An Atlas of the Skeletal Components of the Crown of Thorns Starfish

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Great Barrier Reef Marine Park Authority

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AN ATLAS OF THE SKELETAL COMPONENTS OF THE CROWN-OF-THORNS STARFISH (*ACANTHASTER PLANCI* (L))

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SUMMARY

In recent years extensive damage has been caused to many reefs in the Great Barrier Reef complex by the crown-of-thorns starfish (*A. planci*). Authors on the subject are divided as to whether the outbreaks are a recurring natural phenomenon or a result of the influence of man. The identification of crown-of-thorns skeletal-rich zones in reef sediment and cores may help to determine if large population fluctuations occurred prior to the arrival of Europeans in central Queensland.

An atlas of crown-of-thorns skeletal components has been compiled to assist in the identification of these parts. The atlas features representative examples of each of the separate skeletal series present in *A. planci* and discusses skeletal architecture, gross morphology, microstructure, and the recognition of elements in the sedimentary record. In addition, the atlas compares skeletal elements of *A. planci* with similar elements from four other stars common on the Great Barrier Reef and concludes that they are readily distinguished.

KEYWORDS: *Acanthaster*, GBR, microstructure, morphology, sedimentary record, skeletal architecture.

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1. INTRODUCTION

Within the last 25 years, large aggregations of Acanthaster planci have been reported on 135 reefs of the Great Barrier Reef from Hilder Reef, north-east of Cooktown to Lady Musgrave Island, east of Gladstone (Great Barrier Reef Marine Park Authority, 1984). Several hundred thousand crown-of-thorns starfish may invade a reef at any one time, resulting in the almost total destruction of living hard corals (Endean, 1982; Moran, 1984). Since the starfish were first observed in abnormally high numbers on Green Island in 1962 (Barnes and Endean, 1964), the threat of A. planci to the reef system has been a constant concern.

The reason(s) for these apparently recent infestations of the crown-of-thorns is not understood. Numerous hypotheses have been put forward to account for these outbreaks. Some authors (for example Dana, 1970; Newman, 1970; Frankel, 1975, 1977, 1978; Vine, 1973; Newman and Dana, 1974; Pearson, 1975; Moore, 1978) believe that fluctuations in A. planci populations are a natural phenomenon which have occurred in the past just as they are occurring at present and are regulated by environmental pressures. Frankel (1977, 1978) estimated, from skeletal debris in sediment, that aggregations occur every 250 to 300 years.

In contrast, another group of authors (for example Fischer, 1969; Chesher, 1970; Brown and Willey, 1972; Randall, 1972; Chesher, 1970; Endean, 1973, 1977, 1982) consider the population explosions to be induced, either directly or indirectly, by the activities of man, for example removal of predators, physical modification of the environment, influx of pollutants and/or nutrients into the water.

An understanding of the causal factors which influence the size and periodicity of starfish outbreaks is fundamental in determining the measures undertaken by governments and government agencies in management of these population explosions. The identification of A. planci skeletal debris in zones within reefal sediment and/or drill cores may reveal aggregations or infestations prior to the arrival of white man in central Queensland and thus help to determine whether these outbreaks are natural or man-induced.

This atlas provides a photographic reference of some of the more common and most likely to be preserved skeletal components of A. planci, as well as higher magnification microstructure studies, so that both whole and fragmentary elements may be identified in sediment cores. The skeletal components of A. planci are briefly compared to those of other sea stars common on the Great Barrier Reef.

2. PREVIOUS LITERATURE ON THE MORPHOLOGY OF A. PLANCI

Madsen (1955) traced the history of the genus Acanthaster and compared the morphology of the Indo-West-Pacific species, A. planci, to that of its East-Pacific (American) relative, A. ellisii (Gray, 1840), concentrating on external features such as body-width to arm-length ratio, ventral and dorsal spines, pedicillariae and mouth plates.

Caso (1961) also compared the external morphologies of A. planci and A. ellisii, emphasising, as Madsen did, the importance of spines, pedicillariae and mouth (bucal) plates in distinguishing the two. She also named a new subspecies, A. ellisii pseudoplanci. In her 1970 paper, Caso confined her description solely to that of A. planci, once again concentrating on spines, pedicellariae and the bucal plates.

Blake (1979) described, or mentioned, most of the skeletal elements present in A. planci in his comparison of A. planci with members of the Oreasteridae and the Echinasteridae. According to Blake, the marginal ossicle series is "the key to the interpretation of these and other ossicle series" as the other series, i.e. the actinals and the abactinals, are recognised according to their position relative to the marginals. The terminology used by Blake was found to be satisfactory during the present study and has been retained wherever possible. For definitions of terms used the reader is referred to Spencer and Wright (1966).

3. MATERIALS AND METHODS

Crown-of-thorns starfish were collected on John Brewer Reef, 70km north-east of Townsville, Queensland. The individual examined was a 19-armed specimen of 35cm diameter.

The flesh was dissolved in 'Woolworths' brand household liquid bleach - active ingredient sodium hypochloride (available chlorine 4% w/v). Skeletal elements were rinsed in tap water and oven dried. Individual elements were then gold plated and examined and photographed on a scanning electron microscope. An electron microprobe analysis of ossicles was carried out to determine mole % $MgCo_3$.

4. MORPHOLOGY

4.1 Skeletal Architecture

As stated by Blake (1979), the key to distinguishing the different ossicle series is determined by their position relative to the double row of marginal ossicles (Figure 1). Elements which lie ventral to the marginals are actinal whilst those situated dorsally are abactinal.

Globose, spine-bearing actinal intermediate ossicles (Figures 1, 2; Plate 1, Number 2) are present in rows of three to four elements for most of the length of the arm, forming 'actinal fields' (Blake, 1979). The innermost actinal ossicles laterally abut the adambulacral ossicles (Figures 1, 2; Plate 1, Number 2) which sit sub-ventrally on the ambulacral ossicles (Figures 1, 2; Plate 1, Numbers 1a, 1b). The adambulacrals and ambulacrals line the ambulacral furrow (Figure 1; Plate 1, Number 1b) providing support and protection for the radial canals and tube feet of the water vascular system. The arms terminate distally in a single arm-tip ossicle, the terminal (Blake, 1979).

Within the ambulacral series, the first ambulacral ossicle, which is situated adjacent to the body cavity, is the largest (Figure 2; Plate 1, Number 4). Ventral to the first ambulacral ossicle, the oral (mouth-angle) ossicle terminates the adambulacral series (Figure 2; Plate 1, Number 4). The interbrachial ossicle sits in the arch formed between the first ambulacral and oral ossicles (Figure 2; Plate 1, Numbers 3, 4). Its function is to space the proximal ossicles of adjacent arms and serve as the basal support to the series of the interbrachial plates (Figure 2; Plate 1, Number 3).

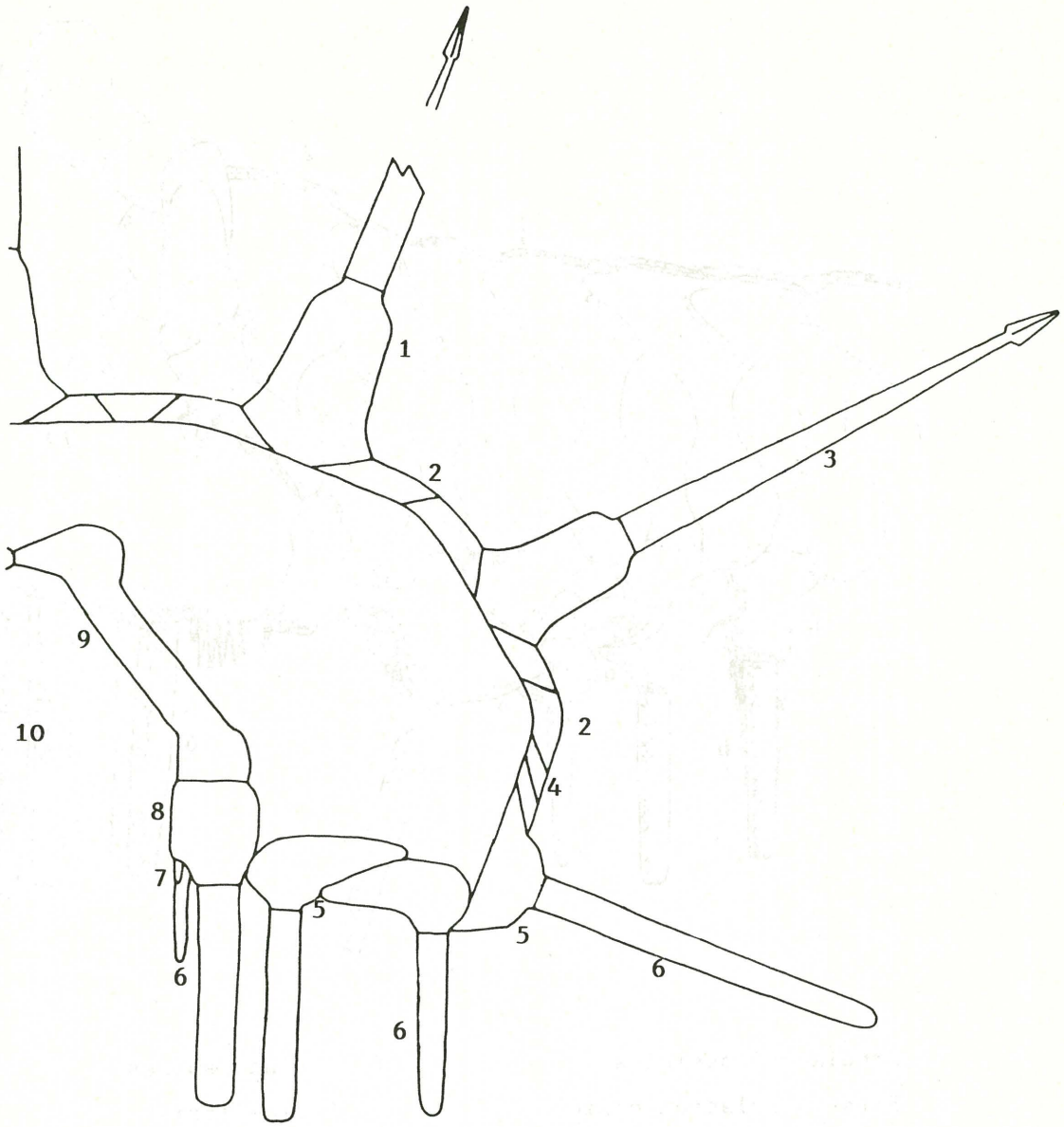
The primary and secondary abactinal ossicles form a meshwork of dermal elements over the dorsal surface of the arms and disc. Plate- and rod-shaped secondary abactinal ossicles provide support for the larger spine-bearing primary abactinal ossicles (Figure 1; Plate 2, Numbers 1, 2).

The crown-of-thorns starfish is covered with a large number of blunt and barbed spines. Ventrally, blunt spines are borne on the adambulacral, actinal intermediate, and oral ossicles (Figure 1; Plate 1, Numbers 2, 3). On the dorsal surface, long barbed and shorter unbarbed spines are present on the primary and, uncommonly, some secondary abactinal ossicles respectively (Figure 1; Plate 2, Number 1).

Bivalved pedicellariae occur on the actinal and abactinal surfaces of A. planci. Pedicellarial pits are present in most, but not all, adambulacral ossicles (Figure 1), whilst, on the abactinal surface, pedicellariae sit in pedicellarial cups embedded in the skin (Plate 1, Numbers 5, 6). Several madreporites are also embedded in the skin of the disc (Plate 1, Numbers 6, 7). These are supported by secondary abactinal ossicles.

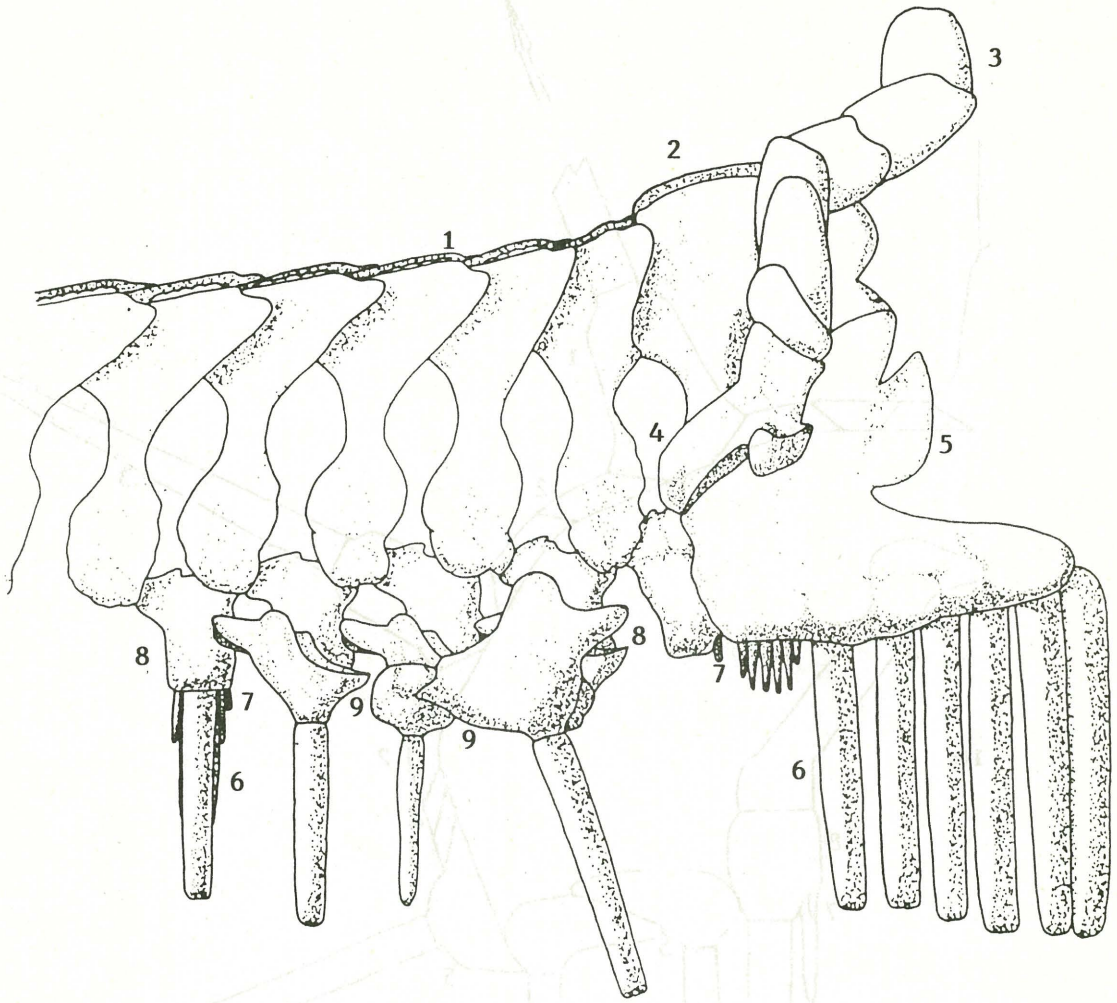
Subspherical to elliptical granules are found in the surface layers of skin on the dorsal surface (Plate 1, Numbers 5-7). Encrusting granules are abundant in the sheath of skin covering the actinal intermediates, primary abactinals, and the basal section of actinal and abactinal spines (Plate 1, Number 5).

Figure 1. Schematic section through the arm of A. planci showing the relative position of elements.



1 Primary abactinal ossicle
2 Secondary abactinal ossicles
3 Abactinal spine
4 Marginal ossicles
5 Actinal intermediate ossicles
6 Actinal spines
7 Pedicellaria
8 Adambulacral ossicle
9 Ambulacral ossicle
10 Adambulacral furrow

Figure 2. Arrangement of elements in the arm of A. planci.



1 Ambulacral ossicles
2 First ambulacral ossicle
3 Interbrachial plates
4 Interbrachial ossicle
5 Oral (mouth-angle) ossicle
6 Actinal spines
7 Pedicellaria
8 Adambulacral ossicles
9 Actinal intermediate ossicles

5. CHARACTERISATION OF INDIVIDUAL ELEMENTS

5.1 Gross Morphology

Adambulacral Ossicles (Plate 3, Numbers 1-5):

Adambulacral ossicles are rectangular elements with a pronounced distal abactinal extension. Well defined interadambulacral muscle depressions are present on both the distal and proximal surfaces (Plate 3, Numbers 5b, 5d). Four subcircular ambulacral - adambulacral articulation surfaces are present on the abactinal surface of each ossicle (Plate 2, Number 6).

Two rows of spines, running parallel to the adamabulacral furrow, are borne on the adambulacrals (Figure 1). Spine bases are small, rounded knolls on the actinal surface (Plate 2, Number 6). The number of pedicellarial pits per adambulacral varies within any row from zero up to an observed maximum of three (Plate 3, Numbers 2-5). One or two pits per ossicle is most common. The pits are located proximally on the furrow surface of the ossicles (Figure 2).

Adambulacral ossicles from the arm tip (Plate 3, Numbers 1a, 1b) are of the same general shape as more proximal ossicles but many of the characteristics for example spine bases and pedicellarial pits, are less pronounced.

Ambulacral Ossicles (Plate 3, Numbers 6-9):

Ambulacral ossicles are elongate with a broad and tapering adradial portion (Plate 2, Number 4). The ambulacral - adambulacral articulation surfaces are deep-set, wings (Plate 2, Number 4) are broad and gently to moderately curved (Plate 3, Number 6c). The abactinal surface is slightly indented. Two distinctly different patterns of ambulacral - ambulacral articulation surfaces (Plate 2, Number 4) are present (Plate 3, Numbers 6a, 7). Adambulacrals from the arm tip are very similar to those more proximal (Plate 3, Numbers 8, 9).

First Ambulacral Ossicles (Plate 4, Number 2):

The first ambulacral ossicle is one of the largest elements in A. planci and is significantly different from the previously described ambulacral ossicle. The first ambulacral - first ambulacral articulation surface (Plate 2, Number 5) varies considerably between individual elements. A prominent ridge runs the length of the abactinal surface (Plate 2, Number 5). The wings, so evident in other ambulacrals, are greatly reduced. Two first ambulacral - oral ossicle articulation surfaces are present (Plate 2, Number 5).

Oral (Mount-Angle) Ossicles (Plate 4, Number 1):

The largest element in A. planci, the oral ossicle, is characterised by a prominent tapering proximal tip with numerous spine bases and a first ambulacral articulation bar (Plate 2, Number 3). The oral ossicle bares five to six large, blunt spines towards the oral cavity and four to six small, tapered spines distally (Figure 2). A large indentation accommodates the first adambulacral ossicle (Plate 2, Number 3). Two oral - first ambulacral articulation surfaces are present (Plate 2, Number 3).

Interbrachial Ossicles (Plate 4, Number 3):

A single anvil-shaped ossicle sits, supported by two stout stubs, between the arms in the arch formed by the first ambulacral and oral ossicles. The abactinal surface is angled sharply to fit the first interbrachial plate (Plate 2, Number 9). The neck is shorter, but thicker than the body (Plate 2, Number 9).

Interbrachial Plates (Plate 2, Number 12):

These elements vary in size and shape but are always flattened laterally. Articulation surfaces are very shallowly angled and typically ridged. In general, each side of the plate has one articulation surface.

Actinal Intermediate Ossicles (Plate 4, Numbers 4-9; Plate 7, Number 7):

Actinal intermediates are variable in size and shape but are essentially globose and spine-bearing. Those adjacent to the marginal ossicles (Plate 7, Number 7) tend to be larger and more tapered than ossicles closer to the adambulacrals. Articulation surfaces and skin and/or muscle attachment scars are readily apparent in this series (Plate 2, Number 10). A notch is often present in the actinal intermediate - actinal spine articulation surface (Plate 4, Numbers 6, 7).

Marginal Ossicles (Plate 4, Number 10):

Two rows of marginal ossicles are present in the arms of A. planci. They may be enlarged, spine-bearing elements but are more commonly discoid in shape (Plate 4, Number 10).

Secondary Abactinal Ossicles (Plate 5, Numbers 7-10; Plate 6, Numbers 1-11):

Secondary abactinals are highly variable in size and form but are generally rod- or plate-like. Those which are platey may resemble interbrachial plates. Articulation surfaces are straight-ridged or, more commonly, curve-ridged (Plate 2, Numbers 7, 8). Although most secondary abactinals are "spineless" some (Plate 6, Number 8) do bare small, unbarbed spines. Very little morphological difference appears to exist between the secondary abactinals of the arms and those of the disc.

Primary Abactinal Ossicles (Plate 7, Numbers 1-6, 8-10):

The most easily distinguished primary abactinals are long, narrow, conical ossicles with basal articulation surfaces (Plate 7, Numbers 1-5, 9-10). Less commonly, however, primary abactinals are incorporated into the meshwork of secondary abactinal ossicles and have dorsal and/or ventral articulation surfaces (Plate 7, Numbers 6, 8; Plate 2, Number 11). Primary abactinal ossicles are always spine-bearing.

Abactinal Spines (Plate 8, Numbers 2-3):

Abactinal spines are long and narrow and taper symmetrically to a sharp, barbed point. They are borne on both primary and secondary abactinal ossicles. Those borne on secondary abactinal ossicles are much smaller and insignificant in number compared with spines borne on primary abactinals. Abactinal spines are circular in cross-section. A basal bulge is often present (Plate 3, Number 2). Colouration is a uniform medium to dark mauve changing to a pale mauve at the base.

Under binocular microscope examination the framework is elongate although frequently fine and fairly indistinct.

Actinal Spines (Plate 8, Numbers 1, 4-8):

The majority of actinal spines taper only slightly along their length to a blunt, often grooved, rounded tip. They are flattened in cross-section, and are very often indented towards the tip on the side facing the distal part of the arm. (Plate 8, Numbers 1, 4). Spines borne on the actinal intermediates adjacent to the marginals may taper uniformly to a blunt point. Very small spines (Plate 8, Numbers 6, 8) line the adambulacral furrow on adambulacral ossicles and at the distal end of the oral ossicle (Figure 2).

Actinal spines are variable in colour, ranging from pale mauve to dark mauve and, rarely, an intense orange-red. The indented or distal surface is darker in colour than that which faces the body cavity and thus actinal spines are readily discernible from abactinal spines. In addition, actinal spines may contain a notch in their articulation surface.

Under binocular microscope the ultrastructure appears coarse, open and distinctly elongate.

Pedicellariae (Plate 8, Numbers 9-17):

Elongate and stout bivalved pedicellariae are situated in pedicellarial pits of adambulacral ossicles (Plate 3, Numbers 1-5) or in pedicellarial cups (Plate 8, Number 18) in skin on the dorsal surface.

Other Elements

The madreporite (Plate 7, Number 11) is a delicate mushroom-shaped ossicle with a pattern superficially resembling brain coral on the dorsal surface. Subspherical granules (Plate 7, Number 12) are variable in shape, being subspherical to subeliptical. Encrusting granules (Plate 8, Number 19) are uniform in size and dome-shaped with an extended flat base.

5.2 Microstructure

The microstructure of A. planci is an open system in which the porosity may be as high as 50% (Bathurst, 1975). Within any one element, however, the mesh thickness, pore size, and hence, porosity, varies considerably from the representative examples shown in Plates 9-11.

In the majority of elements, the microstructure is very similar with fine calcite arranged in a subrounded to pentagonal pattern forming large pores. Pedicellariae retain this predominantly pentagonal structure but the presence of a series of ridges, terminating in blunt peaks (Plate 11, Number 4), gives the pedicles an overall elongate appearance. Abactinal and actinal spines do not generally have the pentagonal form. Their fabric is elongate, parallel to the long axis of the element (Plate 11, Number 1).

5.3 Chemistry

Electron microprobe analysis reveals the skeleton of A. planci to be composed of high magnesium calcite with 8.2 - 11.6 mole percent $MgCO_3$.

6. RECOGNITION OF A. PLANCI IN THE SEDIMENTARY RECORD

Frankel (1974, 1978) identified whole and fragmented skeletal debris in the "very poorly sorted and unconsolidated (reefal) sediment" that he examined. According to Frankel (1978) the parts most often preserved are spines, pedicels and ambulacral ossicles. The preservation of elements in the sedimentary record will largely depend on their original size, shape and abundance and the hydrodynamic conditions at the time of deposition.

If crown-of-thorns starfish are present in hundreds of thousands during an outbreak on a single reef, as suggested by Endean (1982), enormous potential exists for the deposition and incorporation into sediment of millions of skeletal elements. This is particularly so for ambulacrals, adambulacrals, actinal intermediates, secondary abactinals, and spines, each of which numbers several hundred per animal.

The hydrodynamic conditions prevelant when each animal dies and disintegrates is clearly a major determinant in the type of element incorporated into the sediment and their state of preservation. Small, fragile pedicellariae, encrusting granules, and subspherical granules would be especially susceptible to transport, dispersion, and physical breakdown by the action of waves and currents.

The elements most likely to survive turbid conditions and be preserved more or less intact are those which are compact and relatively robust. Based on this criterion, adambulacrals, actinal intermediates and the less common interbrachial ossicles should be present in any A. planci-rich zone in which ossicles are present.

Spines, and ornately-sculptured ambulacrals, orals, primary abactinals, and some secondary abactinals, would be susceptible to physical disintegration.

The prominence of pedicles and spines in Frankel's samples may be due to their size and shape which allowed them to fall into cracks and crevices, thereby avoiding perturbation.

Despite the potential for the preservation of some elements, the recognition of large numbers of crown-of-thorns parts in sediment will necessarily lead to the identification of elements via a detailed study of the microstructure.

The recognition of whole or fragmentary elements in sediment is assisted by the distinct mauve colouration of A. planci parts. Only the madreporite, pedicellariae, and pedicellarial cups lack this pigmentation.

Intensity of pigmentation varies between ossicle series and within some series. Those in which the colour is most pronounced are the ossicles situated close to the surface of the animal i.e. the primary and secondary abactinals, actinal intermediates, marginals, and spines. Adambulacrals and ambulacrals are considerably lighter in colour although still with a distinct purple tinge. First adambulacrals, orals and the interbrachial ossicles are a very pale mauve. Actinal spines display a large range of colours from pale mauve to dark mauve.

The ossicles of other stars examined by the author and all other "stelleroids" studied by Frankel (1974, 1977, 1978) are white or cream. Blake (1979) reported that the ossicles of some specimens of Echinaster modestus Pervier are pale purple in colour whilst the Oreasteridae have white ossicles.

Skeletal elements of four stars common on the Great Barrier Reef were compared to those of A. planci. Species considered were three starfish (Echinaster luzonicus (Gray), Euretaster insignis (Sladen), Linkia laevigata (L.)) and one brittle star (Ophiocoma sp.). Elements which resemble ossicles in A. planci were studied. Those with no physical similarity were not considered.

Some elements, particularly ambulacral and dermal ossicles, superficially resemble their counterparts in A. planci (Plate 12). Major morphological differences exist, however, especially in ossicle size and the sculpturing of articulation surfaces. Possible confusion is avoided by the smaller size and brilliant white colouration of ossicles examined from each of the four species.

According to Maxwell (1971), most asteroids can be differentiated from Acanthaster by their "dense, moderately porous skeletal material"; it is the Ophiuroids which most closely resemble Acanthaster. Maxwell considered that fragmented portions of Acanthaster skeleton can only be distinguished from Ophiuroids if coarser meshwork fragments are present.

These conclusions are not readily apparent in Plate 13. The ossicle microstructure of some other sea stars does appear to be similar to that of A. planci. In the species examined, this was particularly the case with the oral ossicle of E. insignis (Plate 13, Number 6). In general, however, the microstructure of the elements of other asteroids is denser and less porous, as suggested by Maxwell.

7. CONCLUSION

An atlas of the skeletal components of the crown-of-thorns starfish (*A. planci*) is an essential tool if whole or fragmentary elements are to be identified in the sedimentary record. The gross morphology, microstructure and colour of crown-of-thorns elements is sufficiently different from corresponding elements of most other common reef-inhabiting stars to avoid serious confusion. With this atlas as an aid, future studies on reefal debris may be able to determine the extent of crown-of-thorns outbreaks in the past.

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APPENDIX

Plates

PLATE 1

ANATOMY OF A. PLANCI

1a Lateral view of mid-arm. 1 Ambulacral ossicles; 2 Adambulacral ossicles.

1b Cross-sectional view of mid-arm. 1 Ambulacral ossicles; 2 Adambulacral ossicles; 3 Adambulacral furrow.

2 Lateral view of mid-arm. 1 Actinal spine; 2 Actinal intermediate ossicles.

3 Lateral view of proximal end of arm. 1 Interbrachial plates; 2 Interbrachial ossicle; 3 Oral ossicle; 4 Actinal intermediate spine; 5 Oral ossicle spine.

4 Lateral view of proximal end of arm. 1 First ambulacral ossicle; 2 Oral ossicle; 3 Arch for interbrachial ossicle.

5 Dorsal skin of arm. 1 Abactinal spine; 2 Pedicellarial cup; 3 Subspherical granule; 4 Encrusting granule on primary abactinal ossicle.

6 Meshwork of dermal ossicles. 1 Subspherical granule; 2 Pedicellaria and pedicellarial cup; 3 Secondary abactinal ossicle; 4 Madreporite; 5 Unbarbed abactinal spine; 6 Primary abactinal ossicle.

7 Dorsal skin of disc. 1 Madreporite; 2 Subspherical granule; 3 Primary abactinal ossicle.

Plate 1

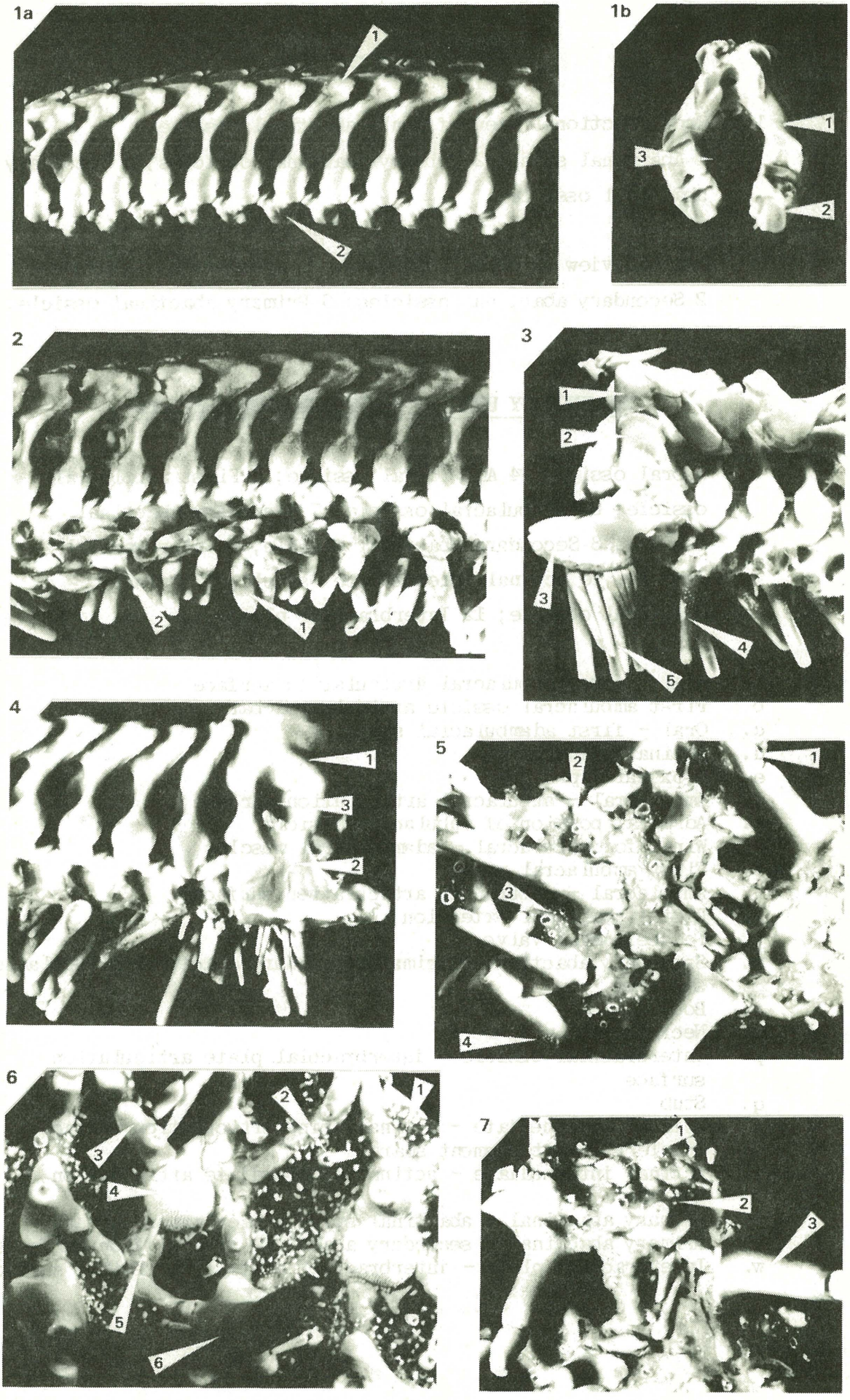


PLATE 2

ANATOMY OF A. PLANCI

1 Cross sectional view of arm's abactinal ossicles.
1 Abactinal spine; 2 Primary abactinal ossicles; 3 Secondary abactinal ossicles.

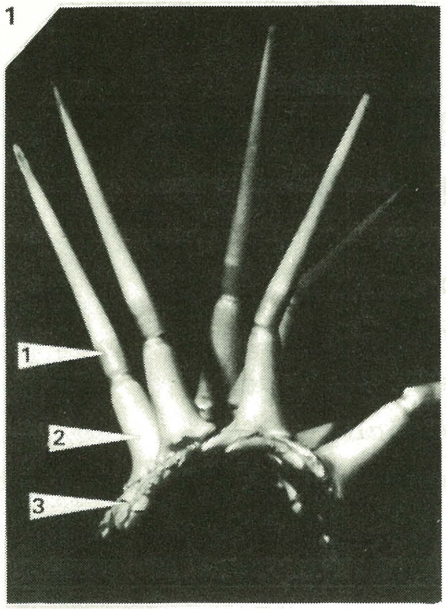
2 Actinal view of dermal ossicles. 1 Subspherical granules; 2 Secondary abactinal ossicles; 3 Primary abactinal ossicle.

TERMINOLOGY USED IN DESCRIPTION OF OSSICLES

3 Oral ossicle; 4 Ambulacral ossicle; 5 First ambulacral ossicle; 6 Adambulacral ossicle; 7 Secondary abactinal ossicle; 8 Secondary abactinal ossicle; 9 Interbrachial ossicle; 10 Actinal intermediate ossicle; 11 Primary abactinal ossicle; 12 Interbrachial plate.

a. Oral - first ambulacral articulation surface
b. First ambulacral ossicle articulation bar
c. Oral - first adambulacral seat
d. Actinal spine bases
e. Proximal tip
f. Ambulacral - ambulacral articulation surface
g. Adradial portion of ambulacral ossicle
h. Wings for ambulacral - adambulacral muscles
i. First ambulacral ridge
j. Ambulacral - ambulacral articulation surfaces
k. Distal abactinal extension
l. Pedicellarial valve
m. Secondary abactinal - primary/secondary abactinal articulation surfaces
n. Body
o. Neck
p. Interbrachial ossicle - interbrachial plate articulation surface
q. Stub
r. Actinal intermediate - actinal spine articulation surface
s. Muscle/skin attachement scar
t. Actinal intermediate - actinal intermediate articulation surface
u. Primary abactinal - abactinal spine articulation surface
v. Primary abactinal - secondary abactinal articulation surfaces
w. Interbrachial plate - interbrachial plate articulation surface

Plate 2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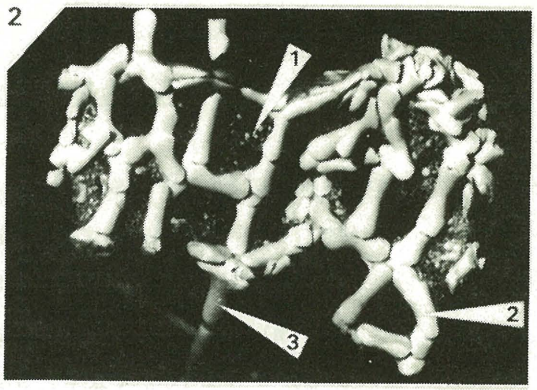
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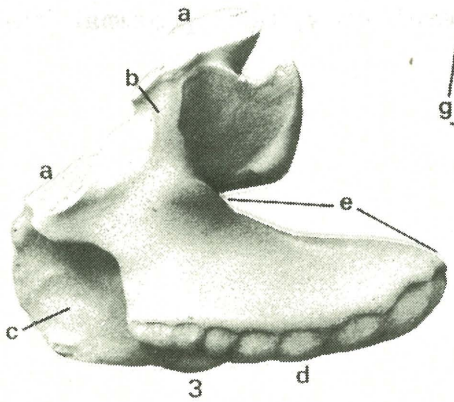
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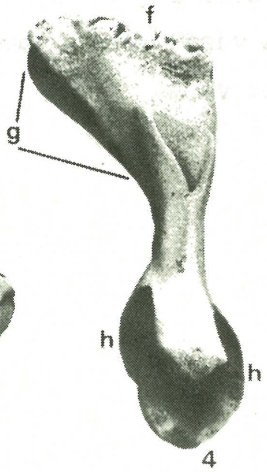
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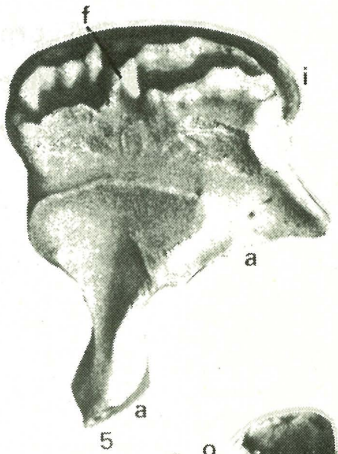
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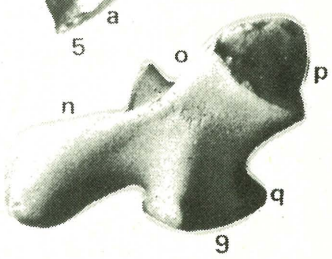
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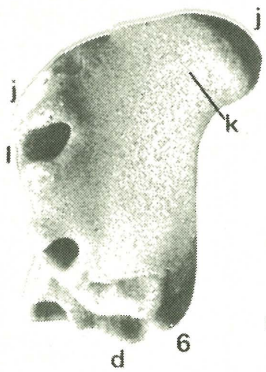
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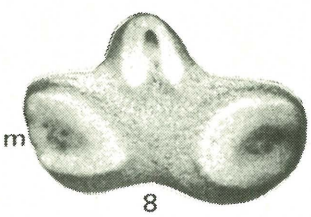
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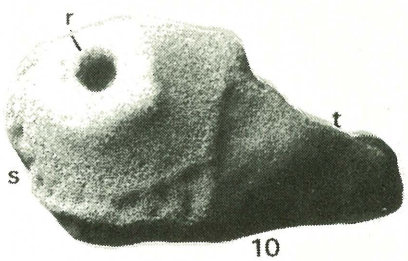
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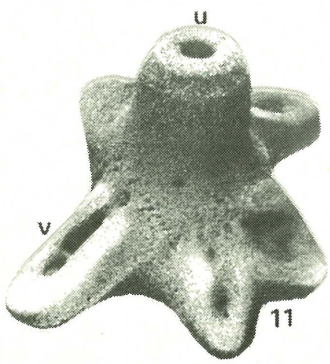
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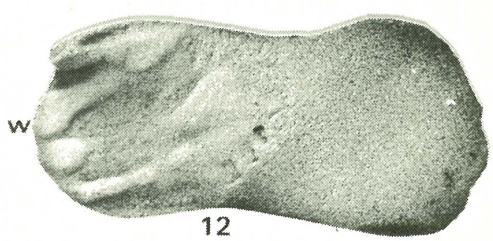
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PLATE 3

A. PLANCI - ELEMENT MORPHOLOGY

1-5 Adambulacral ossicles 1a x 18.8; 1b - 5d x 8
Actinal surface towards top of page
1 Distal (arm-tip) ossicle lateral view
2-5 Mid- to proximal arm ossicles
2-5a = furrow view; 5b = distal view; 5c = lateral view;
5d = proximal view

6-9 Ambulacral ossicles 6a-c, 7, 8a, 9a x 6.8; 8b, 9b x 14.6.
6a = furrow view; 6b = lateral view; 6c = proximal view;
7-9 = furrow views

Plate 3

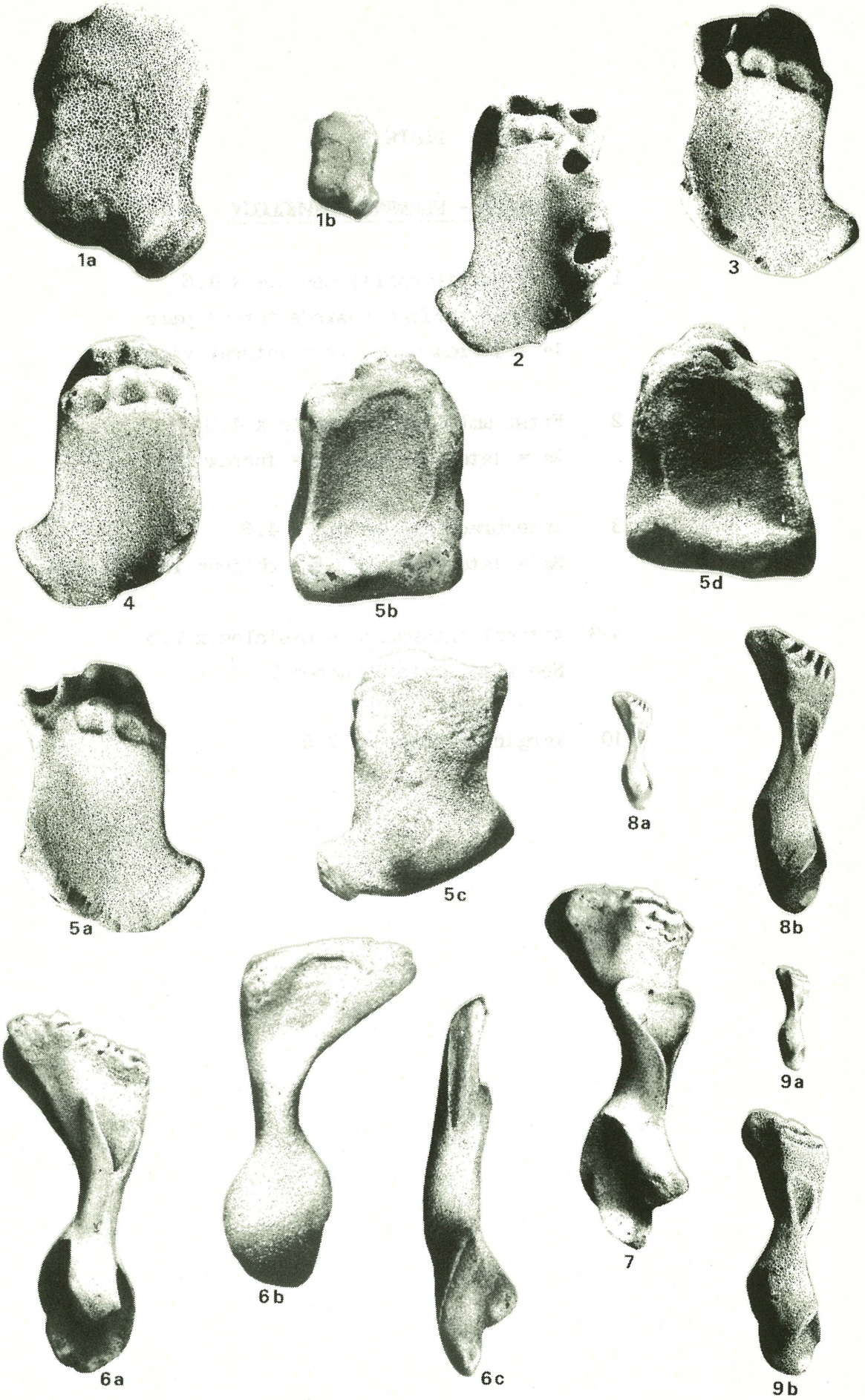


PLATE 4

A. PLANCI - ELEMENT MORPHOLOGY

1 Oral (mouth-angle) ossicle x 4.6
Actinal surface towards top of page
1a = furrow view; 1b = lateral view

2 First ambulacral ossicle x 4.6
2a = lateral view; 2b = furrow view

3 Interbrachial ossicle x 4.6
3a = lateral view; 3b = oblique lateral view

4-9 Actinal intermediate ossicles x 7.5
See also Plate 5 Number 7

10 Marginal ossicle x 7.5

Plate 4

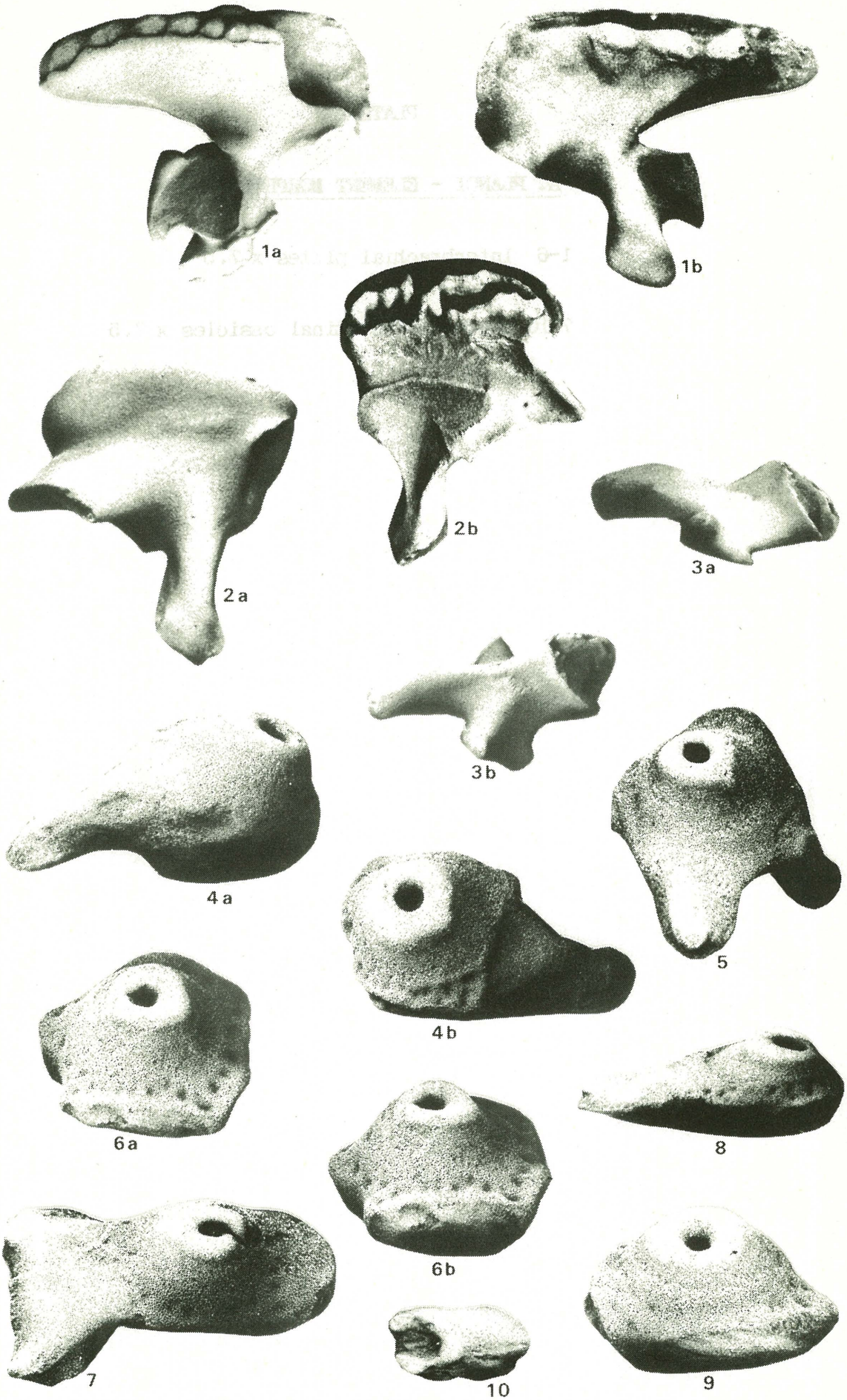


PLATE 5

A. PLANCI - ELEMENT MORPHOLOGY

1-6 Interbrachial plates x 7.5

7-10 Secondary abactinal ossicles x 7.5

Plate 5

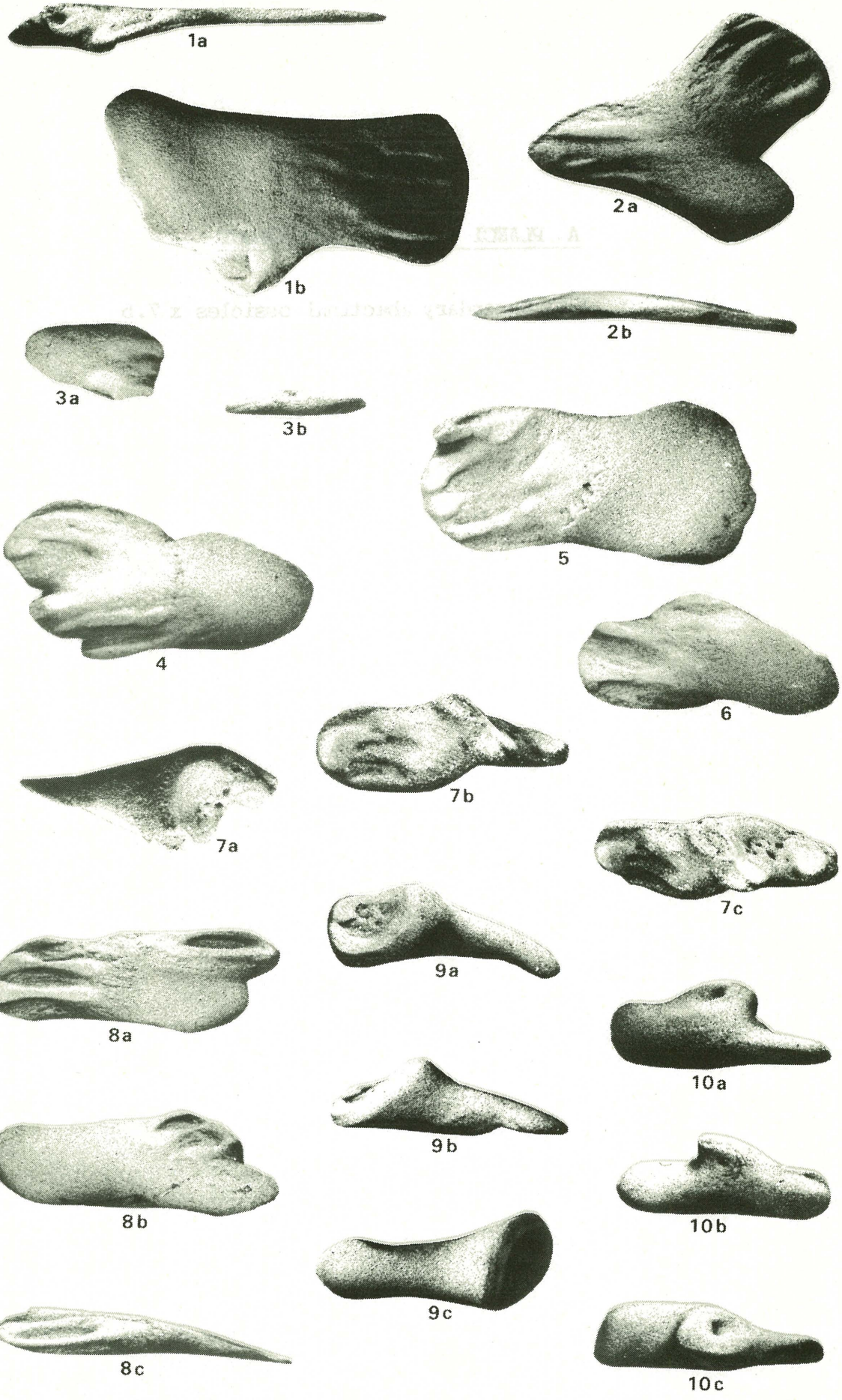


PLATE 6

A. PLANCI - ELEMENT MORPHOLOGY

1-11 Secondary abactinal ossicles x 7.5

Plate 6

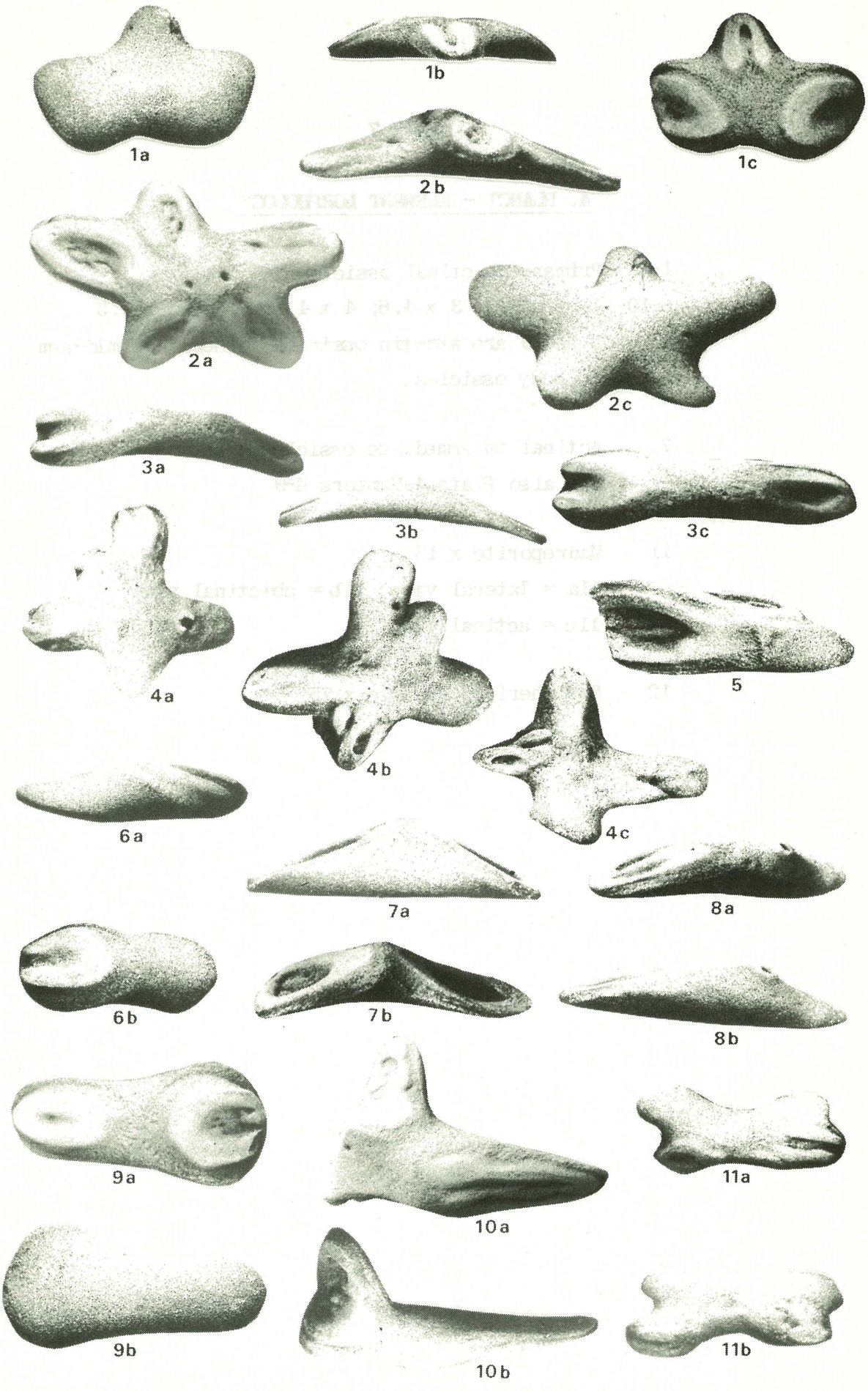

1a
1b
1c
2b
2a
2c
3a
3b
3c
4a
4b
4c
5
6a
7a
8a
6b
7b
8b
9a
10a
11a
9b
10b
11b

PLATE 7

A. PLANCI - ELEMENT MORPHOLOGY

1-6, Primary abactinal ossicles

8-10 1, 2 x 7.5; 3 x 4.6; 4 x 4; 5-6, 8-10 x 7.5
5 and 9 are arm-tip ossicles, others are mid-arm to body ossicles.

7 Actinal imtermediate ossicle x 7.5
See also Plate 4 Numbers 4-9

11 Madreporite x 13
11a = lateral view; 11b = abactinal view;
11c = actinal view

12 Subspherical granule x 75

Plate 7

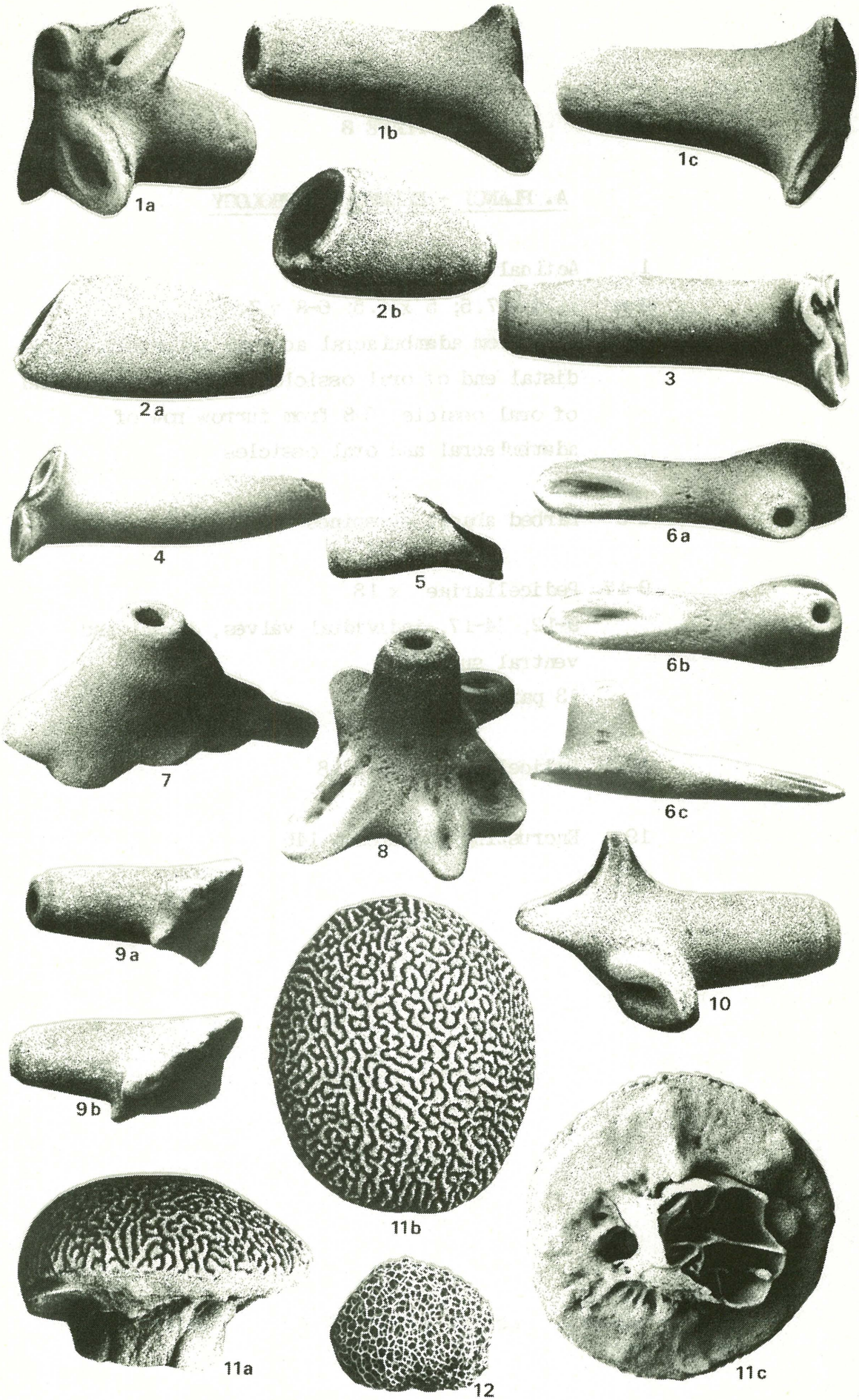


PLATE 8

A. PLANCI - ELEMENT MORPHOLOGY

1, Actinal spines

4-8 1, 4 x 7.5; 5 x 4.5; 6-8 x 7.5
1, 4 from adambulacral actinal intermediate and distal end of oral ossicle, 5 from proximal end of oral ossicle, 6-8 from furrow row of adambulacral and oral ossicles.

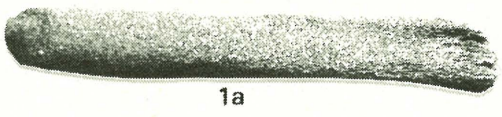
2-3 Barbed abactinal spines

9-17 Pedicellariae x 18
9-12, 14-17, individual valves, dorsal and ventral surfaces
13 paired valves

18 Pedicellarial cup x 18

19 Encrusting granules x 146

Plate 8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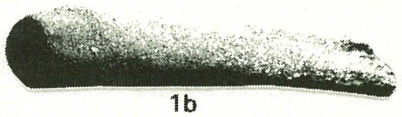
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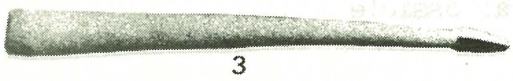
2a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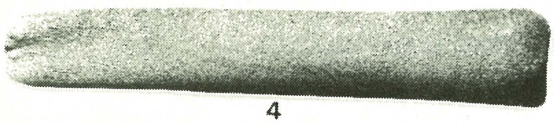
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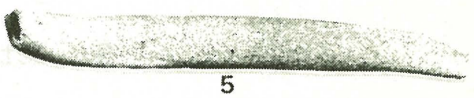
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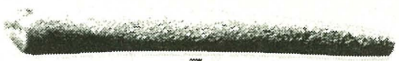
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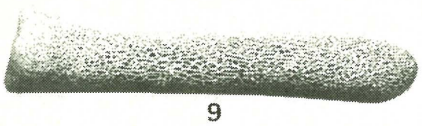
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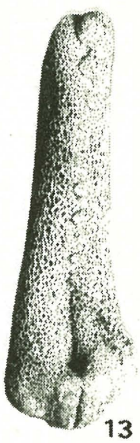
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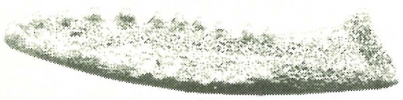
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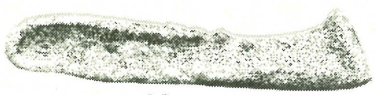
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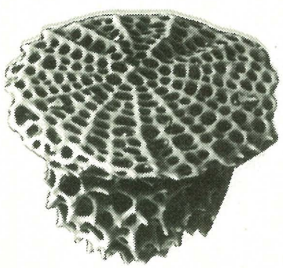
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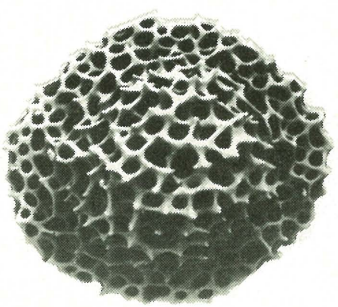
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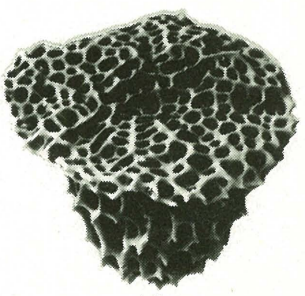
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PLATE 9

A. PLANCI - MICROSTRUCTURE OF ELEMENTS

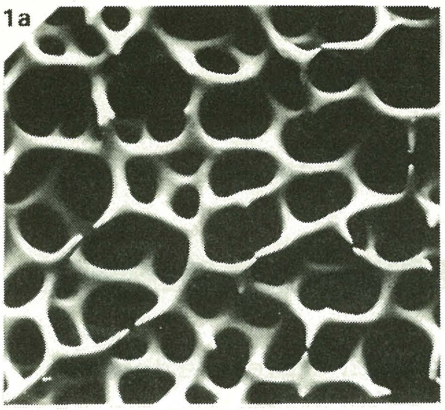
1 Adambulacral ossicle

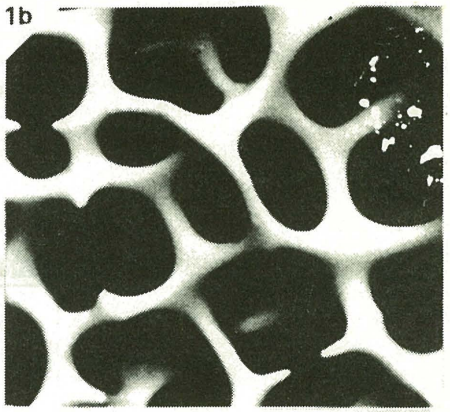
2 Ambulacral ossicle

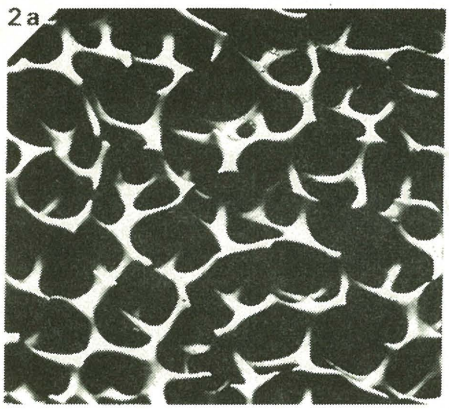
3 Actinal intermediate ossicle

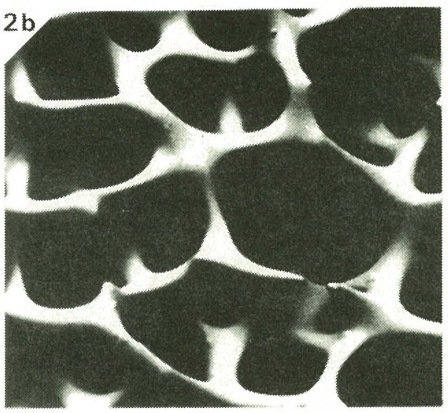
4 Secondary abactinal ossicle
a = x 300 b = x 600

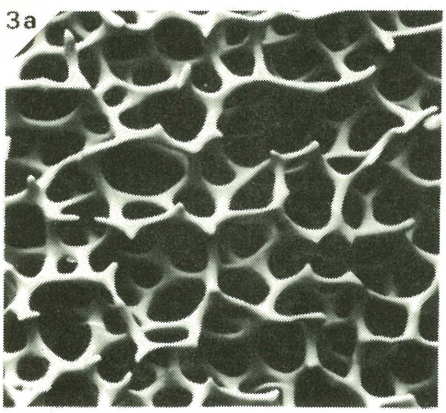
Plate 9

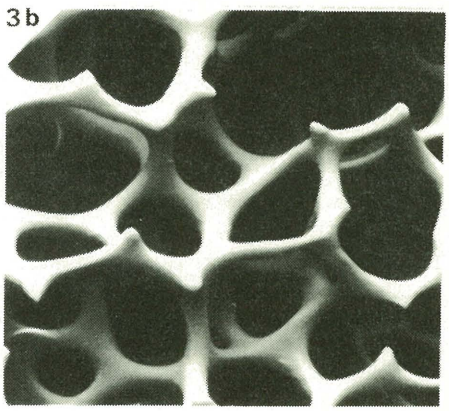


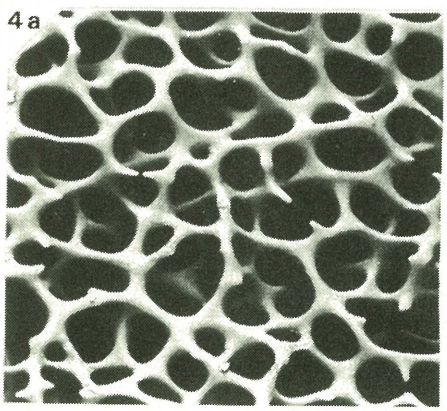












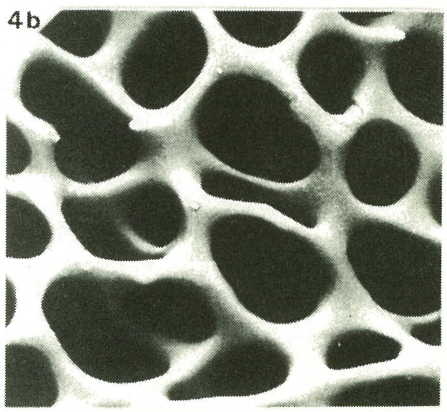


PLATE 10

A. PLANCI - MICROSTRUCTURE OF ELEMENTS

1 Oral (mouth-angle) ossicle

2 Interbrachial ossicle

3 Madreporite

4 Interbrachial plate
a = x 300 b = x 600

Plate 10

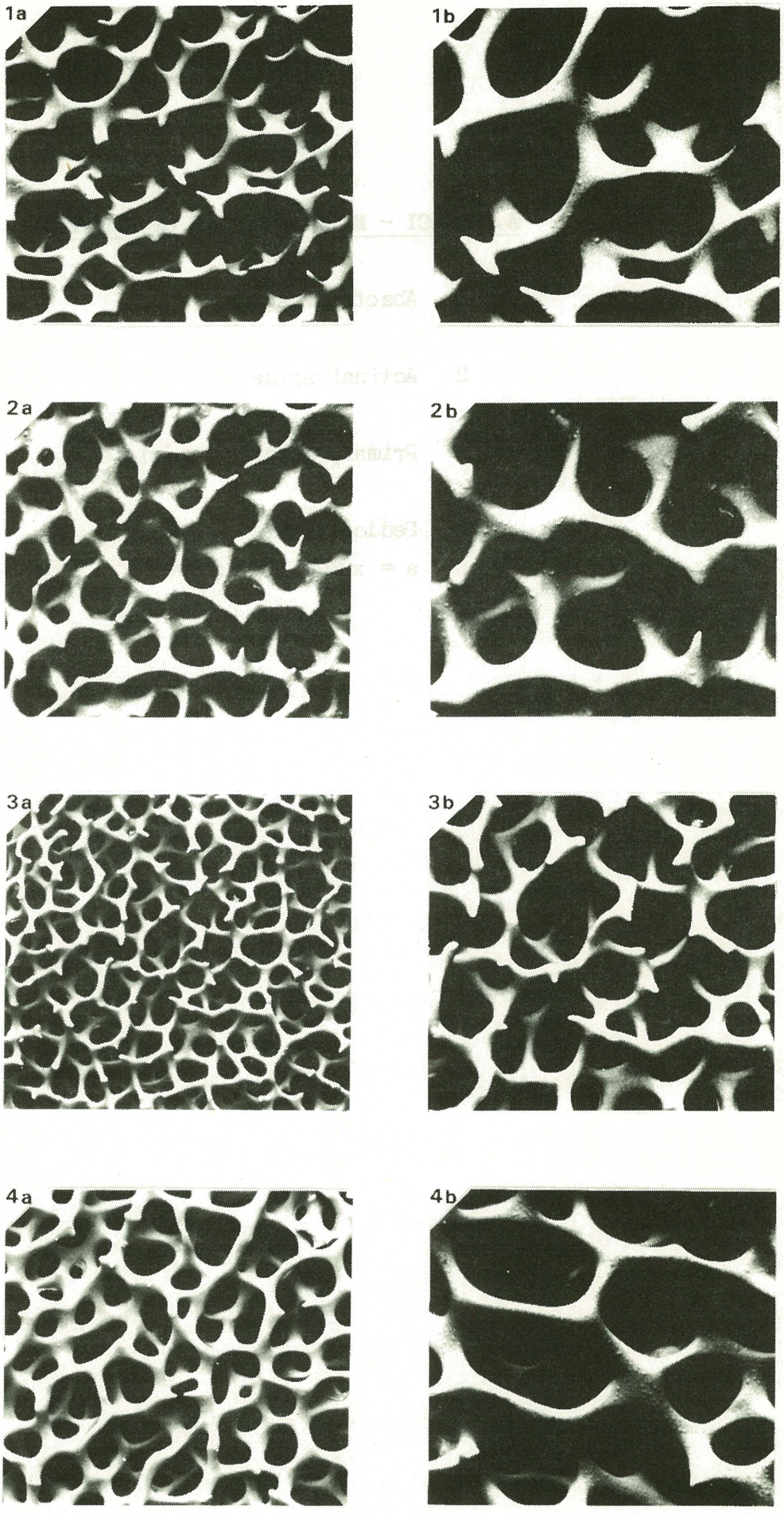


PLATE 11

A. PLANCI - MICROSTRUCTURE OF ELEMENTS

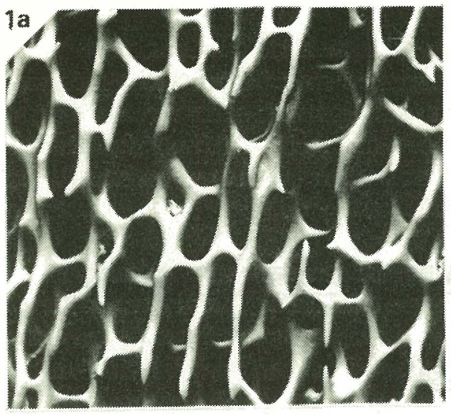
1 Abactinal spine

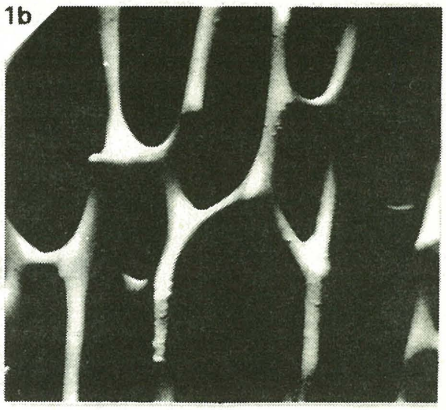
2 Actinal spine

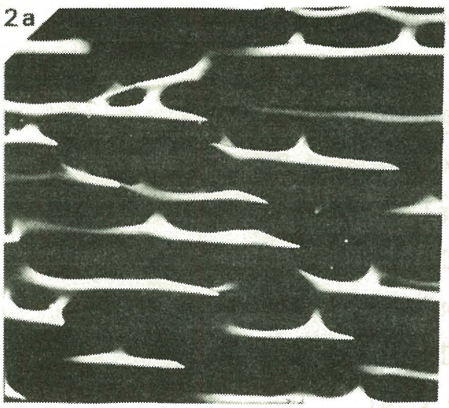
3 Primary abactinal ossicle

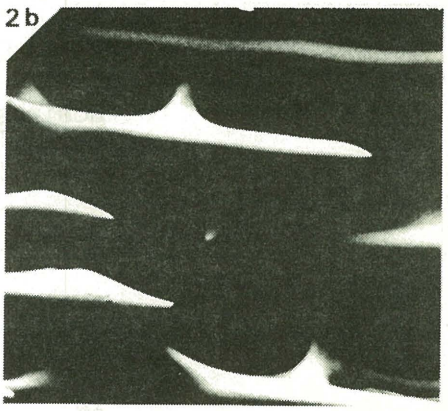
4 Pedicellariae
a = x 300 b = x 600

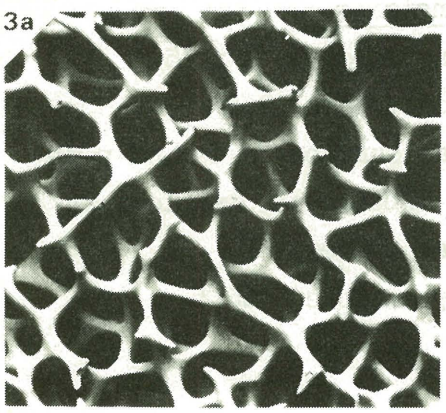
Plate 11

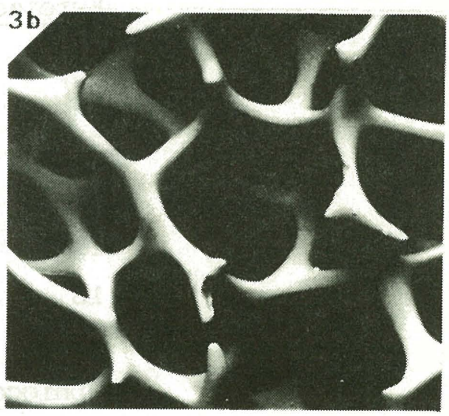


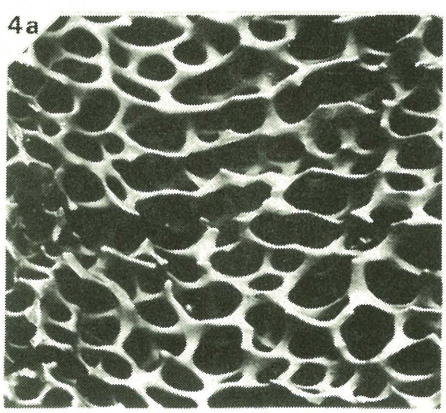












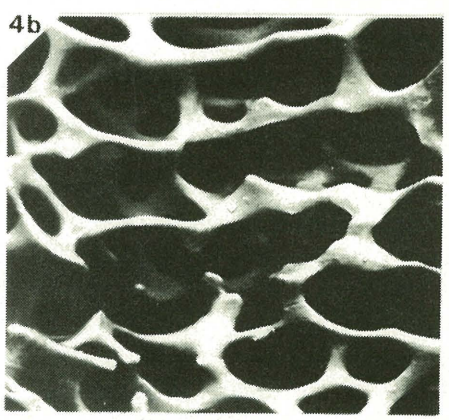


PLATE 12

OTHER SEA STARS - ELEMENT MORPHOLOGY

Linkia laevigata

1 Ambulacral ossicle x 15

2 Dermal ossicle x 30

3 Adambulacral ossicle x 22.5

Echinaster luzonicus

4 Oral ossicle x 23.5
Actinal surface to top of page

5 Amabulacral ossicle x 15

6 Adambulacral ossicle x 30

7-11 Dermal ossicles x 22.5

12 Spine x 30

Euretaster insignis

13 Ambulacral ossicle x 15

14 Oral ossicle x 22.5
Actinal surface to top of page

15 First ambulacral ossicle x 28.5

16-17 Ventral spines x 15

18 Spiney ossicle x 25.5

Ophiocoma sp.

19 Arm spine x 15

Plate 12

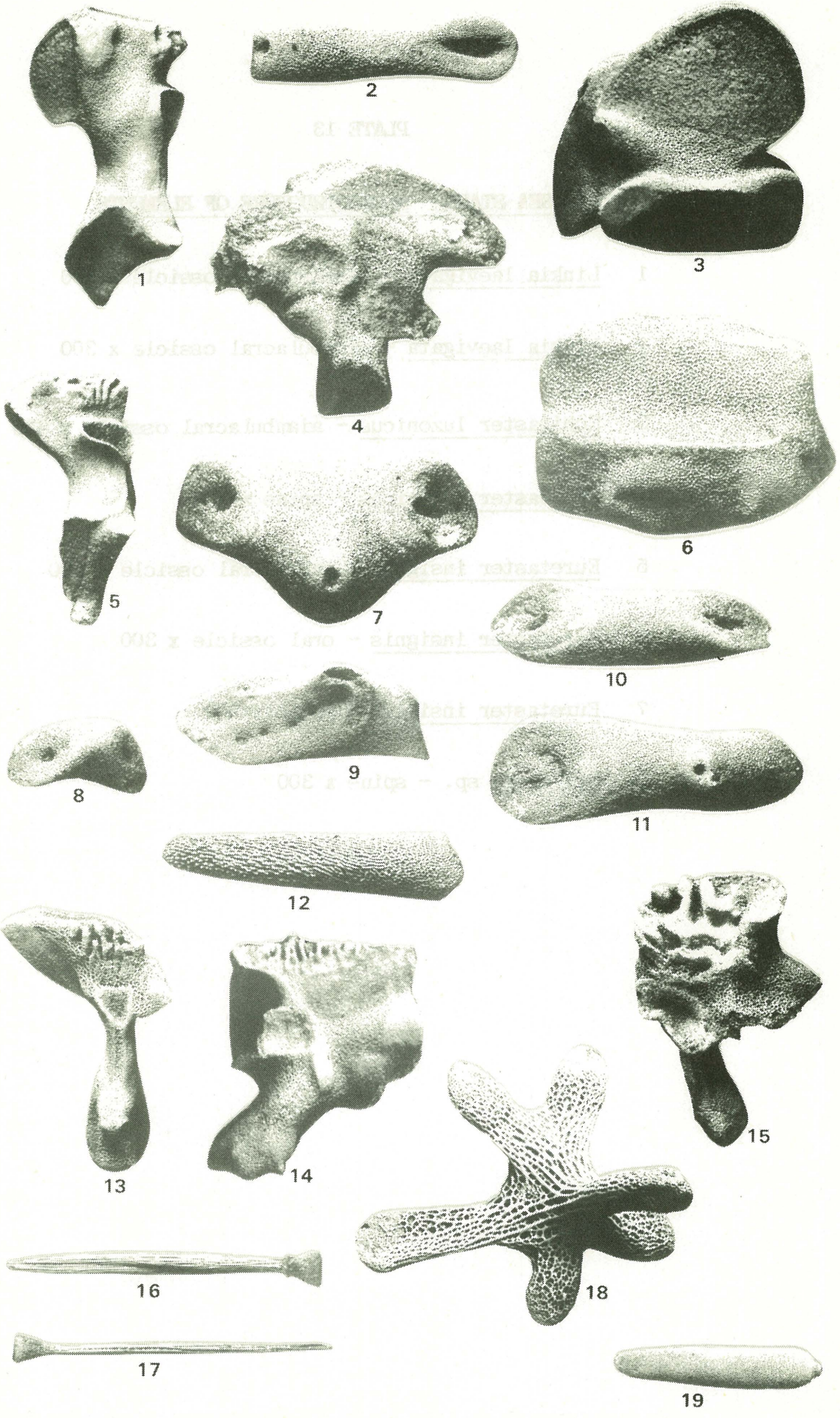


PLATE 13

OTHER SEA STARS - MICROSTRUCTURE OF ELEMENTS

1 Linkia laevigata - adambulacral ossicle x 300

2 Linkia laevigata - adambulacral ossicle x 300

3 Echinaster luzonicus - adambulacral ossicle x 300

4 Echinaster luzonicus - spine x 300

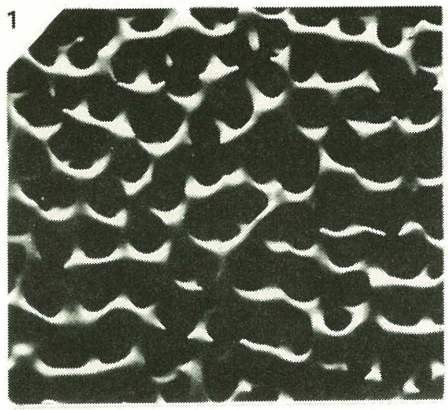
5 Euretaster insignis - ambulacral ossicle x 300

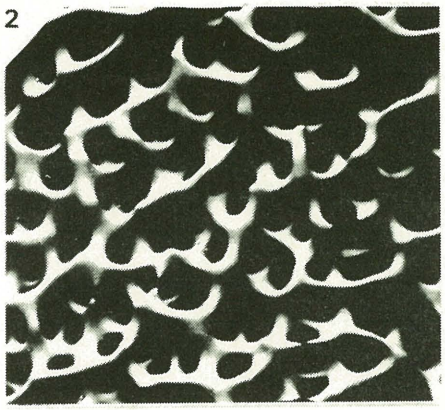
6 Euretaster insignis - oral ossicle x 300

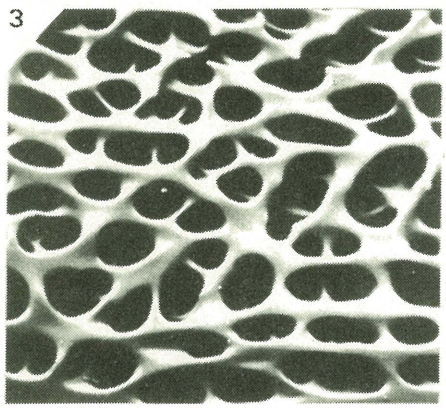
7 Euretaster insignis - spine x 300

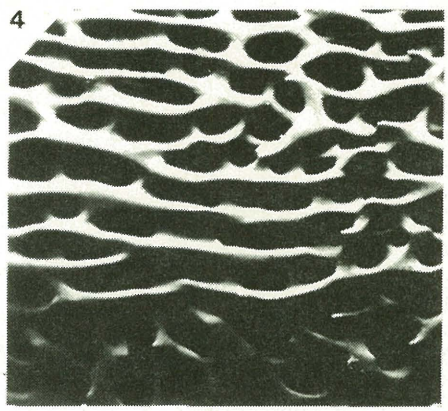
8 Ophiocoma sp. - spine x 300

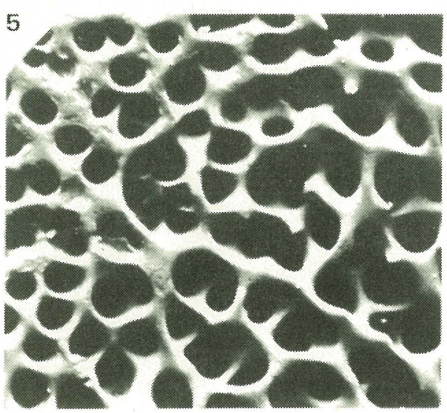
Plate 13

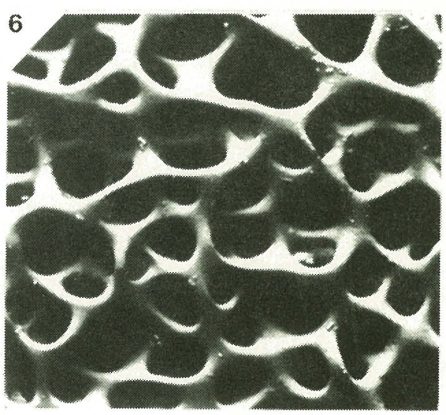


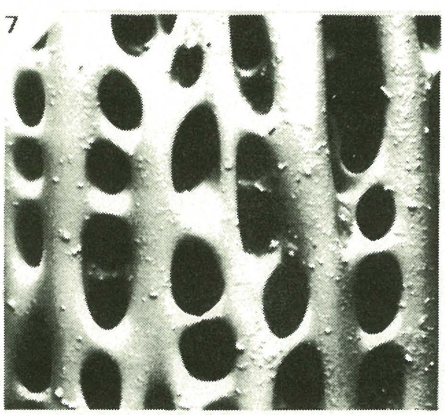


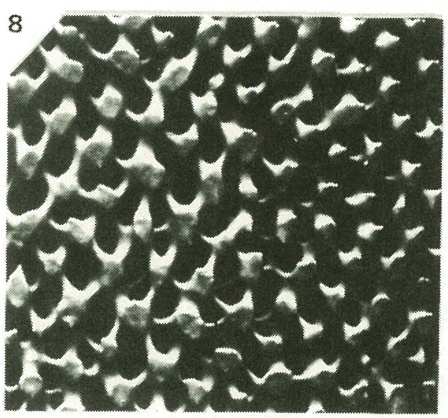


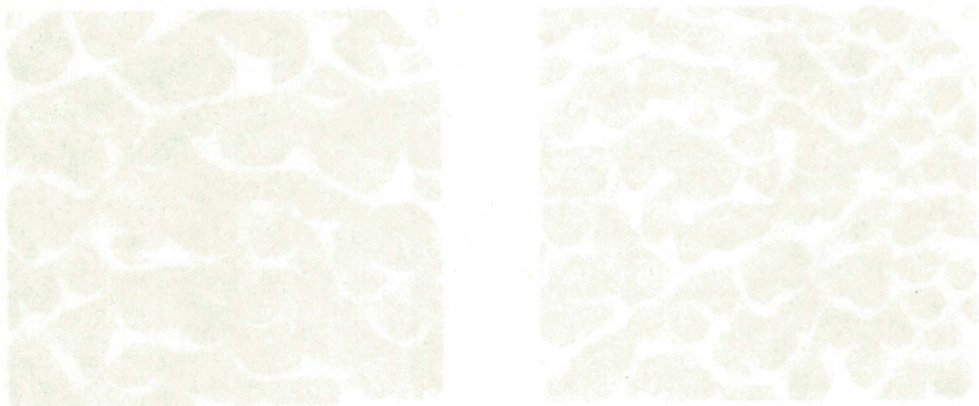


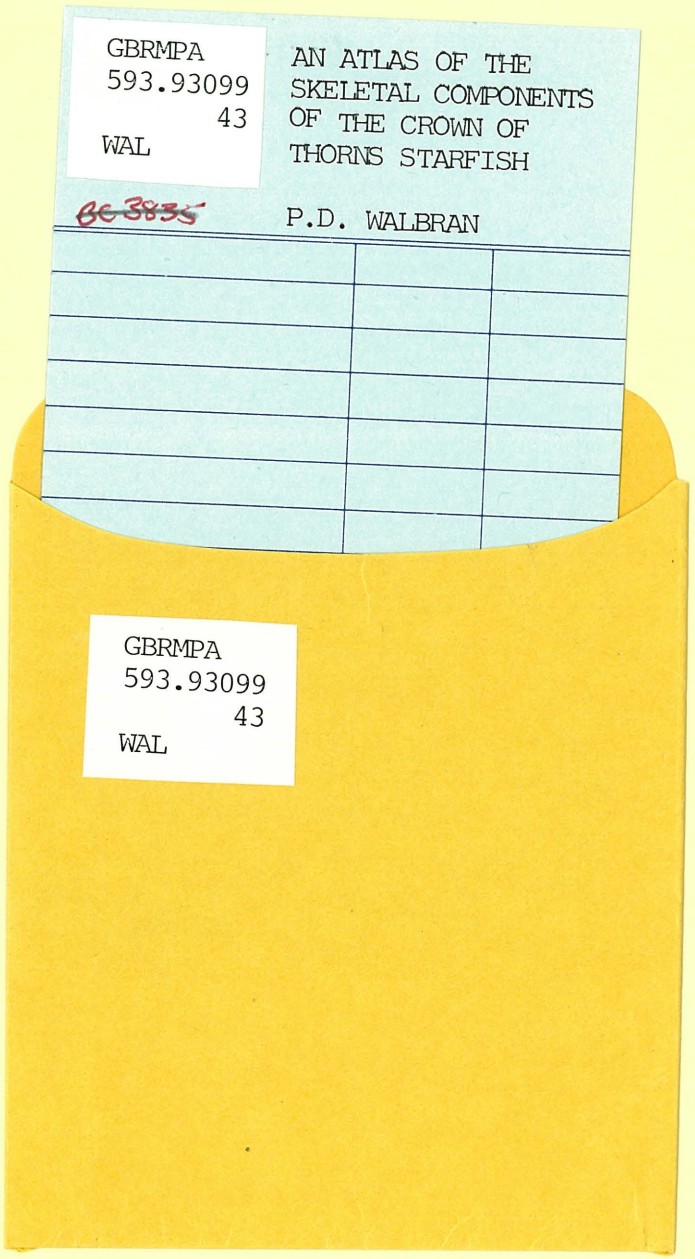








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