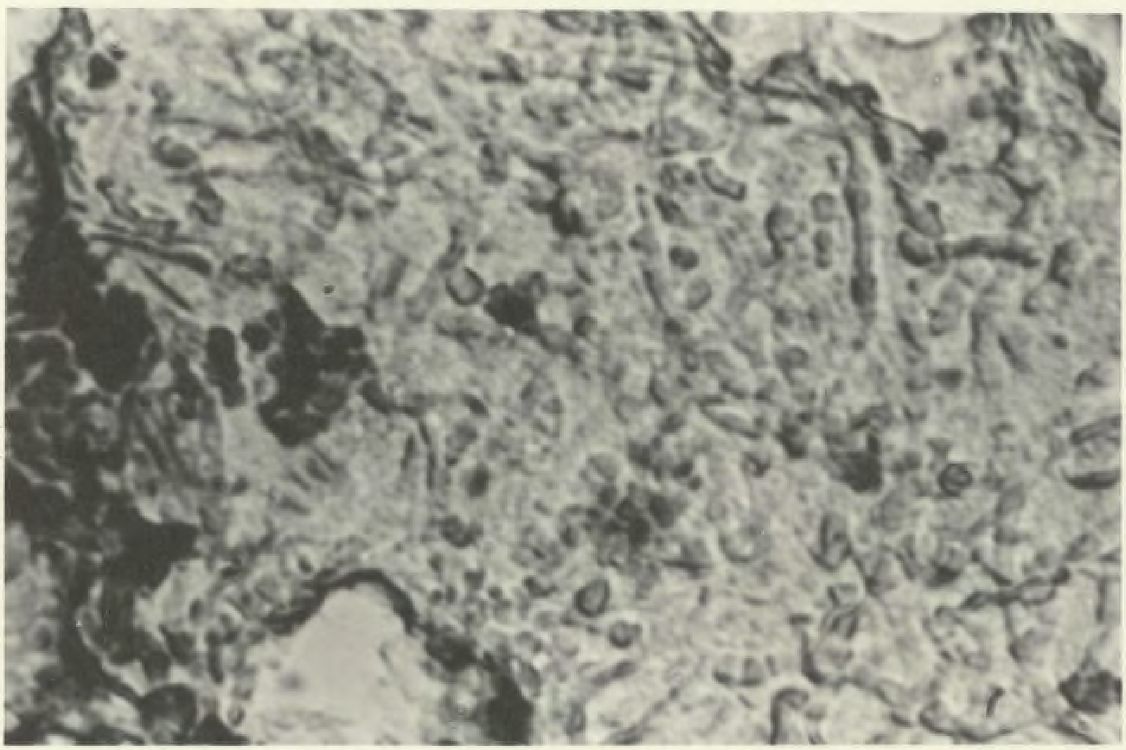
Observations on Lithophytic (Rock-Dwelling) Fungi and Algae

More than seventy years ago, Duerden (1902) recognized the importance of boring micro-organisms in the disintegration of subtidal limestone substrates, specifically stony reef corals. Ginsburg (1950) commented on the ability of algae to erode Pleistocene intertidal limestones in Florida and Purdy and Kornicker (1958) described algal disintegration of Bahamian limestone coasts. More recently, work has been carried out on the mode of boring, boring patterns and consequences of microborer attack on limestones (Ranson, 1955a, b; Bathurst, 1966, 1971; Klement and Toomey, 1967; Golubic, 1969; Kohlmeyer, 1969; Swinchatt, 1969; Golubic, Brent and LeCompion, 1970; Margolis and Rex, 1971; Perkins and Halsey, 1971; Rooney and Perkins, 1972; Fogg, Stewart, Fay and Walsby, 1973; Alexandersson, 1975). Evidence of grain destruction by endolithic microborers has been noted in rocks as old as the Lower Ordovician (Klement and Toomey, 1967).

Lukas (1973) has reviewed the terminology used in the description of marine lithophytic (rock-dwelling) microphytes. Terms proposed by Lukas (1973) are employed in the present study. She distinguished three types of lithophytic microphytes: epilithophytes (or epiliths, those living on rock surfaces), chasmolithophytes (or chasmoliths, those living within crevices), and endolithophytes (or endoliths, those which bore into carbonate substrates).

In the present study, the importance of chasmoliths and endoliths is considered. These organisms bring about the erosion of coastal limestones in two ways. Firstly, their presence stimulates the epilithophagic activity of those organisms that erode the rock as they rasp rock surface to obtain food, [filaments have been noted in the guts and faecal material of both epilithophagic echinoderms (Ogden and Gerhard, 1974) and gastropods (present study, Plate 15).] Secondly, lithophytic algae and fungi are

Plate 15. Faecal material from littorine grazers, showing the presence of endolithic algal filaments. Nomarski illumination, 510x.



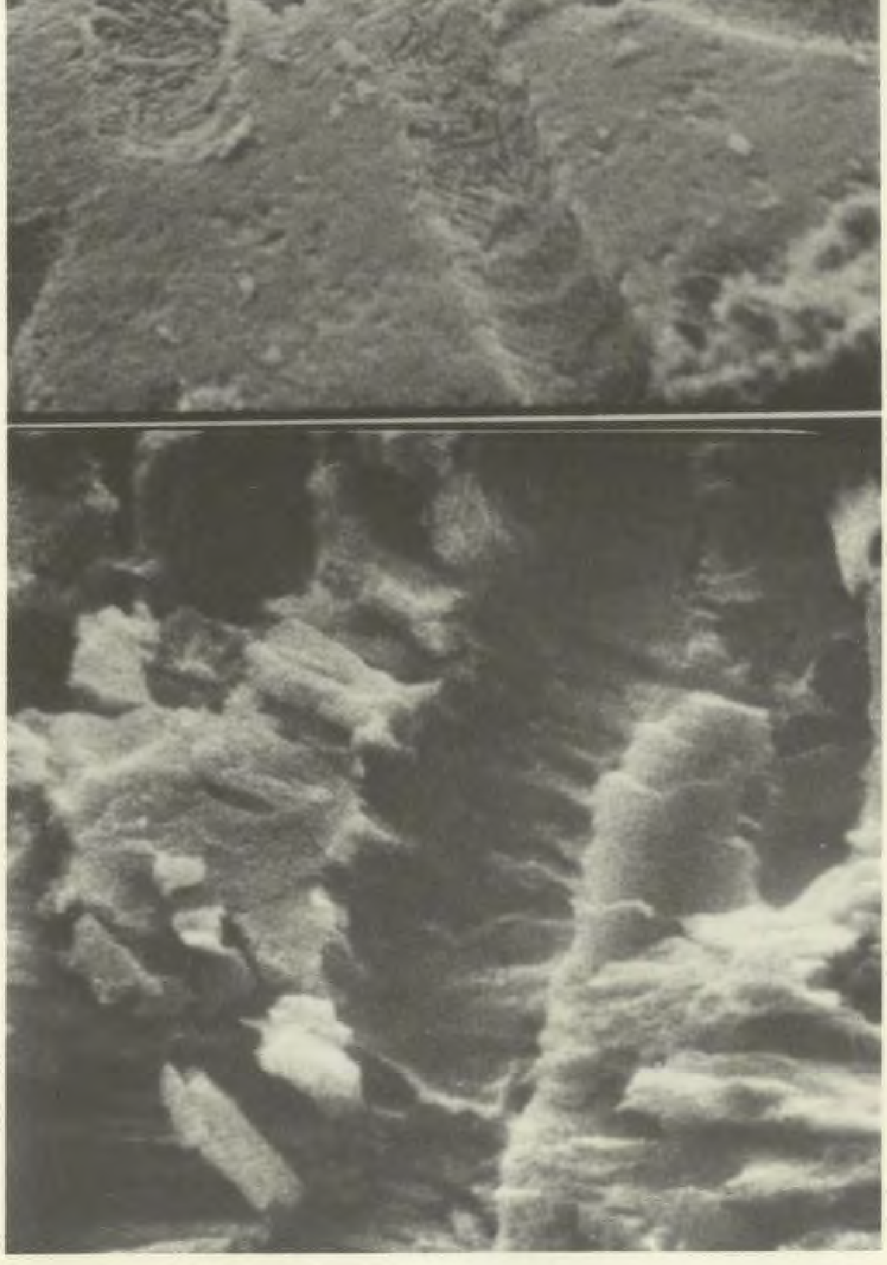
important bioeroders in their own right as they are capable of penetrating the substrate, thus weakening its structural integrity.

The exact mechanism of algal penetration into the limestone substrate is unknown. It has been suggested (Fogg et al., 1973) that a chemical dissolution process may exist in which the terminal cell of the algal filament secretes either an acid or chelating fluid in order to dissolve the limestone substrate. This would result in a step-by-step penetration of the substrate (Plates 16 and 17). Alexandersson (1975) has suggested that specific organelles may exist which are responsible for the dissolution. Evidence has also been presented (Golubic, 1969) that the direction of tunnels and the wall sculpture may be determined by the planes of crystal cleavage and twinning.

Regardless of the mode of boring, this activity serves to weaken the structure of individual grains of the rock or the cement binding the grains together. Hence, bioerosion on this scale may be either intergranular or intragranular (Figure 5). Intergranular microborers are important in that they chemically attack the cement, weakening the bonding between grains. Destruction of the cement causes a loss of cohesiveness, making the rock more susceptible to mechanical and biomechanical breakdown. Present evidence shows that both filamentous and coccoid algal forms are active in this intergranular erosion (Plates 18 and 19).

Plate 16. Scanning electron micrograph of algal borings, showing etched walls. 2250x.

Plate 17. Scanning electron micrograph of etched walls of algal boring. 1100x.



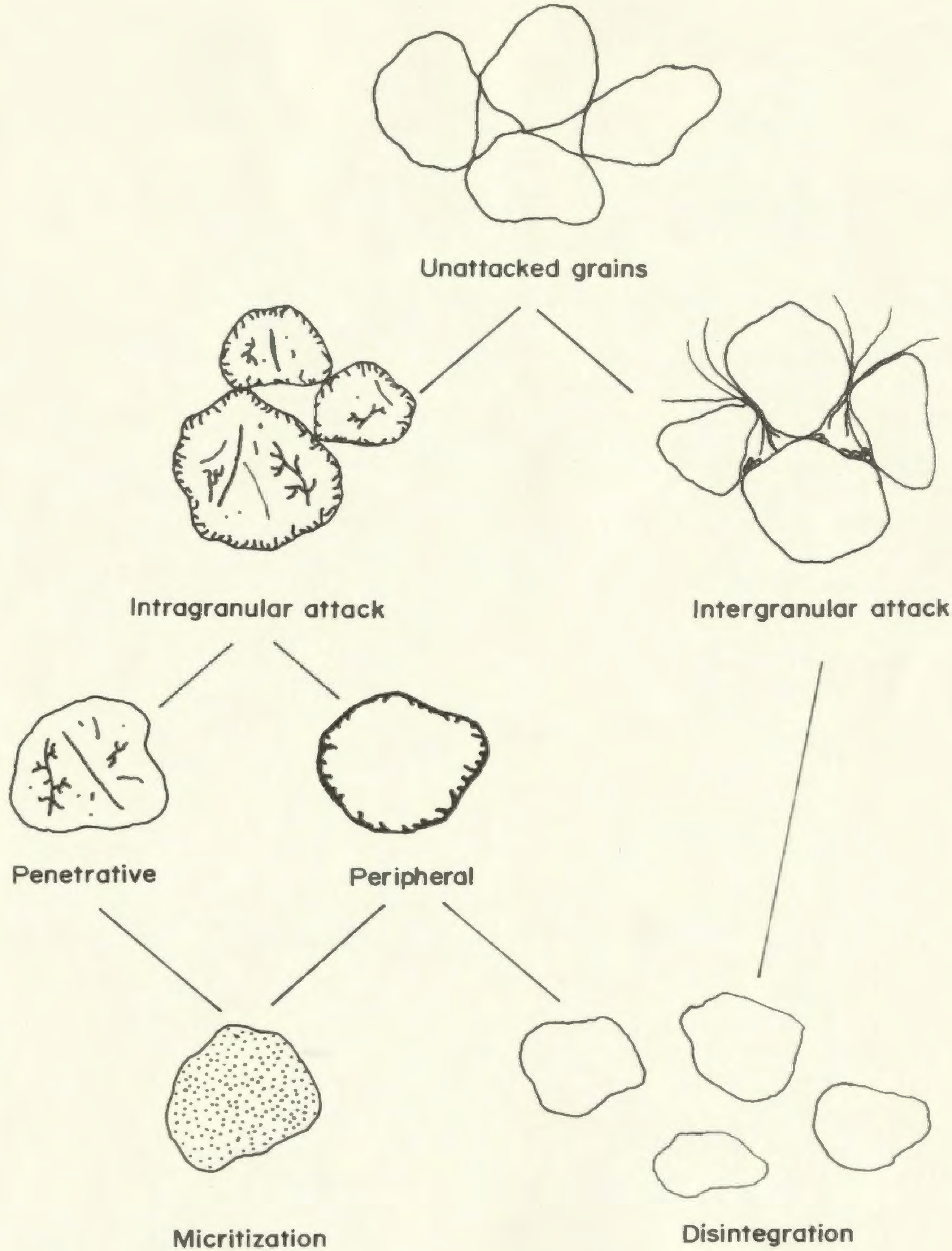
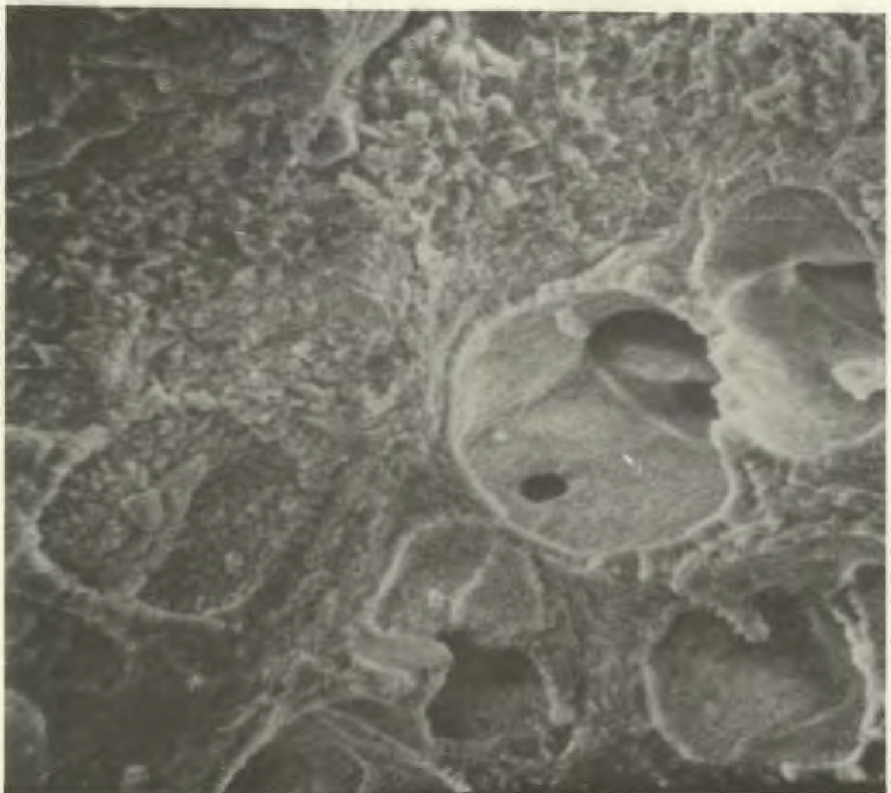


Figure 5. Modes of microborer attack and results

Plate 18. Intergranular etching by coccoid chasmolithic algae. 2000x.

Plate 19. Intergranular filaments plucking cement crystals. 500x.



Intragranular boring is of two kinds: peripheral or penetrative boring (Figure 5). Peripheral boring has been extensively studied by various workers, most notably Bathurst (1966, 1971), as being of prime importance in the micritization process. Peripheral boring implies a centripetal direction of boring which results in a centrally progressive micritization of a bored grain from the outside to its centre (Plates 20 and 21). The ultimate result of this type of boring is a structureless grain composed totally of micrite.

Penetrative boring is not a progressive centripetal process. In many cases, algae and fungi have been observed to bore deep into, and, in some cases, to pass entirely through, a grain (Plates 22 and 23). Penetrative boreholes may vary from relatively straight, smooth-walled tubes to a twisting sausage-like pattern (Plates 24, 25 and 26). In several cases, filaments were found to double back on themselves and re-enter grains which they have previously passed through (Plate 27).

Numerous descriptions of microborers and microborings, by geologists and biologists, have appeared in the literature. In general, geologists tend to describe microborings and often attempt to identify organisms by their borings. This ichnological (trace fossil) approach is unsatisfactory at present due to the fact that no conclusive evidence exists to show that algal and/or fungal boring patterns are uniquely characteristic of the organism. In fact, evidence exists

Plate 20. Thin section showing micritized halo around grain, caused by peripheral algal borings. White light, 295x.

Plate 21. Scanning electron micrograph of a fractured grain, showing the algal filaments which cause the micritization halo. Some penetrative borings can also be seen in the central part of the grain. 200x.

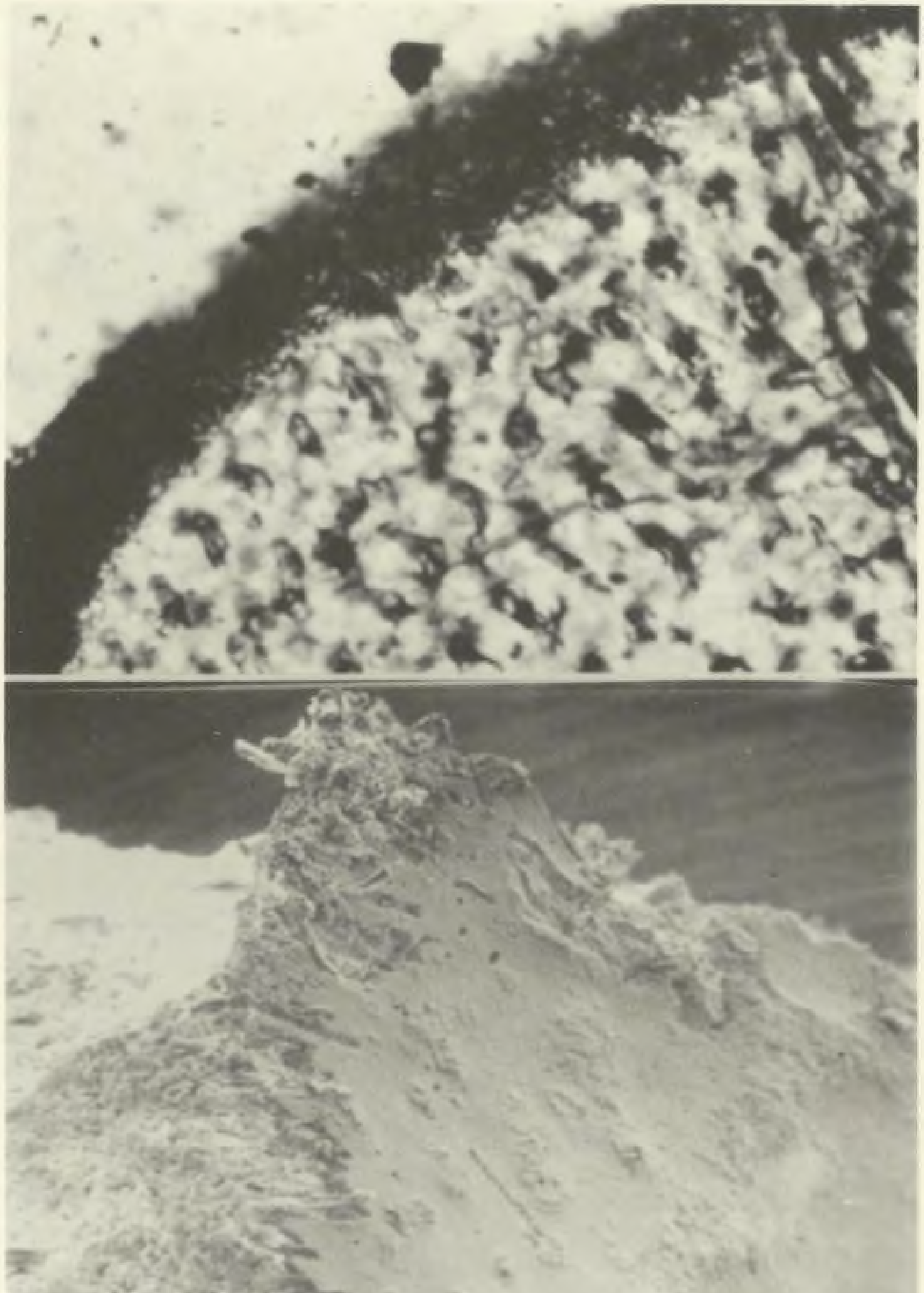


Plate 22. Thin section photomicrograph of a bored grain. The straight to slightly arched filaments are ~1.6μ in diameter. The larger borings are 9-10μ. White light, 285x.

Plate 23. Macrophotograph of grains and powdery appearing cement. Filaments (arrows) can be seen penetrating the grains. 88x.

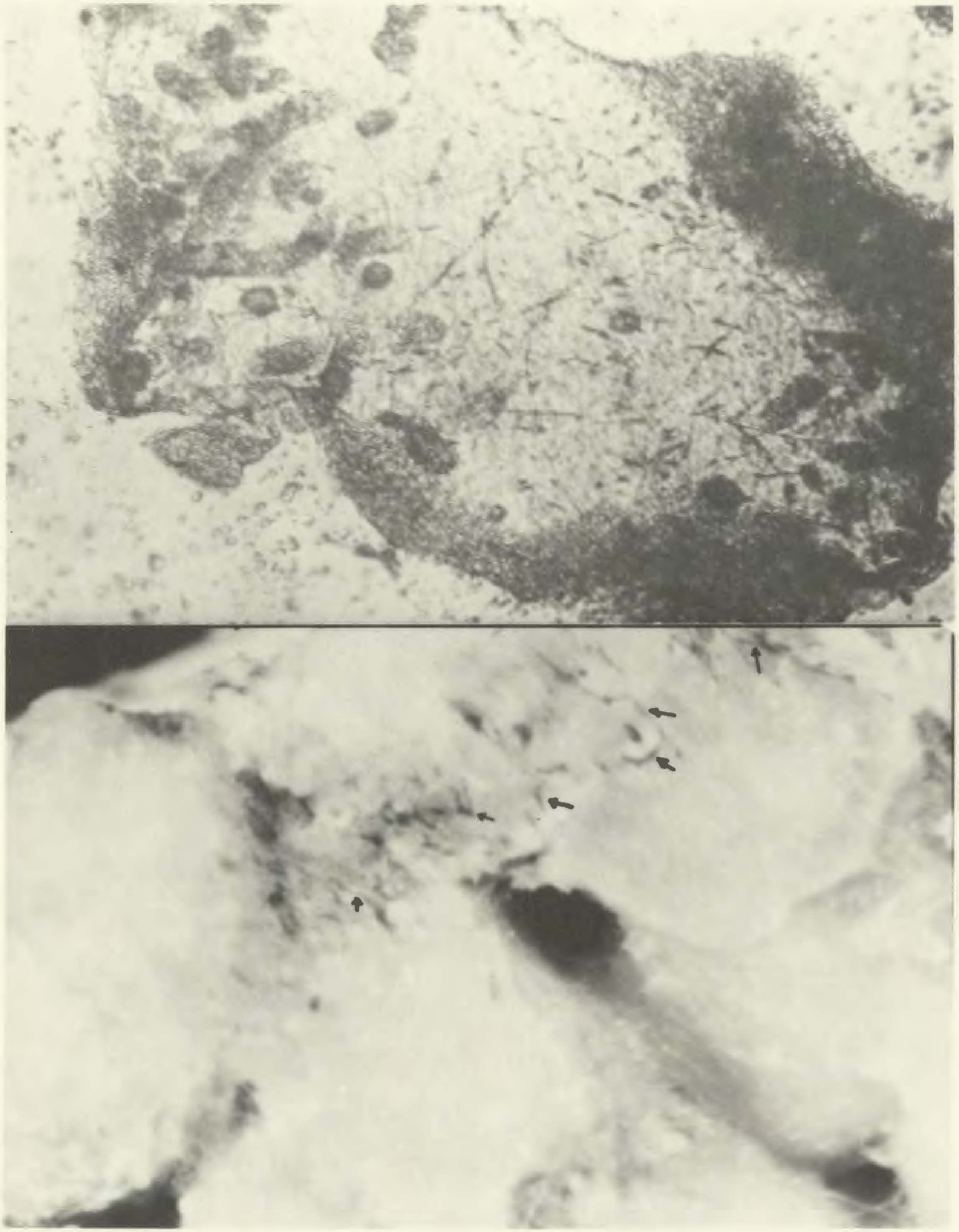


Plate 24. Thin section photomicrograph showing both peripheral and penetrative boring. Note that the micrite halo is overgrown by acicular cement. Two types of penetrative borings are evident. Fine, thin, thread-like borings (indistinct) are present, together with ~4μ diameter "sausage link" borings. Crossed nicols, 50x.

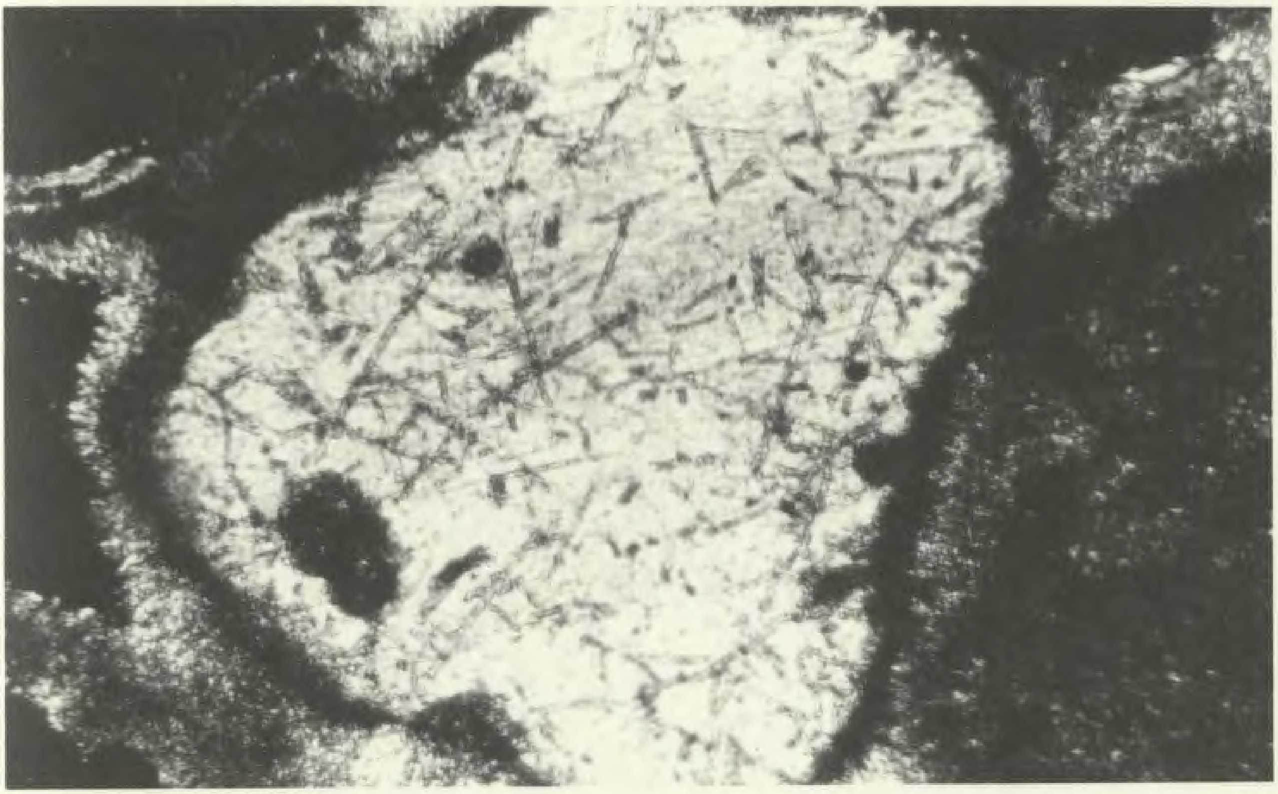


Plate 25. Scanning electron photomicrograph of a fractured grain disclosing straight-walled, penetrative type of boring. 1000x.

Plate 26. Scanning electron photomicrograph of a "sausage-like" boring, surrounded by straight-walled borings. 2200x.

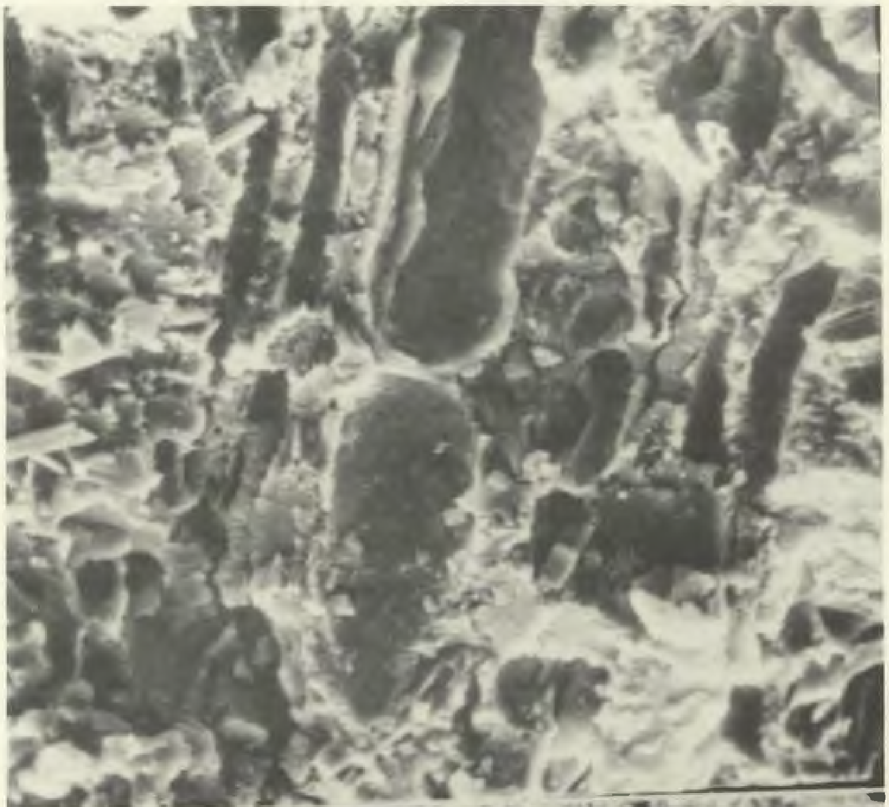
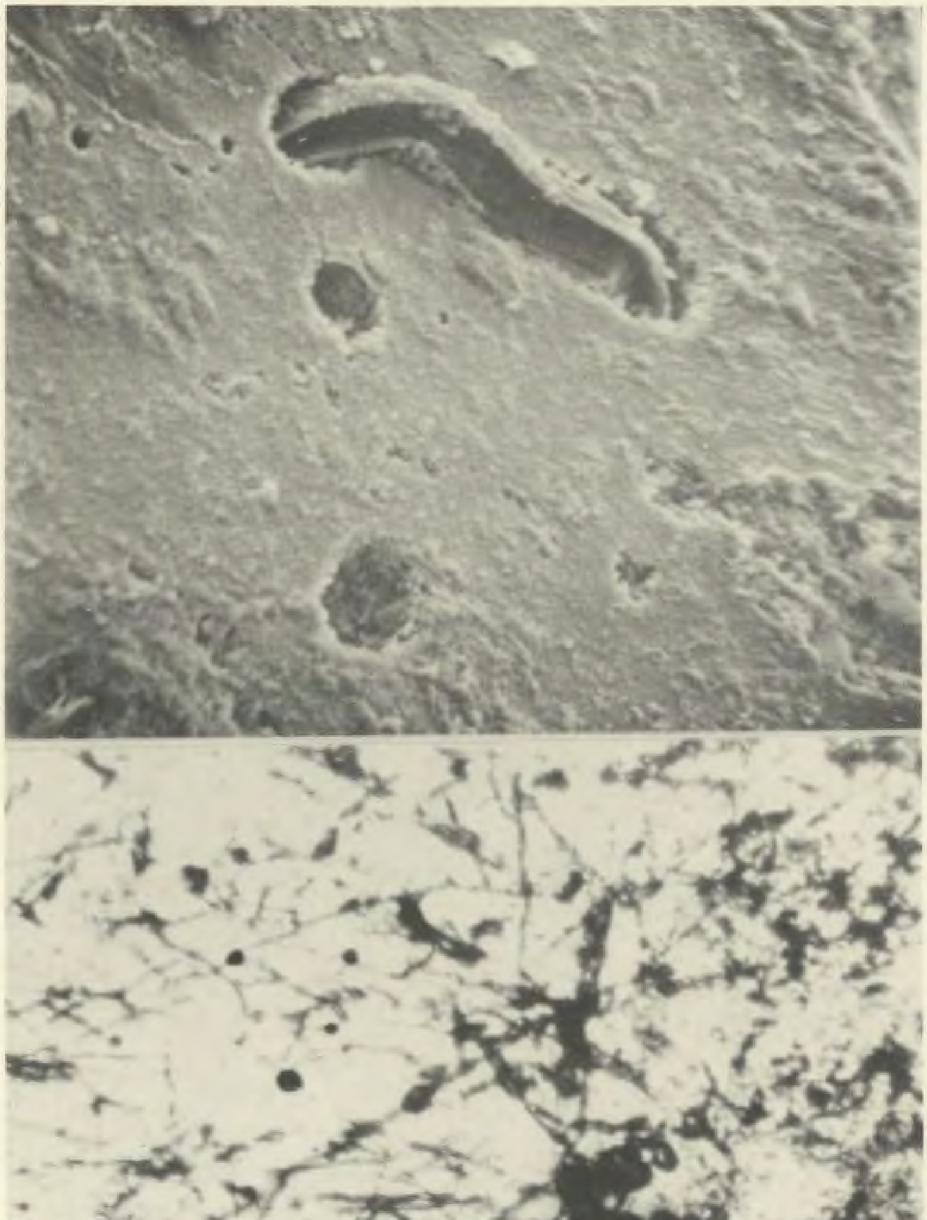



Plate 27. Scanning electron photomicrograph showing bending of algal filament while boring a single grain. 2000x.

Plate 28. Thin section photomicrograph of 1-2μ diameter fungal (?) borings. The 6-8μ dark blobs may represent spore cases. White light, 500x.



(Golubic, 1969) that, to some extent, substrate mineralogy/ crystallography influences boring patterns. On the other hand, the biological approach to lithophytic organisms is often limited to an examination of the morphology of the organism with no examination of the result of the boring activity.

Both coccoid and filamentous algae have been reported in the microborer literature. The filamentous forms may be either septate or non-septate, branching or non-branching. Table 5 lists some of the recently-reported types of boring lithophytes and lithophytic boring patterns.

Three major groups of microborers are recognized in material from the present study. These include fungi, as well as myxophycean and chlorophycean algae. In general, the myxophycean (cyanophycean) algae seem to be able to tolerate more dessication than the chlorophycean algae and thus are more abundant in the higher intertidal to supratidal zones. They are not, however, excluded from the lower zones. The chlorophycean algae are generally less tolerant of dry conditions and are found from the mid to low intertidal zones. Fungal distribution does not appear to be controlled by this factor.

Fungal hyphal borings are approximately one to three microns in diameter and show occasional branching (Plate 28). Swellings of the filaments are occasionally observed, possibly representing conidia or sporangia. The filaments are

TABLE 5

RECENTLY-REPORTED BORING LITHOPHYTES

Plant Division	Researcher and Date	Description	Identification Based On
Eumycophyta	Margolis & Rex, 1971	"branching fungi" - no description offered.	preserved material.
	Perkins & Halsey, 1971	"1-4μ fungi" - hyphae straight to slightly curved; filaments 1-4μ in diameter; occasional branching; no intersection; singly or in great masses.	live material; borings; boring casts.
	Rooney & Perkins, 1972	"endolithic fungi" - long, thin tubules (hyphae) with 1-4μ diameter; spherical pores (spore cases) ~10μ diameter; septate and non-septate filaments were recovered.	live material; borings; boring casts.
	Lukas, 1973	Deuteromycetes (Fungi Imperfecti) (a) brown to reddish-brown; septate; endophytic in and growing to fill <u>Ostreobium</u> filaments. (b) colourless; septate; 1-2μ diameter; intercalary and terminal swellings; associated with but never within <u>Ostreobium</u> filaments. Size of filaments overlaps with size of smallest <u>Ostreobium</u> filaments.	live and preserved material; borings; boring casts.

TABLE 5 (Continued)

Plant Division	Researcher and Date	Description	Identification Based On
Cyanophyta (Myxophyta)	Ranson, 1955b	*Entophysalis granulosa*-coccoid alga cells from 2-5μ diameter, grouped in masses more or less 20-50μ in diameter (free translation from the French).	live material.
	Purdy & Kornicker, 1958	"algae similar to or identical with" 1. *Entophysalis* sp.* 2. *Hyella* sp.* 3. *Calothrix* sp.* 4. *Gomphosphaeria* sp.* * no description offered.	prepared material.
	Golubic, 1969	1. *Hormatonema paulocellulare* - endolithic filaments 8-12μ and ~50μ in length, seldom branched, composed of a few (1-4) nearly isodiametric cells separated by long, stalk-like gelatinous segments of filament. Extracellular pigment is dark blue and turns red at pH <6. 2. *Hyella caespitosa*-endolithic filaments 4-5μ and several 100's of μ long; frequently branched and contain very elongated (10-30μ) proximal	live and preserved material; borings and resin casts.

TABLE 5 (Continued)

Plant Division	Researcher and Date	Description	Identification Based On
		cells. Extracellular pigment is yellow-brown, turning green at low pH.	
Cyanophyta	Margolis & Rex, 1971	"unicells resembling Entophysalis deusta" - no description offered.	prepared material (acid maceration of oolites).
	Lukas, 1973	Plectonema terebrans - filaments 2-3 decimenters long; slightly curved, cylindrical filaments with rare false branching; sheath thin and colourless; cells 0.95 to 1.5μ diameter, 2-6μ long with refractive granules (rarely visible) at each end; apical cell round; bluish to reddish in colour.	live and prepared material; borings; boring casts.
Chlorophyta	Margolis & Rex, 1971	"similar to Gomontia polyrhiza (?)"* - branching, 5μ diameter filamentous algae.	prepared material (acid maceration of oolites.
	Perkins & Halsey, 1971	1. "8-10μ green alga" - ramose, 8-10μ filament diameter.	preserved material; borings; boring casts.

* Wilkinson and Burrows (1972) have shown that at least six species of algae can be confused under this name.

TABLE 5 (Continued)

Plant Division	Researcher and Date	Description	Identification Based On
		2. "siphonaceous green alga" - represented in plastic casts by stubby tubules, 15-20μ diameter; widely varying growth form, from simple, slightly arcuate rods, which occasionally bifurcate, to complex radiating masses.	
Chlorophyta	Rooney & Perkins, 1972	"septate green alga" - filaments straight to gently curved; 8-10μ diameter; branching.	borings; boring casts.
	Lukas, 1973	1. <u>Ostreobium quekettii</u> - filaments straight; 0.75 to 24.0 μ diameter; sparsely branched; occasional elaborate swellings; chloroplasts variable to indistinguishable.	live and preserved material; borings; boring casts.
		2. <u>Ostreobium brabantium</u> - filaments 30-40μ diameter; subdichotomously branched; rounded at tips.	
	Lukas, 1974	<u>Ostreobium constrictum</u> - filaments of two types: cylindrical 3-20μ diameter and inflated 13-60μ diameter; branching with constrictions.	live and preserved material; borings; boring casts.

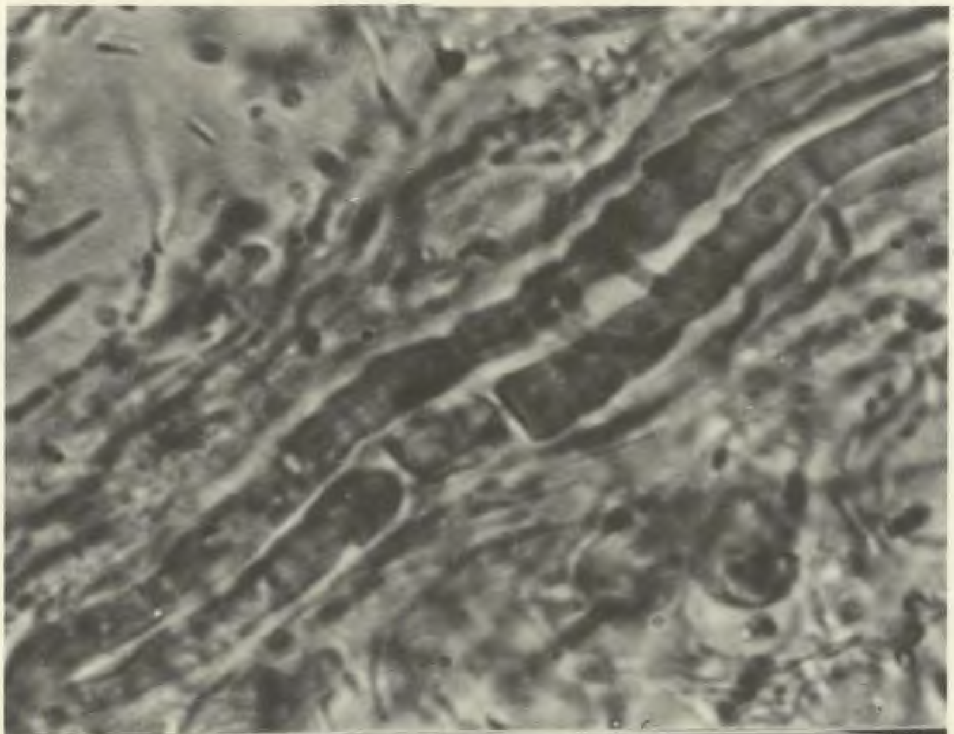
common and penetratively bore the grains. No identification was attempted.

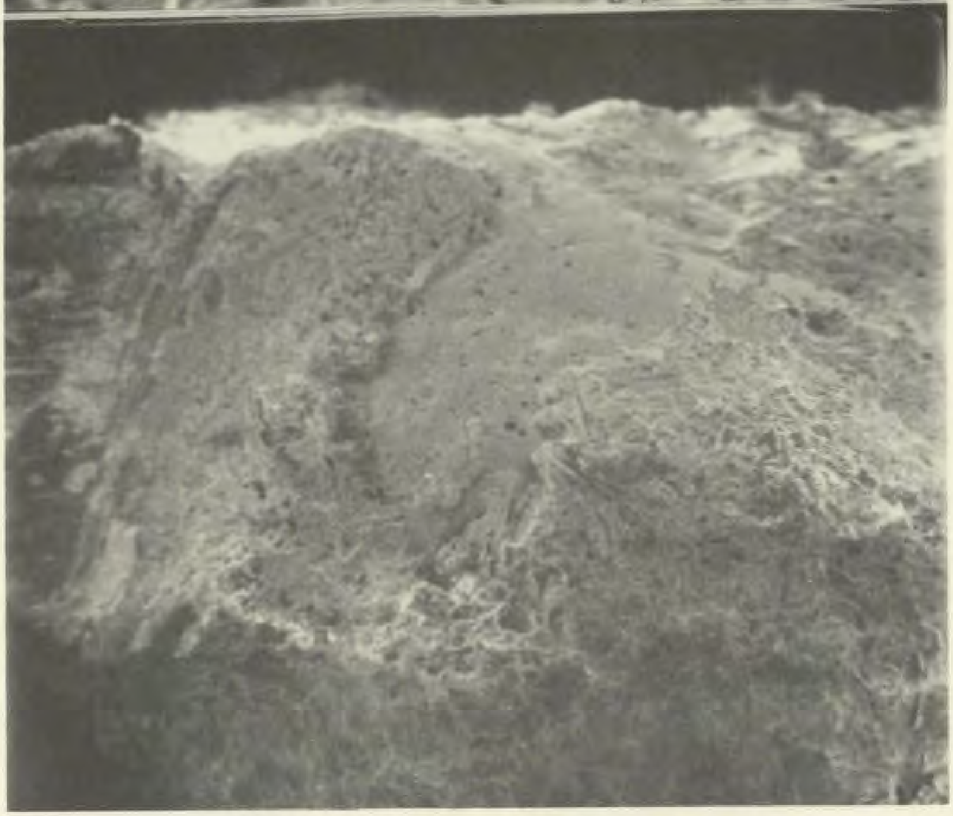
The myxophycean (cyanophycean) algal division is represented by both coccoid and filamentous forms. Coccoid algae similar to Entophysalis deusta (Chapman, 1961) are present as chasmolithic, intergranular etchers. The cells are ovoid to spherical and of unequal sizes, ranging from five to ten microns in diameter.

Three types of filamentous blue-green borers are recognized. The first is characterized by a filament eight to ten microns in diameter with a thick outer sheath enclosing a single trichome, cylindrical cells four to five microns in diameter by four to five microns long and the occasional presence of rounded apical cells, ten to twelve microns in diameter. The second type of filamentous myxophyte is distinguished by filaments approximately five to seven microns in diameter, with a thick outer sheath enclosing a single trichome, slightly conical cells (or at least cells constricted at one end) approximately four microns diameter by two or four microns long and intercalary heterocysts. There is often a distinctive U-bending of a filament (Plate 29). Both of these filamentous borers are believed to be of the family Scytonemataceae. The third filamentous cyanophyte borer is believed to be a species of the genus Hyella (Pleurocapsales) as described by Golubic

Plate 29. A cyanophyte borer. Note the conical appearance of the cells, the thick sheath, the intercalary heterocyst, and the U-bend in the filament (lower left). 2100x.

Plate 30. Evidence of microexfoliation, due to heavy peripheral boring action. 220x.





(1969). Cells are cylindrical, 3-4μ in diameter and in length when near the rock surface but are alongate (7-12μ in length) deeper in the rock. Some irregular branching is observed.

The Chlorophyta are represented by a filamentous, septate, green endolith. Individual cells in the thallus vary in shape and size, although the outer sheath remains relatively uniform in diameter (eight to approximately ten microns). Chloroplasts give a granular appearance to the cells. Branching is evident and reproductive structures are often observed. This alga appears morphologically similar to a septate green alga described previously by Rooney and Perkins (1972). No species identification was possible.

These algal microborers are observed to attack the rock in both an intergranular and intragranular manner. Scanning Electron Microscope observations show that upon exit from a particular grain, the boring filaments join a much thicker surficial mass of filaments which lie on or in the heavily-bored surficial grain crust. "Microexfoliation" of this heavily-bored crust is occasionally seen (Plate 30) and is an obvious indication that grain, matrix and cement may be affected by algal boring behaviour.

CHAPTER IV

STUDY SITE ANALYSIS AND PHOTOGRAMMETRIC RESULTS

Spot depth readings were obtained for between 300 and 400 points in each section for the years 1971, 1972 and 1973. These values were used to generate annual contour maps for each section.[1] In addition, residual values were calculated by substracting one year's set of values from the previous year's values. These were then used to generate residual contour maps. Average yearly residual values for each section are listed in Table 6. These values were arrived at after careful elimination of all readings which fell on an errant epilithic organism or on an ephemeral macroalga, for any one or more years. Also eliminated were any points which were considered unreliable due to photogrammetric analysis limitations. These included readings on points in heavy shadow and on points in areas of unresolvable parallax.

In addition to displaying average residual values per section, Table 6 shows average residual values for intra-sectional zones displaying a distinctive or characteristic surface morphology. These data have been statistically analysed to determine whether the residual values differ significantly from section to section and from zone to zone

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[1]Examples are given in Appendix IV.

TABLE 6

AVERAGE ANNUAL RESIDUAL VALUE STATISTICS

Section	Surface Morphology (zones)	$\bar{y}$ (mm/yr)	S^2	Range in y (mm/yr)	n
4	Vermetid pavement	1.8	0.48	0.1 to 2.3	13
	Cascade depressions	1.4	0.51	0.0 to 2.4	15
	Steep slope	1.7	0.80	1.0 to 2.4	48
	Resistant ridge	0.9	0.32	0.1 to 2.0	30
	Ridge/Wall	1.6	0.40	0.0 to 2.4	57
	Overall	1.5	0.60	0.0 to 2.4	163
6	Depressions	1.4	0.28	0.4 to 2.2	51
	Basins	0.9	0.21	0.0 to 2.2	52
	Ridge/Slope	1.4	0.25	0.1 to 2.4	164
	Overall	1.3	0.28	0.0 to 2.4	267
18	Barnacle zone	1.1	1.31	-2.2 to 2.0	94
	Pitted surface	1.2	0.57	0.1 to 2.4	173
	Barnacle growth	-1.1	0.48	-2.2 to 0.0	22
	Overall	1.2	0.91	-2.2 to 2.4	267
30	Overall (Pitted Surface)	1.3	0.46	0.0 to 2.4	123
47	*E. lucunter* bioerosion	2.4	2.74	0.0 to 9.9	244
48	Runoff channel	2.4	0.70	0.8 to 3.9	22
	Ridges	1.6	1.65	0.3 to 4.9	188
	Depressions	3.2	0.62	1.6 to 4.9	99
	Overall	2.2	1.81	0.3 to 4.9	309

Average annual residual values ($\bar{y}$), variance of average residual values (S^2), range of residual values and number of data points measured (n) for each surface zone of each section studied. Positive residual values represent erosion, negative residual values indicate accretion. Average residual values were based on 1971 and 1973 data with the exception of Section 48 values which were based on 1972 and 1973 data.

within a particular section. Results of these analyses are presented in the Appendix (Tables A1, A2, A3 and A4). It has been found that several groupings of sections is possible, i.e., groupings of sections whose erosion values do not differ significantly. These include a grouping of Section 6, Section 18 and Section 30 and a pairing of Sections 47 and 48. Zonal differences do not vary in any clear pattern.

Wait's Bay

Wait's Bay (Figure 2) is a small embayment located on the northeastern coast of Barbados (metric coordinates 1472125N by 661850E).[1] The mouth of the bay opens to the north and thus the eastern headland protects the beach to a certain extent from direct onslaught by the predominantly easterly and northeasterly swells (Plate 31). A large outcropping of Pleistocene calcarenite occupies most of the beach and extends from the supratidal into the subtidal zone. This rock surface exhibits a shallow, seaward dip of ~5°. A number of weathered, inclined rock layers are evident at this site (Plate 32). Two photogrammetric sections, 4 and 6, were established on this rock surface.

Section 4 was established in the mid- to low-intertidal zone (Figure 4). This section displays a topography

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[1]British Directorate of Overseas Surveys, Map #418 (Series #749, Barbados, West Indies), 1:50,000.

Plate 31. View of Wait's Bay locality, facing northeast. The eastern headland and cup reef (arrow) at the mouth of the bay partially shield the area from north-easterly and easterly swells.

Plate 32. Section 4, Wait's Bay. This section was established in the mid- to lower-intertidal zone.

of irregular, knife-edged ridges separating depressions ranging from 2 to 50 cm. across (Plates 33, 34, 35 and 36). In a number of cases, these depressions have coalesced by breaching of common walls, to form cascades or elongate step-like depressions parallel to the dip (and drainage) direction.

This topography provides a number of microenvironments and allows for a zonation of the organisms inhabiting this site (Plate 37 and overlays). It appears that the most important factor in biologic zonation is the dampness of the rock surface. This is controlled by steepness of slope and drainage (including porosity and permeability) of the rock. The behaviour of the organisms appears to be primarily a response to avoid dessication or to avoid stagnant water conditions. Distribution based on moisture conditions is evident in both the floral and faunal communities.

The floral community (lithophytic community) is for the most part limited to microboring cyanophytes (myxophytes) and a chlorophyte. The cyanophytes are tentatively identified as ?Mastigocoleus sp., ?Plectonema sp., and ?Entophysalis sp.; while the chlorophyte could only be identified as a septate green filamentous form. These organisms are found to penetrate and weaken the rock to a depth of up to a centimeter. The microphytes have little or no means of combatting dessication and hence are relatively unsuccesful

Plate 33. Surface of Section 4, Wait's Bay, 18 April, 1973, showing general surface appearance and ground control points (a,b,c,d,f,g,h). The areas outlined on the left side of this section were investigated photogrammetrically and are treated in more detail in Plates 34-37.

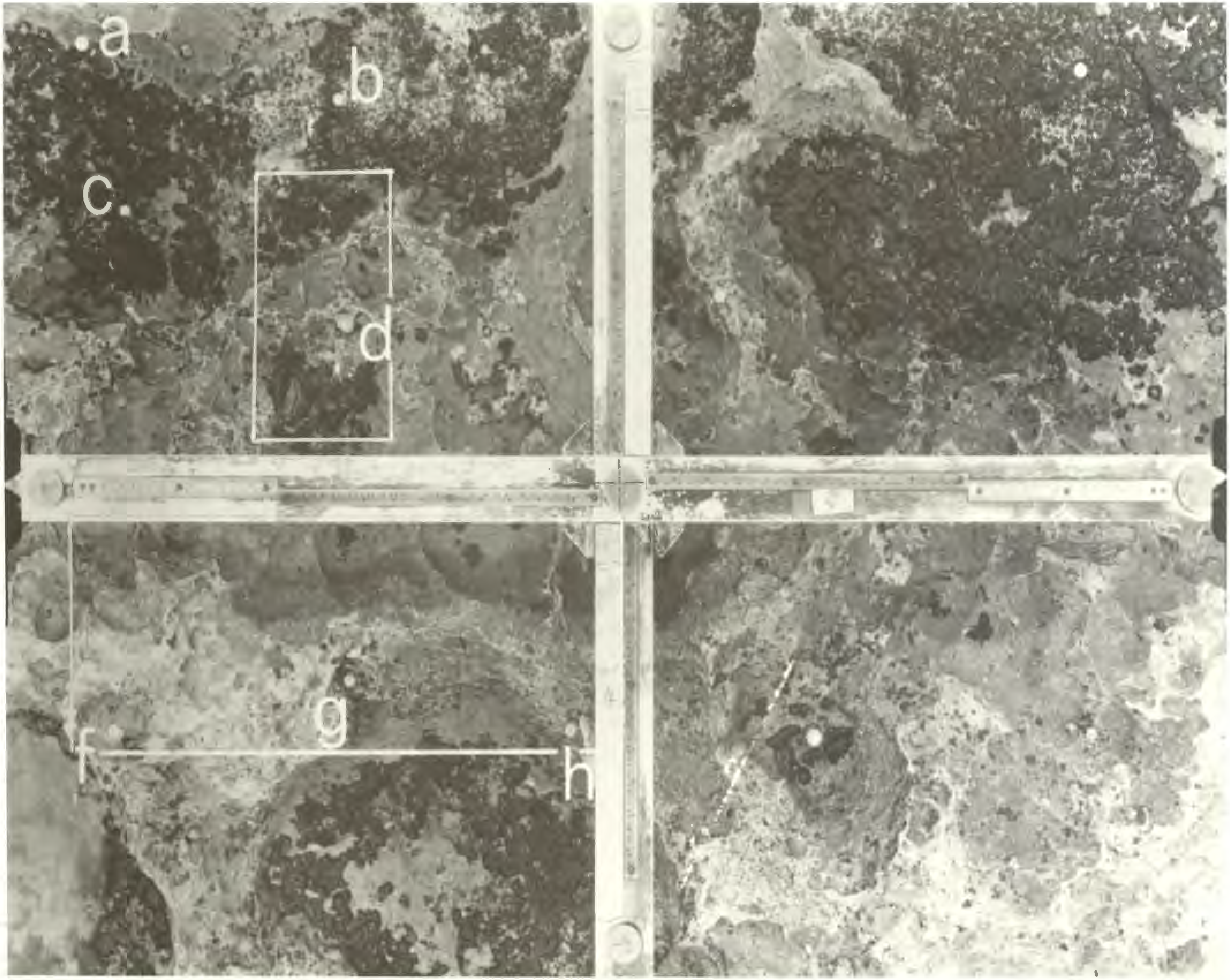
a
b
c
d
f
g
h

Plate 34. Stereophotographs of Section 4, Wait's Bay, 29 April, 1971, showing round-bottomed depressions and coalesced pits forming step-like drainage channels. Note encrustation by Petaloconchus sp. on the floors of the larger depressions. Grazing limpets of the genus Acmaea may be seen in pits or on the walls of the depressions. The grazing gastropod, Littorina meleagris can be seen in clusters on rock peaks and divides. Note the presence of the chiton, Acanthopleura granulata in the shadowed depression slightly left and below the letter "d".

Plate 35. Stereophotographs of Section 4, Wait's Bay, 12 May, 1972. A decrease in the number of Acmaea sp. and L. meleagris from 1971 and a slight increase in filamentous macroalgal cover can be seen and is tabulated in Table 7.

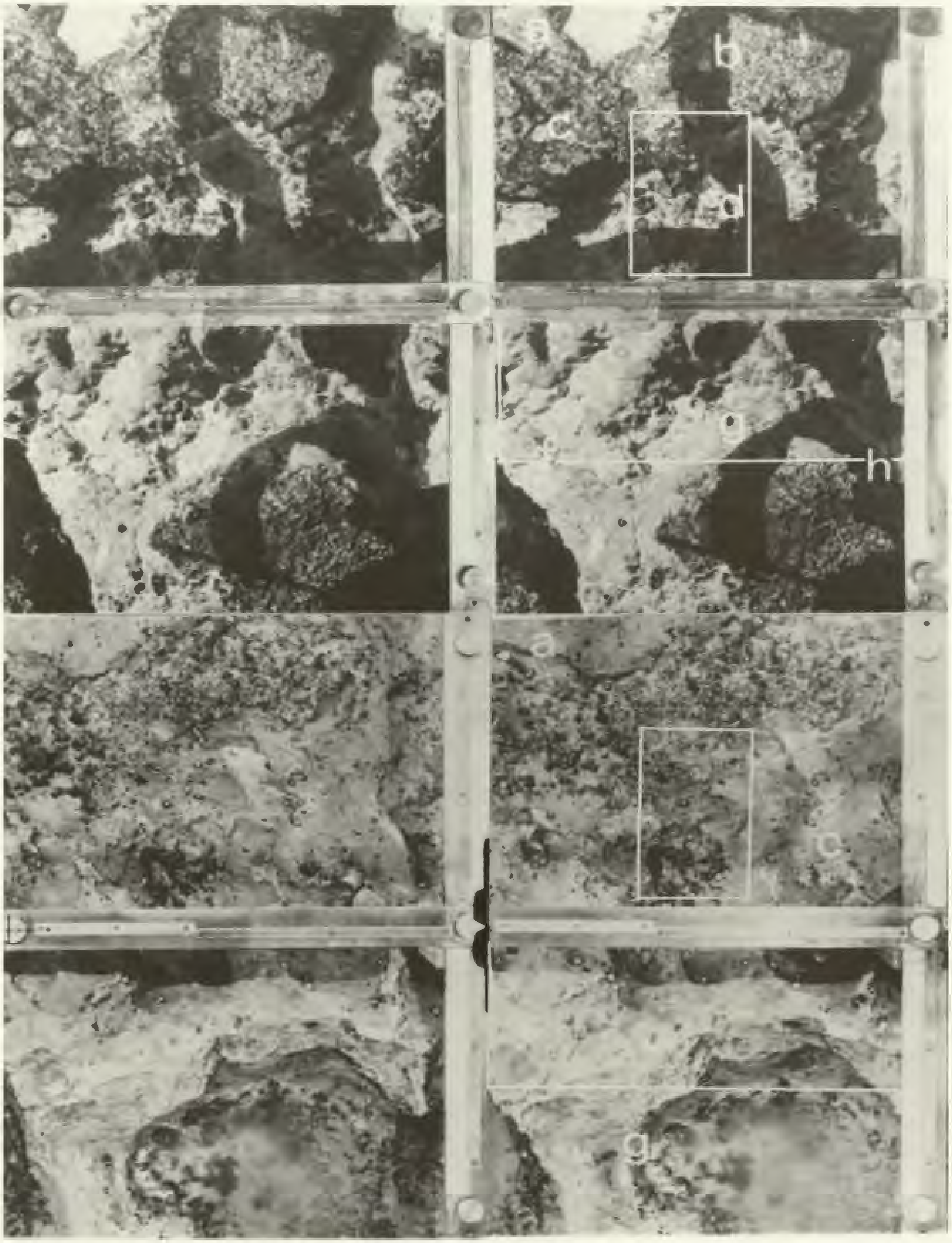
a
b
c
d
g
h
a
c
g

Plate 36. Stereophotographs of Section 4, Wait's Bay, 18 April, 1973. Note presence of a chiton (Acanthopleura granulata) in the small depression to the left of and below the letter "d" and compare with the location of a chiton in the 1971 photo (Plate 34). Vermetid cover has been partially removed from the floor of the lower right depression.

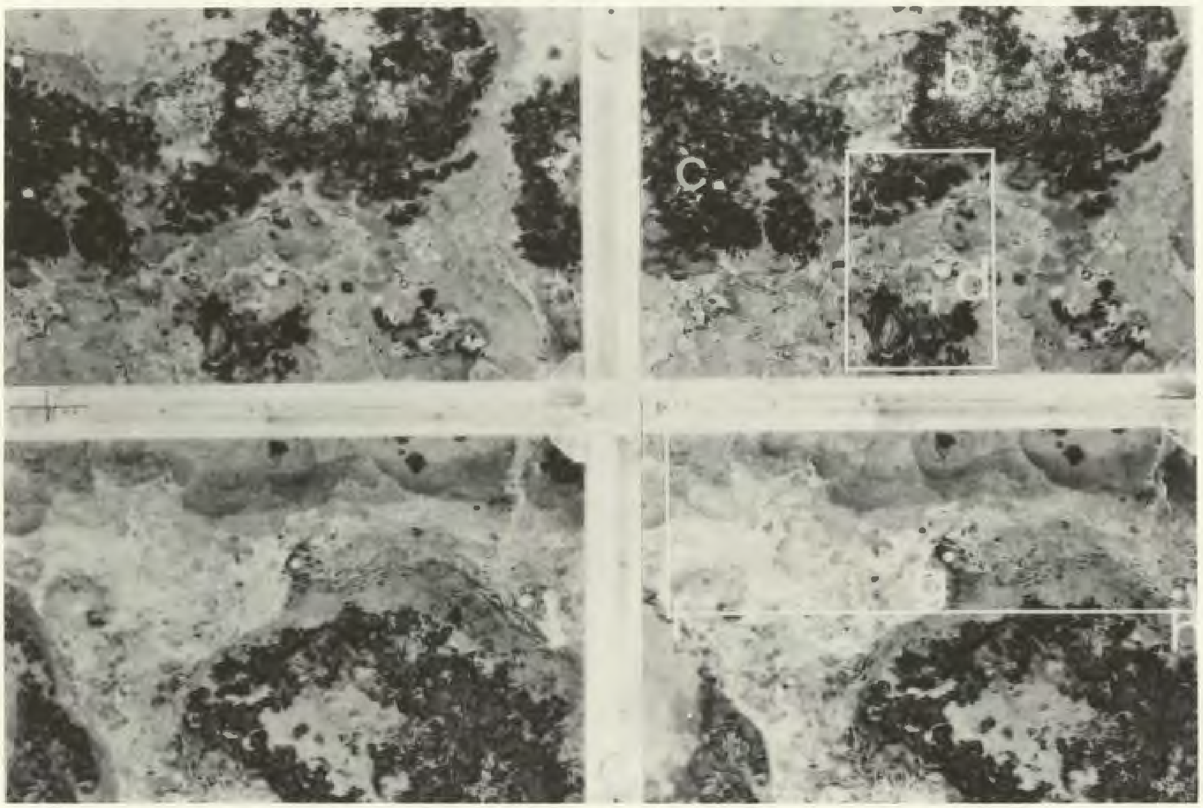
a
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Plate 37. Photograph of the left half of Section 4, Wait's Bay (1973 photo). Areas outlined were analyzed photogrammetrically. The results of this analysis were used to generate the geomorphic zonal map shown as overlay 1. The zones shown are:

- the resistant ridge zone
- the ridge/wall zone vvvv
- the steep slope zone ++++
- the vermetid pavement
- the cascade depression

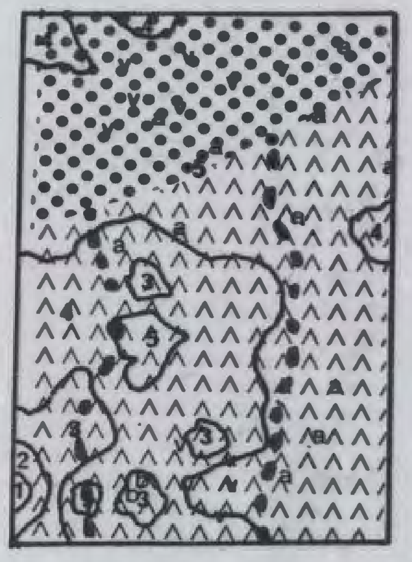
Overlay 2 displays the cumulative distribution of organisms from the 1971, 1972 and 1973 photographs:

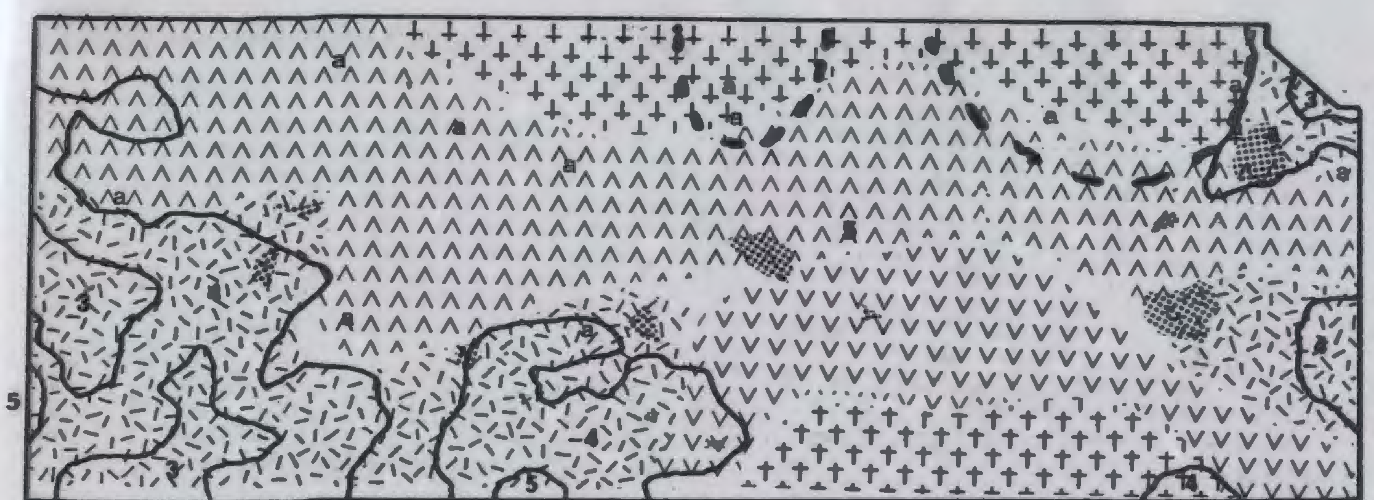
a = Acmaea jamaicensis
b = Acanthopleura granulata
v = vermetid gastopods
= littorine concentrations

Overlay 3 displays the results of residual contour mapping of this surface. Numbers correspond to ranges of erosion as follows:

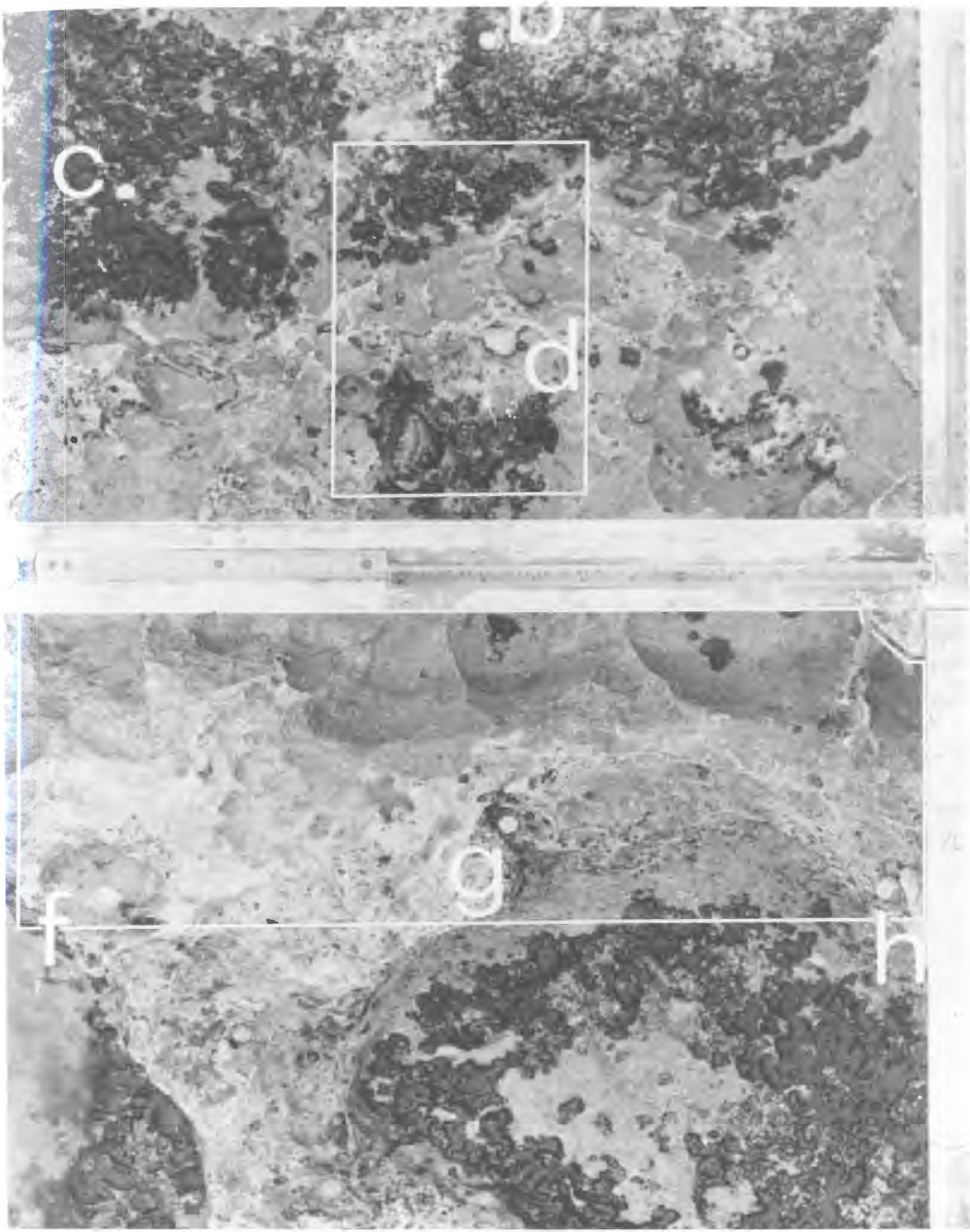
1 represents -3.0 to -5.0 mm/yr erosion
2 represents -1.0 to -3.0 mm/yr erosion
3 represents +1.0 to -1.0 mm/yr erosion
4 represents +3.0 to +1.0 mm/yr erosion
5 represents +5.0 to +3.0 mm/yr erosion

Negative erosional values indicate accretion.





37-3
37-37-2


b
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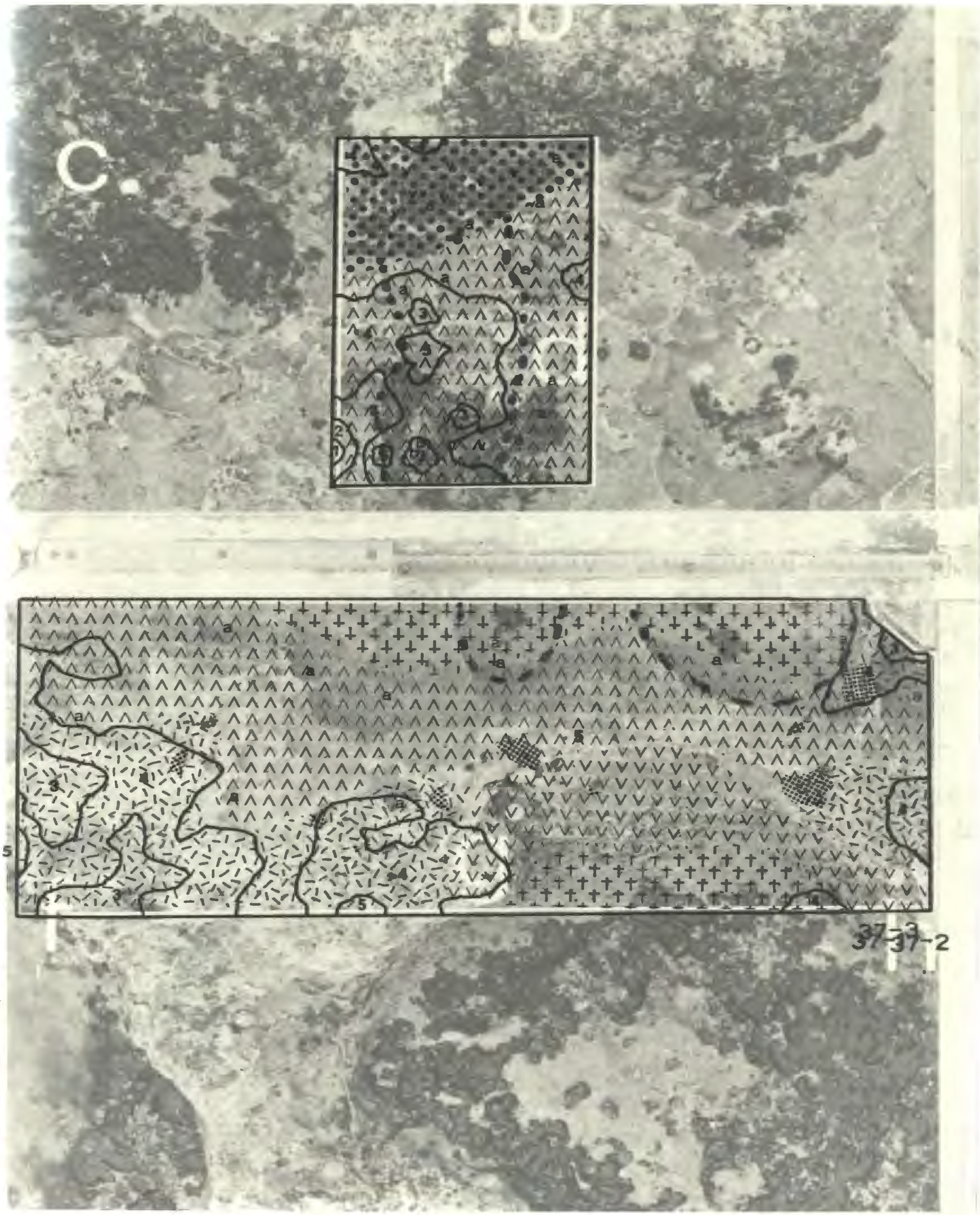

C.
37-3
37-37-2

in colonizing the higher and drier surfaces. These surfaces drain rapidly due to the porous nature of the rock and dry rapidly due to the high tropical insolation. The microalgae become more abundant as one moves from the high, dry rock surfaces to the lower, damper and more shaded slopes and rock depressions. Depression floors in this section are often covered by fine, dark carpets of the epilithic red alga _Bostrychia_ sp.

A number of epilithic invertebrates are found in this section (Table 7). Under the _Bostrychia_ carpet, may be found the encrusting vermetid gastropod, _Petaloconchus_ cf. _varians_ (Plate 38) whose shells impose a roughness and irregularity on the otherwise smooth-bottomed bowls. A single specimen of the chiton, _Acanthopleura granulata_ (Plate 39), has been noted in this area. It was found at the bottom of a small depression which closely approximates its body outline. The limpet, _Acmaea jamaicensis_, is also found in Section 4 (Plate 39). It is generally present on vertical walls of the depressions. Less commonly, it is found on depression floors and then only if there is good drainage of the basin. _Littorina meleagris_ is found on the upper walls of the depressions as are small numbers of _Littorina ziczac_.

With the exception of _Petaloconchus_ cf. _varians_ which secretes a mucous web from the foot gland to trap plankton, all of the organisms described above are grazers, that is, they gather food by rasping and scraping at their substrate

Plate 38. Heavy surficial encrustation by _Petaloconchus_ cf. _varians_., Section 4, Wait's Bay.

Plate 39. _Acmaea jamaicensis_ (arrow) in company with _Acanthopleura granulata_, Section 4, Wait's Bay. Apertures of vermetid gastopods (_Petaloconchus sp._) can be seen in upper left. Small scale pitting, most evident in the left central section, is caused by the activity of boring lithophytes. Coin is 18 millimeters in diameter.

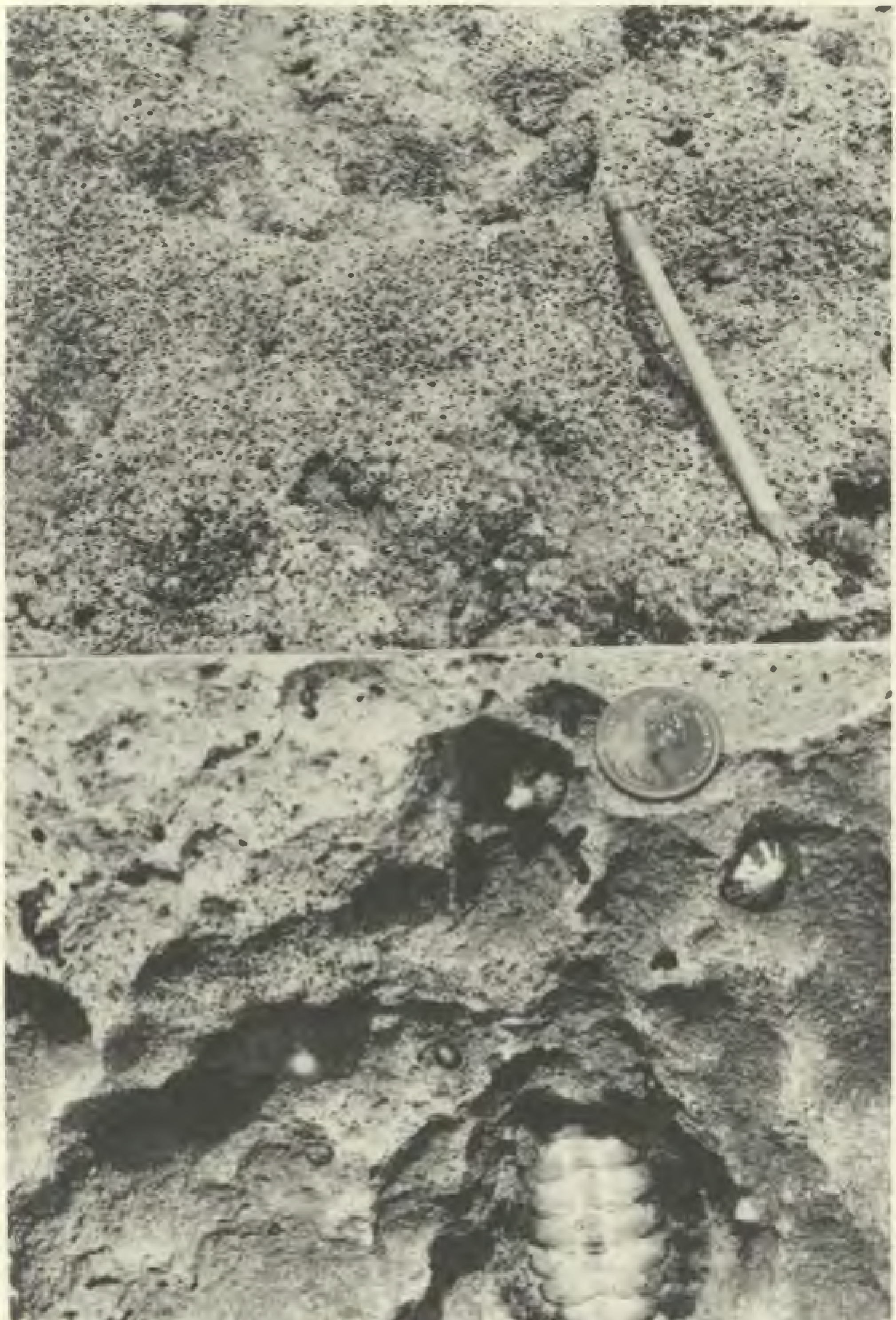


TABLE 7

SPECIES ABUNDANCE DATA, SECTION 4, WAIT'S BAY

Organisms	1971	1972	1973
Sessile:			
Filamentous algae	5%	10%	20%
Coralline algae	-	-	<1%
Petaloconchus sp.	10%	10%	5%
Mobile:			
Littorina meleagris	75	132	198
Littorina ziczac	36	21	-
Nerita versicolor	3	3	2
Nerita peloronta	1	-	-
Acmaea jamaicensis	106	112	120
Chiton marmoratus	-	-	12
Total number of species	7	7	7

Species abundance (in numbers of individuals or per cent coverage per square meter) for each year of study at Section 4, Wait's Bay.

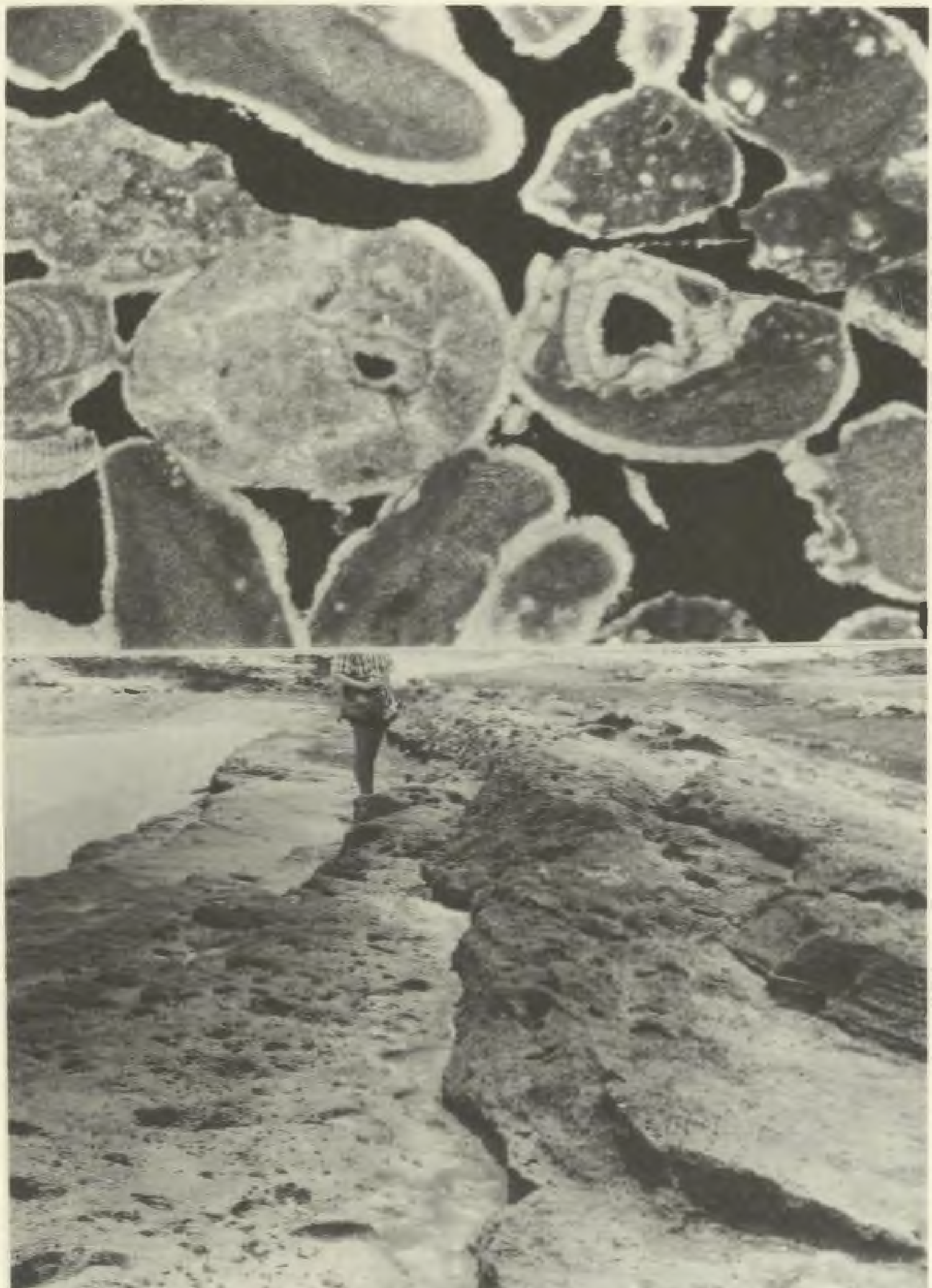
to collect the microflora on and in the rock. The ability of the grazers to remove substrate by their feeding activities is to a large extent dependent upon the nature of the substrate, that is, the mineralogy, structure and degree of lithification of the rock. All of the grazing organisms present in this section are equipped with radulae capable of rasping and dislodging the calcarenite grains of the rock surface.

Petrographic analysis of the rock of Section 4 reveals an essentially pure biocalcarenite with an average grain size of 0.65 mm. (thin section estimate) and very good sorting characteristics (standard deviation in grain size = 0.23 mm.). Cores taken at this locality show the rock to be well lithified. However, average grain size varies with depth in the rock and coarser-grained horizons are somewhat more friable than finer-grained horizons. Staining procedures (Friedman, 1959) indicate a calcitic cement. This cement is present as a thin (0.02 mm.) equant crust coating essentially all grains (Plate 40).

Five surface morphologies can be found at this locality. They include the resistant ridges, the slopes, the cascade depressions, the steep slope/wall, and the vermetid pavement. Statistical analysis of the residual values for these surfaces (Figure 37, overlay) indicates that of the five surface morphologies displayed, only the resistant ridge area displays a significantly lower mean

Plate 40. Equant crusts of calcitic cement coating essentially all grains. Section 4, Wait's Bay. Crossed nicols, 47x.

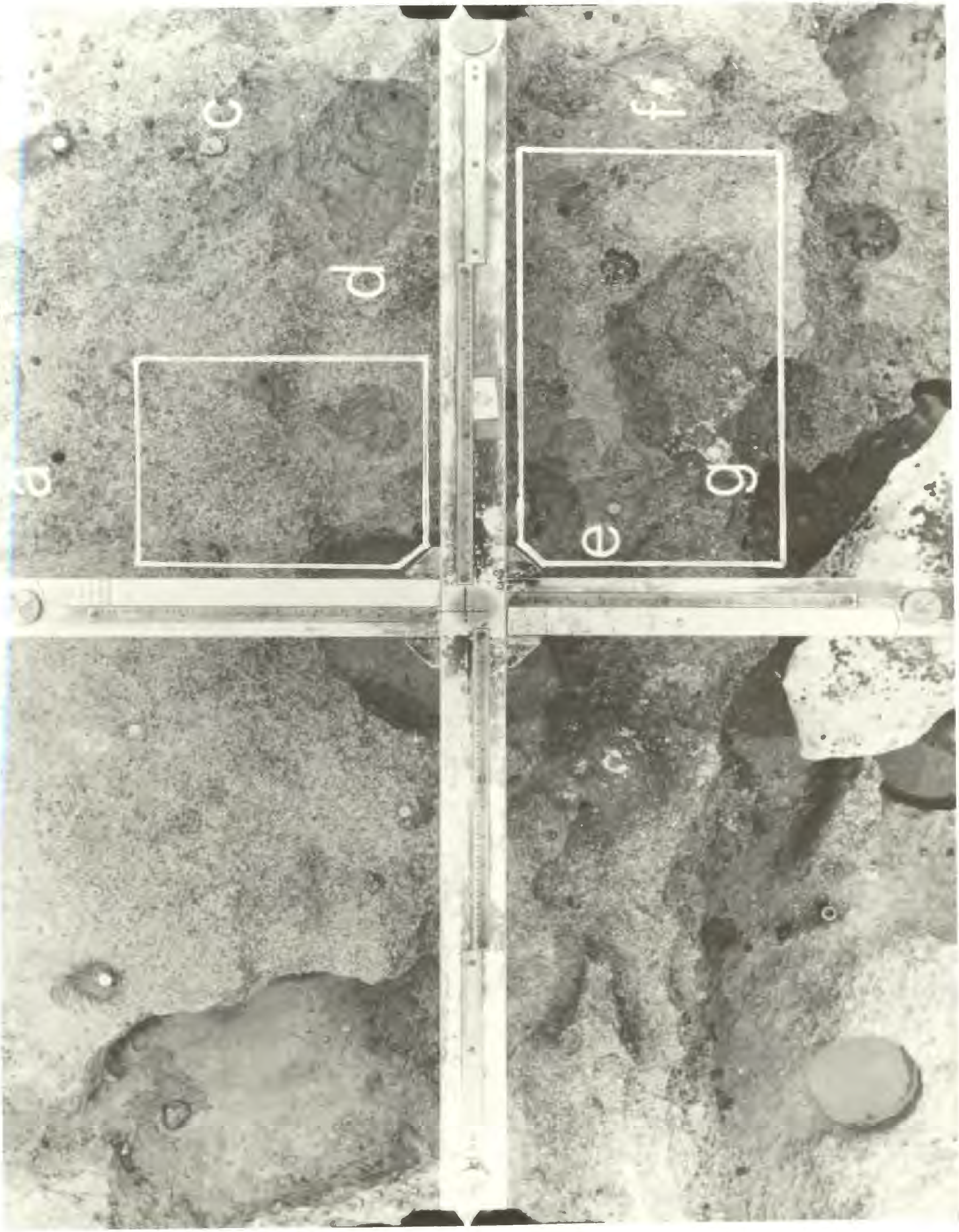
Plate 41. Seaward-dipping, weathered rock layers at the Wait's Bay locality. A sand flat appears landward (left) of the outcrop of beachrock. Section 6 is located on the dark ridge in the central part of the photograph.



erosional value than the other zones (Appendix, Table A4). This dry, highly insolated ridge area displays an annual average residual value of 0.9 mm./year ($n = 30$, $s^2 = 0.32$). The slopes beneath these ridges show somewhat higher erosion values with an average of 1.6 mm./year ($n = 57$, $s^2 = 0.40$). The cascade depressions display similar values to the slopes, with an average annual residual value of 1.4 mm./year ($n = 15$, $s^2 = 0.51$). The steep slopes and walls of the depressions offer still higher residual values with an average annual residual value of 1.7 mm./year ($n = 48$, $s^2 = 0.80$). The greatest annual average residual value, 1.8 mm./year ($n = 13$, $s^2 = 0.48$), is found on the vermetid pavement which covers the floors of the depressions. The differences in the erosion means for these last four zones is not statistically significant at the 95 per cent confidence level. Hence, statistically, two erosional zones exist on this surface. These zones differ in that the first zone (the resistant ridge), which displays the lower erosional mean, is higher, drier, has lower lithophytic microphyte content and has essentially no epilithic grazers.

Section 6 is located in the upper intertidal/splash zone of Wait's Bay (Figure 4; Plate 41). The rock surface is characterized by both open and closed bowls or depressions of various sizes and depths, sunk into shallow, seaward-dipping strata. In some cases, the walls of the depressions are undercut (Plates 42, 43, 44, 45 and 46). As

Plate 42. Surface of Section 6, 18 April, 1973, showing general surface appearance and ground control points (a-g). The areas outlined on the right side of this section were investigated photogrammetrically and are treated in detail in Plates 43-47.


c
f
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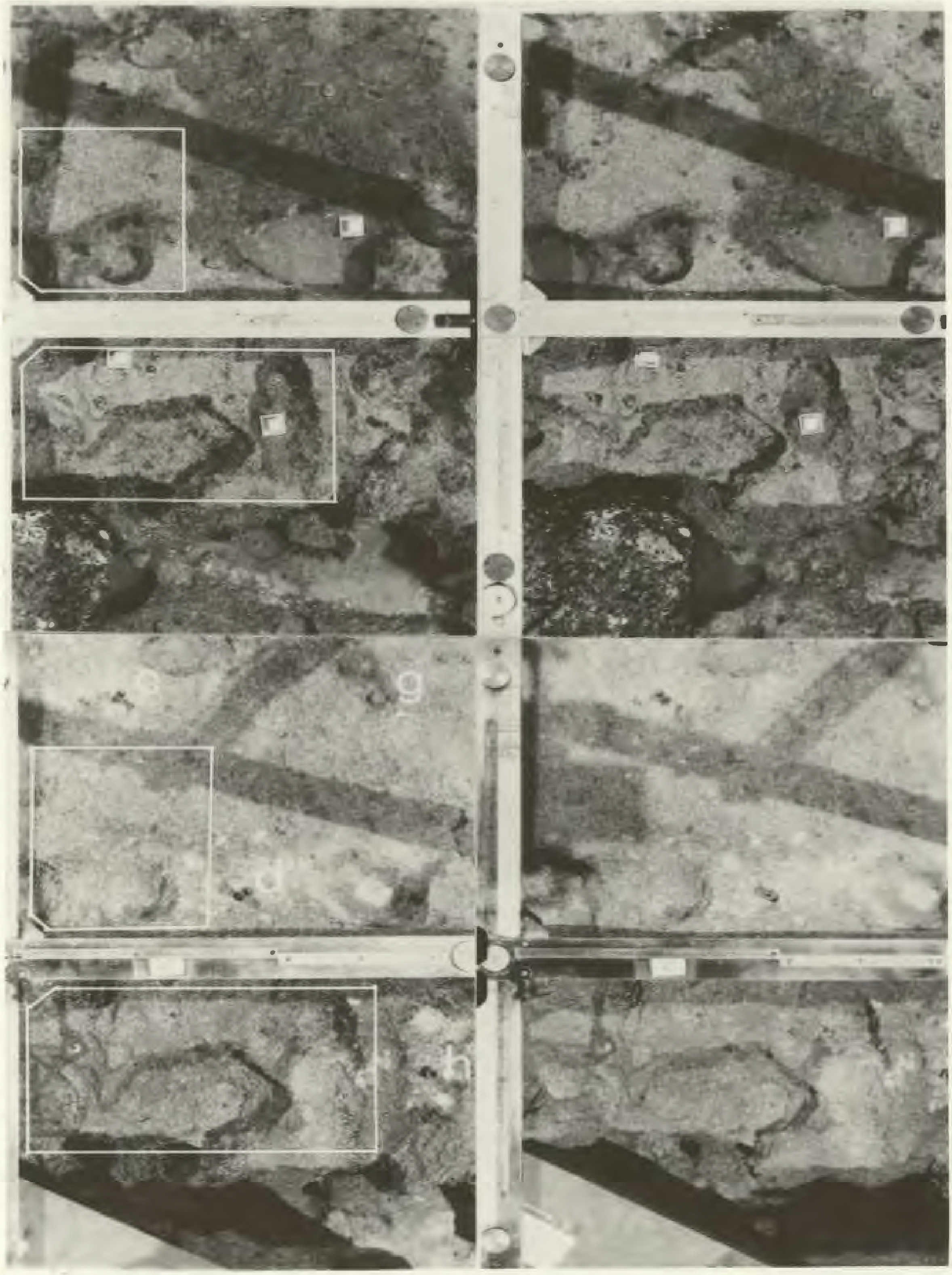
a
g
e

Plate 43. Stereophotographs of Section 6, Wait's Bay, 23 April, 1970. Surface is characterized by "bare" rock and conspicuous absence of all epifauna with the exception of littorinid gastropods (Littorina ziczac, L. meleagris and Nodilittorina tuberculata) which may be found singly, in small groups or in large aggregations on the rock surfaces.

Plate 44. Stereophotographs of Section 6, Wait's Bay, 29 April, 1971. Surface characteristics similar to previous plate.


c
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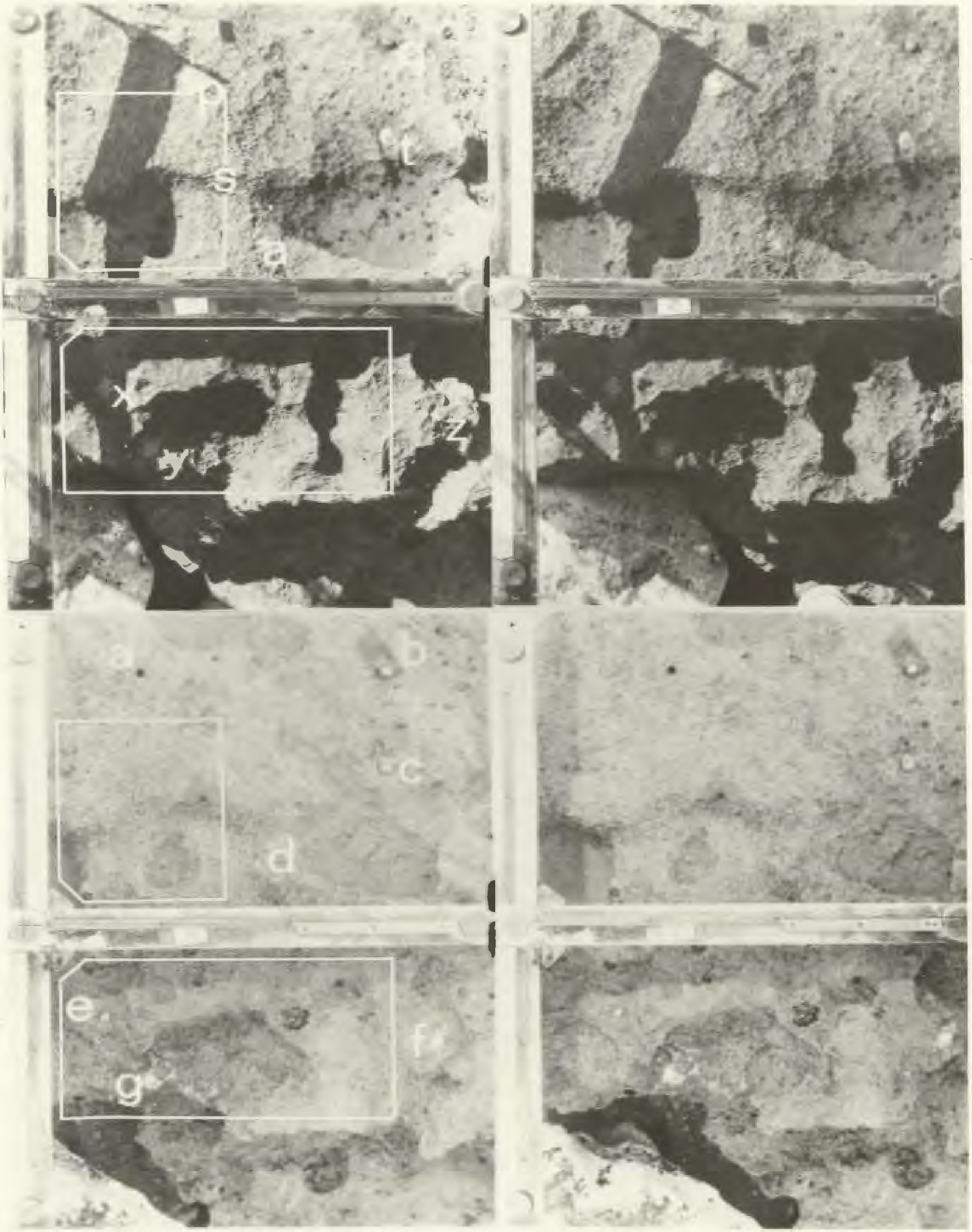
d
h

Plate 45. Stereophotograph of Section 6, Wait's Bay, 3 May, 1972. Surface characteristics similar to preceding two plates.

Plate 46. Stereophotographs of Section 6, Wait's Bay, 18 April, 1973. Similar to preceding three plates. Note presence of tar patch (5 cm. diameter) in lower central area.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in Section 4, several geomorphic zones may be delineated (Plate 47 and overlay). They are not, however, as distinct as in the lower intertidal section. Due to its location in the high intertidal zone, Section 6 is a much drier area than Section 4. This is reflected in the lower diversity of fauna (Table 8). The most abundant organisms found on this surface are the littorine gastropods--*Littorina ziczac*, *L. meleagris*, and *Nodilittorina tuberculata* (Plate 48). They are commonly found on the walls and higher areas of the section. These littorines tend to aggregate in large numbers on the rock surfaces but are also found as isolated individuals or in small groups of five to ten individuals. Neritid gastropods, such as *Nerita peloronta*, *N. tessellata* and *N. versicolor*, are also found in this area, commonly on the bottom of depressions. These gastropods prefer the moist conditions found in these depressions (Plate 48). Both the littorine and neritid gastropods are grazers and their major food source is the lithophytes found on and in the rock of Section 6. Examination of the gut contents of these organisms revealed masses of algal filaments and ovoid algal bodies presumably rasped from the rock surface. The microboring algae in this case are believed to be exclusively cyanophytes, tentatively identified as ?*Mastigocoleus* sp., ?*Hyella* sp. and ?*Plectonema* sp. Also noted in the gut contents of the gastropods were small particles of $CaCO_3$ indicating the bioerosional capabilities of these organisms.

Plate 47. Photograph of right half of Section 6 (1973 photo). Areas outlined were analyzed photogrammetrically. Results were used to generate a geomorphic zonal map shown as Overlay 1. Two major zones were distinguished:

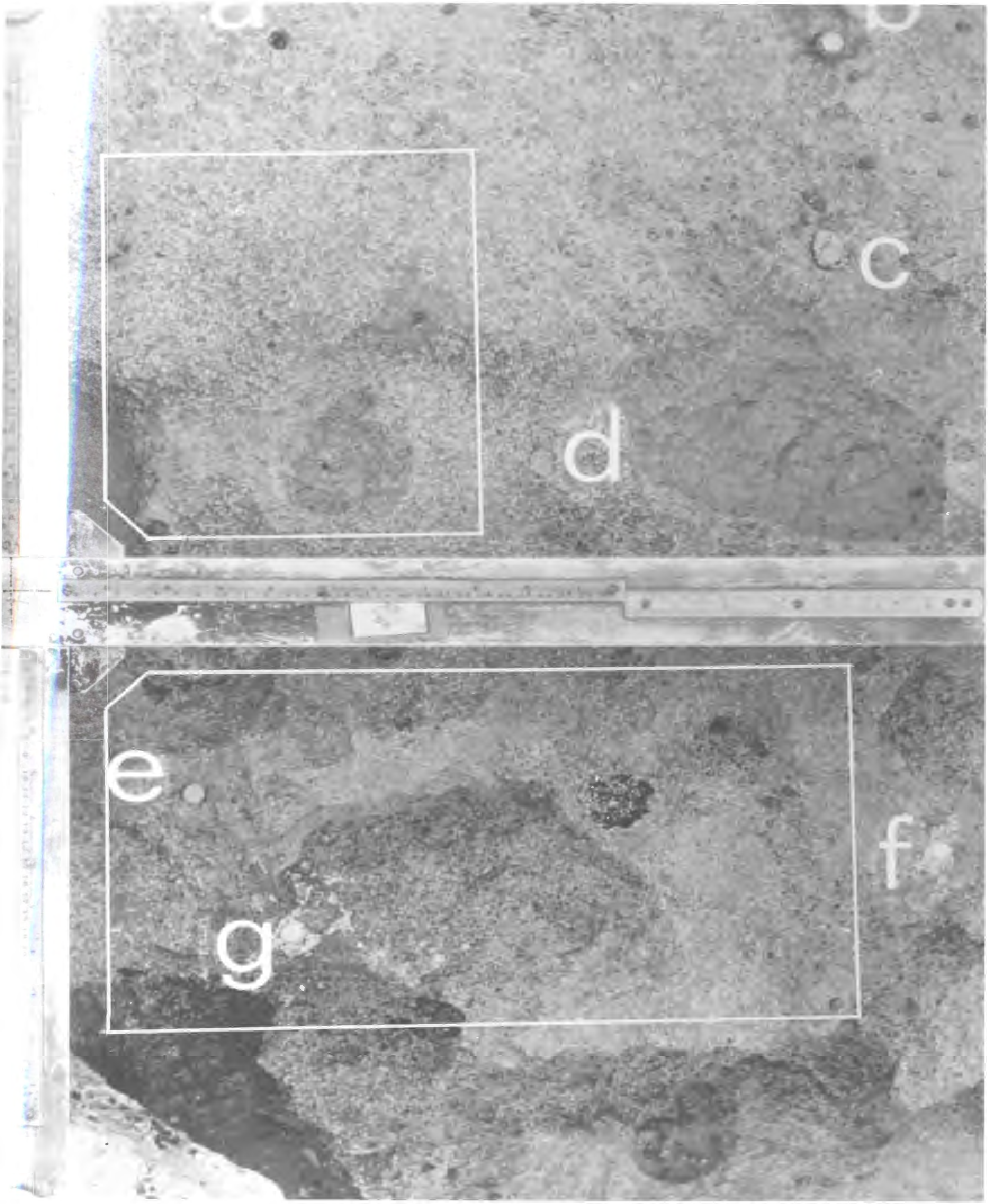
- basins
- ridge/slopes ^^^^ (which included several cascade depressions which are outlined with dashed lines.)

Overlay 2 shows the cumulative distribution of littorine gastropods (1970-1973) based on 1970-73 photographs.

Overlay 3 displays the results of residual contour mapping for this surface. Numbers correspond to ranges of erosion as follows:

1 represents -3.0 to -5.0 mm/yr erosion
2 represents -1.0 to -3.0 mm/yr erosion
3 represents +1.0 to -1.0 mm/yr erosion
4 represents +3.0 to +1.0 mm/yr erosion
5 represents +5.0 to +3.0 mm/yr erosion

Negative erosional values indicate accretion.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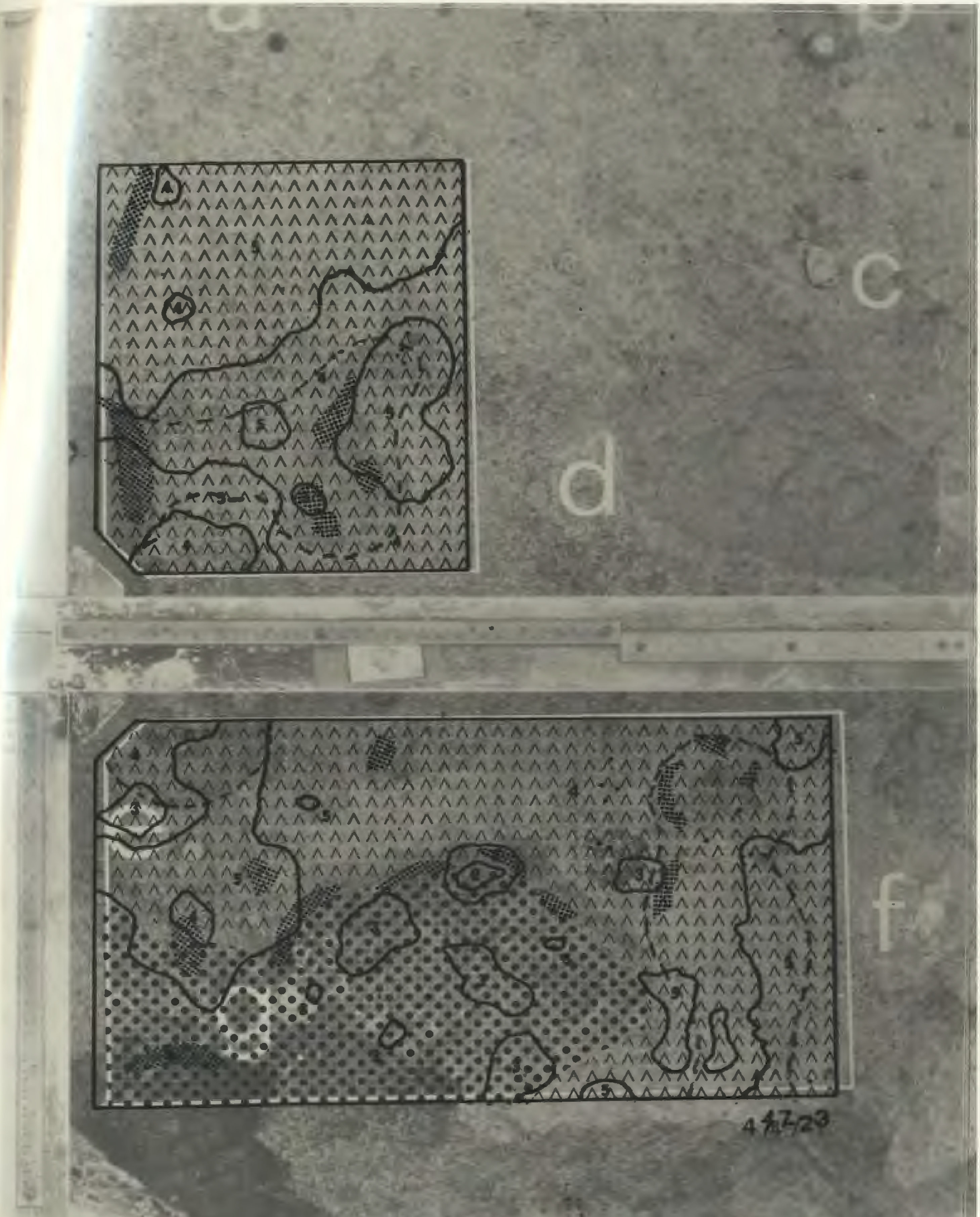

a
b
c
d
f

TABLE 8

SPECIES ABUNDANCE DATA, SECTION 6, WAIT'S BAY

Organism	1970	1971	1972	1973
Sessile:[1]	-	-	-	-
Mobile:				
Littorina meleagris	-	-	2	4
Littorina ziczac	536	15	1004	214
Nodilittorina tuberculata	1384	90	842	470
Nerita versicolor	-	-	18	2
Nerita peloronta	2	-	2	-
Total number of species	3	2	5	4

Species abundance (number of individuals per square meter) for each year of study at Section 6, Wait's Bay.

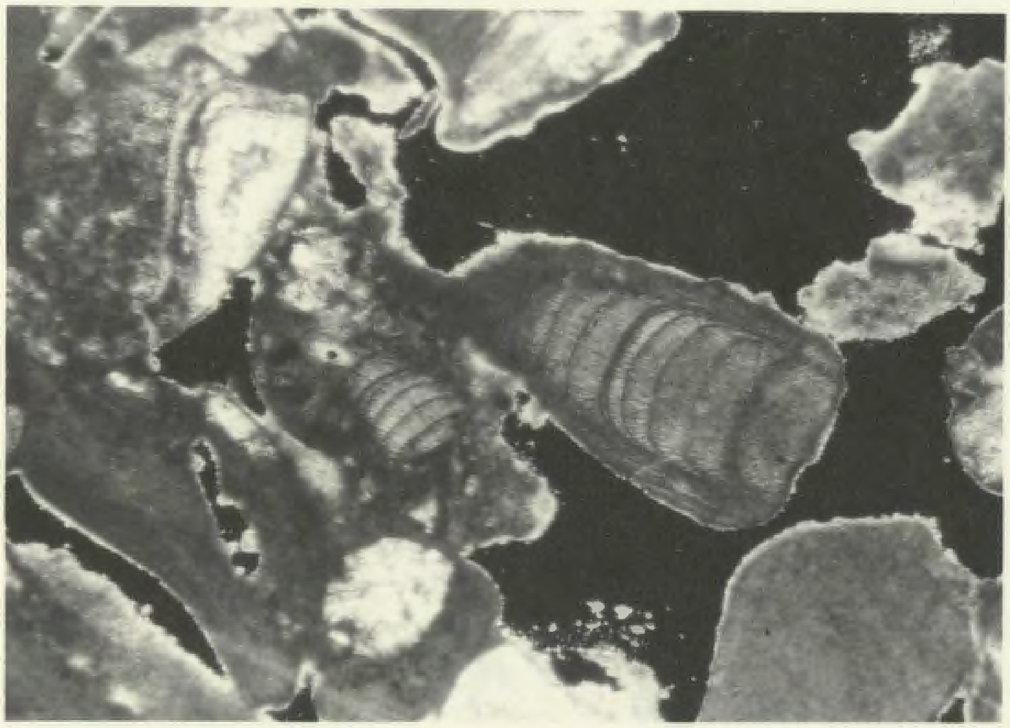
[1]No meaningful method of determining endolithic algal abundance was developed during the course of this study.

Plate 48. Littorinid and neritid gastropods at Section 6, Wait's Bay. The littorinids tend to aggregate on the higher parts of this section whereas the neritids (arrow), fewer in number, are usually found on the lower walls and floor of the depressions.

Petrographically, Section 6 is very similar to Section 4, with the exception of the cementing agent. Average grain size, based on thin section estimate, is found to be slightly over 0.68 mm. and the rock displays very good sorting (standard deviation = 0.26 mm.). Both aragonite and calcite bioclasts are present. Thin sections taken from the surface rock reveal that irregular micritic "halos" of 4 to 8μ thickness are present around most grains (Plate 49). The mineralogy of these halos is that of Mg-calcite. Staining also indicates the presence of some calcite in the voids between grains. Thin sections, prepared from a core sample at 7.25 cm. depth, show a downward decrease in Mg-calcite and the appearance of aragonite cement.

Photogrammetric data on this section show an overall erosion value of 1.3 mm./year (n = 267, s^2 = 0.28). In contrast to Section 4, the basins of Section 6 display the lowest average erosion value of 0.9 mm./year (n = 52, s^2 = 0.21) while the slopes and cascade depressions both display an average annual erosion value of 1.4 mm./year (n = 164, s^2 = 0.25, and n = 51, s^2 = 0.28, respectively). As can be seen in Table 6, the erosion values are very similar between Section 4 and Section 6 with respect to slopes and shallow (cascade) depressions. However, the difference in values in the basins is worth considering, especially since the characteristics of the floors of the basins are so different.

Plate 49. Thin, irregular micritic halos around bioclasts. Central grain shows characteristic coralline algal microstructure. Wait's Bay, Section 6. Crossed nicols, 50x.



In Section 4, the basins are not closed, that is, they are flushed with water relatively often compared to those of Section 6 which are poorly drained and tend to contain standing pools of warm seawater which are flushed only at high tidal periods. Hence, the depressions of Section 6 present a considerably different microenvironment from those of Section 4. The warm, stagnant water in the depressions of Section 6 minimizes the epilithic habitation. In addition, the lithophytic microphytes appear to be more restricted in these pools. This is evidenced by the buff colours of the rock on the pool bottom which may be contrasted to the grey to black colour of the surrounding rock. This grey-black colour is caused by pigmentation of the microalgae found in the rock and is not observed in the depressions of Section 6. In addition, the pools of Section 4 are often encrusted to some extent by vermetid gastropods. Discontinuous patches of the alga, Bostrychia sp., are also found attached to the floor of the pools.

Heywood's Beach

Heywood's Beach is located on the leeward coast of Barbados, just north of Speightstown (metric coordinates 1465950N by 655000E). A beachrock outcrop, striking roughly north-south, parallels the shore and is separated from it by a narrow moat or tidal channel (Plate 50). Three sections were initially established on this beachrock slab (Sections 18, 20 and 22). One of these sections (18) has been analysed

Plate 50. The inclined beachrock slab at Heywood's Beach parallels the shoreline and is separated from it by a shallow tidal channel. Section 18 is located in a sinuous barnacle ridge area (arrow).

photogrammetrically.

Section 18 was established on the shoreward side of the beachrock outcrop (Figure 4). The surface of this section is approximately horizontal and displays a rough, pitted appearance due to the presence of the barnacle Tetraclita squamosa (Plates 51-57). Single and multiple barnacle pedestals characterize much of this section. These pedestals, up to 2 cm. in height, are formed by undermining of the rock around the base of the barnacle shell. This shell isolation and pedestal formation affects both living barnacles and empty shells. With continued undermining, break off of the pedestal can be expected.

In addition to the encrusting barnacles, encrusting vermetid gastropods (Petaloconchus cf. varians) are found in this section and generally form a thin veneer on the rock surface. Based on population counts (Table 9, p.148) their numbers have increased from 1970 to the present while the barnacle population has decreased.

The only epilithic grazer observed annually is the keynote limpet, Fissurella barbadensis. This mollusc is found in the deeper depressions and between barnacle pedestals. The limpet is an active grazer and has available to it both macrophytic detritus that might be deposited in the crevices and pits of this area and microphytic organisms found in the substrate. In addition, F. barbadensis contributes significantly to the formation and subsequent collapse of the

Plate 51. Surface of Section 18, Heywood's Beach, 18 April, 1973, showing general surface characteristics and ground control points (b,c,e,h,l,m). The areas outlined on the right were investigated photogrammetrically and are treated in Plates 52-56.

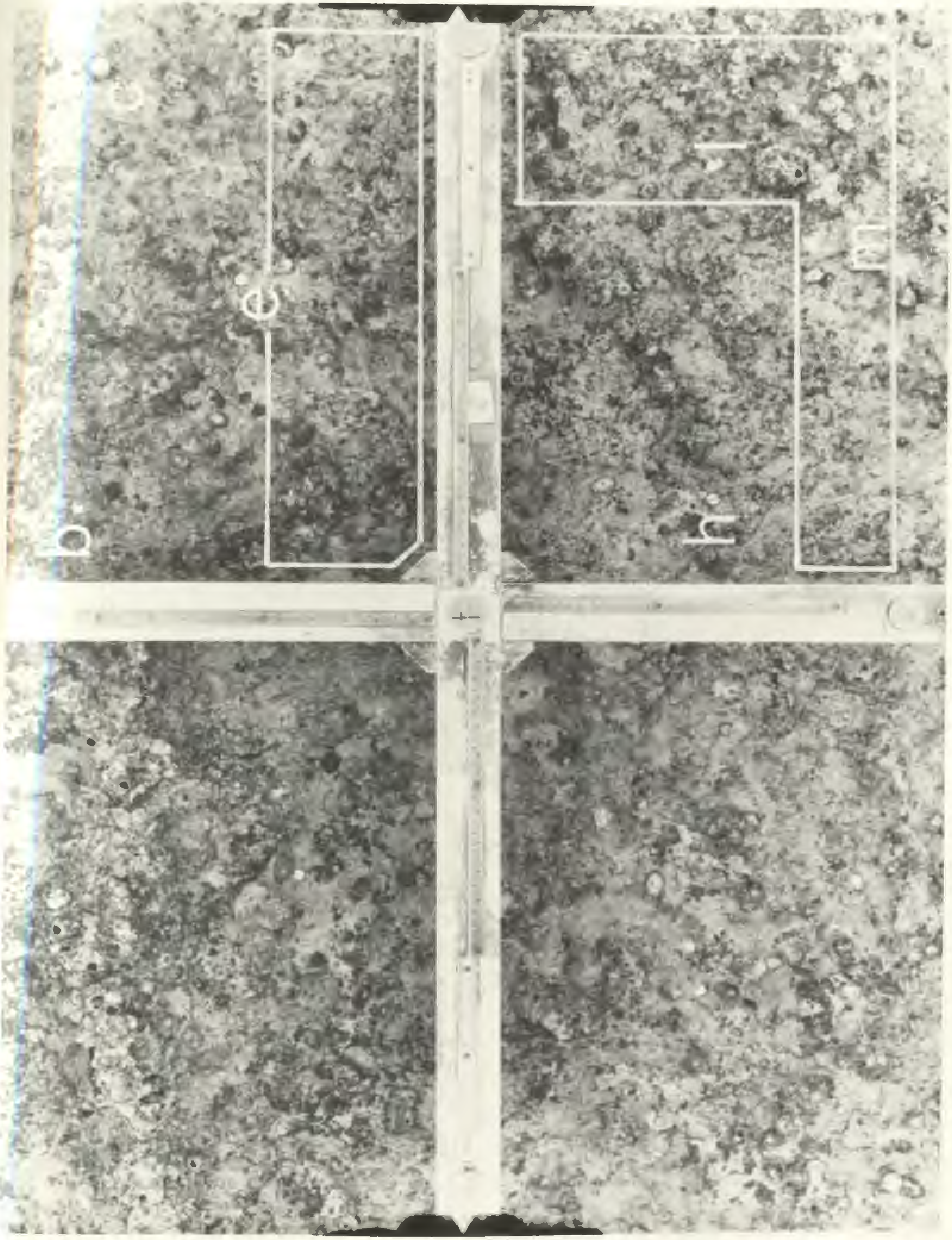


Plate 52. Stereophotographs of Section 18, Heywood's Beach, 4 May, 1970. Surface is characterized by small scale peaks and depressions, formed by the pyramidal shells of the encrusting, sessile barnacle, Tetraclita squamosa. Dark mottling of the surface is caused by dessicated patches of the filamentous rhodophytes, Bostrichia sp. and Polysiphonia sp. Note the presence of the keyhole limpet, Fissurella barbadensis in the depressions between peaks and ridges of the microlapies surface. Also evident are two large fractures in the rock surface--one in the upper half of the section and trending northeast and the other in the lower left and trending south-southeast.

Plate 53. Stereophotographs of Section 18, Heywood's Beach, 11 May, 1971. Similar to preceding plate. However, filamentous algal cover is less apparent due to dessication and bleaching of the filaments by the sun.

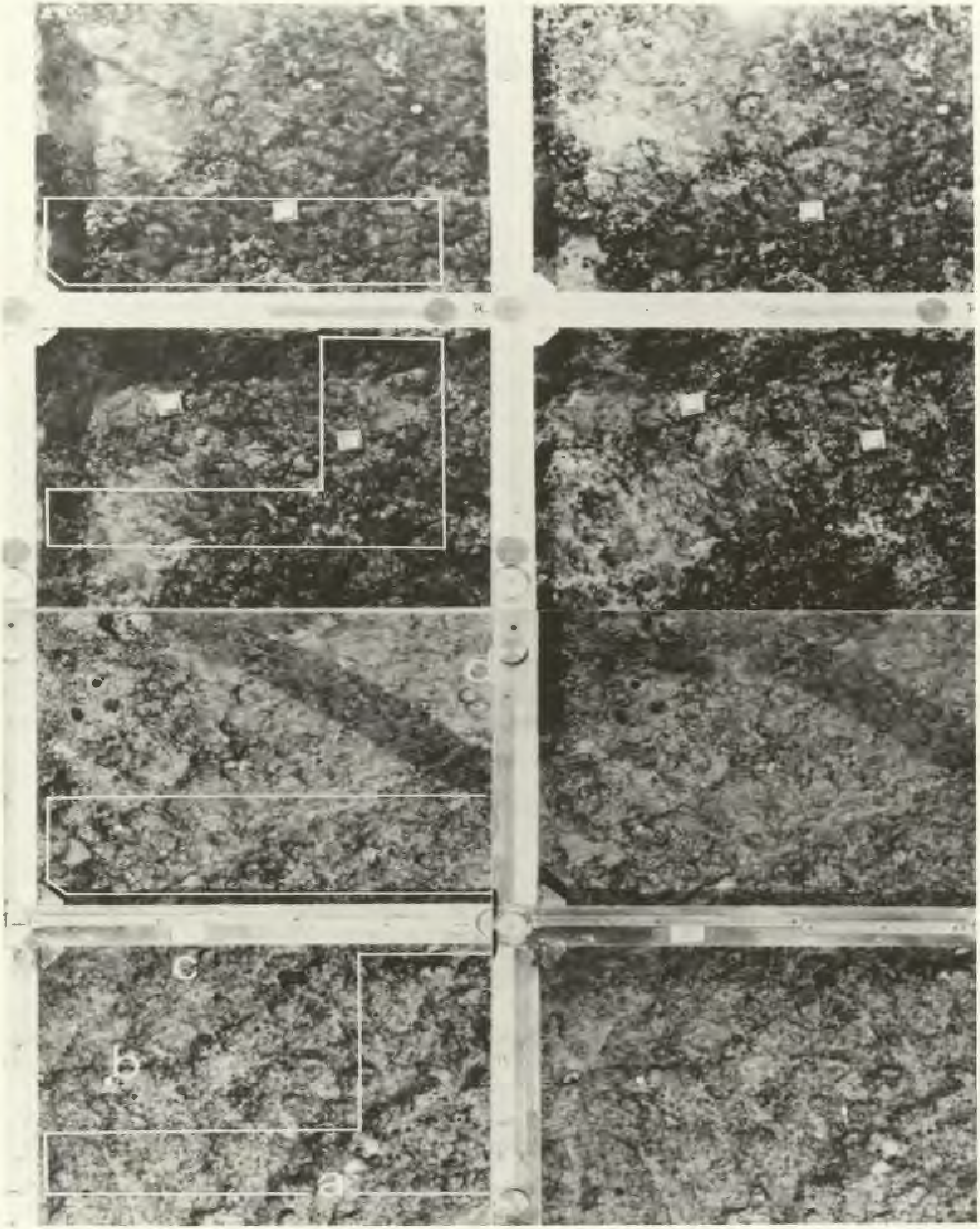
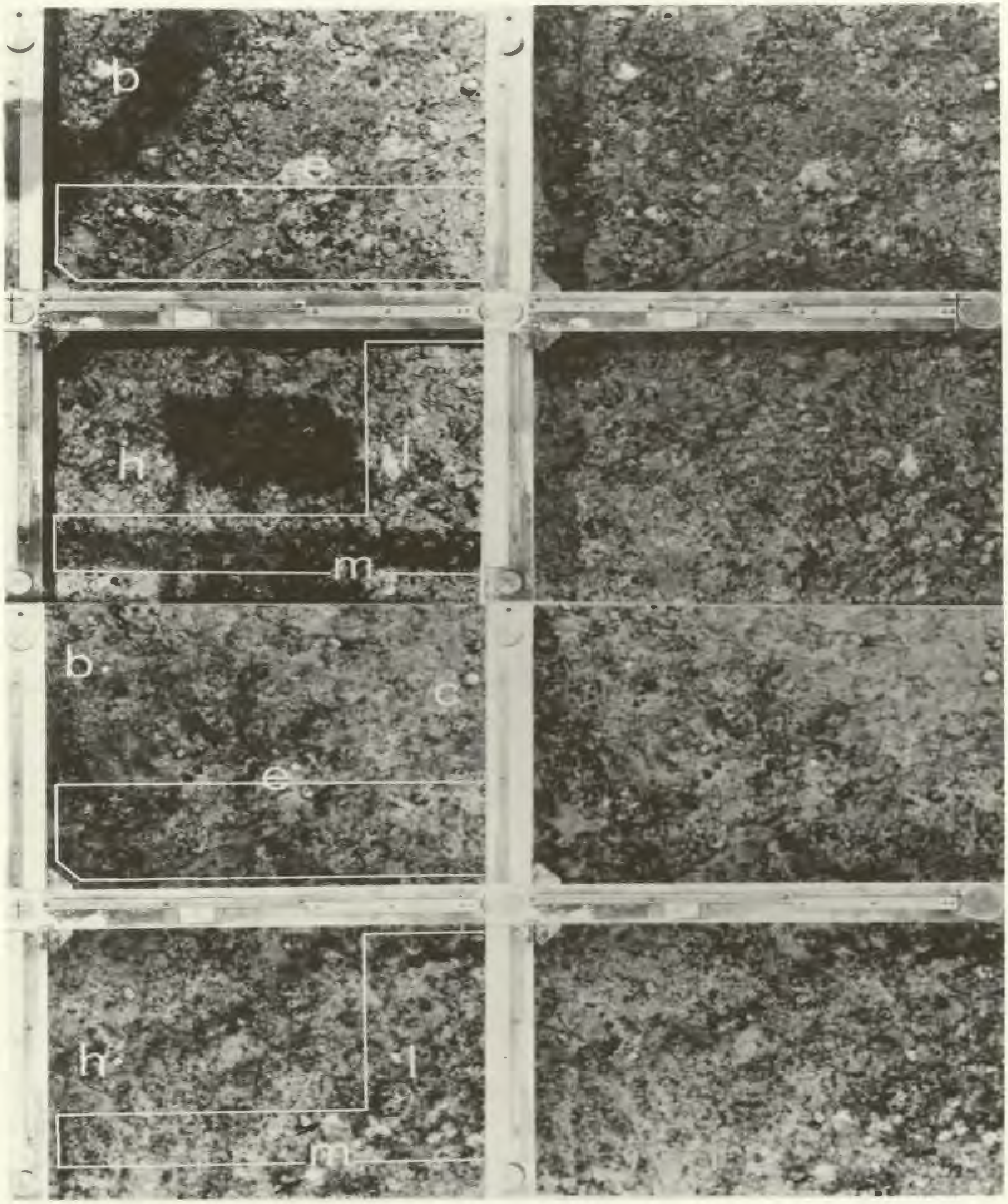

c
b
a

Plate 54. Stereophotographs of Section 18, Heywood's Beach, 30 April, 1972. Similar appearance to preceding two photographs. Note presence of limpets in the same depressions as shown in 1971 photograph.

Plate 55. Stereophotographs of Section 18, Heywood's Beach, 18 April, 1973. Evidence of catastrophic erosion of barnacle pedestals is seen in the lower part of this section. Arrows point to the remnant scars. Again, note keyhole limpets in the same depressions as in preceding years.



b
e
h
l
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b
c
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l
m

Plate 56. Photograph of right hand of Section (1973 photo). Areas outlined were analyzed photogrammetrically. Results were used to generate geomorphic zonal maps. Two distinct zones, shown in Overlay 1, were established:

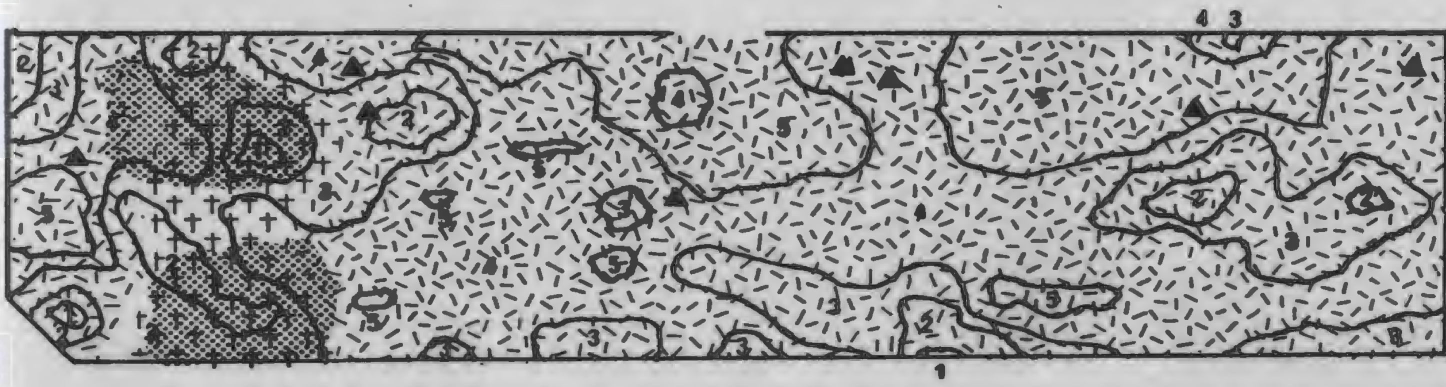
- a "microlapies" zone
- a living barnacle zone

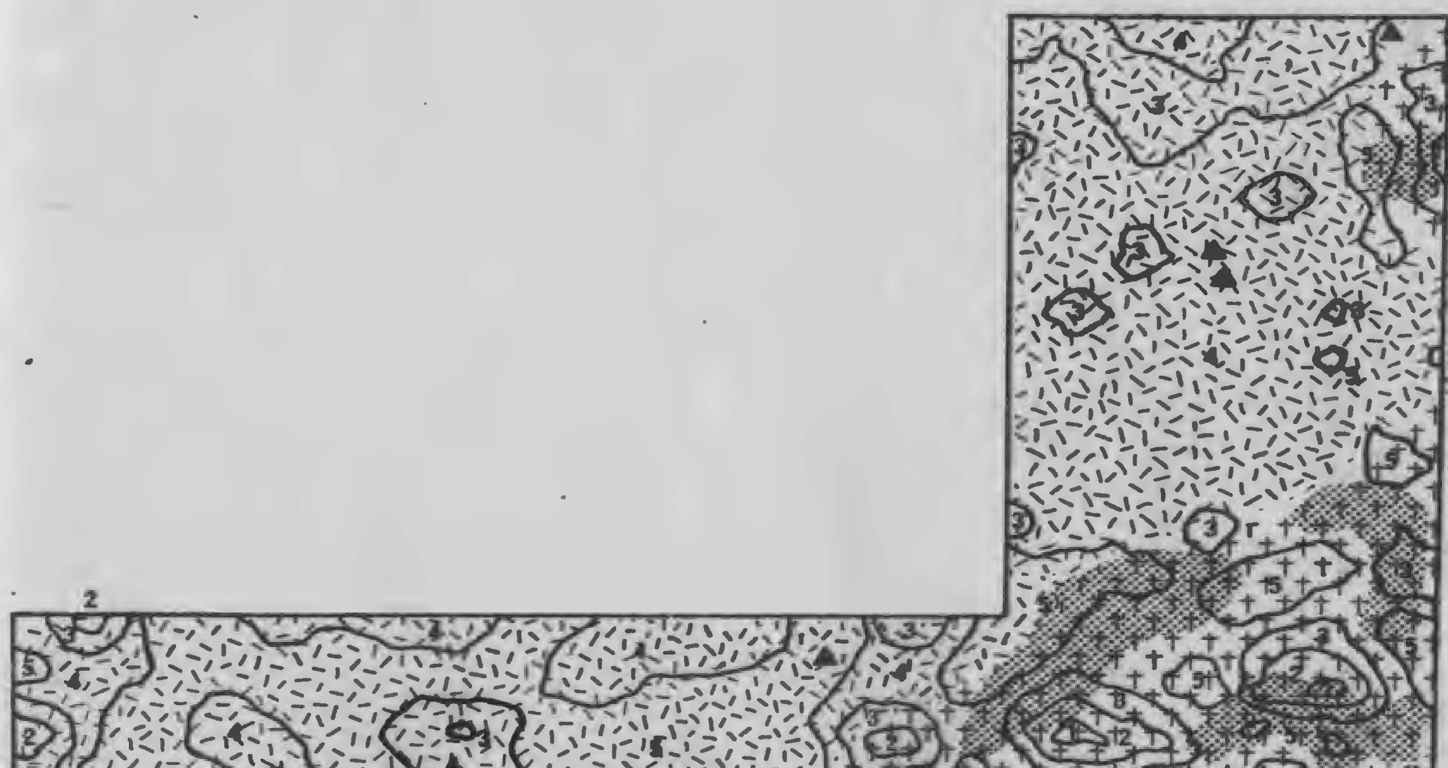
Overlay 2 shows the cumulative epifaunal distribution for this zone. Living barnacles and keyhole limpets, *Fissurella barbadensis* ▲ were found epifaunally.

Overlay 3 displays the results of residual contour mapping of this surface. Numbers correspond to ranges of erosion as follows:

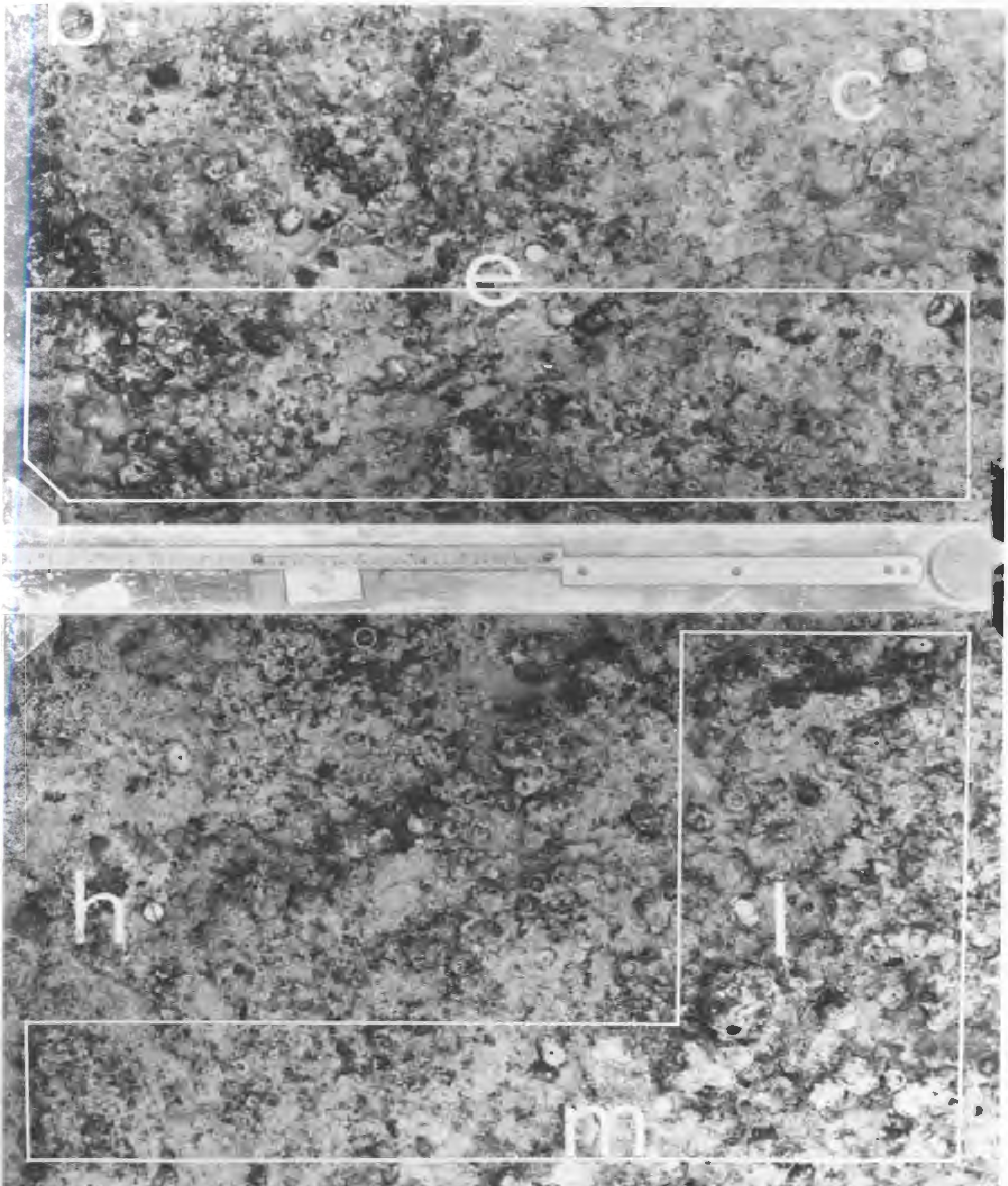
1 represents -3.0 to -5.0 mm/yr erosion
2 represents -1.0 to -3.0 mm/yr erosion
3 represents +1.0 to -1.0 mm/yr erosion
4 represents +3.0 to +1.0 mm/yr erosion
5 represents +5.0 to +3.0 mm/yr erosion

Negative erosional values indicate accretion.





56-2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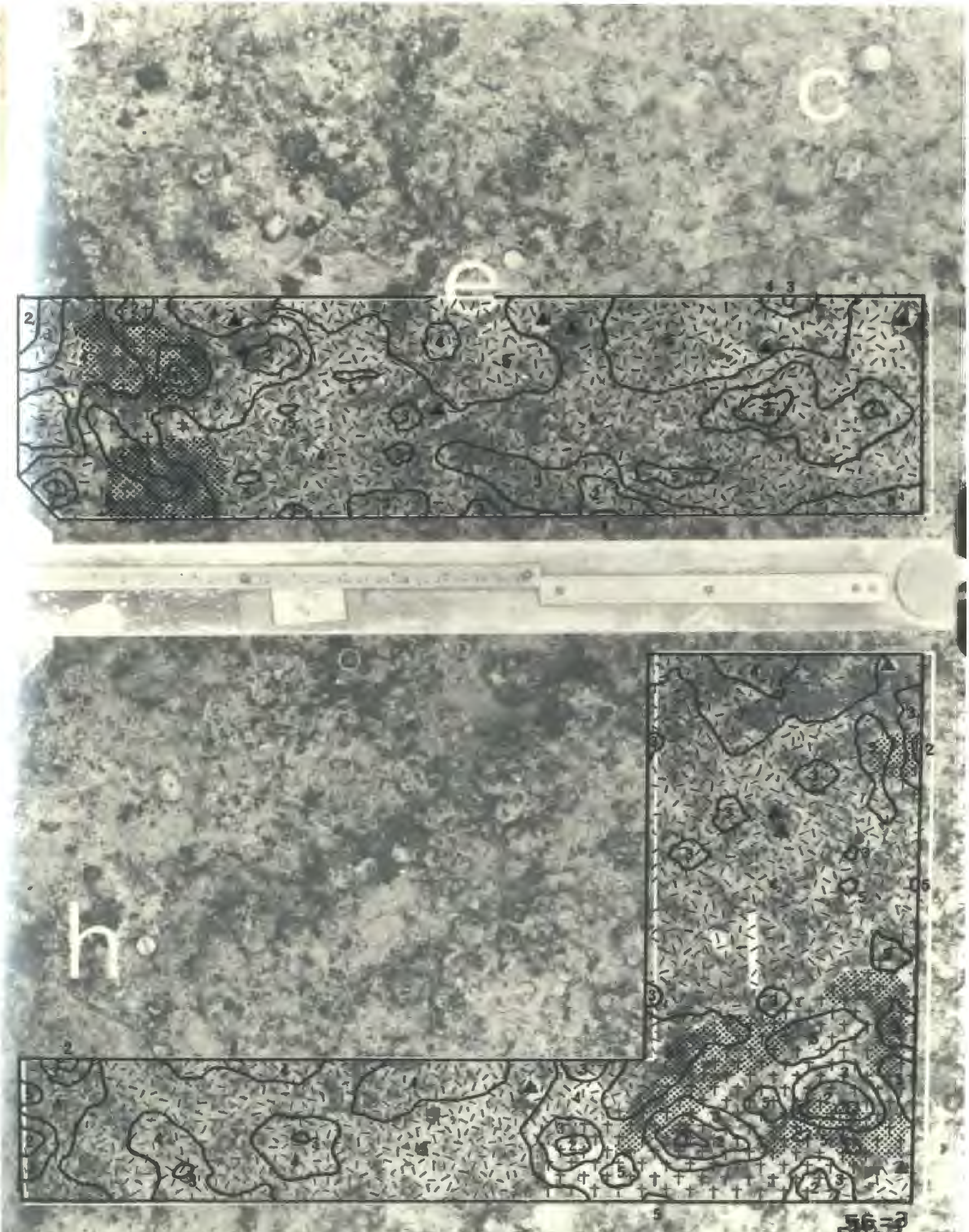
c
e
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i
56-2

Plate 57. Encrustation near Section 18, Heywood's Beach, composed of the sessile barnacle _Tetraclita squamosa_ (a). Note multiple barnacle pedestals immediately above and to the right of "a". Entrance to a boring of the barnacle _Lithotrya dorsalis_ may be seen immediately to the right of "b". Lens cap is 55 millimeters in diameter.

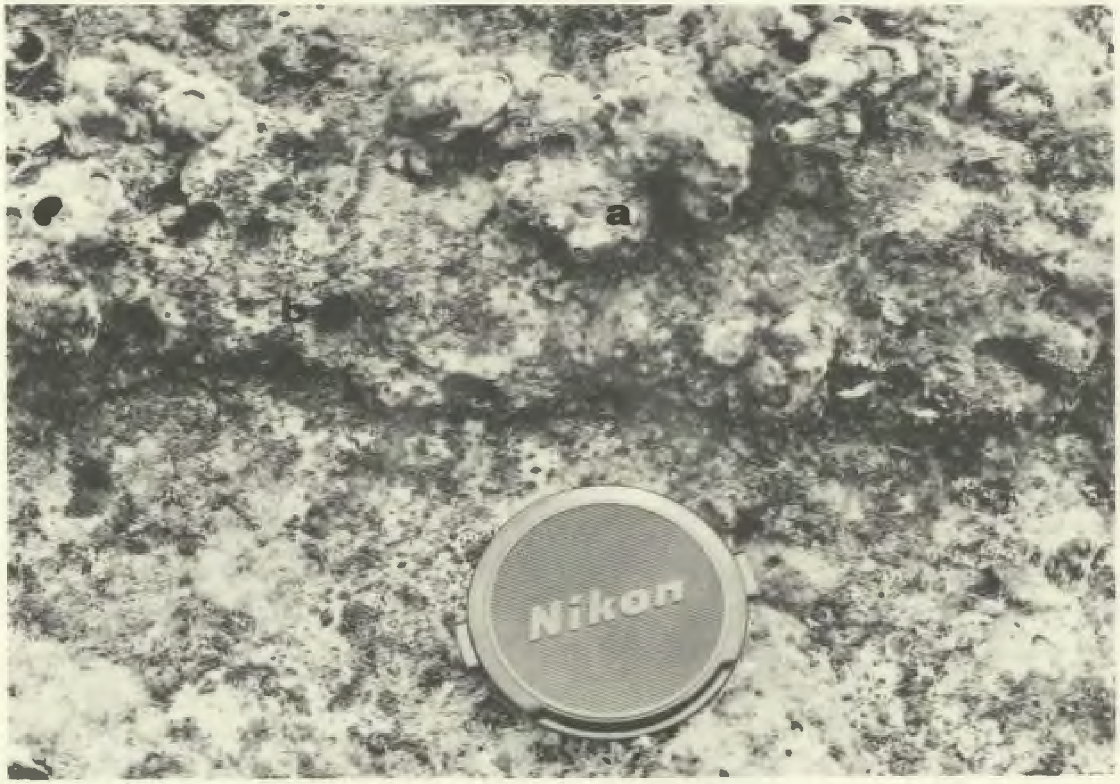

a
b
Nikon

TABLE 9

SPECIES ABUNDANCE DATA, SECTION 18, HEYWOOD'S BEACH

Organisms	1969	1970	1971	1972	1973
Sessile:					
Filamentous algae	-	-	50%	19%	35%
Coralline algae	-	-	-	-	22%
Petaloconchus sp.	22%	15%	38%	28%	47%
Tetraclita squamosa	460	224	320	204	196
Mobile:					
Fissurella barbadensis	4	28	48	50	36
Acanthopleura granulata	4	-	-	-	-
Total number of species	4	3	4	4	5

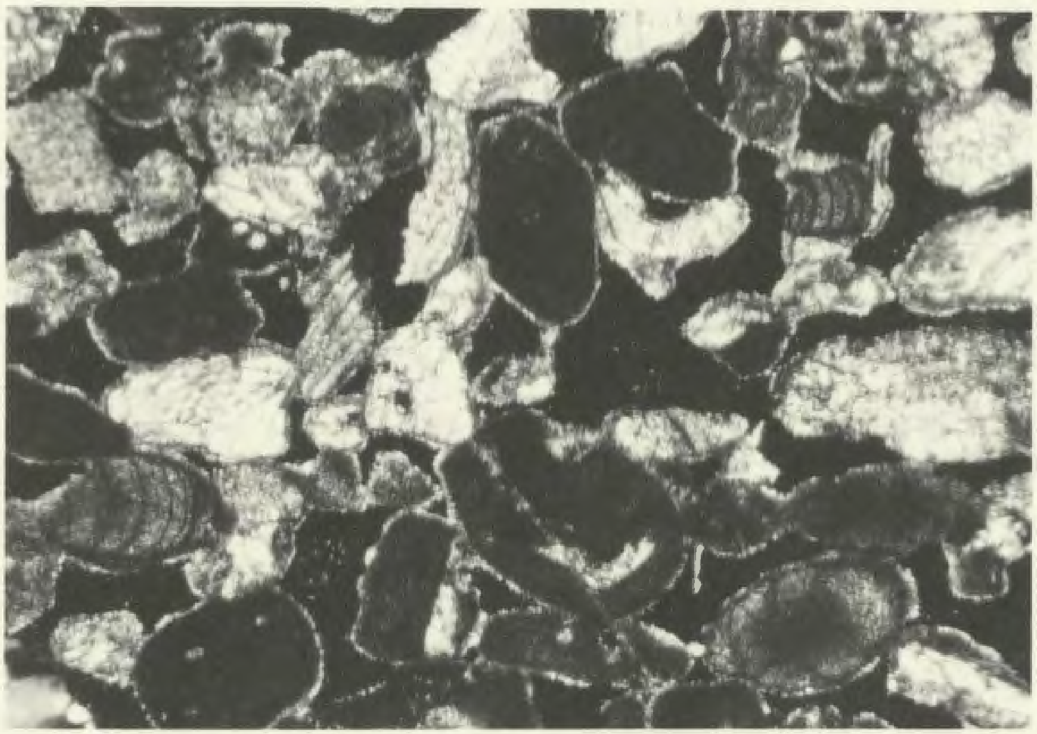
Species abundance (number of individuals or per cent coverage per square meter) for each year of study at Section 18, Heywood's Beach.

barnacle pedestals, due to its grazing activities around the barnacle bases. Four specimens of the chiton, Acanthopleura granulata, were noted in 1969 but have not been present since that time.

Petrographic analysis of Section 18 shows the rock to have a somewhat finer average grain size (= 0.38 mm.) than Section 4 and 6 (Table 3). Very good sorting characteristics are displayed (standard deviation of grain size = 0.12 mm.). No matrix material is present. Thin (1-2μ), discontinuous "halos" of calcite cement (Plate 58) are present around the grains. Coring of the rock indicates that the rock is well lithified with no weak horizons at depth.

Photogrammetric analysis of this section gives an annual average erosion value of 1.0 mm./year (n = 289, s^2 = 0.91). No distinctly different geomorphic zones are evident. Areas which are encrusted by barnacles are characterized by a temporary retardation in rock erosion. In localized spots, barnacles are able to reverse the erosional trend to give negative residual values, that is, bioaccretional values which represent growth rates. Spot height readings on living barnacles indicate a maximum growth rate of 2.2 mm. ± 1.1 mm./year. As suggested above, however, this organism is not very successful in protecting the rock surface over long periods. Barnacles are rapidly undermined and isolated on rock pedestals which become unstable and

Plate 58. Thin section photomicrograph showing thin, discontinuous, micritic halos. Section 18, Heywood's Beach. Crossed nicols, 48x.



eventually break away from the rock surface. The results of this process are exemplified in Plate 55 (see arrows).

The pitted surface of Section 18 displayed an erosion rate of 1.2 mm./year ($n = 173$, $s^2 = 0.57$), only slightly higher (and not statistically significant) than in the barnacle zone which showed an average annual erosion value of 1.1 mm./year ($n = 94$, $s^2 = 1.31$) and where bioaccretion is partially offsetting the erosional effects. The pitted area is, in fact, a relict barnacle zone and therefore no great difference between these areas should be expected.

Long Bay (Sam Lord's)

Long Bay (Sam Lord's) is located on the windward (east) coast of Barbados at metric coordinates 1478500N by 652225E. Beachrock outcrops extend from the northern boundary of this beach to the Sam Lord's beach, and then parallel to the shoreline (Plates 59 and 60). Beachrock at the northern end of the beach has been examined in this study. A narrow tidal channel separates the beachrock from a sand beach. The shoreward face of the beachrock outcrop forms a steep, jagged slope which drops approximately 1 to 1½ m. from the beachrock surface to the tidal channel. This exposed beachrock slab appears to be resting on a separate, buried beachrock pavement (Plate 60). Considerable fracturing of the lower pavement is evident.

Plate 59. Long Bay locality. Section 30 is found on the light, "bare" rock surface behind the dark, macroalgal zone.

Plate 60. Broken and fragmented beachrock slabs shoreward of beachrock shown in Plate 59. Landward slabs are smoother surfaced than, and dip under, the seaward slab. Stratigraphic position with respect to age of formation is uncertain.

A single sedtion (Section 30) has been established at this locality and is located immediately seaward of the shoreward face (Figure 2) in the high intertidal zone. The surface morphology of this section is that of intense pitting (Plates 61-66). The pits are roughly circular and vary from 1 to 5 cm. in diameter with depths generally less than their radii. This surface gives the impression that solutional effects dominate in sculpting the rock. A variety of organisms are found at this locality (Table 10). Chitons of the species Acanthopleura granulata, limpets of the species Acmaea jamaicensis and keyhole limpets of the species Fissurella barbadensis are often found in the pits. The vermetid gastropod Petaloconchus cf. varians forms a thin, discontinuous crust over some parts of the area. The herbivorous gastropod, Littorina meleagris, can be observed on the higher parts of the rock surface.

Lithophytic organisms, while not conspicuous, are nevertheless common in this area. The endoliths and chasmoliths are more common than epilithic flora. The rock surface reflects the presence of the former microphytes by its greenish to black hue. However, some areas of the rock appear pinkish-grey in colour. The green to black colouration is caused by the presence of both coccoid and filamentous cyanophytes (two of which could be tentatively identified as Mastigocoleus sp. and Hyella sp.) while the pinkish rock colour is ascribed to the presence of a boring

Plate 61. Surface of Section 30, Long Bay, 20 April, 1973, showing general surface characteristics and ground control points (a,b,c,d, e,g,h). The areas outlined were investigated photogrammetrically and are treated in more detail in Plates 62-66.

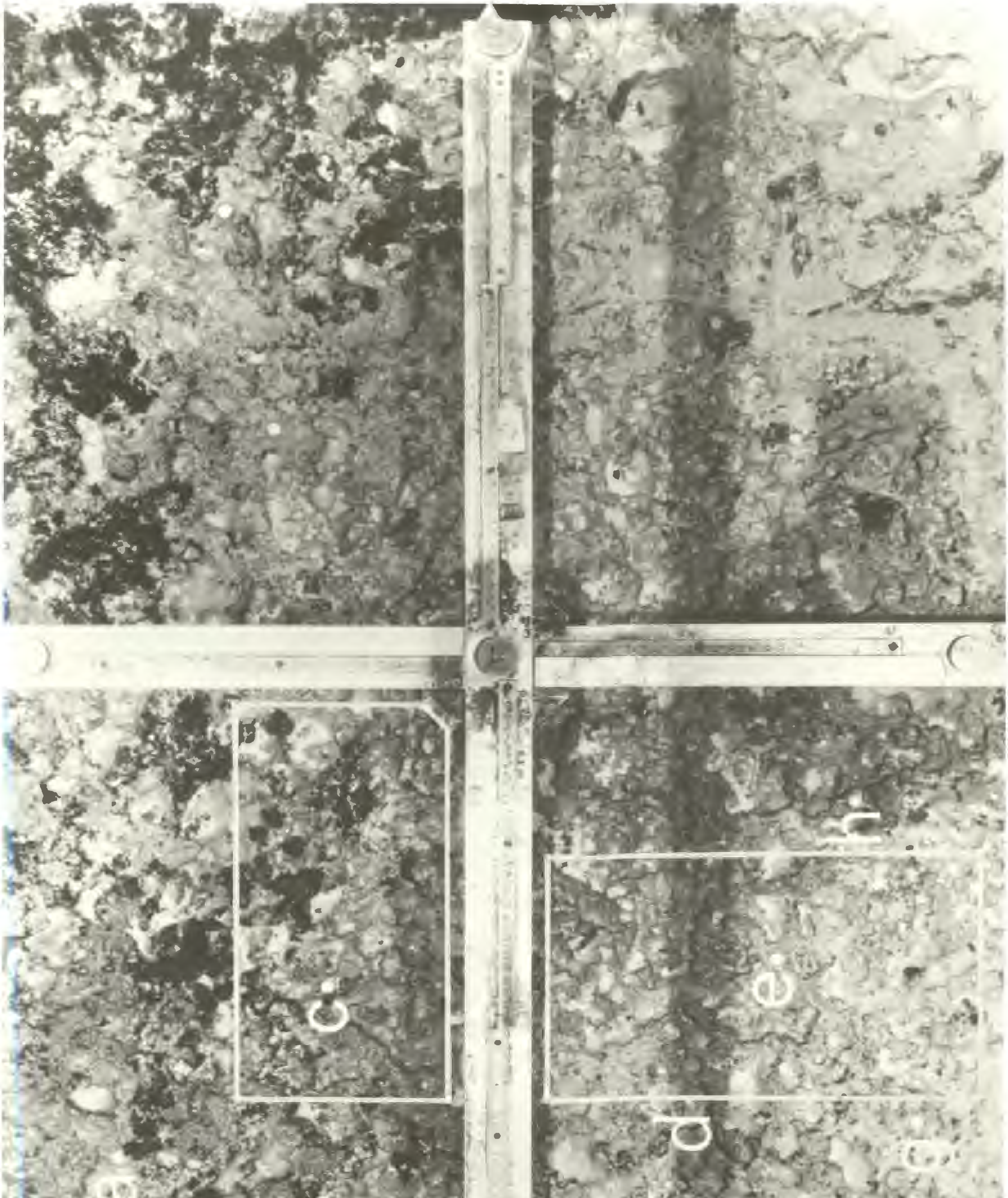


Plate 62. Stereophotographs of Section 30, Long Bay, 6 May, 1970. Surface is characterized by small scale pitting with some pits occupied by the chiton, *Acanthopleura granulata* or the limpet, *Acmaea jamaicensis*.

Plate 63. Stereophotographs of Section 30, Long Bay, 10 May, 1971. Vandalism of benchmarks emplaced in 1970 necessitated repositioning of section as can be seen in this stereopair. Note slight shift in position of surface features relative to reference bar between 1970 and 1971 photographs.

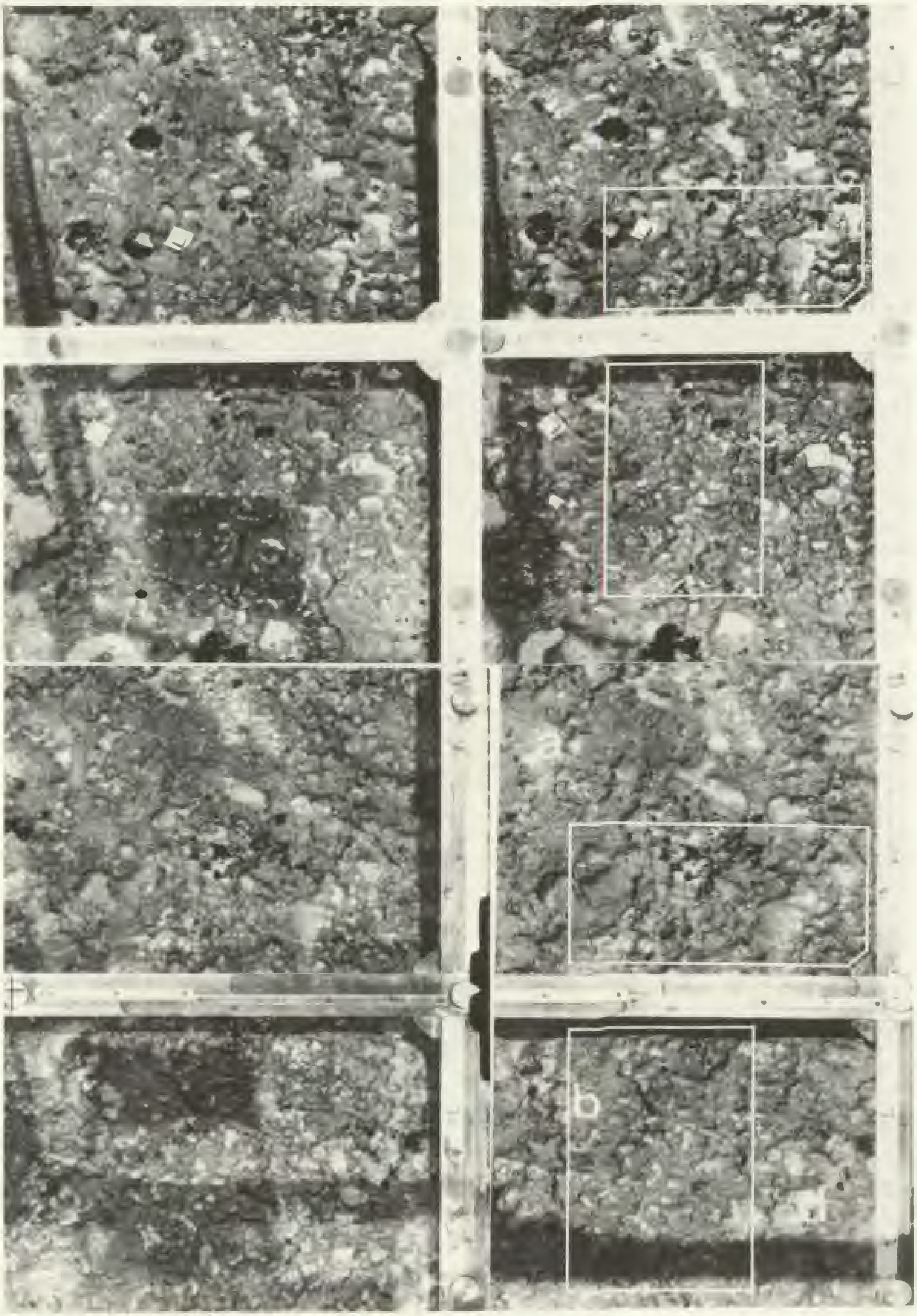
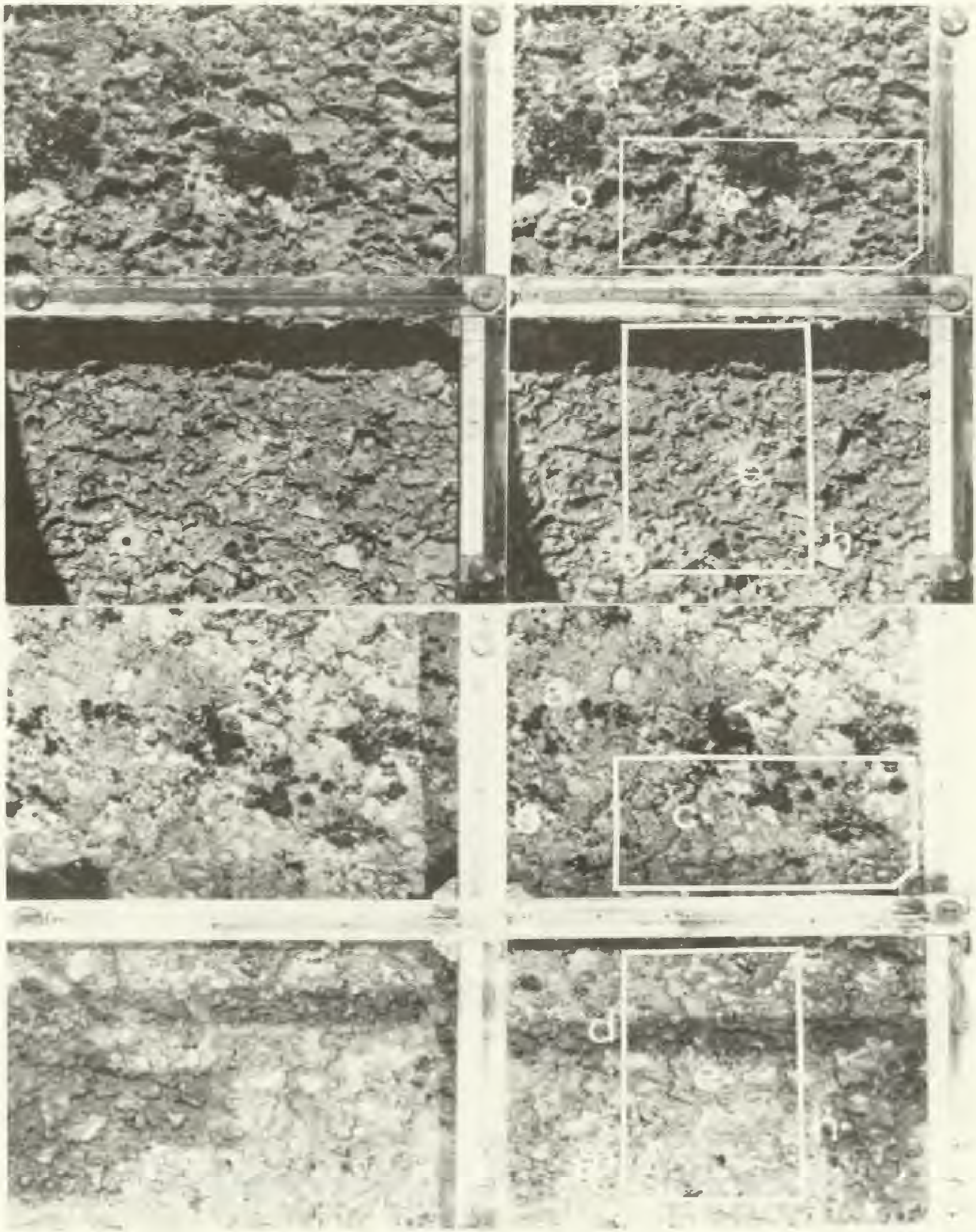


Plate 64. Stereophotographs of Section 30, Long Bay, 13 May, 1972. Similar in appearance to preceding plate. Note that some chitons are occupying the same depressions as in the previous plate.

Plate 65. Stereophotographs of Section 30, Long Bay, 20 April, 1973. Note increasing coverage of dark macroalgal coverage from 1971 to 1973.


a
b
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d

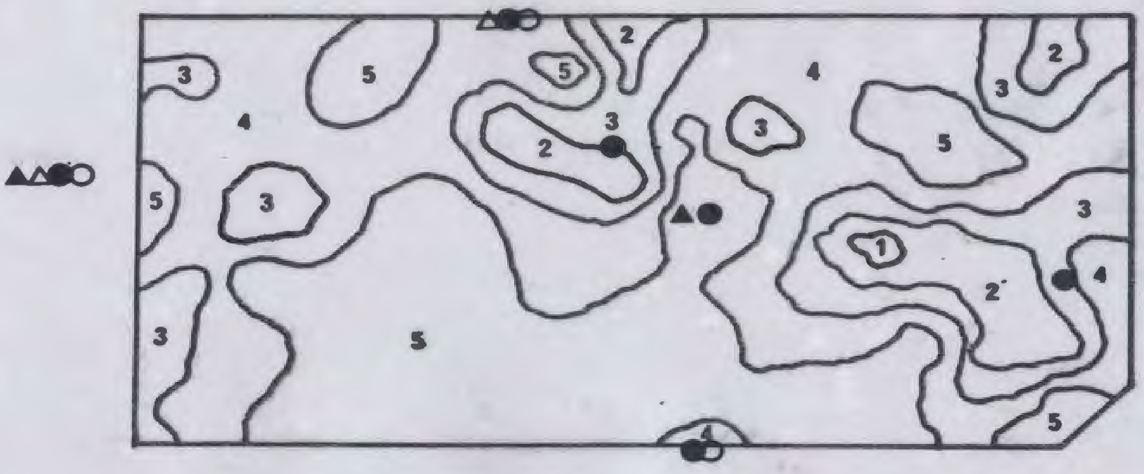
Plate 66. Photograph of left half of Section 30 (1973 photo). Areas outlined were analyzed photogrammetrically. No clearly distinguishable geomorphic zones became apparent from this analysis.

Overlay 1 shows cumulative distribution of Acanthopleura granulata (▲-1970 positions, △-1971 positions, ○-1972 positions, and ●-1973 positions). A. granulata was the only epifaunal organism found in the areas analyzed.

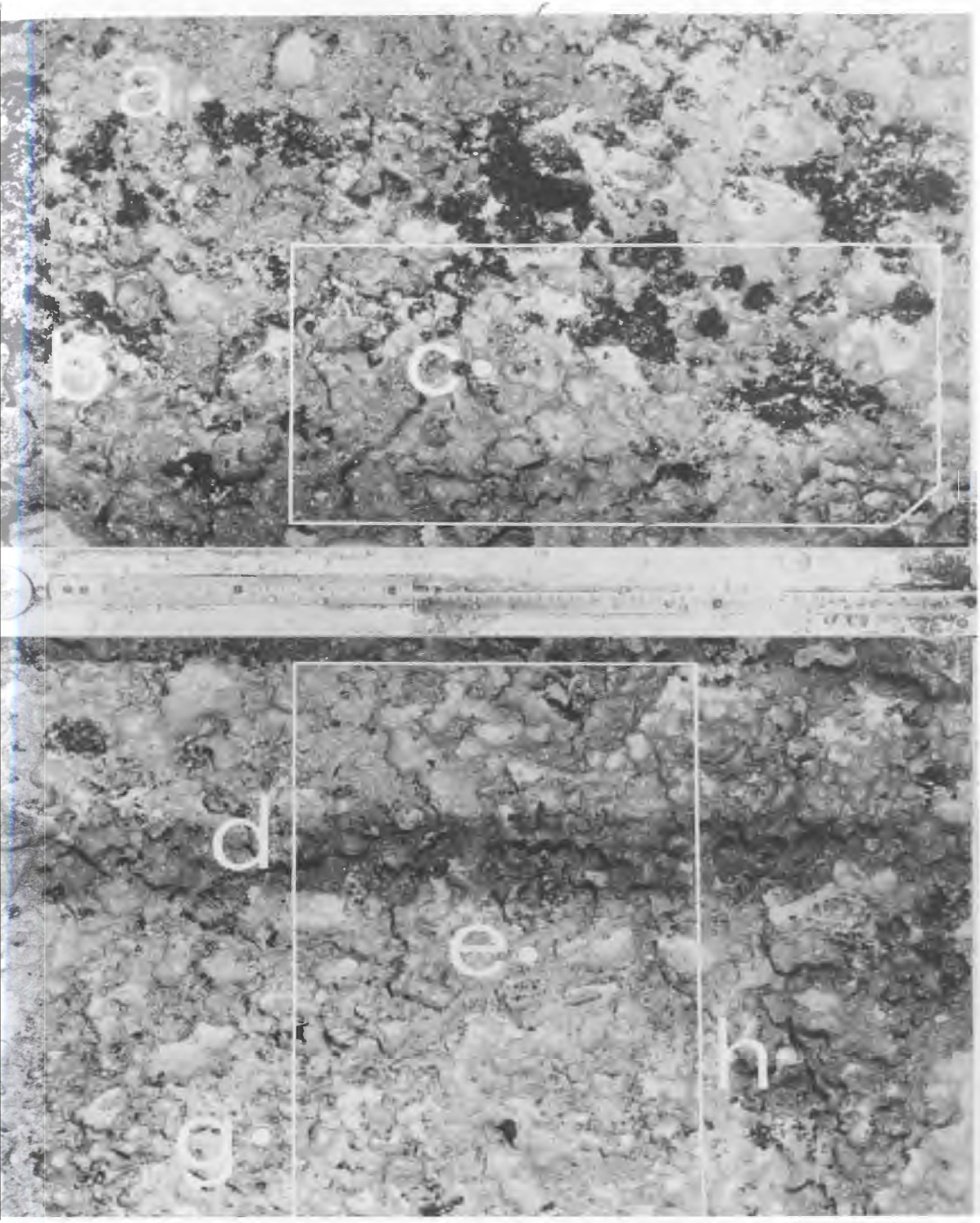
Overlay 2 displays the results of residual contour mapping of the surface. Numbers correspond to ranges of erosion as follows:

1 represents -3.0 to -5.0 mm/yr erosion
2 represents -1.0 to -3.0 mm/yr erosion
3 represents +1.0 to -1.0 mm/yr erosion
4 represents +3.0 to +1.0 mm/yr erosion
5 represents +5.0 to +3.0 mm/yr erosion

Negative erosional values indicate accretion.



66621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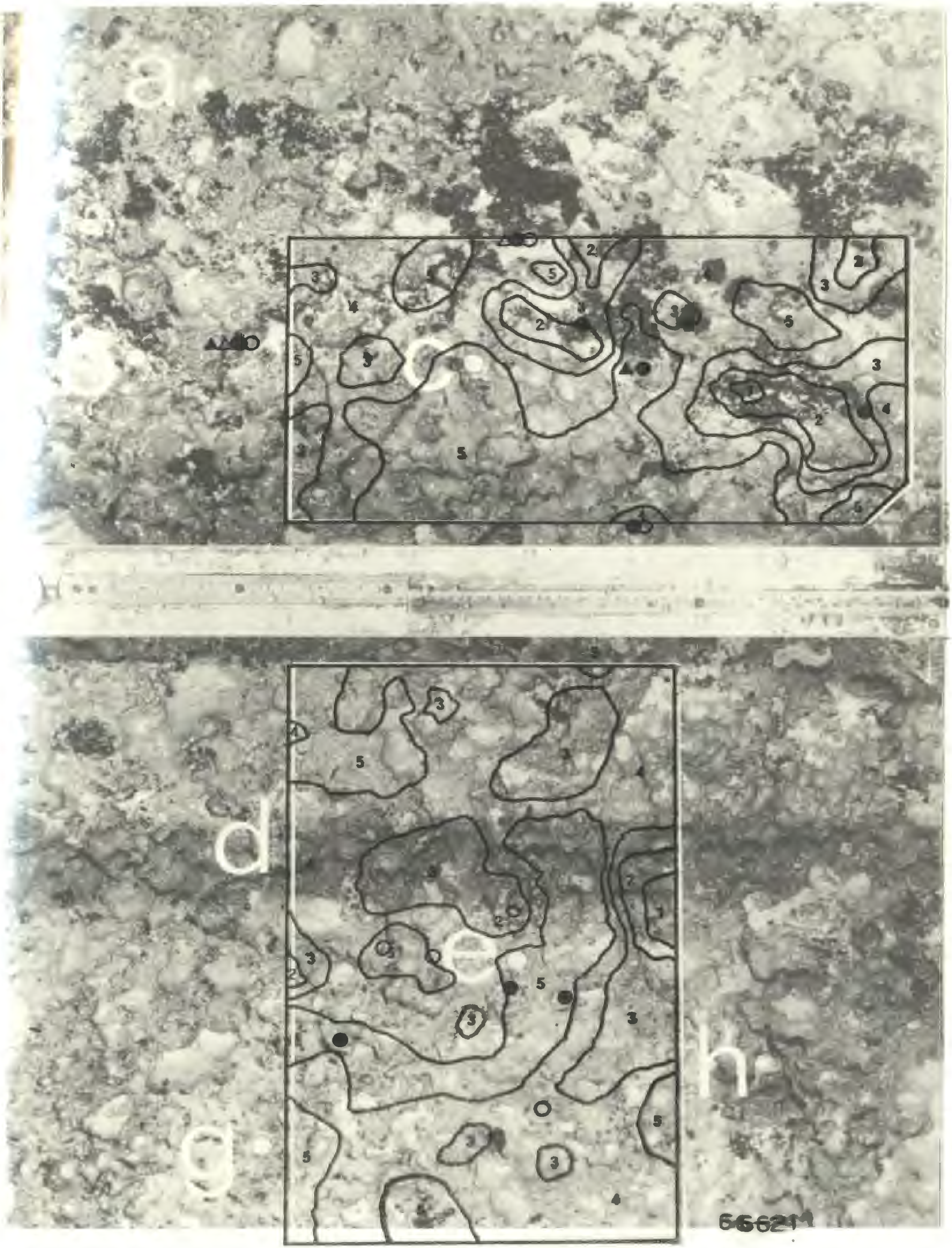


a
b
c
d
e
g
h

TABLE 10

SPECIES ABUNDANCE DATA, SECTION 30, LONG BAY

Organisms	1969	1970	1971	1972	1973
Sessile:					
Filamentous algae	-	5%	<5%	5%	10%
Petaloconchus sp.	70%	60%	50%	30%	30%
Tetraclita squamosa	1	~~1~~	1	1	-
Mobile:					
Littorina meleagris	-	-	-	-	20
Acmaea jamaicensis	248	-	11	12	18
Fissurella barbadensis	-	-	-	1	12
Acanthopleura granulata	8	12	7	12	34
Echinometra lucunter	-	-	-	-	2
Total number of species	4	4	5	6	7

Species abundance (number of individuals or percentages surface coverage per square meter) for each year of study at Section 30, Long Bay.

alga of unknown affinity.

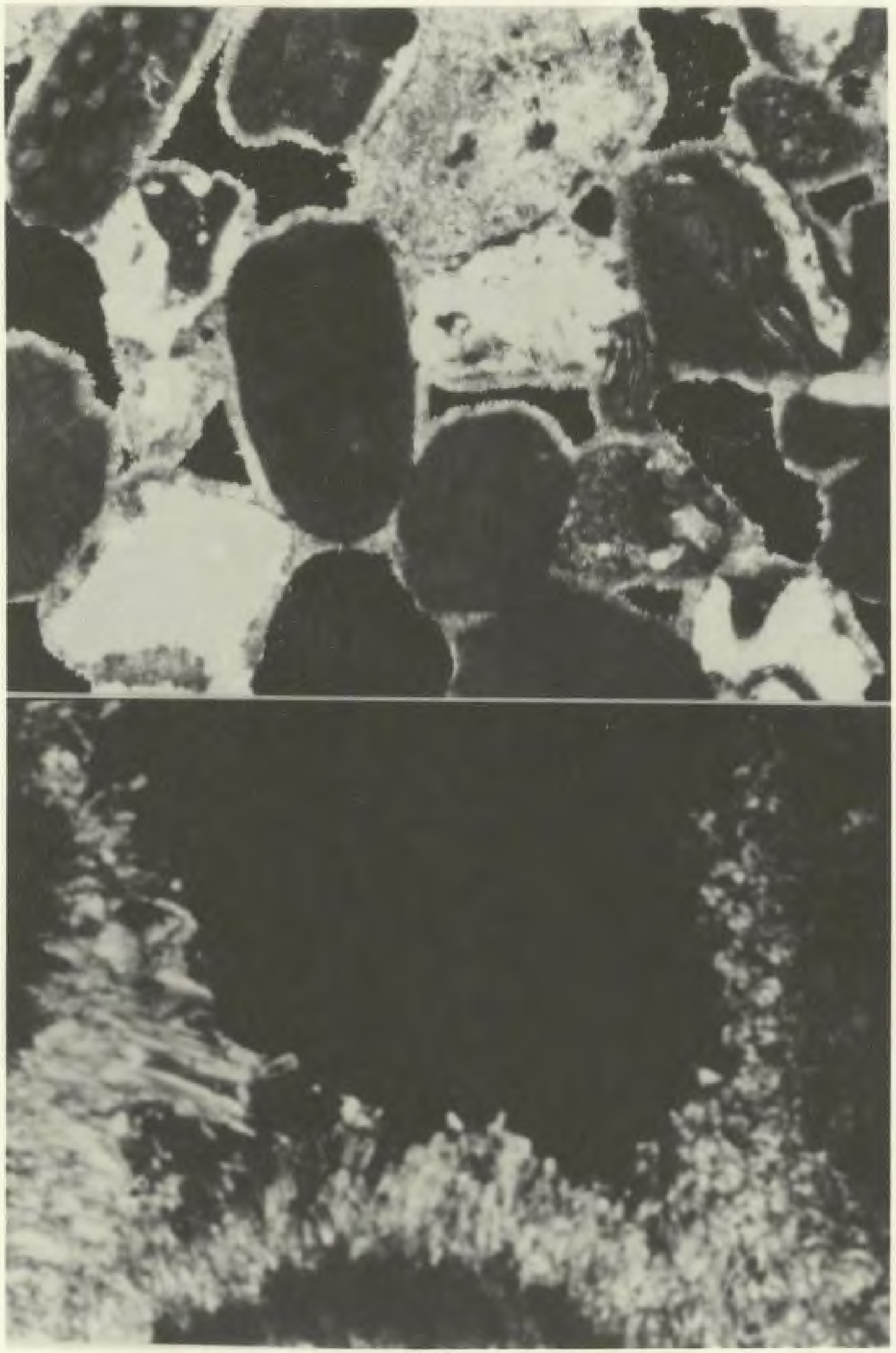
The microboring algae serve the erosional process in two ways. First, they are important erosional agents in their own right due to their boring activity. Secondly, they serve to trigger the erosional activities of the grazing gastropods and amphineurans present on the surface.

Petrographically, the rock in Section 30 displays an average grain size of 0.58 mm. with very good sorting characteristics (standard deviation of grain size = 0.27 mm.). Very little matrix material is present. Grains are bioclastic, mainly coral, coralline algal or molluscan fragments. Cement is aragonitic. Halos composed of long (20μ), thin, acicular aragonite crystals, oriented perpendicular to the grain surface, cover most of the grains (Plates 67 and 68). Cores from this section show the rock to be well lithified throughout the entire core length (35 cm.).

The average annual erosion value for this surface is 1.3 mm./year ($n = 123$, $s^2 = 0.46$). No geomorphic zonation is evident on the scale of this study and residual value contouring shows no apparent pattern. The chief erosional agents appear to be the microboring algae and the grazing molluscs. The pitted surface morphology would appear to be imposed by the action of grazing chitons and limpets. With repeated radular rasping of the rock surface, possibly aided by biochemical acid secretion (Warme, in Frey, 1975, p. 217), the epilithic grazers form depressions or pits which

Plate 67. Thin section photomicrograph of rock from Section 30, Long Bay. Note the halos of acicular aragonite needles on most grains and infilled pore spaces. Crossed nicols, 48x.

Plate 68. Aragonite needles growing perpendicular to grain surfaces, Section 30, Long Bay. Crossed nicols, 420x.



generally conform to and accommodate their bodies. It has been suggested (Frank, 1964; Glynn, 1970) that these grazing molluscs have a "home range" or homing instinct that causes them to return to the same resting spot between their food gathering activities. Hence they would tend to continue erosive activity on a specific site.

(N.B. Local inhabitants state that this section of rock is sometimes covered by sand during winter storms, possibly implying sand-scour erosion of the surface. This could not be confirmed or negated in the present study. However, lack of characteristic smoothing of the surface would suggest that any such scour is relatively ineffectual).

Six Men's Bay

Six Men's Bay is a fairly broad, open embayment on the west coast of Barbados, north of Speightstown (metric coordinates 1466950N by 655075E). A low-angle, seaward-dipping surface, characteristic of beachrock, is present at this locality (Plate 69). A narrow moat/tidal channel separates the main beachrock section from the beach. Five sections were established at this locality. One of these, Section 47, was chosen for photogrammetric analysis.

Section 47 is located in the low intertidal zone on the seaward edge of the beachrock platform (Plates 69 and 70). The seaward boundary of the platform is a steep (~45°) heavily dissected terrace. Above this (landward), a roughly

Plate 69. Six Men's Bay locality. Strike of seaward-dipping beachrock strata parallels the beach strandline.

Plate 70. Section 47 (arrow) is established on a low intertidal shelf of beachrock in a zone of zooanthids (colonial anemones) and *Echinometra lucunter* "burrows".


horizontal ledge is found. Section 47 is located on this ledge (Figure 4). The left half of this section is characterized by a thick Zooanthus pulchellus carpet, while the right half of the section is a labyrinthine zone of crevices and fissures inhabited by the sea urchin, Echinometra lucunter (Plates 71-76). Three specimens of Thais deltoidea, a carnivorous gastropod, were noted in this labyrinthine zone in 1973, while Fissurella barbadensis and Acmaea jamaicensis were found in reduced numbers after 1970 (Table 11). The raised pinnacles and pedestals of the zone often exhibit clumps of Sargassum sp. or a thin coating of coralline algae (Neogoniolithon sp.), while small crevices harbour the coralline alga Lithophyllum congestum. Associated with the zooanthid blanket and feeding from it are the carnivorous gastropods Heliacus cylindricus, Nitidella nitida and Coralliophila caribea (Robertson, personal communication). Boring sipunculids (Phascolosoma antillarum) are present in the rock surface under the zooanthid blanket.

The rock of Section 47 is similar in particle composition to the previous sections but is more indurated. The average grain size (thin section estimate) is 0.43 mm., with very good sorting characteristics (standard deviation of grain size = 0.24 mm.). The cement in this case is calcitic--blocky, dogtooth spar (20-30μ long) surrounding the grains, with anhedral filling of void spaces (Plates 77, 78 and 79).

Plate 71. Surface of Section 47, Six Men's Bay, 2 May, 1973, showing general surface appearance and ground control points. Rock surface in left half of the section is blanketed by the zooanthid, _Zooanthus pulchellus_. The right side of the section displaying a labyrinthine system of _Echinometra lucunter_ burrows was investigated photogrammetrically. Due to the nature and geometry of the surface in this area, depth readings were restricted to burrow floors, hence, a measure of bioerosion by _E. lucunter_ was obtained. Plates 72-76 deal with this in more detail.

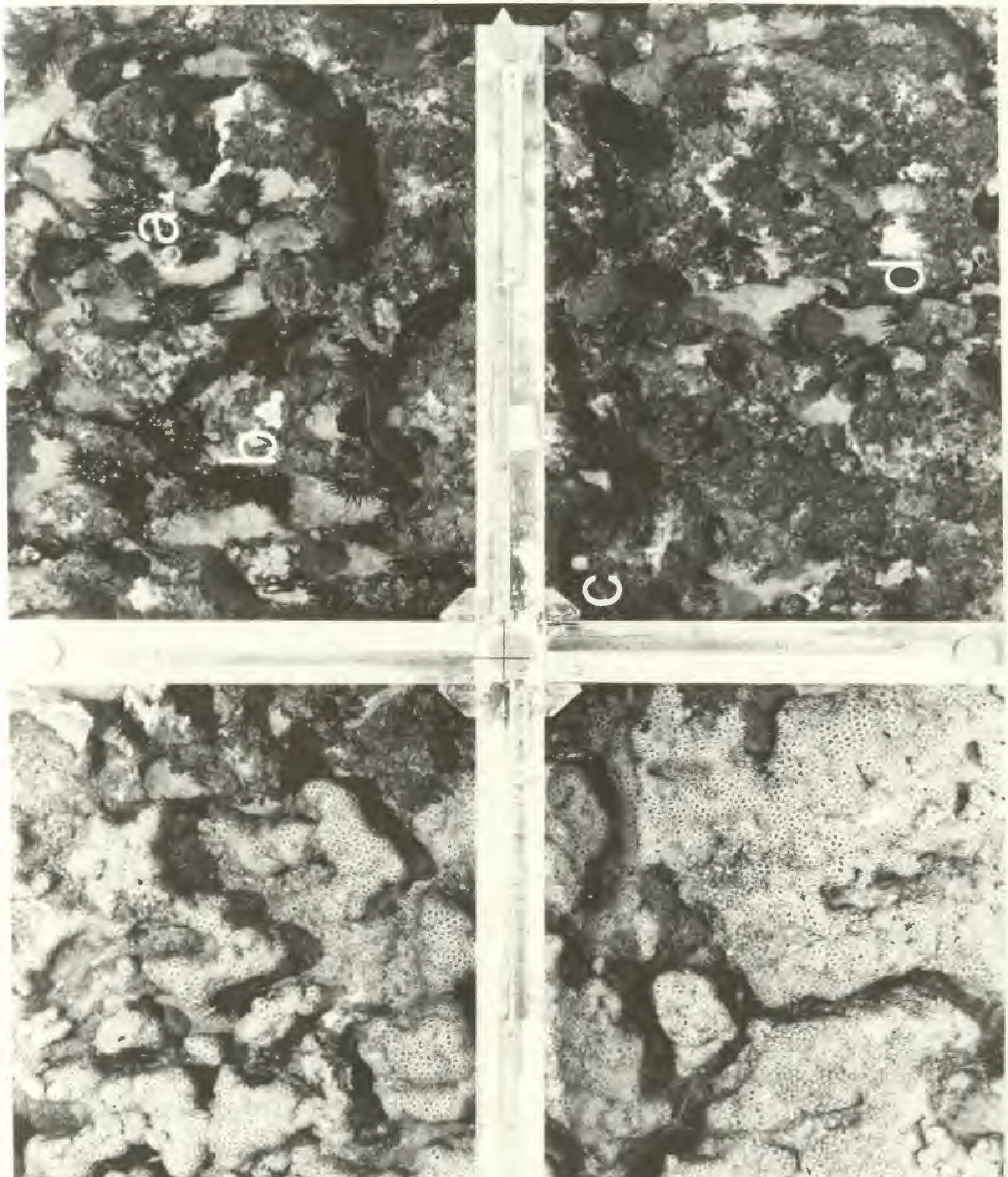

a
b
c
d

Plate 72. Stereophotographs of Section 47, Six Men's Bay, 5 May, 1970. Surface is characterized by dissection of the rock by the erosive activities of the sea urchin, Echinometra lucunter. Elongate tunnels of these urchins oriented roughly perpendicular to the strike of the rock surface.

Plate 73. Stereophotographs of Section 47, Six Men's Bay, 27 April, 1971. Similar to 1970 stereopair. E. lucunter may be seen in the bottoms of the sinuous burrows. White patches are encrustations of coralline algae (Neogoniolithon sp.).

Plate 74. Stereophotographs of Section 47, Six Men's Bay, 12 May, 1972. Similar to preceding two plates. Note that the burrow floors are free from encrustation or drift algae. (For explanation of circle, see next plate).

Plate 75. Stereophotographs of Section 47, Six Men's Bay, 2 May, 1973. Note considerable increase in macroalgal cover with an accompanying decrease in coralline presence. Also evident is the breakup of a burrow wall in the upper right (arrow), probably resulting from lateral bioerosion by the urchin. Establishment of crustose rhodophyte (Squamariacean) on burrow floor can be seen inside circled area (compare with circled area in preceding plate).

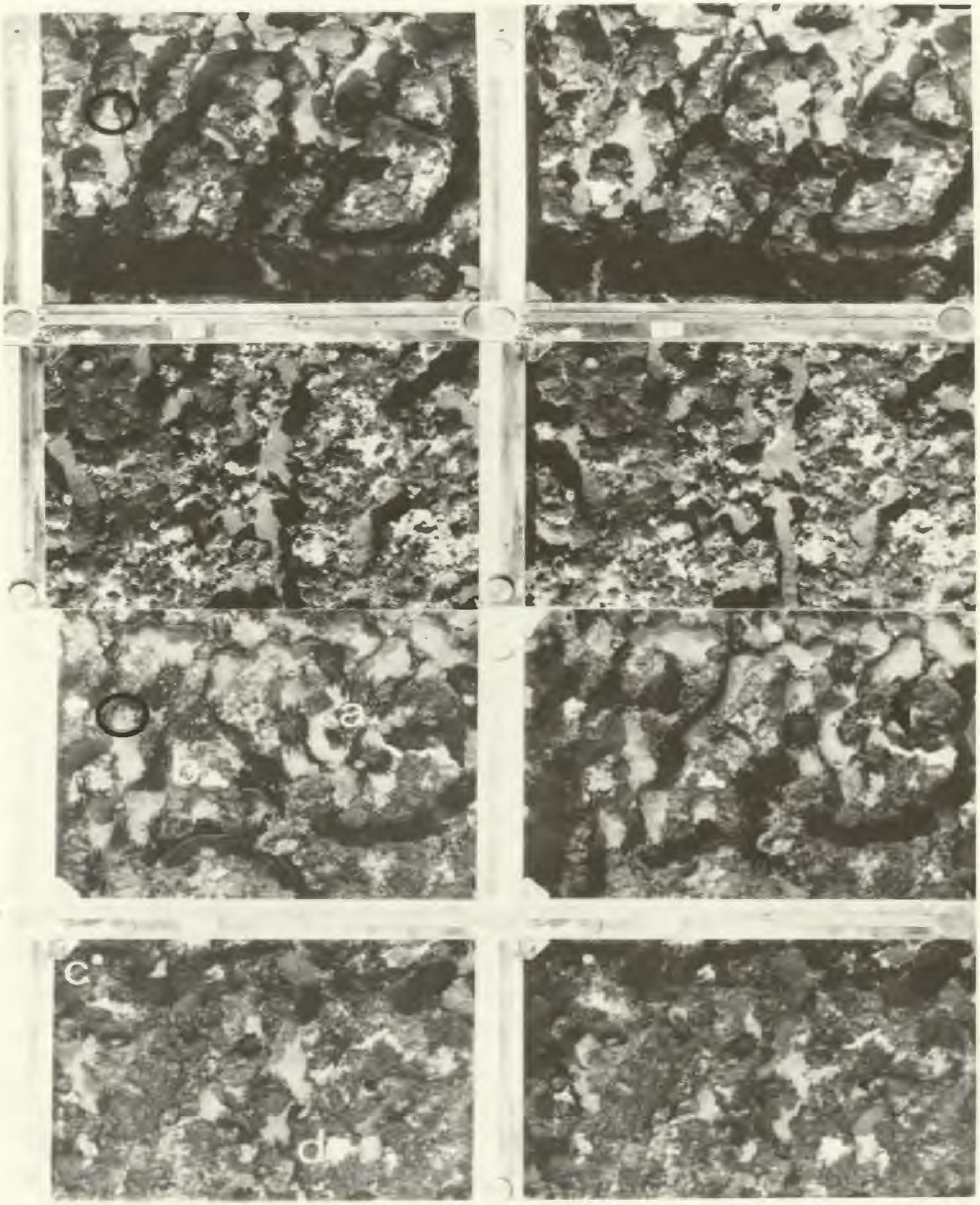
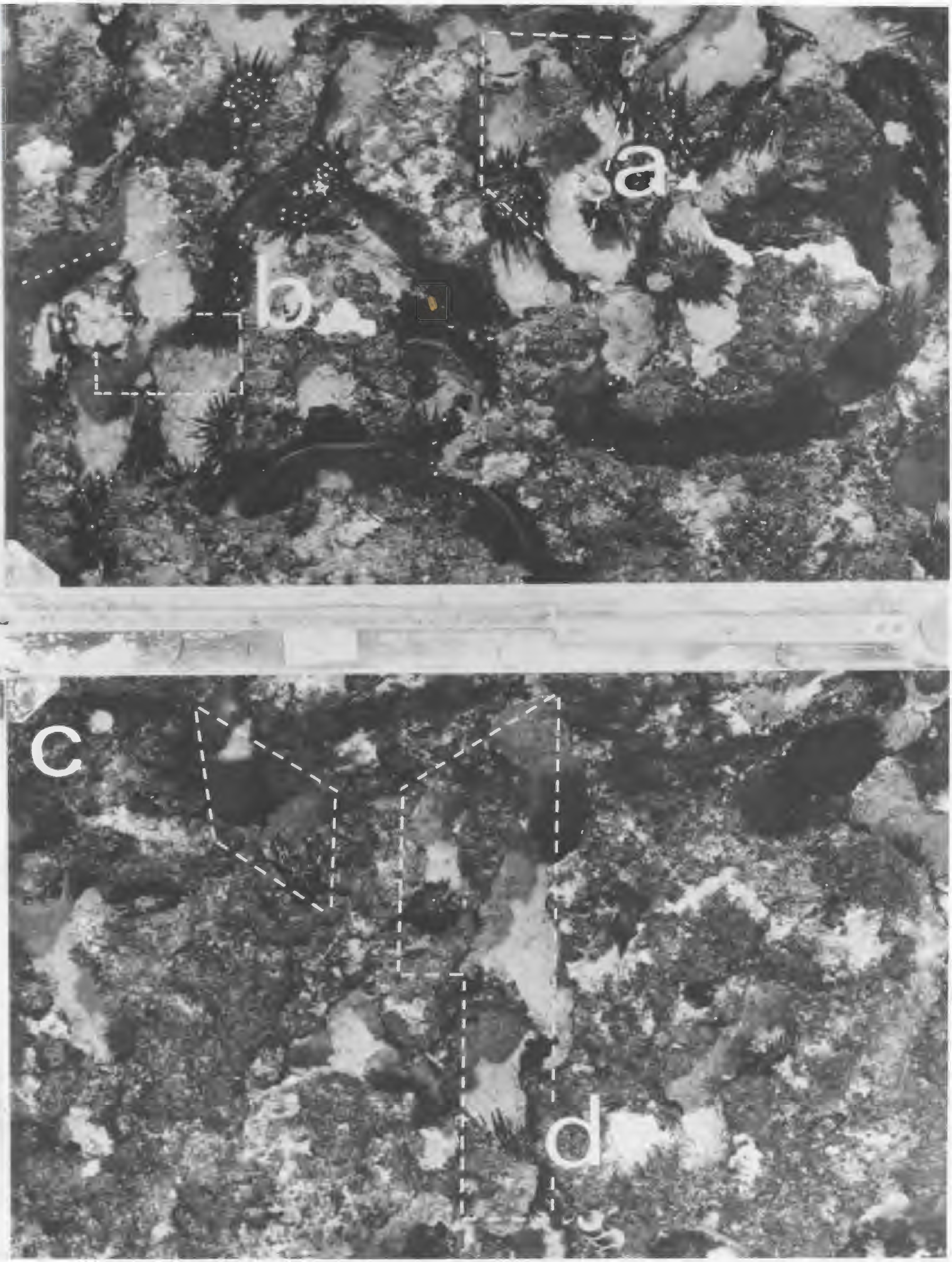

a
c
d

Plate 76. Photograph of right half of Section 47 (1973 photo). Areas from which burrow erosion data were collected are outlined by dashed lines. Burrow floor area is indicated, in Overlay 1, with a "honeycomb" pattern. Overlay 2 shows *Echinometra lucunter* (★) cumulative distribution (1971-73).

76-1
76-2


a
b
c
d

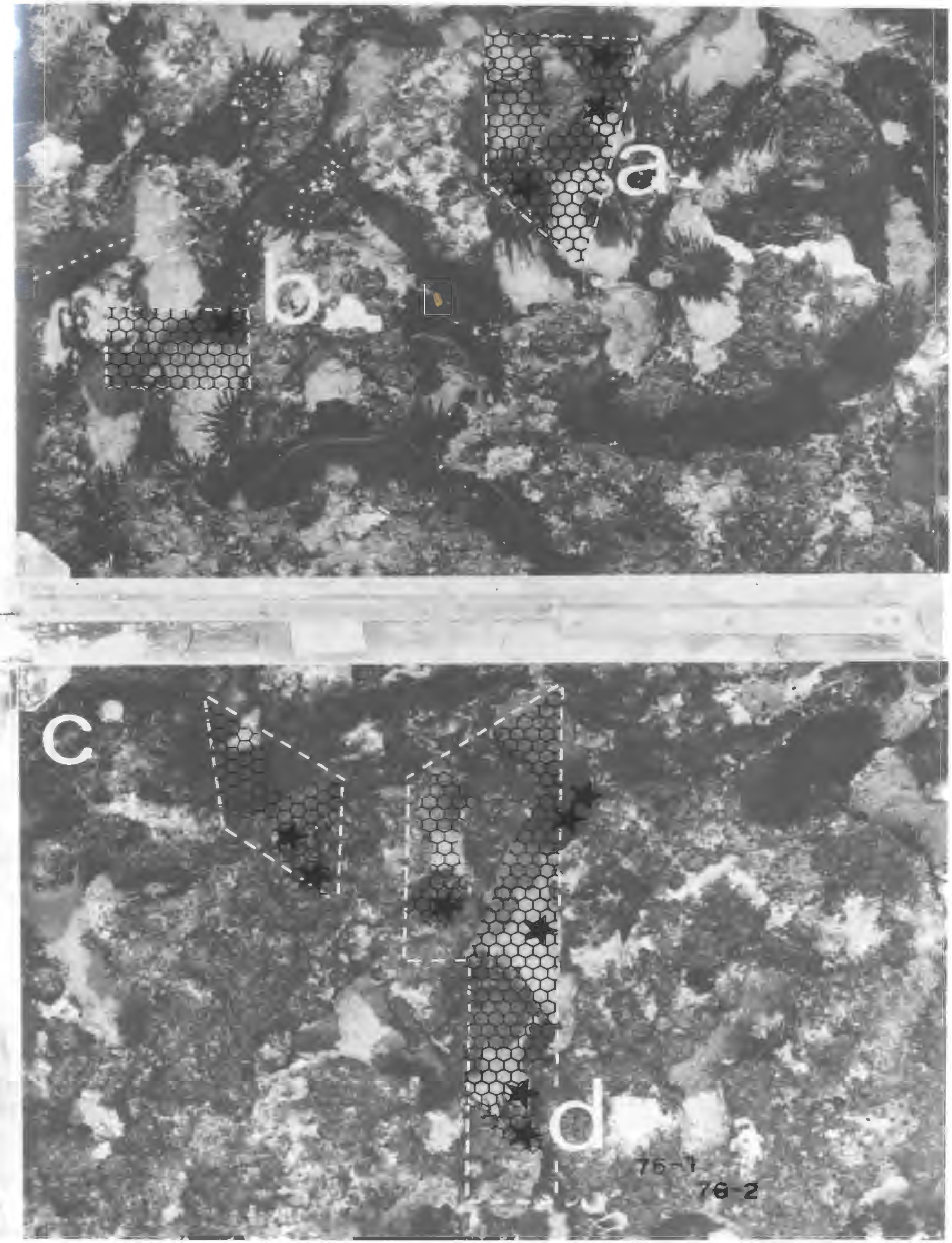

a
b
c
d
76-1
76-2

TABLE 11

SPECIES ABUNDANCE DATA, SECTION 47, SIX MEN'S BAY

Organism	1969	1970	1971	1972	1973
Sessile:*					
Non-calcareous macroalgae	-	-	50%	47%	20%
Coralline algae	-	-	20%	3%	30%
Zooanthus pulchellus	27%	28%	37%	47%	47%
Mobile:					
Thais sp.	-	-	-	-	2
Acmaea jamaicensis	-	10	2	-	-
Fissurella barbadensis	8	20	-	2	-
Echinometra lucunter	88	98	90	78	56
Total number of species	3	4	6	6	5

Species abundance (in number of individuals or per cent surface coverage per square meter) for each year of study at Section 47, Six Men's Bay.

*Total percentage in 1971 exceeds 100% due to overlap or "layering" of sessile organisms. For example, it is common for coralline algae to serve as attachment surfaces for non-coralline macroalgae, hence the same surface is recorded as serving as a substrate for both organisms.

Plate 77. Thin section photomicrograph of rock from Section 47, Six Men's Bay. Halos of calcitic spar cement are present and, in some cases (as shown in Plate 79) anhedral spar infills the pores. Crossed nicols, 46x.

Plate 78. Thin section photomicrograph of rock from Section 47, Six Men's Bay. Note dogtooth spar growing roughly normal to the grain surface. Crossed nicols, 650x.

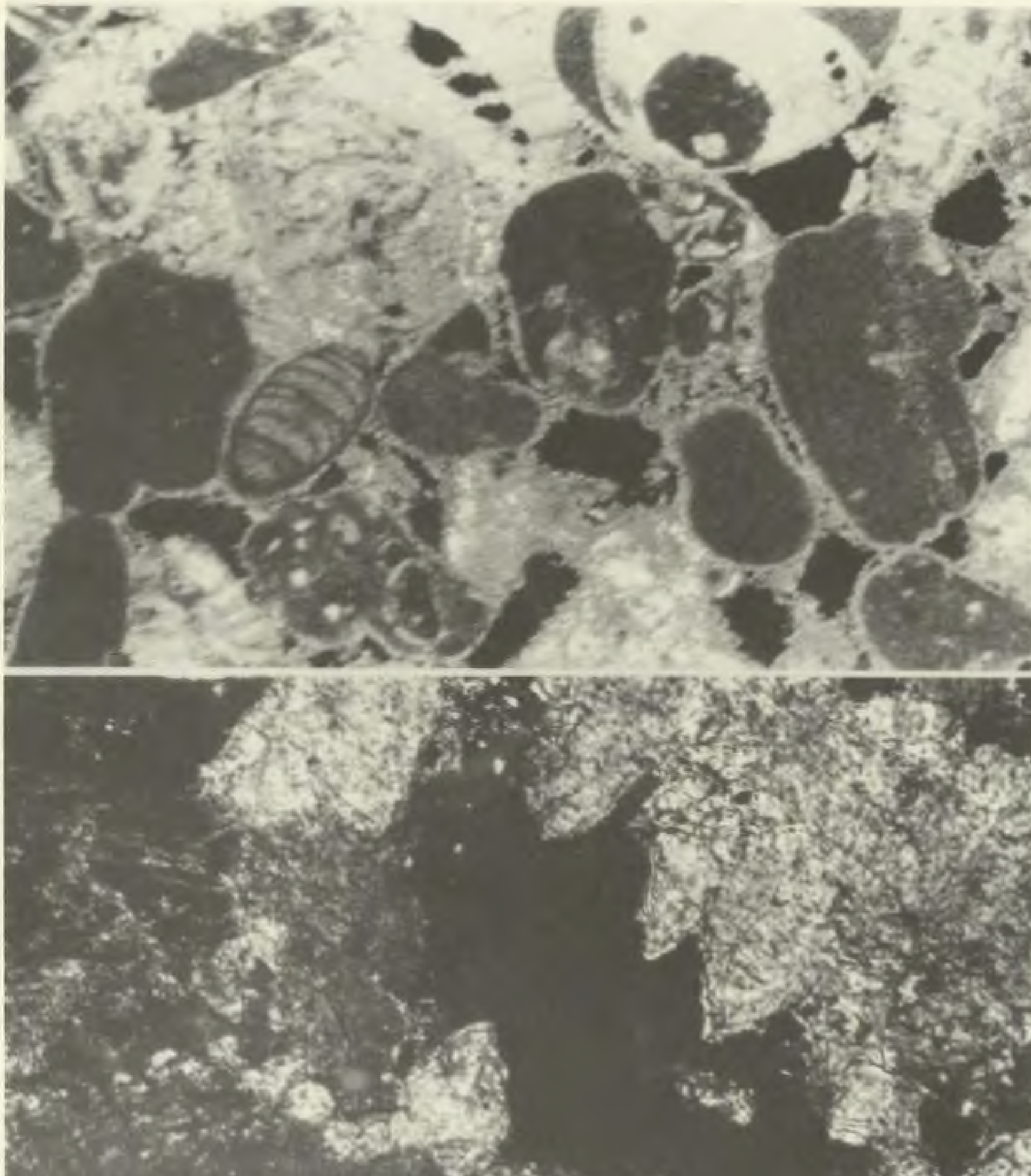
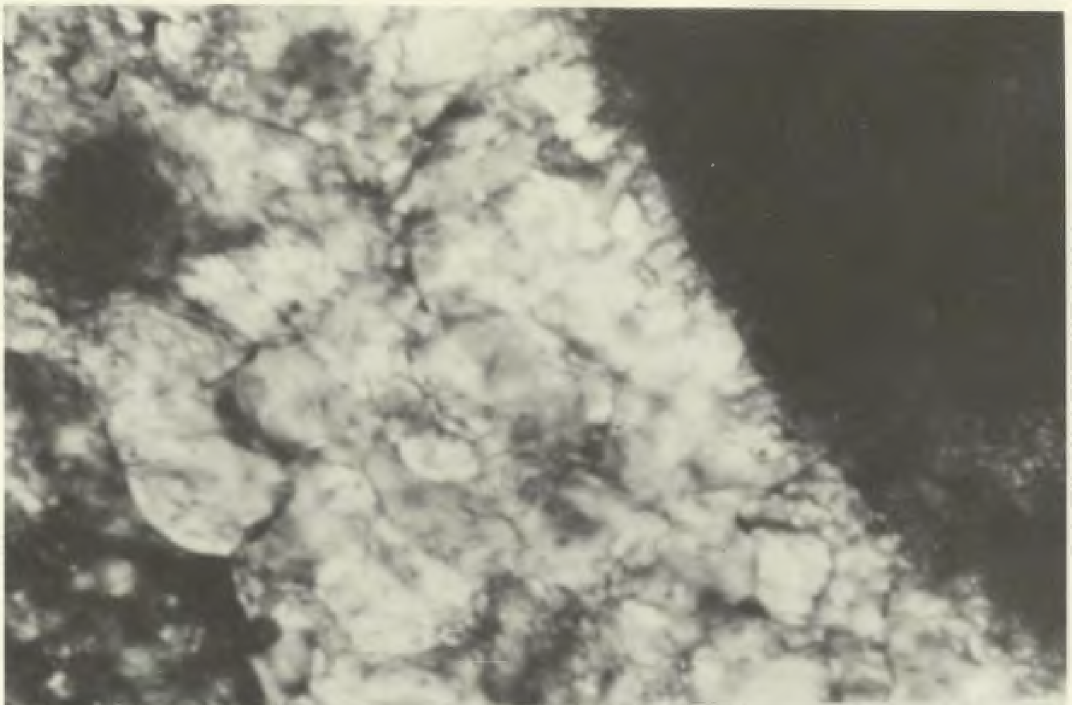


Plate 79. Thin section photomicrograph of rock from Section 47, Six Men's Bay, showing anhedral infilling of pore space by calcite. Note smaller dogtooth crystals perpendicular to the grain surface. Plane polarized light, 480x.

Plate 80. Stroud's Bay limestone terrace, displaying sharp, peak-and-depression topography.



Section 47 has not been analysed photogrammetically in the same manner as previous sections. The topography of the right side of the section is that of intense rock dissection in the form of large diameter (up to ~10 cm.), coalescing, sinuous channels upon which spot readings and contouring would be meaningless, as would erosion rate determinations, since much of the surface is obscured by articulated coralline algae and fleshy macroalgae. For this reason, only the sloping walls and floors of the channels have been measured, thus giving a rate of destruction of these surfaces. Erosion values of the channel floors show a wide range of values up to 9.9 mm./year, with an average 2.4 mm./year ($n = 244$, $s^2 = 2.74$). Much erosion in this zone is caused by the sea urchin, E. lucunter, which tends to erode laterally as well as vertically. This eventually leads to coalescence of burrows and loss of large blocks of rock by undercutting (as seen in Plates 74 and 75).

McLean (1964) observed that E. lucunter spends much of its time moving up and down the burrow, scraping filamentous and coralline algae from the walls of the burrow and ingesting any fleshy algae which come to rest there. At this particular location, the floors and sidewalls of the passages are for the most part devoid of coralline flora. However, a thin covering of filamentous algae is present. It can also be seen that between 1972 and 1973, corallines have been able to establish on the burrow floor (Plates 74 and 75).

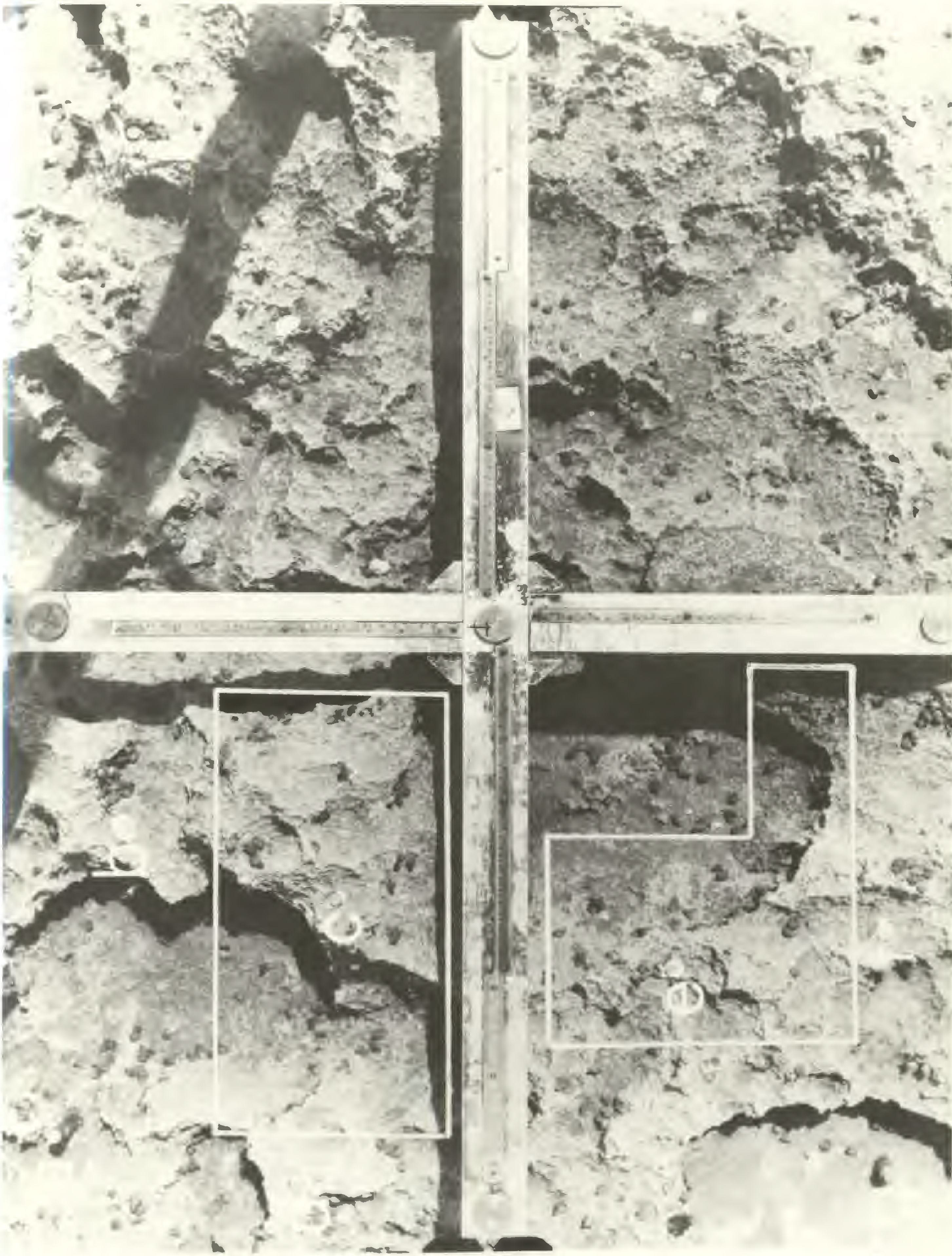
Adey (personal communication) has observed that although *E. lucunter* may damage small areas of the coralline surface by its scraping, for the most part, the meristemal cells are unharmed, allowing the algae to continue growth. Only a few readings could be obtained on the accreting crustose coralline algal colonies. However, these give accretion rates of 0.8 mm./year to 3.0 mm./year (unfortunately based on only five points) and averaged 1.66 mm./year.

No photogrammetric readings have been collected from the left half of Section 47 since the rock is overgrown by the colonial anemone, *Zooanthus pulchellus*. As can be seen by comparing the yearly sequential stereopairs of this section (Plates 72-75), the zooanthid colony is overgrowing the *Echinometra lucunter* area.

Stroud's Bay

Stroud's Bay is located on the rugged, cliffy, northwest tip of the island (metric coordinates 1472850N by 655150E). Section 48 has been established at this locality in the spray/supratidal zone (Figure 4) on a jagged surface of Pleistocene calcarenite (Plate 80). The surface of this supratidal section (Plate 81) is notable for the low epibiotic diversity and displays a topography very similar to that of Section 6, Wait's Bay. A topography with large depressions of up to 30 cm. across and approximately two-thirds as deep, with undercut sides, is quite common (Plates

Plate 81. Surface of Section 48, Stroud's Bay, 19 April, 1973, showing general surface characteristics and ground control points(a-g). The areas outlined on the left side of the section were investigated photogrammetrically and are treated in more detail in Plates 82-86.



82-86). In most cases, the depressions are breached in such a manner as to allow drainage to a lower level. The higher "pinnacles" are of a lighter grey colour and are more brittle and "case-hardened" than the substrate of the channels and depressions. Occasional discontinuous caliche crusts are encountered on and in the rocks of this locality (James, 1972; present study, Plate 87).

Organisms inhabiting this zone include three species of littorine gastropod, Nodilittorina tuberculata, Littorina ziczac and L. meleagris (Table 12) as well as lithophytic coccoid cyanophytes and filamentous cyanophytes (Mastigocoleus sp., Hyella sp., and Plectonema sp.). The gastropods tend to aggregate on the walls of the depressions when the rocks are hot and dry, whereas they are more likely to be found on the floors of the depressions and on the pinnacle surfaces when the section is damp or the rock surface cool. They avoid the very wet situations which arise when the depressions are flooded. In addition to these gastropods, the surfaces of the lower areas (depressions) are inhabited by endolithic microalgae which often penetrate the rock to a depth of 2 to 3 mm.

Section 48 displays an average grain size of 0.63 mm. and shows generally good sorting characteristics (standard deviation of grain size = 0.32 mm.). It differs from previous sections, however, by the presence of occasional hard, surficial crusts of microcrystalline calcite (Plates

Plate 82. Stereophotographs of Section 48, Stroud's Bay, 3 May, 1970. Surface is characterized by rough rock surfaces encompassing deep, undercut rounded depressions. Large numbers of littorinid gastropods are evident on the surface.

Plate 83. Stereophotographs of Section 48, Stroud's Bay, 30 April, 1971. Similar to preceding plate. Fewer littorinid gastropods are in evidence. Due to loss of positioning following this series of photographs, no photogrammetric data were collected from this or the preceding stereopair.

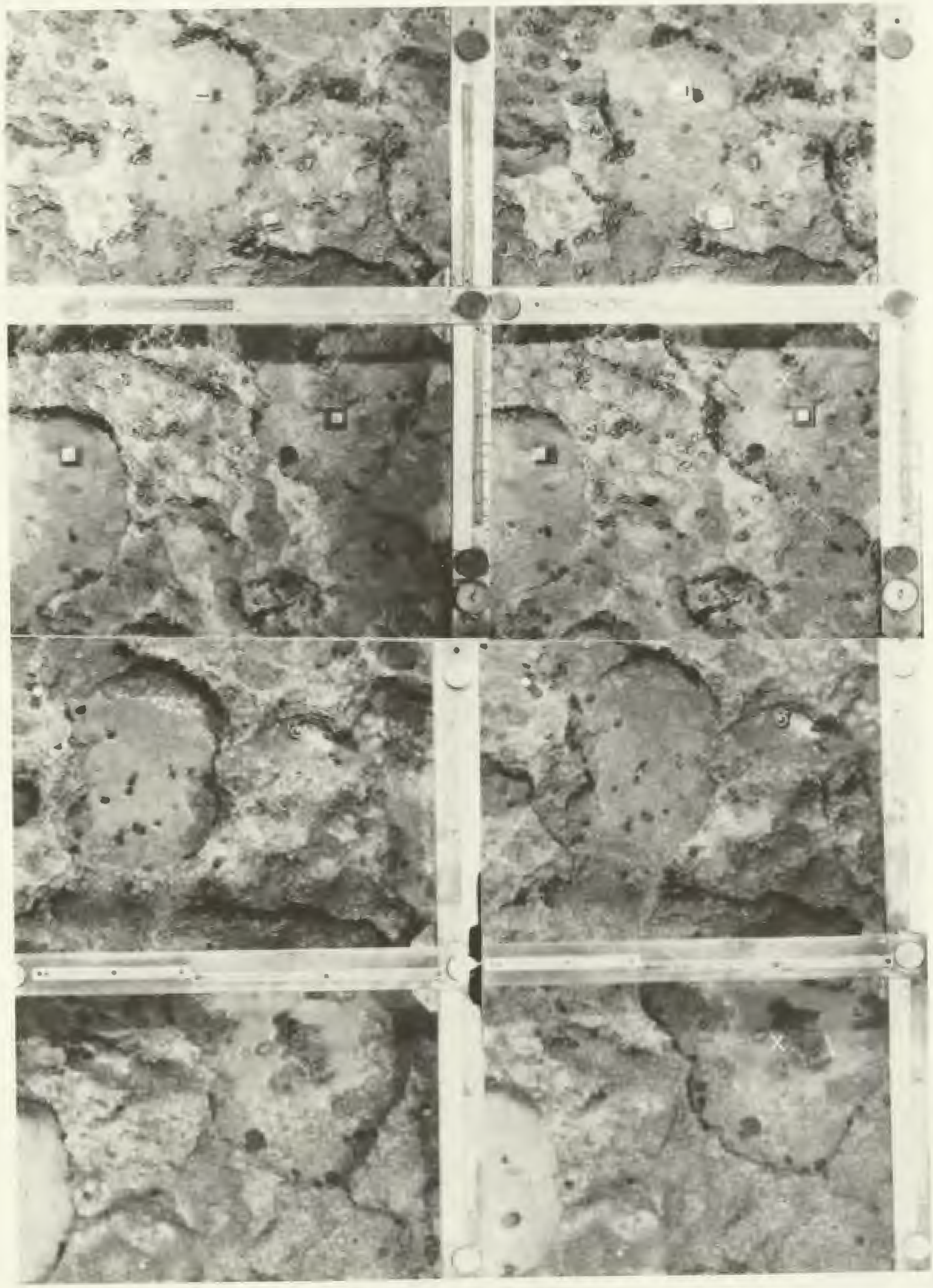
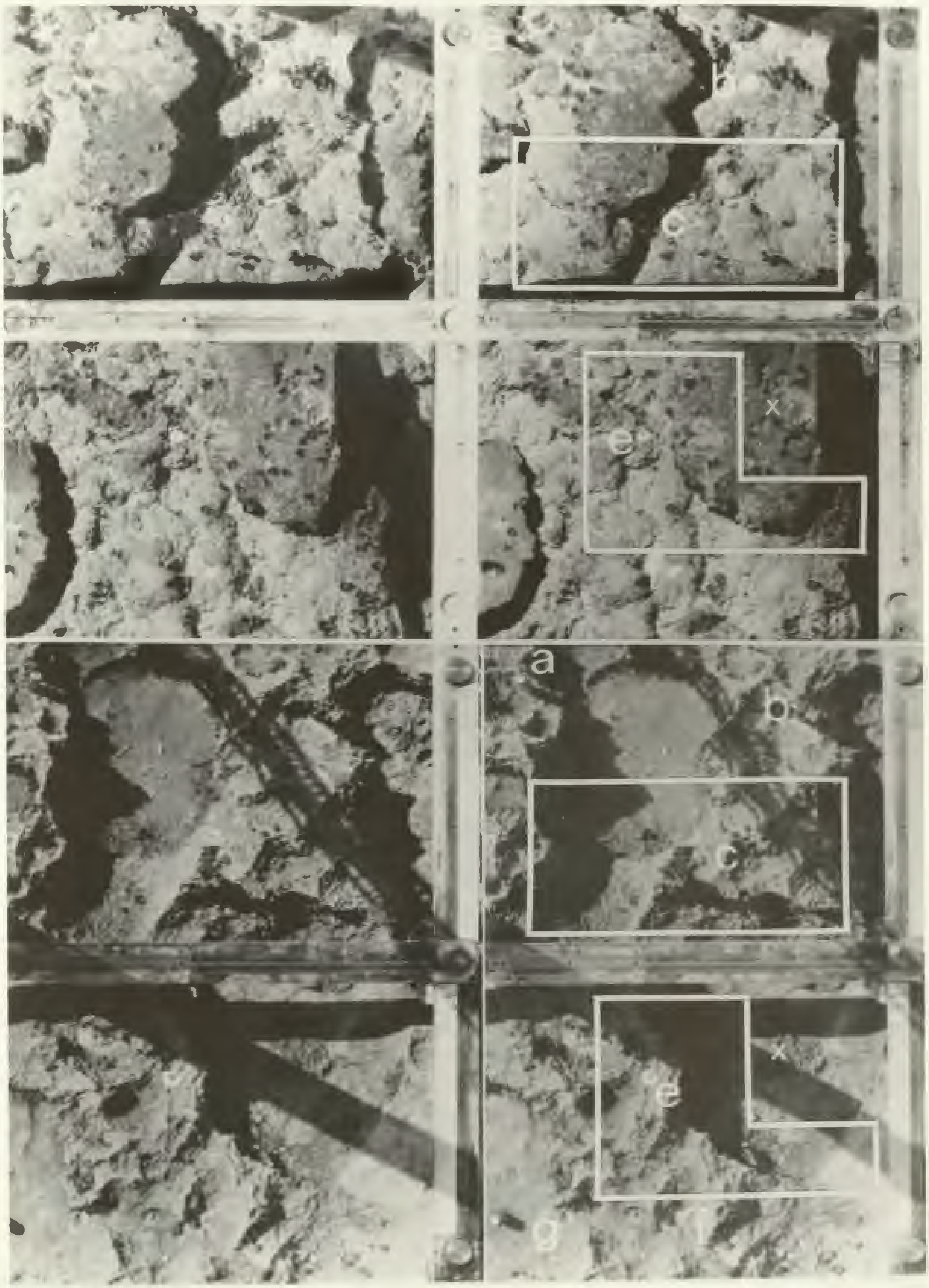


Plate 84. Stereophotographs of Section 48, Stroud's Bay, 4/5 May, 1972. Sharp, lapies character of surface is emphasized by deep shadows. Note relief created by a fossil coral (indicated by an "X") in the floor of the depression in the lower right. Large numbers of littorinid gastropods are scattered over the entire section.

Plate 85. Stereophotographs of Section 48, Stroud's Bay, 19 April, 1973. Similar to previous year. Fewer gastropods are present.



c
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x
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f

Plate 86. Photograph of left side of Section 48 (1973 photo). Areas outlined were analyzed photogrammetrically. Results were used to generate geomorphic zonal maps. Three major zones, shown in Overlay 1, were apparent:

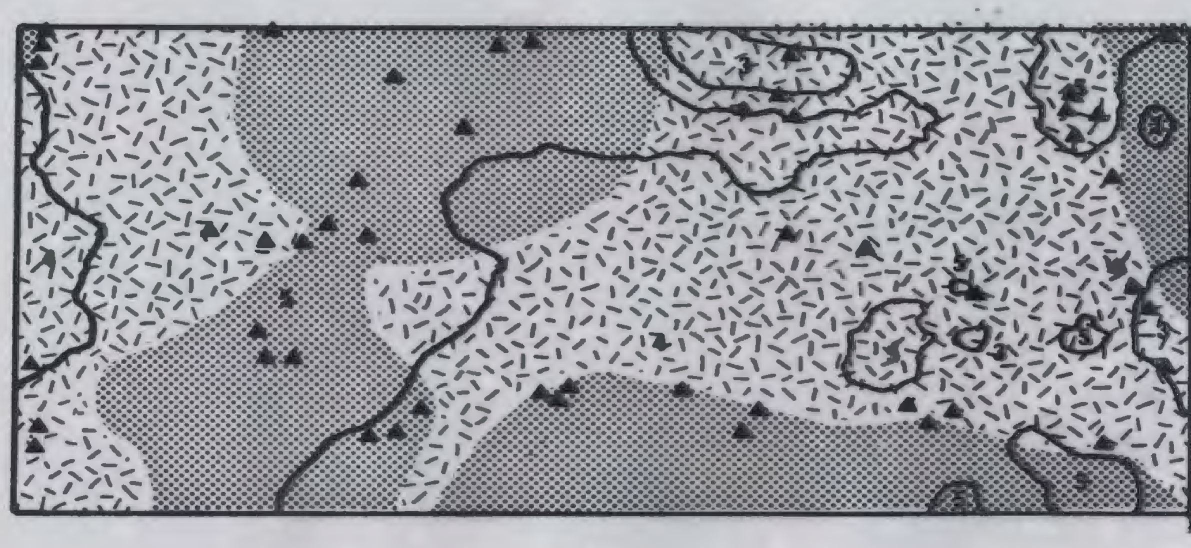
- ridges
- runoff channels
- depressions

Overlay 2 shows 1971-73 littorine gastropod distribution over the area.

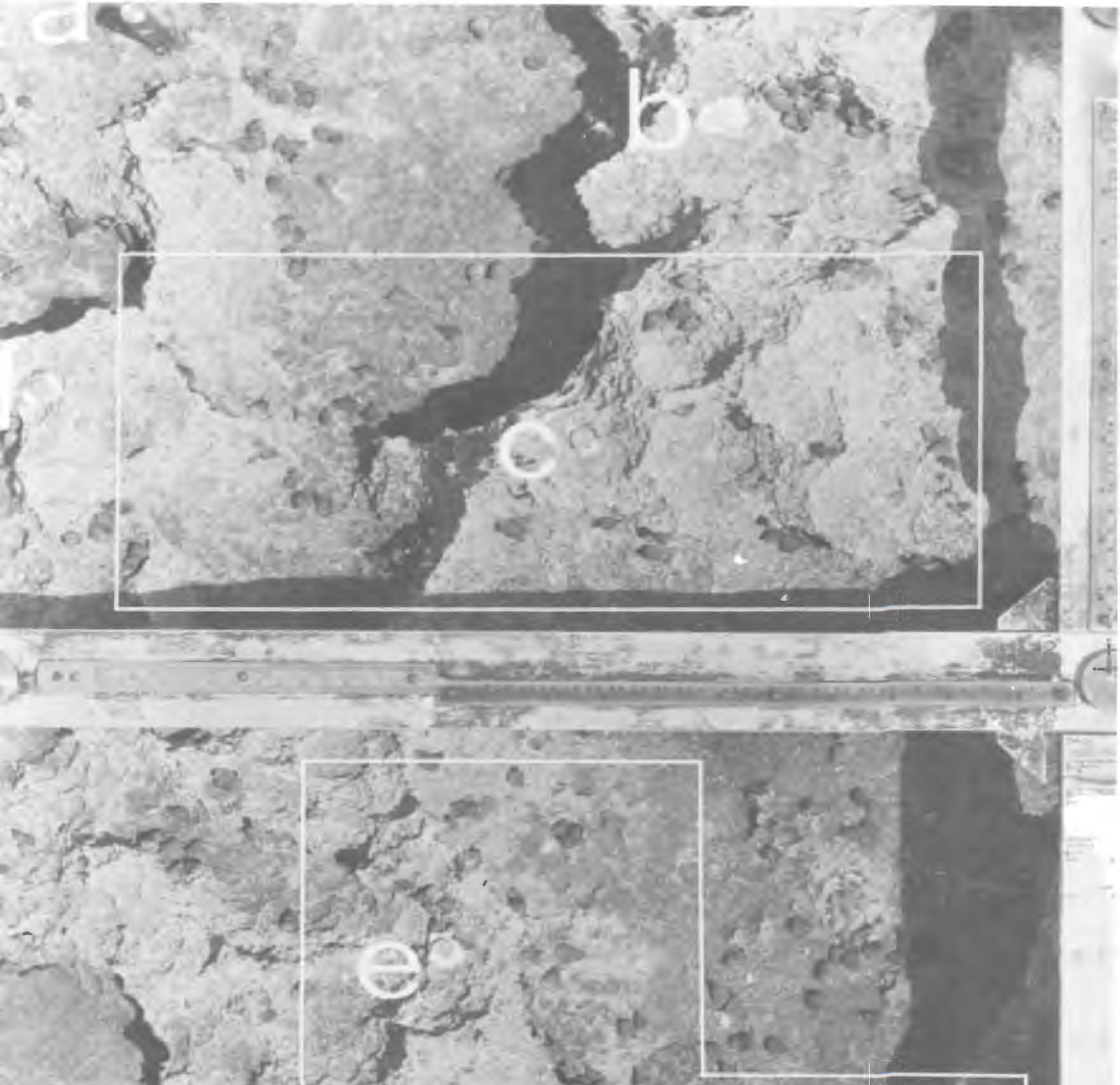
Overlay 3 displays results of residual contour mapping of the surface. Numbers correspond to ranges of erosion as follows:

1 represents -3.0 to -5.0 mm/yr erosion
2 represents -1.0 to -3.0 mm/yr erosion
3 represents +1.0 to -1.0 mm/yr erosion
4 represents +3.0 to +1.0 mm/yr erosion
5 represents +5.0 to +3.0 mm/yr erosion

Negative erosional values indicate accretion.



86-2
86-3



a
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c
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86-2
86-3

Plate 87. Irregular caliche crusts (arrow), overlying calcarenite. Stroud's Bay terrace. Scale is in inches.

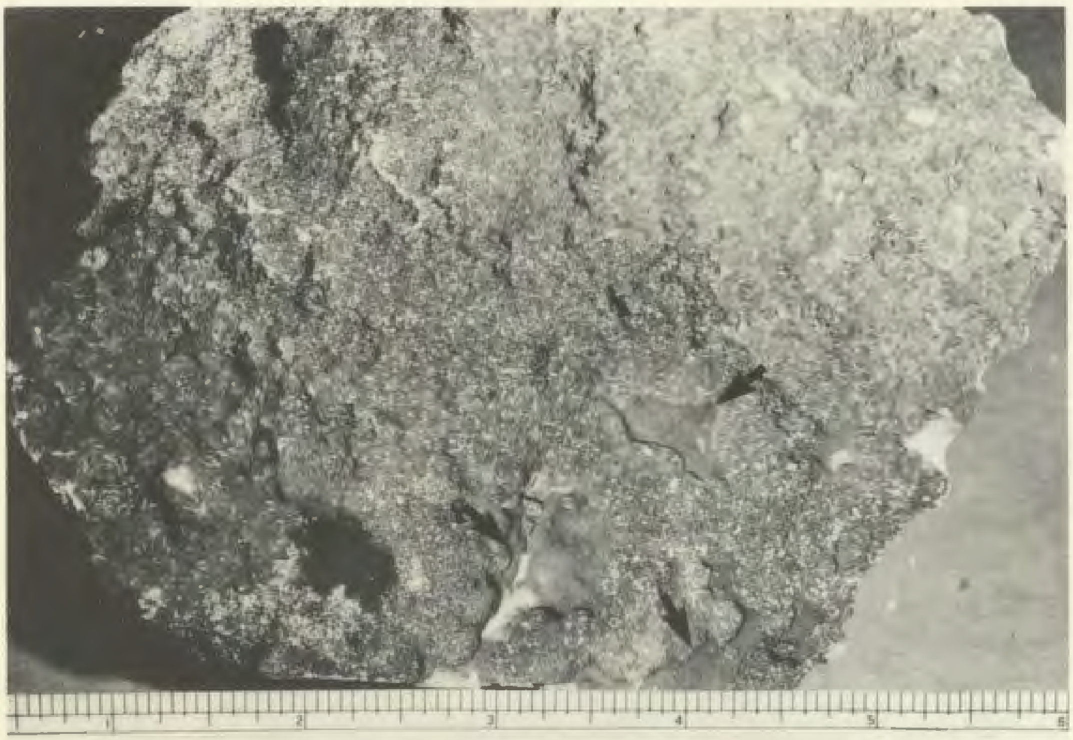


TABLE 12

SPECIES ABUNDANCE DATA, SECTION 48, STROUD'S BAY

Organism	1970	1971	1972	1973
Sessile:				
None observed				
Mobile:				
Littorina meleagris	-	33	59	29
Littorina ziczac	-	87	53	67
Nodilittorina tuberculata	478	460	1267	1066
Nerita peloronta	4	-	-	-
Total number of species	2	4	4	4

Species abundance (in number of individuals or percentage surface coverage per square meter) for each year of study at Section 48, Stroud's Bay.

88 and 89). These crusts have been identified by James (1972) as caliche crusts. The crusts are composed of densely packed, 1 to 3μ, equicrystalline, brown micrite. Crusts at this location are discontinuous and less than 5.0 mm. thick. These crusts are underlain by biocalcarenite (Plate 90). Cement in the underlying calcarenite is calcitic in the form of 10 to 20μ halos around grains and infilling pore space (Plate 91). Dissolution effects are also observed at this locality. These effects are exemplified by remnant micritic halos whose enclosed grains have been partially or completely dissolved (Plate 92). In some cases, these halos have been overgrown by spar (Plate 93). Coring of the rocks at this location shows the rock to be heterogeneous with respect to cementation and lithification at depth. The rock is often very friable and cavities up to 1 cm. have been encountered during coring procedures.

Photogrammetric analysis of Section 48 is based on 1972 and 1973 data due to the fact that the bench mark anchoring system was destroyed after the 1971 data were collected. Based on these data, an overall average annual erosion of 2.2 mm./year ($n = 309$, $s^2 = 1.81$) was obtained. Statistical significance of erosion value averages varies for each of the three surface morphologies displayed at this locality. The average erosion value obtained for the closed (non-drained) depressions is 3.2 mm./year ($n = 99$, $s^2 = 0.62$), while in the runoff channels and drained basins the

Plate 88. Cross section of caliche crust from Stroud's Bay locality. Note banding in crust. Variation in porosity of underlying calcarenite is also evident. Scale is in inches.

Plate 89. Thin section photomicrograph of caliche, showing dense microcrystalline matrix with oval inclusions. Plane polarized light, 45x.

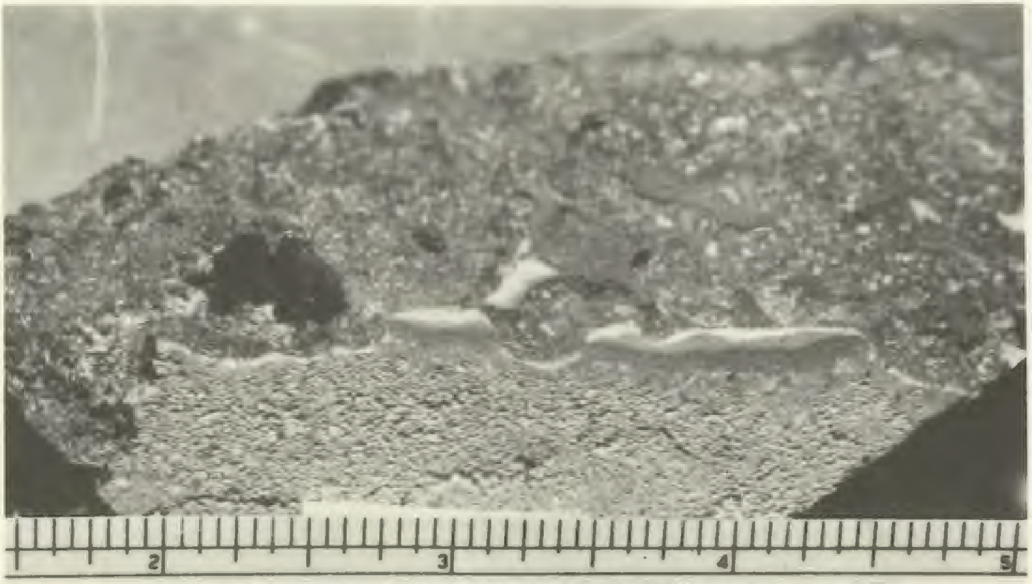

2
3
4
5

Plate 90. Photomicrograph of contact zone between dark caliche area and underlying calcarenite, from Stroud's Bay locality. Note calcitic cement infilling pores. Crossed nicols, 45x.

Plate 91. Photomicrograph of calcitic infilling cement overlying micritic halos on grains from Section 48, Stroud's Bay. Plane polarized light, 290x.

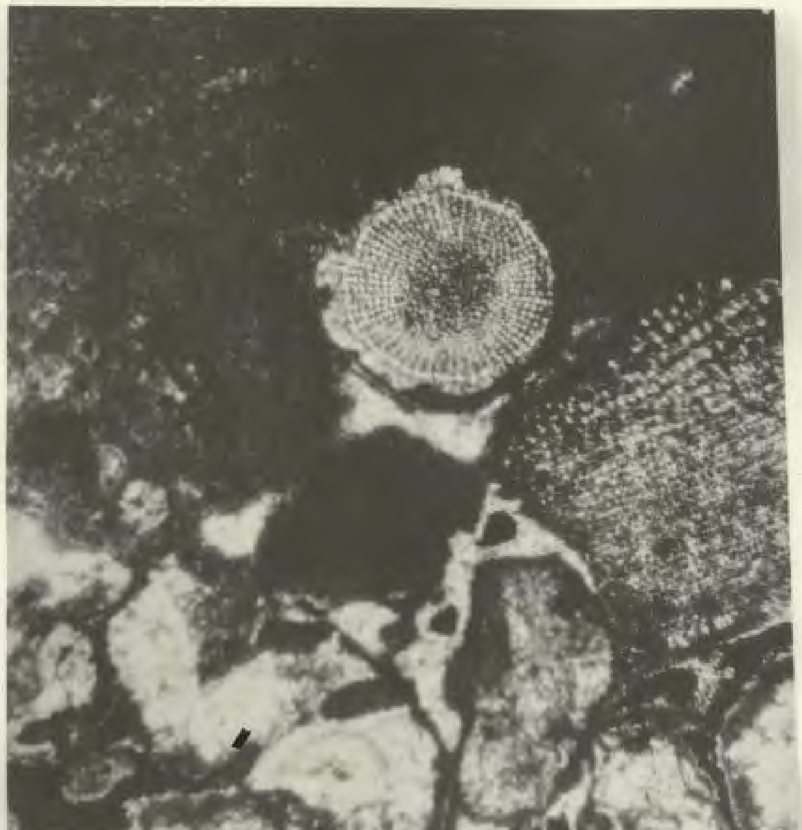
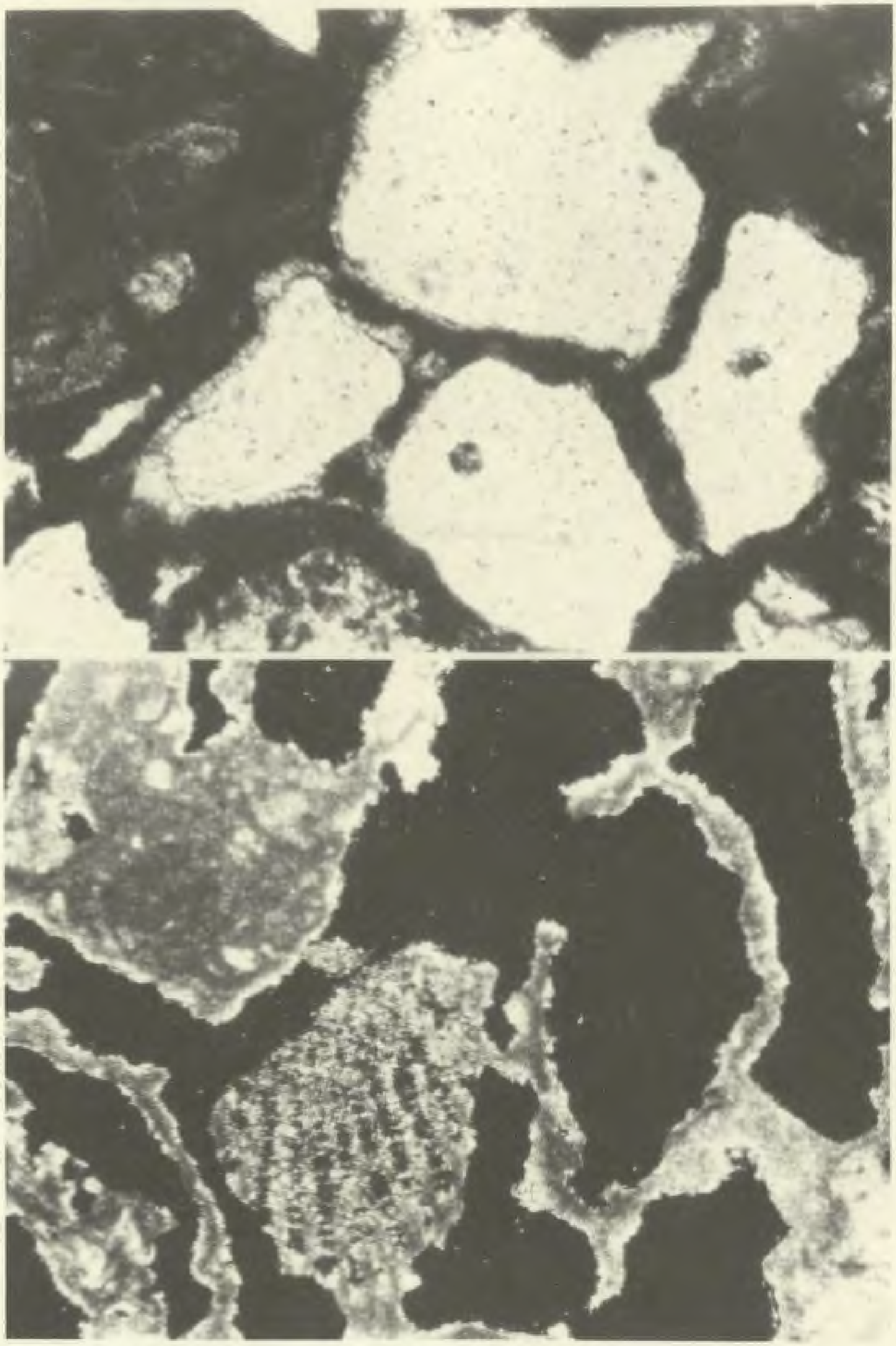


Plate 92. Photomicrograph showing dissolution of calcarenite grains at Section 48, Stroud's Bay, leaving only irregular micritic halos. Crossed nicols, 75x.

Plate 93. Photomicrograph showing micritic halos overgrown by calcitic spar. Stroud's Bay, Section 48. Plane polarized light, 107x.



average erosion value is 2.4 mm./year (n = 22, $s^2 = 0.71$). The ridges between the basins and channels show the lowest erosion value (1.6 mm./year, n = 188, $s^2 = 1.65$).

A Consideration of Epilithic Bioerosional Capabilities

Based on the data presented above, it is possible to examine the importance of the epilithic organisms on the overall erosion of each study site. To quantitatively evaluate the biological erosional contribution of the various elements of the epifauna at each locality, faunal abundance data have been collected and combined with results of previous work by McLean (1964) to obtain an estimate of the total epilithophagic erosional contribution per section. Data collected in the present study are in the form of yearly population counts of epilithic grazers at each locality. Previous work by McLean (1964) has established an erosional potential in grams per year for individuals of selected epilithic invertebrate species. These determinations are based on measurement of the amount of faecal material produced by a known number of individuals in a known period of time and then determination of the amount of $CaCO_3$ in the defecated material. An erosive potential per individual can then be calculated in grams per year. It is then a simple matter to convert the grams per year to cubic centimeters per year (assuming a density of calcium carbonate of 2.8 grams per cubic centimeter). This is tabulated in Table 13.

TABLE 13

EROSIONAL CAPABILITIES OF EPILITHOPHAGIC INVERTEBRATES

Organism	Erosion Capabilities in grams/year/organism	Erosion Capabilities in cubic centimeters/year/organism
Littorina meleagris	0.18	0.06
Littorina ziczac	0.56	0.20
Nodilittorina tuberculata	1.30	0.46
Nerita versicolor	2.40	0.86
Nerita peloronta	8.00	2.86
Nerita tesselata	1.10	0.39
Acmaea jamaicensis	2.40	0.86
Fissurella barbadensis	8.00	2.86
Acanthopleura granulata	22.00	7.86
Chiton marmoratus	14.00	5.00
Echinometra lucunter	24.00	8.57

Erosional capabilities of selected epilithophagic invertebrates in grams per year as reported by McLean (1964) and equivalent erosion in cubic centimeters per year (based on a density of $CaCO_3$ of 2.8 grams per cubic centimeter).

Using these values (and correcting for the various porosities of each study site) in conjunction with the tabulated population counts for each area, it is possible to establish annual epilithic erosion values for each section for each year and then to determine the percentage of total erosion caused by epilithophagic activity at each locality. This information has been summarized in Table 14. These percentages, while indicating considerable variability in epilithophagic contribution from year to year, show that in no case is the "grazing" bioerosion a dominant influence on overall erosion.

Several possible weaknesses in the calculations must be considered. Firstly, the population counts vary considerably from year to year.[1] This most likely reflects not yearly variance but tidal or daily variance, in that the molluscs move with the tide which controls the state of the rock surface, that is, dampness and temperature. Hence, it may be assumed that an average of the numbers gathered in the population counts would give a reasonable estimate of the effective numbers of individuals at that site.

A second criticism of the calculations concerns the assumption that all ingested $CaCO_3$ is processed and defecated in solid form. It is known that the gut pH of

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[1]The author is aware that mass calculations with fluctuating populations, including extrapolations from small areas of analysis, are rather speculative.

TABLE 14

YEARLY AND AVERAGE EPILITHOPHAGIC CONTRIBUTION TO EROSION AT STUDY SITES[1]

Section	Epilithophagic erosion (mm/yr) 1969	1970	1971	1972	1973	Average	Total erosion (mm/yr)	Epilithophagic Contribution (%)
4	-	-	0.12	0.19	0.29	0.20	1.5	13%
6	-	0.90	0.06	0.77	0.33	0.52	1.3	40%
18	0.05	0.10	0.18	0.29	0.12	0.15	1.2	12%
30	0.31	0.11	0.12	0.38	0.41	0.27	1.3	21%
47	0.85	1.02	0.87	0.76	0.54	0.81	2.4	34%
48	-	0.28	0.28	0.73	0.62	0.48	1.8	27%

Yearly and average erosional contribution by epilithophagic organisms[1] for each study site. Also shown is the total annual erosion by all agents for each study site. The percentage of this total erosion which may be accounted for by epilithophagic activity is presented in the final column. Erosion values are presented in millimeters per year (representing surface lowering). Average porosity of the rock at each section is taken into consideration in these calculations.

[1]Based on McLean's (1964) data and Table 13 (present study) in conjunction with species abundance data (Tables 7-12, present study). Details of calculations appear in Appendix V.

molluscs can fall as low as 5.3 (Prosser and Brown, 1961). Hence, it is possible that some proportion of the ingested limestone may be dissolved during digestive processes. Experiments have been carried out to determine the importance of this possibility. Calcium carbonate fragments, 550μ sand, and finely powdered limestone samples have been placed in a buffered pH 4.01 solution and allowed to stand for periods of up to forty-eight hours (with occasional stirring). In no case has more than 9 per cent (weight) of the $CaCO_3$ dissolved. Hence, at worst, McLean's calculations are conservative by less than 10 per cent. The essential order-of-magnitude correctness of McLean's data for mollusc bioerosion has also been substantiated by studies of other workers (Emery, 1946; North, 1954; Kay, 1959; Lowenstram, 1962; Hodgkin, 1964; Neumann, 1966; Healey, 1968). It would thus appear that the estimates of epilithophagic erosion are in order.

CHAPTER V

DISCUSSION

Average Annual Erosion and Epilithophagic Erosion

With the initiation of this project, it was hoped that several aspects of two geomorphologic problems could be elucidated. These problems deal in a broad sense with the nature and magnitude of tropical coastal erosion and, in a more restricted sense, with the relative importance of various erosional agents on a particular limestone surface. While numerous studies have evaluated either erosion rates of rock surfaces or erosional capabilities of various agents, none has, to the author's knowledge, combined the two types of study in an attempt to determine with some degree of quantitative accuracy the relative importance of these agents in the overall picture of erosion. The present study has established average annual erosional rates for selected coastal limestone substrates and has then attempted to quantitatively evaluate the role of various organisms in this total erosion based on data from previous invertebrate studies. With this information, it is possible to discuss the importance of bioerosional as well as other erosional agents, be they of a physical, chemical or biochemical nature.

Before beginning discussion of erosional agents which may affect the Barbadian localities, it might be useful to briefly summarize results drawn from data presented in the previous chapter:

1. Average vertical rock erosion at selected sites of the intertidal and supratidal zones of the tropical island of Barbados are in the order of 1.5 mm. per year. This is based on evaluation of approximately 1375 data point residual values gathered from six sections around the island. The sections are located in the upper, middle and lower intertidal zones as well as in the supratidal/splash zone.
2. Variation in average residual values (erosion rates) between intertidal localities ranges from 1.0 mm./year to 1.5 mm./year.[1] Section 4 of Wait's Bay low intertidal zone shows a statistically higher mean erosional value (1.5 mm./year) than the mid-intertidal sections (Section 6, Wait's Bay = 1.3 mm./year; Section 18, Heywood's Beach = 1.0 mm./year; and Section 30, Long Bay = 1.3 mm./year). All intertidal localities show significantly lower average erosion rates than does the splash/supratidal zone at Stroud's Bay (Section 48) which displays a 2.2 mm./year average residual value.

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[1]Although Section 47 is, strictly, an intertidal locality, it is treated separately since residual values are specifically Echinometra lucunter bioerosion values.

3. Intralocality variation in erosion rates for varying surface morphologies is significant in some cases (Appendix) but cannot always be correlated with changing surface morphology.
4. Epilithic organisms appear to account for a minimum of 12 per cent and a maximum of approximately 40 per cent of the total annual erosion on the rock surfaces studied (Table 14).

The first finding above is in accord with the results of other erosional studies (cited previously).

The second finding suggests that erosion rates depend to a certain extent on location of the rock surface with respect to mean sea level. Mid-intertidal locations display a lower average erosion rate than either the higher splash/supratidal section or the lower intertidal section. Another implication of the second point is apparent from the mid-intertidal data. Although the mid-intertidal rock surfaces are lithologically similar, they differ considerably in gross topographic characteristics, epibiotic assemblages and in their geographic locations. Hence one might expect considerable (statistically significant) differences in their erosion rates. This is not observed. The implication would then be that gross topography, epifaunal assemblages and geographic location are not of overriding importance as factors influencing erosion of the rock surfaces in a situation such as that of Barbados.

This tentative conclusion is supported by the third and fourth findings above in that while some correlation between geomorphic surface configurations and erosion rates exists, this is not always the case. Additionally, the epibiotic contribution to erosion accounts, in all cases, for less than half of the total erosion observed.

Non-Epilithophagic Erosion

To account for the non-epilithophagic erosion, other erosional processes must be considered. The possibilities to be considered fall into four categories: (a) physical erosion, (b) chemical solution, (c) biomechanical erosion, and (d) biochemical erosion.

Physical erosion in the form of physico-mechanical abrasion (corrasion) appears to be of little importance at the present study sites. The most distinct and obvious morphologic result of this type of physical erosion is a rounded, smooth, polished surface (Emery and Cox, 1956; Emery, Tracey and Ladd, 1954). This type of surface is generally lacking in the localities analysed.

A second type of physical erosion in the form of interstitial salt crystallization has also been considered as an agent in the erosion of coastal rocks (Wellman and Wilson, 1965; Brückner, 1966; and Coleman, Gagliano and Smith, 1966). Very little quantitative information is available on this erosive mechanism. Necessary conditions for salt weathering are a supply of salts, sites for salt to accumulate protected from the elements and changes in temperature and humidity that affect crystallization. Based on observational evidence and on air-salt load data (Hudson, 1963), it would appear that only two sections (Section 6, Wait's Bay and Section 48, Stroud's Bay) could be appreciably affected by this phenomenon. Both of these localities are susceptible to salt splash during tidal level fluctuations. Both sections are located in areas of very high (>200 grams NaCl/sq.ft./day) air-salt load. However, much of this salt is in crystalline form before it is deposited. Hence, the crystal formational energy has already been expended before it comes into contact with the rock and is not available initially for crystal wedging of the rock particles. There are, however, small pools in these sections which hold water for short periods of time before evaporation and drainage remove the water. This makes obvious the possibility of appreciable concentrated brine formation and subsequent crystallization in these pools. No quantitative evaluation of the significance of this process is possible at present.

The potential for direct inorganic chemical solution by runoff rainwater has been considered by Ginsburg (1953). When applied to Barbados rainfall data, calculations show that with an average annual rainfall of approximately 127 cm./year (Rouse, unpublished M.Sc. thesis, 1962; Hudson, 1963), approximately 20.4 $cm.^3$ of calcite could be dissolved from a square meter of limestone in one year (based on a solubility of 0.044 grams $CaCO_3$ per liter of rainwater at 25°C). This means that surface lowering of the rock by rainwater solution would amount to approximately 0.02 mm./ year. As Ginsburg (1953) points out, this assumes that the rainwater is in contact with the rock long enough to become saturated with $CaCO_3$. This is not likely in the porous, honeycombed intertidal rocks. Also, depending upon its relative tidal position, the rock surface is periodically covered by seawater which is in all cases in the present study saturated and often supersaturated (up to 400%) with respect to $CaCO_3$. Hence, no dissolution of limestone substrate can be expected when the rock surface is submerged. The greater the amount of time the rock surface is submerged, the lower is the effective amount of time for rainwater solution of the surface. Hence, for practical purposes, the 0.02 mm./year cited above can be considered the maximum erosive effect contributed by direct inorganic chemical solution. This value is insignificant in the present context, being at most 5 per cent of the annual erosion.

Biomechanical erosion in the form of rock boring by infaunal organisms must also be considered in the context of contribution to overall erosion. It has been found that the common biomechanical borers are conspicuously absent from the study sites with two exceptions. A boring sipunculid <u>Phascolosoma</u> sp. is found at the Six Men's Bay locality in a substrate overgrown by zooanthids. On the same rock ledge, an Echinometra luçunter burrow system (described in previous section) is present. No rock samples from the Echinometra area have been found to contain sipunculid borings. This may be explained by the fact that the urchins continuously work their burrows and minimize the possibility that larval forms can settle and begin excavation. The sipunculid is not found in the photogrammetrically analysed section and hence no quantitative information is available on this infaunal organism.

The second biomechanical borer found in the general vicinity of the study sites is the acrothoracic barnacle, Lithotrya dorsalis. This organism is present landward of Section 18, Heywood's Beach, where it is found boring subhorizontally into the strata of the beachrock slab. Again, as this organism is not actually found in the photogrammetric area, no quantitative information on its activities is available.

The importance of biologically induced chemical solution in the intertidal zone has been considered by a number of workers (Revelle and Emery, 1957; Kuenen, 1950; Wentworth, 1938; Hills, 1949; Emery, 1946). No agreement has been reached with respect to the importance of this process. Geologic evidence indicates that a process of solution is active in the erosion of intertidal tropical limestones. However, published data on solubility products of $CaCO_3$ indicate that nearshore seawater is apparently always supersaturated in tropical carbonate environments such as Barbados. In a study of chemical erosion of beach-rock of the Marshall Islands, Revelle and Emery (1957) concluded that fluctuations in alkalinity of tidal pool water, caused by plant photosynthesis and animal respiration, makes possible either solution (during the night) or precipitation (during the day) of $CaCO_3$. Their calculations, based on calcium fluctuation in seawater basis, show a rate of solution of 0.83μ/day or 1 cm. in thirty-three years or 0.3 mm./year.

In conjunction with chemical solution effécts induced indirectly by the metabolic processes of the biota of the intertidal basins, direct biochemical boring is important in the erosion of limestone substrate. The most important and most abundant group of intertidal biochemical borers in the present study are the microalgae. While both chlorophytes and cyanophytes are found on low, damp areas, cyanophytes are also present on high, dry rock surfaces. These organisms are found to be present in all sections, penetrating the rock to an average depth of 5 to 6 mm. Species identification of these algae is tentative. It is believed, however, that at least five genera are active in the rock deterioration. The algae attack both the interstitial cement and individual grains of the rock. Previous work on these algae (Duerden, 1902; Ginsburg, 1953; Purdy and

Kornicker, 1958; Margolis and Rex, 1971; Rooney and Perkins, 1972) has suggested their significance in coastal limestone erosion. Golubic (1975) calculated rates of boring of up to 0.5 mm. in a two week period. Based on this information and the high algal densities observed in the Barbadian coastal limestones, the author believes that these algae are responsible for a high percentage of the non-epilithophagic erosion at all localities. Unfortunately, no quantitative estimate of algal bioerosion can be obtained from procedures used in this study.

The microboring algae may act as either intergranular or intragranular agents of erosion. In the first case, they are found in the interstitial spaces of the rock, destroying the cement or the surface of the grains. Evidence indicates that for the most part, the algae are chemically etching the carbonate surfaces. However, to some extent, they may mechanically pluck grains and cement during growth of the filaments. Both filamentous and coccoid algal forms have been found in the interstitial spaces of the limestones. These chasmoliths may pull grains from the surrounding rock walls during dessication. This is accomplished by the formation of a mucilaginous bond between the algal thallus and the surrounding rock matrix. This bond is in actuality the drying mucous sheath which surrounds many of the cyanophytes. As the thallus continues to dry and shrink, fragments of rock material may be pulled loose.

Intragranular boring has been subdivided into peripheral and penetrative boring in the present study. Peripheral boring is most common and has been described by many workers and summarized by Bathurst (1971) as the micritization process. Grains undergoing micritization are subject to algal boring around their periphery. As Bathurst emphasizes, the process is a centripetal one and may result in complete destruction of original grain structure, with concurrent infilling of algal borings by either Mg-calcite or aragonite. Penetrative intragranular boring, while less common than peripheral (micritic) boring is often observed in thin sections. Borings of various sizes, lengths and shapes are found to penetrate grains to a much greater depth than the peripheral borings. They are penetrative to the extent that their length equals or exceeds the radial dimension of the grain.

The algal microphytes described above also serve an indirect function in erosion. Their presence ensures the bioerosive activities of the various epilithic grazers which must rasp away at the rock in order to avail themselves of the nourishment provided by the lithophytes. This activity in turn creates fresh new surfaces for algal colonization and subsequent boring.

Erosional Influence on Geomorphology

Table 6 shows average residual values for specific geomorphic zones in each section. The influence of erosive processes on this topography is of some interest. With the exception of the areas encrusted by bioaccretional organisms, the surface topography consists of depressions of various dimensions, runoff channels, ridges and slopes.

The origin of the large basins or pits, as found in Sections 6 and 48 is speculative. Recent experiments by Purdy (1974) suggest that some depressions may be a result of meniscus effects on surfaces, caused by an undersupply of the rainwater necessary to flood the entire surface. As well, the pits in the rock may be remnant solution channels or reflections of a previous post-lithification history of the rock. The underlying theme, however, of all these speculations is that the depressions are for the most part due to solutional effects. These solutional effects may be directly caused by the acidic nature of rainwater or indirectly caused by fluctuating alkalinity induced by biochemical processes as described previously.

Data presented in Table 6 show that erosion of the basins exceeds the erosion of the surrounding substrate in Section 48 whereas it is significantly lower in Section 6. The reasons for this dissimilarity are suggested by petrographic information and relative position of these sections in the coastal environment. Section 6 is located in the high intertidal on the shoreward edge of a beachrock surface. Immediately shoreward of Section 6, the beachrock outcrop abruptly terminates in an essentially vertical scarp to a broad sandy backshore beach. Section 48, on the other hand, is located in the supratidal spray zone and is backed by a continuous rock surface which becomes a sharply rising slope covered with thick vegetation. Petrographic analysis of rocks of Section 6 show that though cementation of grains is poorly developed, no grain solution is evident. At Section 48, however, considerable grain dissolution is evident. These observations suggest that a possible explanation for the disparity between the two sections may be explained by the relative amounts and characteristics of surface rainwater runoff. At Section 6, little rainwater runoff would be expected since no "watershed" is available to channel rainwater over the section. However, at Section 48, a large collecting surface exists landward of the section and, in addition, high vegetative cover supplies humic acids which are carried by the runoff rainwater, This, in turn, would be channelled over the section to collect in the basins, and to enhance erosion by dissolution.

Section 4 appears to be a later stage in the erosion of the rock surface than is represented by Sections 6 and 48. The characteristics of this later stage are the breakdown of walls between depressions and overall lowering of the surface. Due to its location in the lower intertidal zone, Section 4 is wet for longer periods of time than are Sections 6 and 48. It displays an abundant endolithic flora even on ridges and high slopes. The presence of these endoliths can be attributed to the fact that the rock is seldom subjected to the degree of dessication that occurs at Section 6 and Section 48, hence, the algae and fungi are capable of existing on the higher rock surfaces of Section 4.

Erosional pitted surfaces, as displayed at Section 30, are again of questionable origin. The sub-rounded pits (up to 5 cm. in diameter), whose walls are often undercut, are more likely of a biochemical solutional nature. Organisms inhabiting these pits are capable of influencing the alkalinity of the water to a greater degree than the organisms of the larger basins (discussed above), since the surface area to volume ratio is larger in the smaller pools and, hence, metabolic processes of organisms inhabiting the depressions would have greater influence on the water chemistry in the depressions.

As stated previously, erosion values for Section 47 are biased and do not reflect overall erosion for the locality. They instead represent <u>Echinometra lucunter</u> burrow-deepening rates. The average rate of burrow-deepening determined in the present study is 2.66 mm./year, while the maximum rate is 9.9 mm./year. In contrast to this, McLean (1964) determined by direct measurement that in a five month period, urchins eroded an average of 5 mm. (12 mm./year). This was based on seven measurements

(McLean, 1964, p. 159). The meaning of this value is not clear to the present author from the data presented.

Recent information indicates that E. lucunter is opportunistic in its feeding in that it captures a great deal (60%) of its food as drift algae (Ogden, personal communication, 1974). Hence, it might be suspected that this echinoid concentrates on endoliths in burrow walls and floors only when the supply of drift algae is short. A direct correlation is suggested between increasing amounts of drift algae and decreasing degree of burrow scraping/excavating activity. Transects perpendicular and parallel to the long axis of the burrow failed to reveal differential erosion.

Table 11 indicates that the number of E. lucunter inhabiting Section 47 is declining. This appears to be due to the fact that the burrowing activities of the urchins have dissected the rock to such an extent that it is no longer a suitable site for their colonization.

Bioaccretion vs. Erosion

A final consideration in the discussion of erosion rates is bioaccretional impact. From the low tide line to considerable depths, the ability of organisms to construct and maintain wave resistant structures has been well documented. In some instances, this bioconstructional capacity extends into the intertidal zone. This is exemplified by the vermetid gastropod/coralline algal cup reefs or "boilers" and shoreline lips which are relatively common throughout the Atlantic, Caribbean and Mediterranean (Adey, personal communication; Iams, 1969, 1971; Pérès and Picard, 1952). In the present study localities, three major bioaccretional agents have been noted. These include the encrusting barnacle _Tetraclita squamosa_, the encrusting vermetid gastropod _Petaloconchus_ cf. _varians_, and encrusting coralline algae of the genera _Lithophyllum_ and _Neogoniolithon_. While it is difficult at present to judge the long-term effects of these organisms in stabilizing and protecting the substrate, it is evident from observation and from short-term quantitative data that bioaccretion by these organisms serves, at best, only to retard persistent erosional tendencies in the localities studied. The localized stabilizing effects of these organisms is reflected by the lower extreme of the range of values found in areas of colonization.

The lowest residual value for the barnacle _T. squamosa_ is -2.2 mm./year. This indicates a definite and statistically significant bioaccretional tendency. It also gives an approximate idea of the growth rate of this organism. As has been described above, the fact that these organisms are not truly colonial but merely gregarious and that they cover and protect only a small area (maximum of 1-2 cm^2.) under their shells makes them relatively ineffective in arresting general erosion. Catastrophic erosion of barnacle pedestals by keyhole limpets and endolithic algae (described above) has been observed in the present study and is indicated in the stereo-photos of Section 18 (1973). Hodgkin (1964) also noted this type of erosion which causes a lowering of the rock surface by several centimeters in localized areas. Furthermore, experimental evidence (Barrington, 1967) indicates that larval behaviour of barnacles is such that settling on raised protuberances on the rock surface, hence on plates of other barnacles, is preferred to settling on lower surfaces or in depressions. This rules in favour of multiple barnacle pinnacles surrounded by eroding depressions. This is seen in Section 18, where the barnacles are rapidly succumbing to erosive forces. The fact that the larval forms choose barnacle pedestals for settling dictates that multiple generations of barnacle accretion will be lost when the pedestal collapses.

The minimum residual value (hence, the largest bioaccretional value) associated with the vermetid gastropod pavement in Section 4 is 0.1 mm./year (Table 6). This value indicates that no positive bioaccretion has occurred. Direct observation of the colonies shows no obvious lateral spreading tendencies and it seems likely that the vermetids maintain only a very precarious existence against the erosive forces acting on them.

Coralline algal encrustation is not common in the sections studied. A few cases have been noted where erosion is retarded and accretion of approximately 1.8 mm./year

(Section 18) occurs. However, these occurrences are so few that overall average rates of erosion are essentially unaffected. Adey (unpublished manuscript) has suggested that for algal ridges to develop (in Martinique), accretion rates of 2 to 3 mm./year are necessary to offset erosive effects. The coralline algae of the present study sites do not appear to be capable of sustaining this rate of accretion. It is quite possible that continued erosion of the intertidal rocks will eventually lower the surface to the point where bioaccretionary organisms will be capable of combatting erosional tendencies.

CHAPTER VI

SUMMARY AND CONCLUSIONS

A photogrammetric system which is capable of measuring small changes in surface morphology has been described. This system has been used to obtain information on rates of intertidal and supratidal limestone erosion in Barbados. Rates of rock destruction have been determined for six localities in the intertidal and supratidal zones. These rates vary from a low of 1.0 mm./year on a barnacle pavement at Heywood's Beach to a high of 2.4 mm./year in an Echinometra lucunter burrow system at Six Men's Bay. It has been found that erosion rates are not necessarily uniform over a particular surface.

A bioerosional contribution to total erosion has been calculated for each locality based on population counts and empirical erosional capability values for epilithic grazing invertebrates. It has been found that in no section does this epilithic biological contribution to total erosion exceed 40 per cent of the total annual erosion.

Other causal factors have been considered to explain the erosion not accounted for by the epilithic organisms. Physico-mechanical factors, such as abrasion are judged to be of minor importance in the sections under study. Physico-chemical and crystallo-chemical erosion, such as salt weathering, may play a role in the erosive processes of several of the localities investigated (Sections 6 and 48). Chemical and more importantly biochemical solution of substrate by microboring flora is suggested to be responsible for much of the remaining erosion.[1]

Long-term ecologic analyses of these areas has only been touched upon due to the relative brevity of the study. However, a number of observations have been made on the floral and faunal communities and associations. Lithophytic algae and fungi are present in both intragranular (endolithic) and intergranular (chasmolithic) positions in coastal limestones of Barbados. While endolithic forms penetrate to an average depth of approximately 5 mm. and destroy the grain itself, chasmoliths function to destroy matrix and cement which bind the mineral grains together. Scanning electron micrographs of the borings indicate that the mode of penetration is biochemical as evidenced by the highly etched borehole walls. At least five genera of endolithic algae are indicated from the present study sites, based on types of borings and microscopic examination of the filaments and fruiting bodies. In addition to contributing directly to erosion, the lithophytic microflora indirectly increase erosion in that they attract chitons, keyhole limpets, limpets and other gastropods, which must rasp away the surface rock to obtain the algal food. Algal filaments have been found in stomach contents of all these organisms.

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[1]Biochemical erosion would, strictly speaking, be considered bioerosion.

Epilithic algae are often found on the rock surfaces. The amount of epilithic algal coverage varies considerably from one year to the next. Only the lowest intertidal sections display large fleshy macroalgae. Higher intertidal areas show finer filamentous algae. Crustose coralline algae are evident at several localities. They have a minor role in the erosional dynamics of the present study areas.

The abundance of grazing molluscs fluctuates from year to year. This necessitates the conclusion that erosion rates calculated from metabolic data are much higher than actual values, since they presuppose continual occupancy of an area by what appears to be an ephemeral population. Gastropods of the species Nodilittorina tuberculata and Littorina ziczac are found in association and inhabit the same relative position in the splash/supratidal zone (Wait's Bay, Section 6 and Stroud's Bay, Section 48), that is, the near-vertical walls of the solution basins. Littorina meleagris is generally found perched on the uppermost part of ridges, while neritid gastropods, Nerita peloronta and Nerita versicolor, are found on basin floors.

The encrusting barnacle, Tetraclita squamosa, is found to be a short-term bioaccretionary organism. The conical skeleton of this creature is susceptible to undermining and subsequent breakage from the rock surface.

Echinometra lucunter is observed to be an effective erosive agent in the low intertidal zone. Burrow walls and floors are largely devoid of epilithic flora and fauna.

The preceding analyses of lithology, biota and photogrammetry of various study sites along the Barbados coastline are preliminary. Data presented from the photogrammetric analysis are, however, quantitative and allow the establishment of average erosion values for selected study sites. Following statistical analysis, it is then possible to report a number of erosional tendencies of Barbadian coastal localities. More important, but also more complicated and difficult, is an explanation of the intersectional and intrasectional differences in erosion rates. The difficulty lies in the fact that a multitude of factors may influence erosion rates. These may be of either a chemical, physical or biological nature or a combination of two or more of these factors. In the present study, quantitative analyses and calculations have defined overall erosional values for various localities and geomorphic zones and have evaluated the epilithic biological contribution to this erosion. It then becomes apparent that only preliminary qualitative discussion of other erosive factors is possible.

As stated previously, many of the observations of this study are temporally limited, that is, they are only meaningful for a particular rock surface at a particular time. As a surface erodes, it is continually subjected to new physical, chemical and biological conditions. The present study suggests that one of the important factors in erosion in the coastal zone is of a biological nature. However, it is necessary to note that this biological erosive potential depends on the physical and chemical environment which controls organism distribution. The precise nature of biologic control and the rates of floral and faunal succession on the changing rock surfaces will only become apparent when long-term analyses of the surfaces have been completed.

CHAPTER VII

SUGGESTIONS FOR FUTURE STUDY

1. Experimental design in the present study allows unbiased sampling of data points in order to establish erosion rates for each study site. An extension of the study would be the nesting of data points in order to allow intensive analysis of smaller areas within the original sections. These could be chosen for any interesting and/or unusual geomorphic or biologic characteristics.

2. Due to present financial and logistical restrictions, it has been necessary to choose between analysing a number of very similar intertidal localities or a number of very different localities. The former has the advantage of minimizing the variables contributing to erosion of a surface, while the latter has the advantage of allowing one to see quantitatively how great an erosional difference can be expected between areas with obviously different biotic, lithologic and geomorphic characteristics. This latter type of study has been carried out in the present case. The logical next step is the complimentary analysis, that is, establishment and analysis of a number of similar rock surfaces in order to minimize variables which might influence erosion rates.

3. The present study establishes overall erosion rates for selected localities and calculates the percentage of this erosion which can be attributed to epilithic organisms. It is now necessary to establish a means to gather quantitative information on non-epilithic bioerosive agents, including chemical, biochemical and physical agents.

4. Study of the zonation of lithophytic microphytes and quantitative distribution in the coastal zone, as well as their rates of boring, should be initiated in order to shed light on their erosive potential.

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APPENDIX I: DETAILS OF ANCHORING OF BENCHMARKS, END BOLTS AND REFERENCE BOLTS IN ROCK SURFACE

A. Benchmarks

These are necessarily substantial devices as they serve to locate and support the entire photographic apparatus. The benchmark consists of a 1/2 inch stainless steel rod (round cross section) which is driven into a pre-drilled hole in the rock. A stainless steel wedge in the hollowed, slotted bottom of the rod forces the sides of the hollowed portion firmly and permanently against the walls of the hole. A special drift is used to drive the rod into the rock without causing damage to the top of the rod.

This technique of anchoring has worked with little difficulty. Some problems arise, however, when the bottom of the rod is in friable rock horizons. The effectiveness of the wedging is then reduced. A new hole must then be used and a new benchmark emplaced.

No corrosion of these stainless steel rods was noted during the course of this study. Minor fouling by coralline algae was noted but was easily removed.

B. End Bolts

These are machined from the same 1/2 inch stainless steel rod as the benchmarks (described above). The end bolts are threaded at one end and screw into holes tapped in the top of the benchmark. The end bolts are further machined with parallel flat surfaces on opposing sides of the rod in such a way as to accept a 3/8 inch open end wrench used for tightening the bolt in the benchmark. Following photography, these bolts are removed, leaving only the benchmarks and reference points (see below) in the rock surface.

C. Reference Points

These consist of 3/8 inch monel machine bolts with ground and polished heads. Holes are drilled into the rock with brace and masonry bit. An epoxy resin (Sea-goin' 'poxy putty brand) is placed in the drilled hole and the bolt is pushed into the resin. The resin is allowed to harden (and will set above or under water).

No problem developed with this technique during the course of the study. All bolts remained securely fixed in the rock. No corrosion was noted.

It was necessary in several cases to use diagrams and photographs from the previous year to locate the reference points as overgrowth by epiphytes occasionally obscured the points.

APPENDIX II

T-Test for matched samples

In order to determine whether a significant change in the mean value of surface height for each section for the years 1971 and 1973 exists, a T-test for matched samples was carried out. This test allows comparison of all values of a particular section for a particular year with the corresponding values for a different year. This comparison is carried out by calculating a t-value for the matched samples populations. This can be done using the formula:

$$t = \frac{\Sigma D}{\sqrt{\dfrac{N\Sigma D^2 - (\Sigma D)^2}{N - 1}}}$$

where D = difference score of each matched pair of values

N = number of sample pairs

Should the calculated value of t be smaller in absolute magnitude than the theoretical value of t'(obtained from tables) for the appropriate degrees of freedom (df = N-1), the null hypothesis (H_0) is retained, that is, the mean of the population of difference scores is considered to be zero. ($H_0:\mu_D=0$). If the calculated t-value is greater than the theoretical t, then the null hypothesis is rejected and the alternative hypothesis, which states that the mean value of the difference scores does not equal to zero ($H_1:\mu_D\neq 0$), is accepted. Acceptance of the alternative hypothesis, H_1, acknowledges that a significant difference in surface height readings does exist between the two samples.

Statistical parameters necessary for the testing are summarized in Table A1. This data has been used to compare the matched values for all sections in the present study and the results are presented in Table A2.

TABLE A1

STATISTICAL PARAMETERS USED IN EVALUATION OF DATA FROM PRESENT STUDY SITES

Section	Surface Morphology	n	$\overline{Y}$	ΣY^2	$(\Sigma Y)^2$	S^2
4	Vermetid pavement	13	1.8	47.84	540.10	0.48
	Cascade depressions	15	1.4	37.55	448.80	0.51
	Steep slope	48	1.7	170.71	6348.90	0.80
	Resistant ridge	30	0.9	36.96	814.25	0.32
	Ridge/slope	57	1.6	171.68	8476.88	0.40
	Overall	163	1.5	464.74	59882.97	0.60
6	Cascade depressions	51	1.4	112.10	4997.08	0.28
	Basins	52	0.9	56.52	2370.72	0.21
	Ridge/slope	164	1.4	361.56	52512.01	0.25
	Overall	267	1.3	530.18	121480.13	0.28
18	Barnacle zone	94	1.1	157.01	3212.06	1.31
	Pitted surface	173	1.2	354.45	44282.99	0.57
	Barnacle growth	22	-1.1	38.73	620.51	0.48
	Overall	267	1.2	511.46	71353.09	0.91
30	Pitted surface Overall	123	1.3	279.77	27443.24	0.46
47	*E. lucunter* boring Overall	244	2.4	2019.15	329418.60	2.74
48	Runoff Channel	22	2.4	138.54	2708.16	0.70
	Ridges	188	1.6	796.33	91348.98	1.65
	Basin	99	3.2	1099.73	102758.68	0.62
	Overall	309	2.2	2034.60	455409.21	1.81

TABLE A2

RESULTS OF T-TEST FOR MATCHED SAMPLES

Section	Years	# Pairs	$t_{0.001}^{\text{theoret.}}$	$t^{\text{calcul.}}$	Accept:
4	1971,1973	163	3.373	24.72	H_1
6	1971,1973	267	3.373	40.12	H_1
18	1971,1973	267	3.373	17.06	H_1
30	1971,1973	123	3.373	21.92	H_1
47	1971,1973	244	3.373	22.14	H_1
48	1972,1973	309	3.373	28.45	H_1

$H_0: \mu_D = 0$

$H_1: \mu_D \neq 0$

T-TEST FOR SAMPLE MEANS: INTERLOCALITY VARIATION

In order to determine whether statistically different mean erosional values exist between sections (localities), a t-test was used. This test compared the characteristic statistical values of the six sections from which quantitative data were collected. The null hypothesis (H_0) in this case states that the two groups of values come from populations with the same mean, while the alternate hypothesis, H_1, states that the two groups of values come from populations having different means.

The T-values in this test are determined using the following equation:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{S_{\bar{X}_1 - \bar{X}_2}}$$

$$\text{where } S_{\bar{X}_1 - \bar{X}_2} = \sqrt{\frac{(N_1 - 1)S_1^2 + (N_2 - 1)S_2^2}{N_1 + N_2 - 2}\left(\frac{1}{N_1} + \frac{1}{N_2}\right)}$$

and where S_n^2 = variance of each sample

and N_n = number of values in each sample.

Table A3 summarizes the statistical analysis. (The customary .05 criterion of significance is used in the test).

TABLE A3

RESULTS OF T-TEST FOR SAMPLE MEANS: INTERLOCALITY VARIATION

	$S_{\overline{X}_1 - \overline{X}_2}$	$t_{0.05}$ theoret.	t calcul.	Accept:
1. Section 4				
a) with Section 6	.063	1.98	4.7	H_1
b) with Section 18	.063	1.98	4.8	H_1
c) with Section 30	.087	1.98	2.2	H_1
d) with Section 47	.139	1.98	6.4	H_1
e) with Section 48	.114	1.98	6.13	H_1
2. Section 6				
a) with Section 18	.067	1.98	1.49	H_0
b) with Section 30	.063	1.98	0.	H_0
c) with Section 47	.106	1.98	10.30	H_1
d) with Section 48	.088	1.98	10.27	H_1
3. Section 18				
a) with Section 30	.096	1.98	1.04	H_0
b) with Section 47	.118	1.98	10.13	H_1
c) with Section 48	.099	1.98	10.13	H_1
4. Section 30				
a) with Section 47	.156	1.98	7.06	H_1
b) with Section 48	.128	1.98	7.06	H_1
5. Section 47				
a) with Section 48	.128	1.98	1.57	H_0

T-TEST FOR SAMPLE MEANS: INTRALOCALITY (ZONAL) VARIATION

In order to evaluate and compare the mean values of groups of non-matched (independent) random samples in a particular section it was necessary to carry out a second t-test. This test served to determine whether significant differences in erosion values existed for specific areas in a certain section which were of distinctly different morphology. The null hypothesis (H_0) in this case states that the two groups of values come from populations with the same mean, while the alternate hypothesis, H_1, states that the two groups of values come from populations with different means.

(The customary .05 criterion of significance is used in the following test). The T-values in this test are determined using the following equation:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{S_{\bar{X}_1 - \bar{X}_2}}$$

where $S_{\bar{X}_1 - \bar{X}_2} = \sqrt{\frac{(N_1 - 1)S_1^2 + (N_2 - 1)S_2^2}{N_1 + N_2 - 2}\left(\frac{1}{N_1} + \frac{1}{N_2}\right)}$

and where S_n^2 = variance of each sample

and N_n = number of values of each sample.

Table A4 summarizes the statistical analyses for each section of the present study. The geomorphic area designations are described in the text and illustrated in transparent overlays in the plates for each section.

TABLE A4

RESULTS OF T-TESTS FOR SAMPLE MEANS: INTRALOCALITY VARIATION

Section 4	$S_{\bar{X}_1 - \bar{X}_2}$	$t^{theoret.}_{0.05}$	$t^{calcul.}$	Accept:
1. Vermetid pavement with:				
a) cascade depression	0.27	2.056	1.50	H_0
b) wall	0.27	2.021	0.37	H_0
c) resistant ridge	0.20	2.021	4.50	H_1
d) ridge/slope	0.20	2.000	1.00	H_0
2. Cascade depression with:				
a) steep slope	0.25	2.000	1.18	H_0
b) resistant ridge	0.20	2.021	2.50	H_1
c) ridge/slope	0.19	2.000	1.06	H_0
3. Steep slope with:				
a) resistant ridge	0.18	2.000	4.40	H_1
b) ridge/slope	0.15	2.000	0.67	H_0
4. Resistant ridge with:				
a) ridge/slope	0.14	2.000	5.08	H_1
Section 6				
1. Cascade depressions with:				
a) Basins	0.10	2.000	5.0	H_1
b) ridge/slope	0.08	1.980	0.0	H_0
2. Basins with:				
a) ridge/slope	0.08	1.980	6.25	H_1

TABLE A4 (Continued)

	$s_{\overline{X}_1 - \overline{X}_2}$	$t^{theoret.}_{0.05}$	$t^{calcul.}$	Accept:
Section 18				
1. Barnacle zone with:				
a) pitted surface	0.12	1.980	0.86	H_0
b) barnacle growth	0.26	2.000	9.03	H_1
2. Pitted surface with:				
a) barnacle growth	0.17	1.980	12.98	H_1
Section 30				
No distinct geomorphologic differences	--	--	--	--
Section 47				
Restricted to E. lucunter burrow floors	--	--	--	--
Section 48				
1. Runoff channel with:				
a) ridge	0.28	1.980	2.84	H_1
b) depression	0.19	2.000	4.30	H_1
2. Ridges with:				
a) depressions	0.14	1.980	11.3	H_1

APPENDIX III: TAXONOMIC LIST OF ORGANISMS

Kingdom: Monera

Phylum: Cyanophyta

Class: Cyanophyceae

Order: Chroococcales

Family: Chamaesiphonaceae

Genus: Hyella

Species: caespitosa Bornet and Flahault, 1889

Genus: Entophysalis

Species: deusta Drouet and Daily

Family: Chroococcaceae

Genus: Mastigocoleus (Lagerheim, 1886)

Species: ? testarum (Lagerheim, 1886)

Genus: Plectonema (Bornet and Flahault, 1889)

Species: ? terebrans (Bornet and Flahault, 1889)

Kingdom: Protista

Phylum: Phaeophyta

Class: Phaeophyceae

Order: Dictyotales

Family: Dictyotaceae

Genus: Padina Adanson, 1763

Order: Fucales

Family: Sargassaceae

Genus: Sargassum c. Agardh., 1820

Phylum: Chlorophyta

Class: Chlorophyceae

Order: Cladophorales

Family: Cladophoraceae

Genus: Cladophora Kützing, 1843

Order: Siphonocladales

Family: Valoniaceae

Genus: Valonia Ginnani, 1757

Species: ?

Phylum: Rhodophyta

Class: Rhodophyceae

Order: Nemalionales

Family: Chaetangiaceae

Genus: Galaxaura Lamouroux, 1812

Order: Ceramiales

Family: Rhodomelaceae

Genus: Bostrychia Montagne, 1838

Genus: Polysiphonia Greville, 1824

Order: Cryptonemiales

Family: Corallinaceae

Genus: Amphiroa

Species: fragilissima Lamouroux

Genus: Jania

Species: rubens Lamouroux

Genus: Porolithon

Species: pachydermum (Foslie, 1906)

Genus: Lithophyllum

Species: congestum (Foslie, 1898)

Genus: Neogoniolithon Setchell and Mason, 1943

Kingdom: Metazoa

Phylum: Coelenterata

Class: Anthozoa

Order: Zoanthidea

Family: Zoanthidae

Genus: Zoanthus

Species: pulchellus (Duchaissang and Michelotti)

Phylum: Mollusca

Class: Polyplacophora

Order: Neoloricata

Family: Chitonidae

Genus: Acanthopleura

Species: granulata (Gmelin, 1791)

Genus: Chiton

Species: marmoratus Gmelin, 1791

Class: Gastropoda

Order: Archaeogastropoda

Family: Fissurellidae

Genus: Fissurella

Species: barbadensis (Gmelin, 1791)

Family: Acmaeidae

Genus: Acmaea

Species: jamaicensis (Gmelin, 1791)

Family: Vermetidae

Genus: Petaloconchus

Species: varians (Orbigny, 1841)

Genus: Spiroglyphus

Species: irregularis (Orbigny, 1842)

Family: Littorinidae

Genus: Nodilittorina

Species: tuberculata (Menke, 1828)

Genus: Littorina

Species: ziczac (Gmelin, 1891)

Species: meleagris (Potiez and Michaud, 1838)

Family: Neritidae

Genus: Nerita

Species: versicolor (Gmelin, 1791)

Species: tesselata (Gmelin, 1791)

Species: peloronta (Linné, 1758)

Family: Muricidae

Genus: Thais

Species: deltoidea (Lamarck, 1822)

Genus: Purpura

Species: patula (Linné, 1758)

Family: Architectoncidae

Genus: Heliacus

Species: cylindricus (Gmelin, 1791)

Family: Columbellidae

Genus: Nitidella

Species: nitida (Lamarck, 1822)

Family: Coralliophilidae

Genus: Coralliophila

Species: caribea Abbott, 1958

Phylum: Sipunculida

Genus: Phascolosoma

Species: antillarum Grube and Oersted

Phylum: Echinodermata

Class: Echinoidea

Order: Echinoida

Family: Echinometridae

Genus: Echinometra

Species: lucunter (Linné, 1758)

Phylum: Arthropoda

Class: Cirripedia

Order: Thoracica

Family: Scapellidae

Genus: Lithotrya

Species: dorsalis (Ellis and Solander, 1786)

Family: Balanidae

Genus: Tetraclita

Species: squamosa (Bruguière, 1789)

APPENDIX IV: CONTOUR MAPS

The following pages display contour maps for the years 1971, 1972 and 1973 for each section described in the text. Contour intervals vary from section to section but are consistent for all years in a particular section. Contour intervals are determined by the SYMAP program band on maximum input data value, minimum input data value and number of contour intervals desired. (The following maps are based on five contour intervals). SYMAP also offers an extreme value point option whereby high and low extreme value limits may be imposed on the program. With this option in effect SYMAP will print an "L" for any values which exceed the extreme values. (In the following pages, the "L" indicates high numerical values which represent deep areas, i.e., low terrain). Numbers associated with contour intervals refer to depth values (in millimeters), i.e., distance below zero datum as established on photogrammetric reference bar (see methods section--photogrammetric procedures).

Contour interval coding for each section is as follows:

Section 4 (all years)

Contour Code	Depth Value Interval (mm.)
1	0 - 40
2	40 - 80
3	80 - 120
4	120 - 160
5	160 - 200
L	>200

Section 6 (all years)

Contour Code	Depth value intervals (mm.)
1	50 - 80
2	80 - 110
3	110 - 140
4	140 - 170
5	170 - 200

Section 18 (all years)

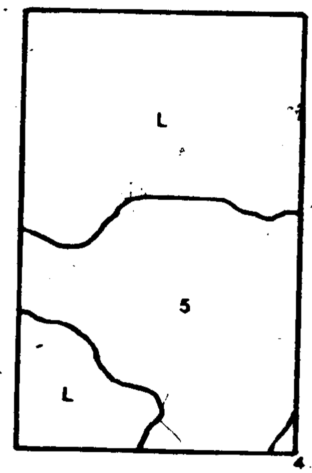
1	50 - 75
2	75 - 100
3	100 - 125
4	125 - 150
5	150 - 175

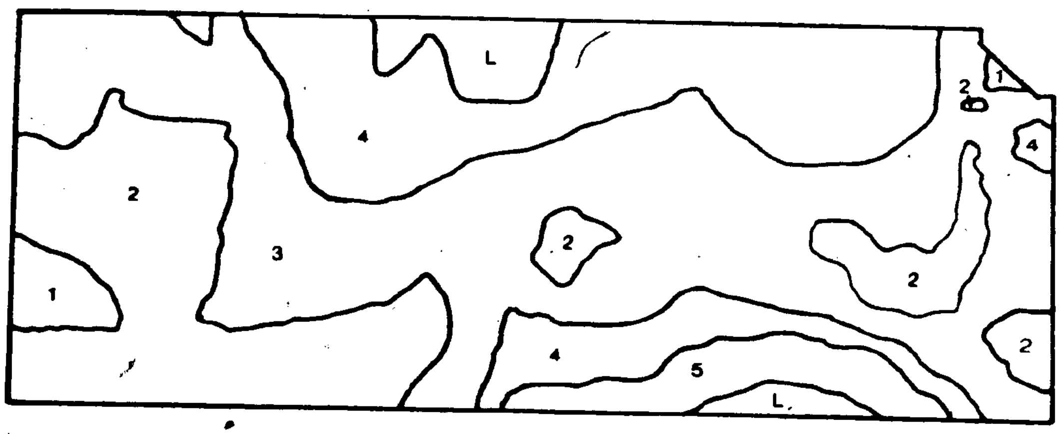
Section 30 (all years)

1	50 - 75
2	75 - 100
3	100 - 125
4	125 - 150
5	150 - 175

Section 48 (all years)

1	0 - 40
2	40 - 80
3	80 - 120
4	120 - 160
5	160 - 200
L	>200





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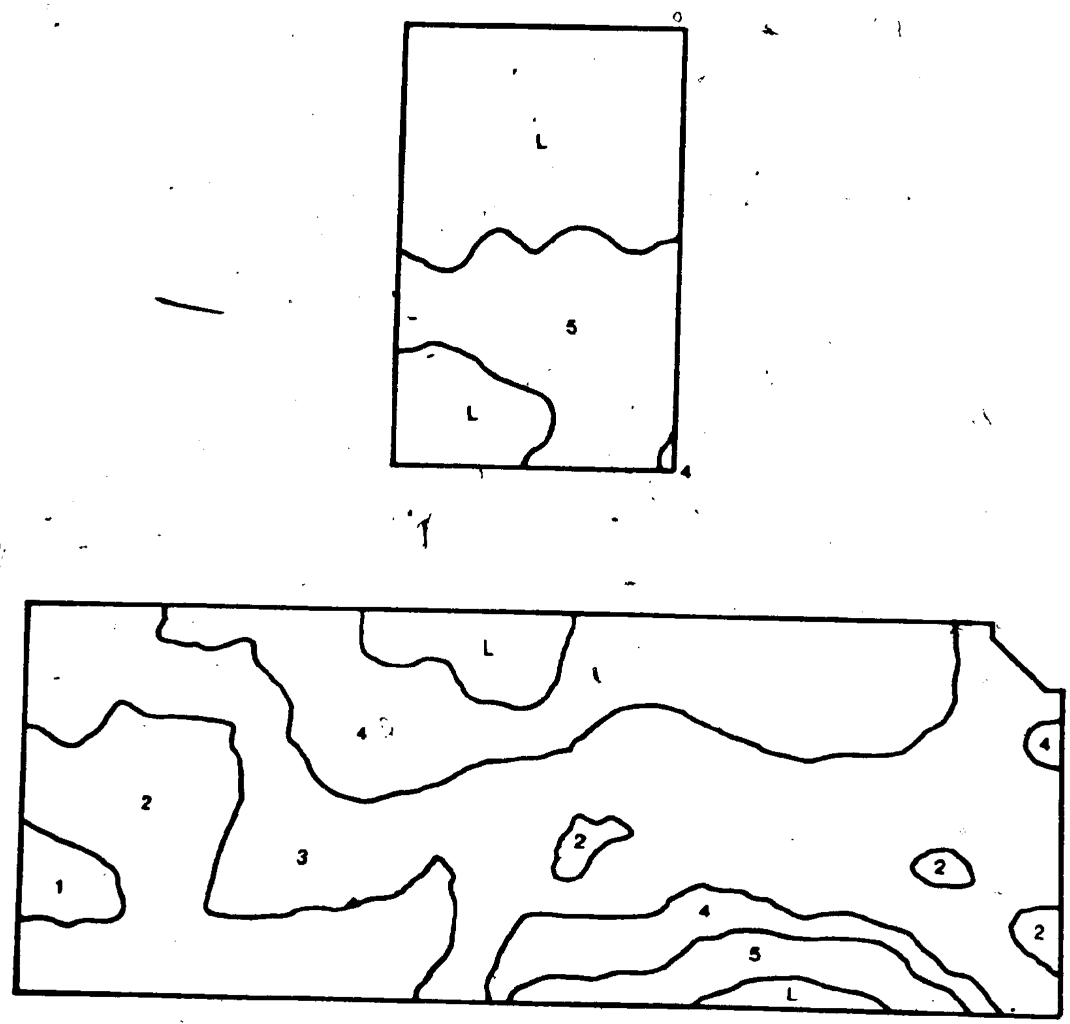
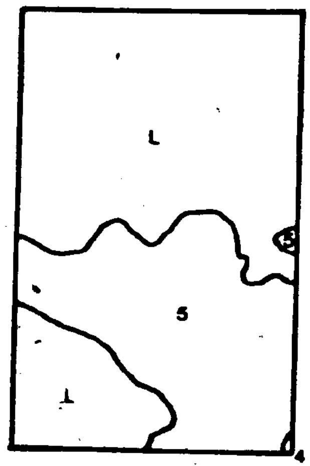
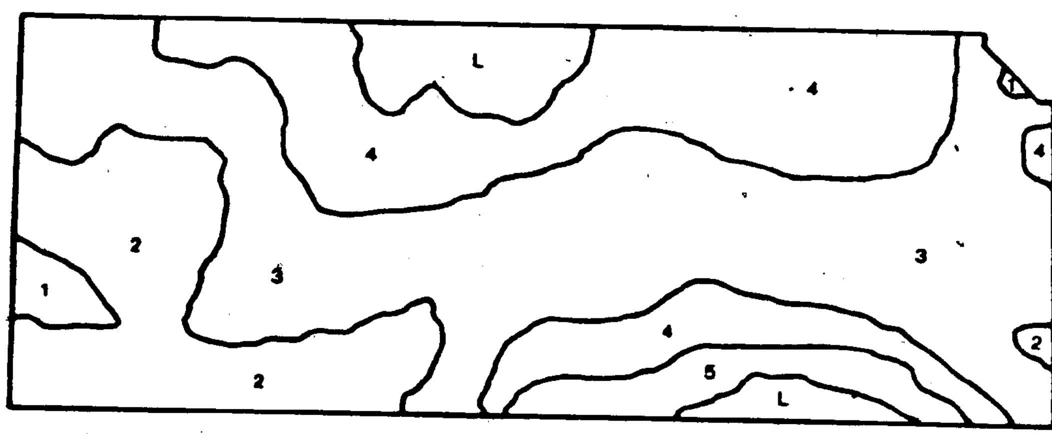
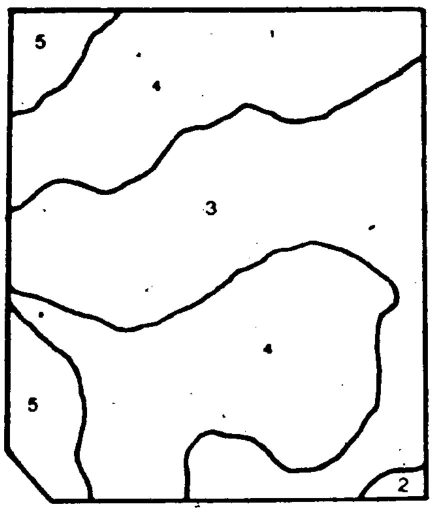


fig. 72





qc- 73



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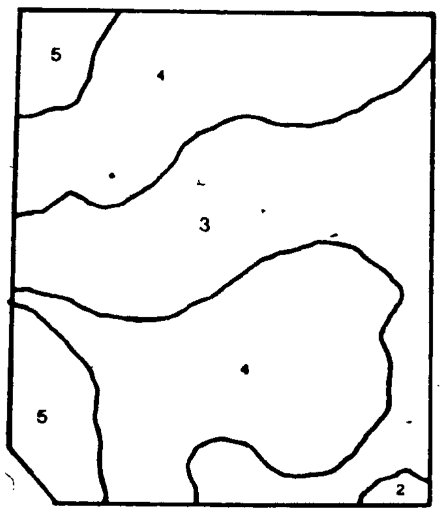

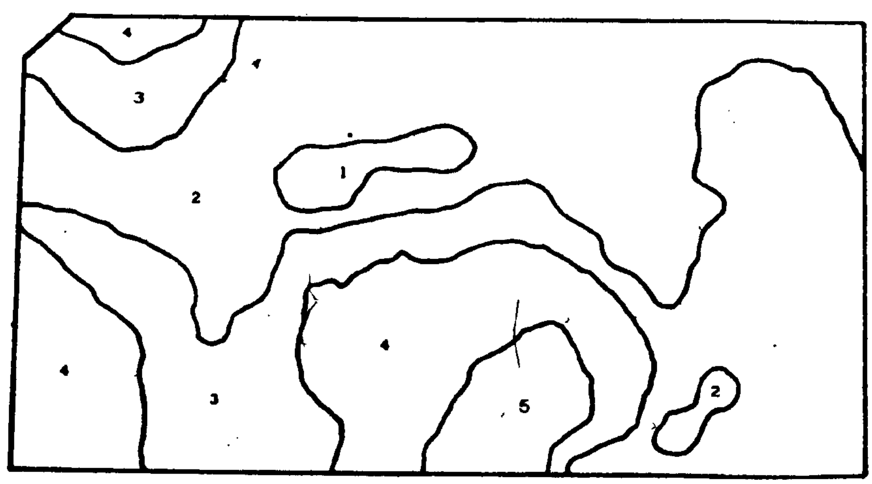

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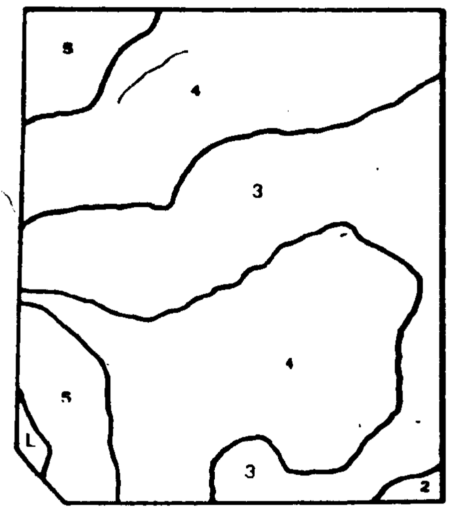
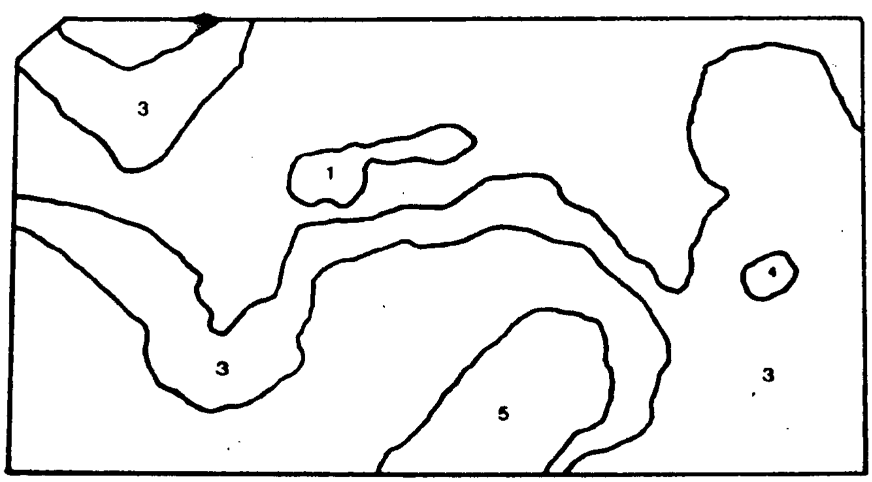
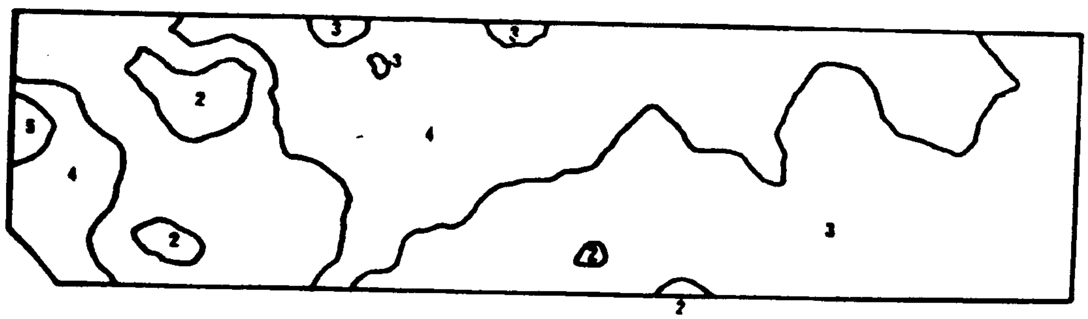




LC- 73



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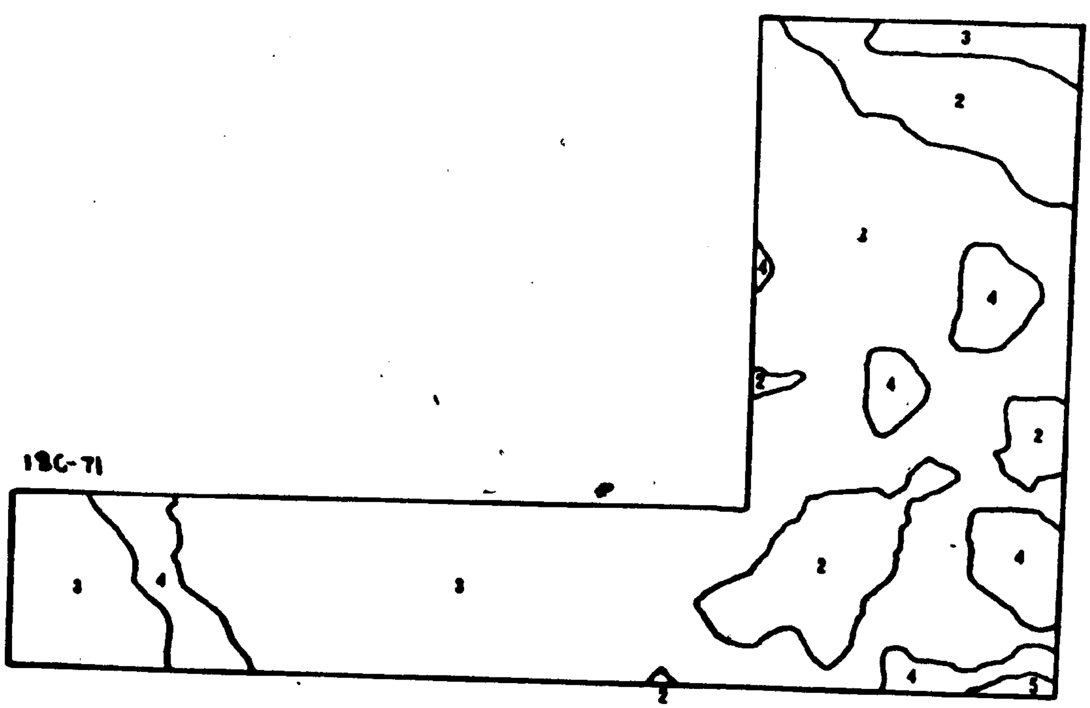
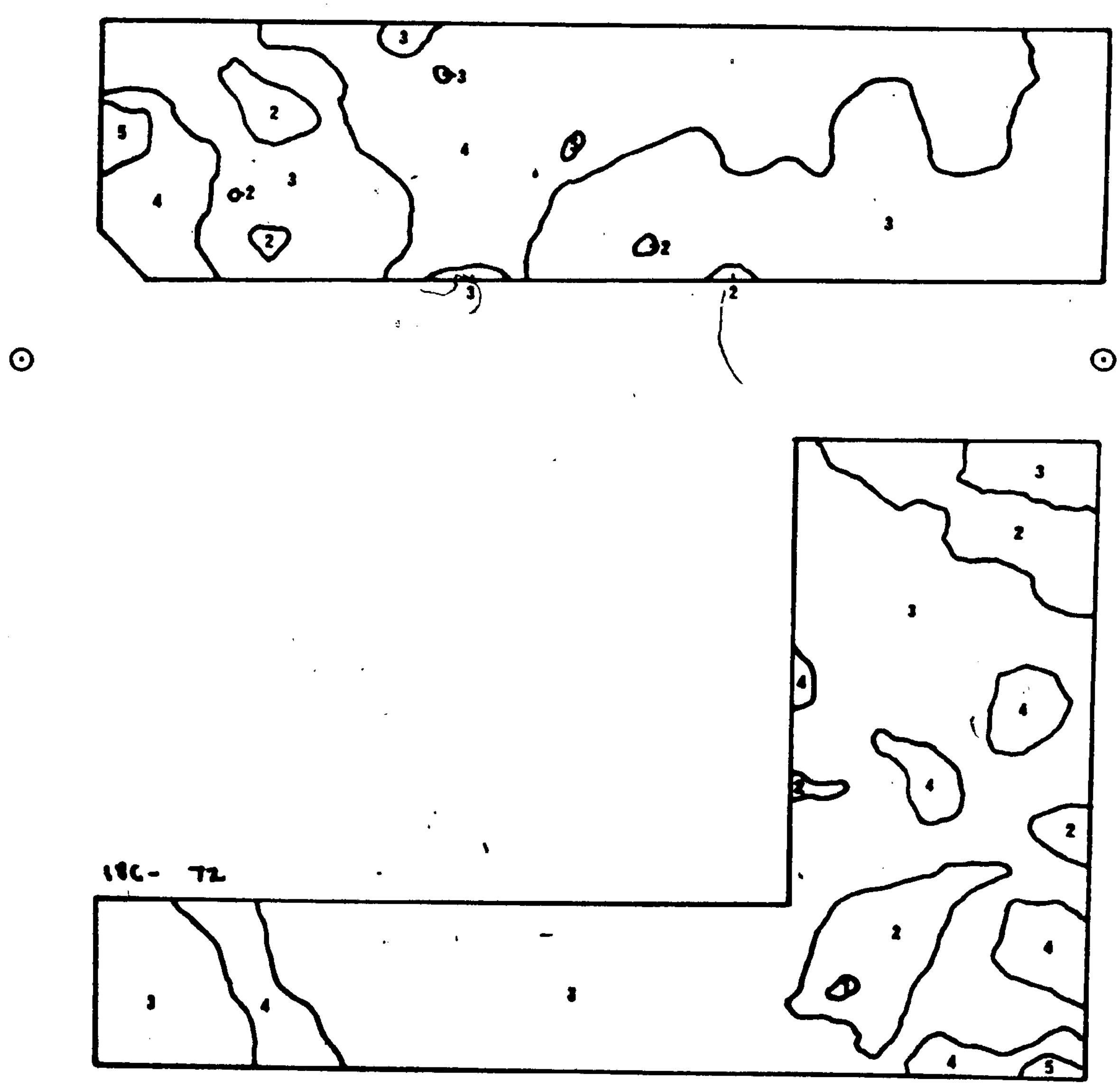
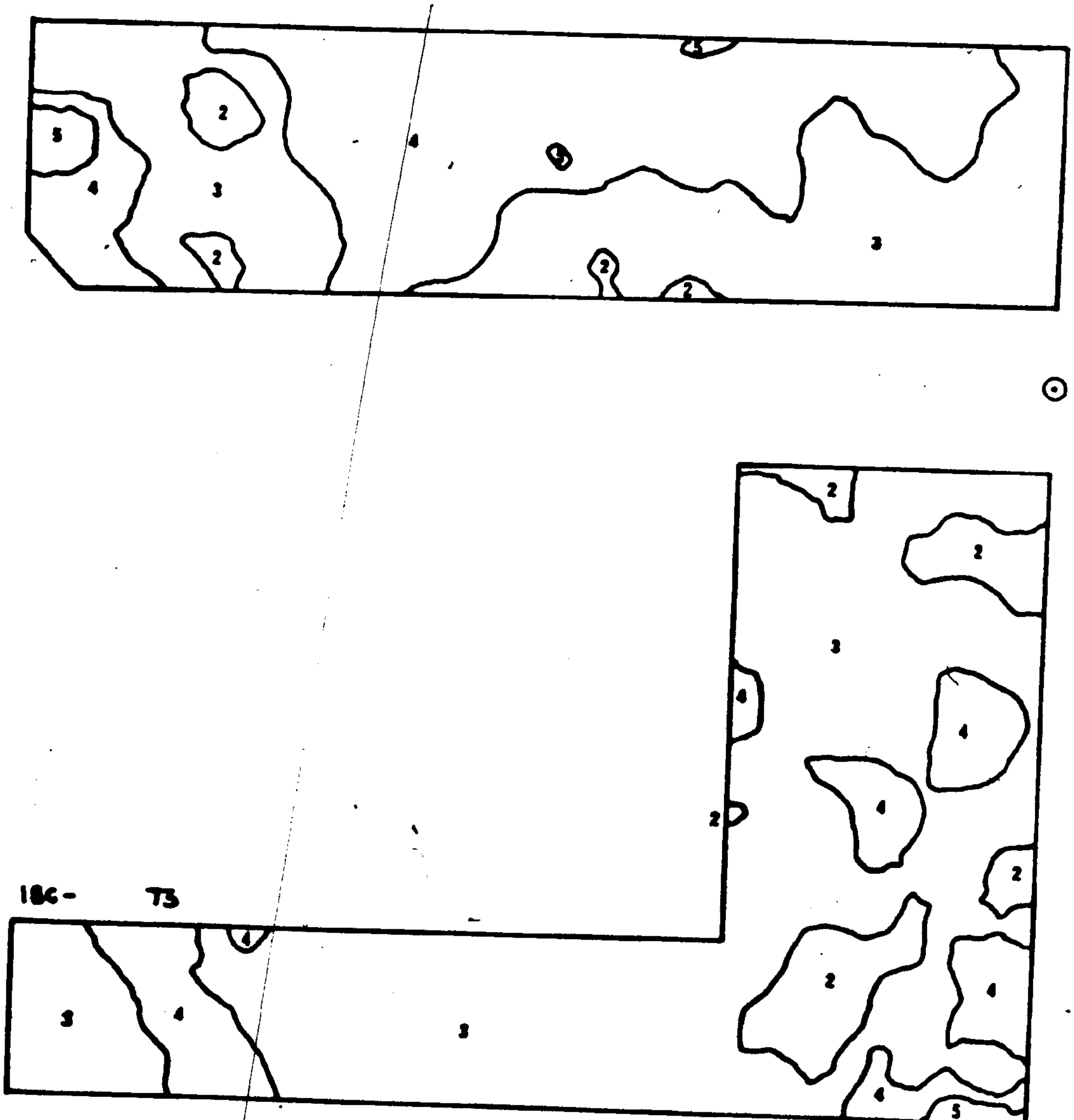



18C- 72
3
2
5
4
1
3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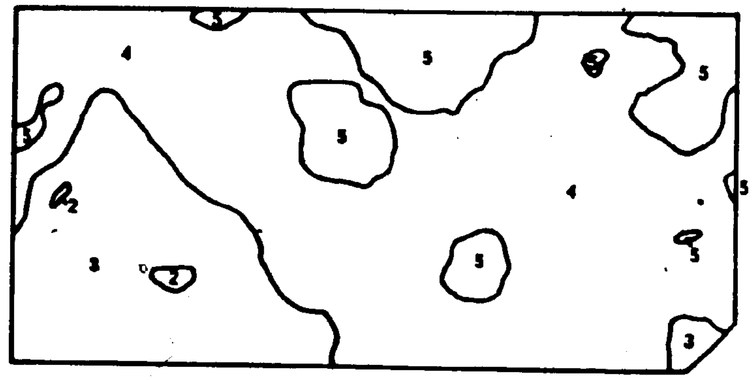
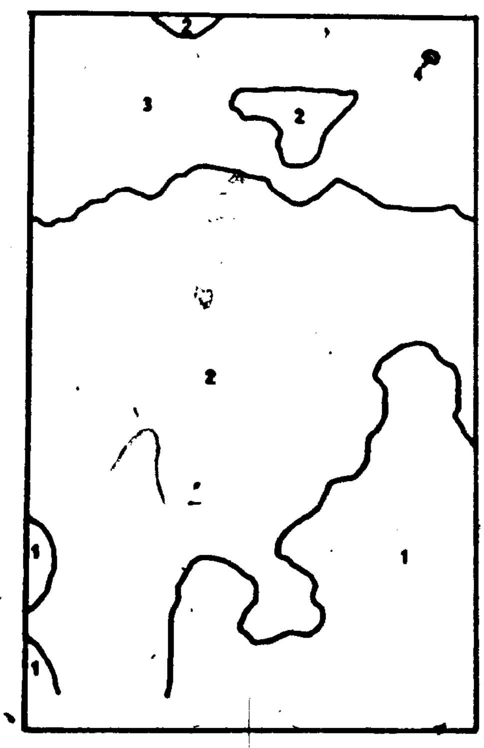
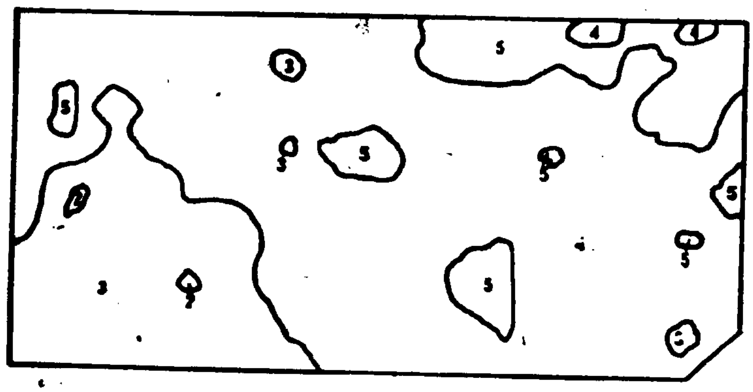
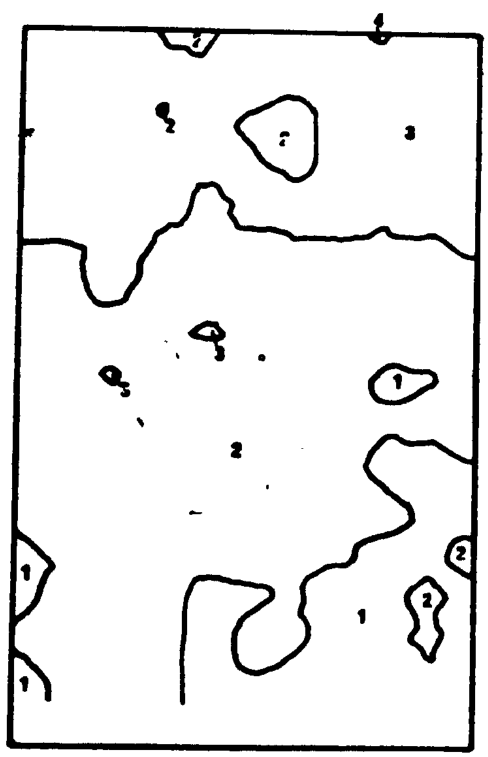




30C - 1971





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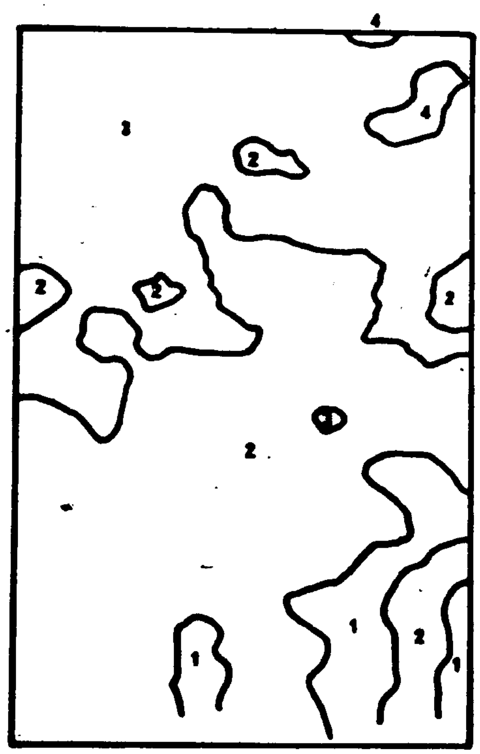
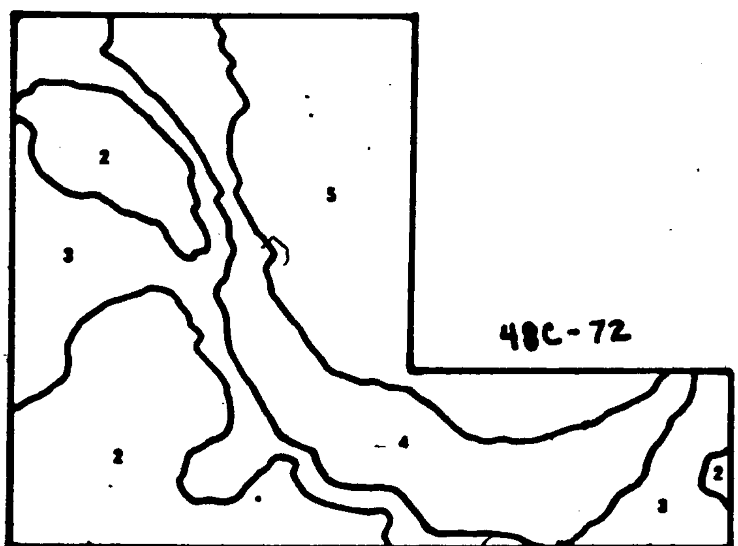
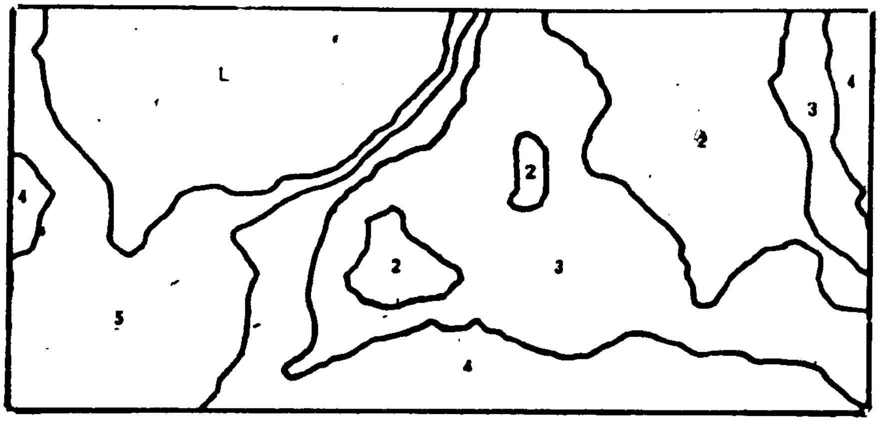
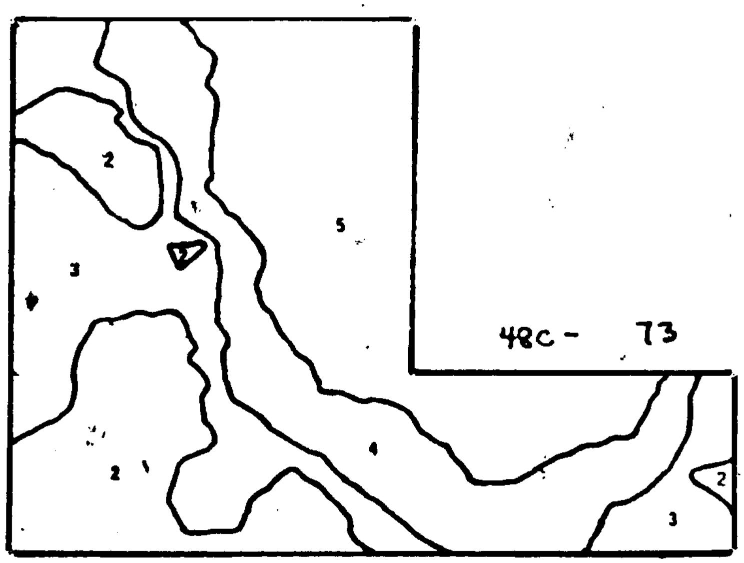


30C- 73



48C-72





48C - 73

APPENDIX V: METHOD USED IN CALCULATION OF YEARLY AND AVERAGE EPILITHOPHAGIC CONTRIBUTION TO EROSION AT STUDY SITES

a) Yearly epilithophagic erosion is obtained by:

1) Converting erosional capabilities (cc/yr) from Table 13, page 207, to surface lowering values (per square meter) by dividing by 10^4 cm^2 and multiplying by 10 mm./cm. This results in surface lowering values in units of millimeters/year.

2) Multiplying the number of individuals of a species present for a particular section and year by the surface lowering potential of that species (calculated in step 1, above). The number of individuals present in a particular section for a particular year is obtained from the appropriate species abundance table (Tables 7 - 12 of present study).

3) Adding the total surface lowering values for all individuals of all species gives a total epilithophagic erosion in millimeters/year. (This value assumes a rock porosity of zero).

4) Adjusting the total epilithophagic erosion (from step 3, above) for rock porosity, based on porosities given in Table 3, page 51.

EXAMPLE USING DATA FOR SECTION 4, 1973:

Species	# indiv/m^2	erosion (cc./yr.)	Surface lowering (1) (x 10^{-3} mm./yr.)	Total surf. lowering/ species (2) (mm./yr.)
Acmaea jamaicensis	190	0.86	0.86	0.16
Chiton marmoratus	12	5.00	5.00	0.06
Littorina meleagris	198	0.06	0.06	0.01
Nerita versicolor	2	0.86	0.86	0.00
				0.23 mm./yr. (3)

(4) Porosity of 25%: (0.23 mm./yr.) x 1.25 = 0.29 mm./yr. 0.29 mm./yr. then represents the total epilithophagic erosion to be expected in 1973 based on the total organisms present.

b) The average yearly epilithophagic erosional contribution for each section is a straightforward average of the yearly epilithophagic values for each section.

c) The percentage epilithophagic erosional contribution is obtained by comparing the average annual epilithophagic erosion value to the total annual erosion as determined by photogrammetric techniques (values presented in Table 6, page 98).