CONTRIBUTIONS FROM THE MUSEUM OF PALEONTOLOGY

THE UNIVERSITY OF MICHIGAN

VOL. 24, No. 8, p. 69–83 (8 pls.) OCTOBER 4, 1973

THE STEREOMIC MICROSTRUCTURE OF THE BLASTOID ENDOSKELETON

BY

DONALD B. MACURDA, JR.

PUBLISHED WITH GENEROUS SUPPORT OF
JOHN W. ARMSTRONG PALEONTOLOGY ASSISTANCE FUND

MUSEUM OF PALEONTOLOGY
THE UNIVERSITY OF MICHIGAN
ANN ARBOR

CONTRIBUTIONS FROM THE MUSEUM OF PALEONTOLOGY

Director: ROBERT V. KESLING

The series of contributions from the Museum of Paleontology is a medium for the publication of papers based chiefly upon the collection in the Museum. When the number of pages issued is sufficient to make a volume, a title page and a table of contents will be sent to libraries on the mailing list, and to individuals upon request. A list of the separate papers may also be obtained. Correspondence should be directed to the Museum of Paleontology, The University of Michigan, Ann Arbor, Michigan 48104.

VOLS. 2–23. Parts of volumes may be obtained if available. Price lists available upon inquiry.

VOLUME 24

THE STEREOMIC MICROSTRUCTURE OF THE BLASTOID ENDOSKELETON

DONALD B. MACURDA, JR.

ABSTRACT—The endoskeleton of a blastoid theca is composed of a stereomic meshwork which is very similar to that of modern echinoderms. Study of a Permian spiraculate with a scanning electron microscope has revealed the presence of long trabecular rods in the lower and median parts of the radial which parallel the directions of growth. The stereom of the upper part of the radial and the ambulacra shows a more irregular pattern. The meshwork is denser at points of plate articulation, such as the brachiolar facet. The meshwork of the deltoid of a Permian fissiculate is similar to the spiraculate and suggests that there are no fundamental differences in the stereom of fissiculate and spiraculate blastoids.

INTRODUCTION

THE SKELETAL SUPPORT of the modern echinoderms differs from that of many other invertebrates. In contrast to most, it is an endoskeleton, secreted by the mesoderm. Its internal configuration is also highly unusual, consisting of a series of rods or trabeculae which are cross-connected to produce a meshwork. The porosity within this spongy or fenestrated meshwork (stereom) has been shown to range from seventeen to fifty-two percent in different types of plates of one echinoid species (Weber, 1969, p. 541). The pores or channels are filled with tissue, some of which is in the form of ligaments. The arrangement of the channels is variable, at times being quite regular (pl. 2, fig. 5), at times quite irregular (pl. 2, fig. 6; pl. 6, fig. 6). The endoskeleton is composed of high-magnesium calcite; analyses of the percentage of magnesium have been presented by Weber (1969). He also demonstrated by the use of the electron microprobe that the magnesium is randomly distributed within the crystal lattice of the endoskeleton and not concentrated at points of intersection within the meshwork. This high-magnesium calcite is unstable geologically, ultimately being converted to a low-magnesium calcite. This conversion does not appear to affect the configuration of the stereom.

Each single plate of the echinoderm endoskeleton has been stated to behave optically as a single calcite crystal. This has prompted the curiosity of mineralogists, leading some to claim that each plate is comprised of a mosaic of tiny crystals all arrayed in the same orientation (e.g., Nissen, 1963; Roux, 1970). Careful study by several workers has led to the conclusion that most of the calcite is secreted in optical continuity and that each plate is a single crystal (Raup, 1966; Towe, 1967; Nichols & Currey, 1968; Donnay & Pawson, 1969; Nissen, 1969). Towe (1967) found some evidence for a polycrystalline aggregate on the surface of some echinoid plates but evidence presented by Donnay & Pawson (1969) seems to nullify this. Some polycrystalline elements are known in echinoids. Those within the tubercles are secondary, resulting from shearing stresses. Some other polycrystalline examples were attributed to mechanical stress but those of the echinoid teeth are apparently primary (Donnay & Pawson, 1969).

In 1966, Raup summarized the information then available on the echinoderm endoskeleton. Since that time, aside from questions of mono- or polycrystallinity, most attention has been directed to the configuration of the trabeculae and pores in modern echinoderms by the use of the scanning electron microscope (SEM). Investigators have been aware for some time of the porous nature of the echinoderm meshwork (e.g., Agassiz, 1892; Bather, 1900, cites other earlier examples). However, the resolving power of the SEM has allowed investigation at a much more detailed level. Most studies have utilized only modern material (e.g., Nichols & Currey, 1968; Donnay & Pawson, 1969; Nissen, 1969; Weber *et al.*, 1969) but Roux (1970) has applied this to the study of Mesozoic crinoids as well. The meshwork of the echinoderm stereom is apparently one of the fundamental characters of the phylum. It has been cited from as far back as the Lower Cambrian (Durham, 1966) and is commonly seen in thin sections of Paleozoic crinoids (e.g., Moore, Jeffords, & Miller, 1968) and blastoids (e.g., Breimer & Macurda, 1972). In almost every case, the porous space within the meshwork has been filled with secondary calcite in optical continuity with the primary endoskeleton, making an investigation of the three-dimensional configuration of the stereom impossible except by normal petrographic means. However, some materials have been differentially weathered, leaving the meshwork in a three-dimensional relief and allowing investigation with the SEM. Some Permian blastoid material, preserved in this manner, has revealed the internal configuration of the blastoid stereom.

THE BLASTOID THECA

The blastoids are a class of stemmed echinoderms with unbranched feeding structures (brachioles) which flourished on a worldwide scale from Silurian to Permian. The theca is comprised of three circles of plates: three basals to which the stem was attached, five radials which form the equatorial portion, and five deltoids which form the border to the peristome (pl. 1, fig. 5). Radially arranged are five ambulacra which are comprised of a lancet, side plates, and outer side plates, and lie upon the radials and deltoids (pl. 1, fig. 6). The three principal series of plates grew by the lateral accretion of calcite on the plate edges as is clearly evidenced by the growth lines on the radials and basals (pl. 1, fig. 5). As may be seen by this illustration, each half of the radial has grown outward in three primary directions: toward the base (thus forming an RB growth sector, comprised of an RB axis, the direction of growth, and an RB front, the area along which calcite is added), laterally toward the interradial suture (RR sector), and toward the oral part of the theca (RD sector). The mesodermal tissue lying between the plate edges has deposited the new increments of calcite. For a further discussion and illustration of blastoid growth phenomena, see Macurda, 1967.

The most primitive of the blastoids are

→

EXPLANATION OF PLATE 1

Rhopaloblastus sp., Permian—*1*, UMMP 60497; view of intersection of growth lines in interradial (*RR*) sector (on right) and radial-basal (RB) sector (on left) in lower right part of a radial; × 100; compare with plate 1, figure 5. *2–4*, UMMP 60499; *2*, view of stereom in interior of radial in weathered right RB sector; note growth lines slanting from upper right to lower left; × 100; *3*, enlargement of left center of figure 2; × 300; *4*, enlargement of upper center of figure 3; × 1000; stereo pair of figure 4 in plate 8, figure 1, at a slightly lower magnification. *5*, *6*, Geol. Surv. West. Austr. F5712; lateral view, centered on E ambulacrum, and oral view, anus at 6 o'clock, of complete theca; both × 3.5.

Neoschisma australe Breimer & Macurda 1972, Permian—*7*, *8*, Geol. Surv. West. Austr. F5714A; oral (external) and aboral (internal) views of isolated deltoid; border of peristome at upper apex; grooves on aboral border of figure 7 hydrospire slits; lines on underside of figure 8 points of hydrospire attachment; both × 3.

EXPLANATION OF PLATE 2

Rhopaloblastus sp., Permian—*1–4*, UMMP 60499; *1*, unweathered surface of a radial in lower right RB sector; growth line crosses from upper right to lower left; × 300; see plate 1, figure 5, for orientation; internal stereomic microstructure visible at some points where surface degraded marginal to fenestrations; *2*, view of stereom in interior of radial in weathered portion of lower right RB sector of a radial; × 300; compare with figures 1, 3; *3*, enlarged view of largely unaltered surface of radial across a growth line in lower right RB sector taken near area of figure 1 with which it should be compared; × 1000; in contrast see figures 2, 4; *4*, enlargement of lower center of figure 2; × 1000; a stereo pair of the area covered by figure 4 is given in plate 7, figure 3, at a slightly lower magnification.

Nemaster grandis Clark 1909, Recent—*5*, *6*, D. L. Meyer collection; views of middle ligament pit and aboral muscle area respectively from arm ossicle; note tunnel-like or galleried effect of stereom in figure 5 compared to labyrinthic configuration in figure 6; photographs courtesy D. L. Meyer; × 1000.

EXPLANATION OF PLATE 3

Rhopaloblastus sp., Permian—*1–3*, *5*, UMMP 60497; *1*, view of upper part of right radiodeltoid (RD sector) and brachiolar facets of an ambulacrum; × 100; location corresponds to upper right part of central radial and adjacent ambulacrum in plate 1, figure 5; *2*, view of stereom in weathered interior of RD sector; × 1000; location corresponds to that in upper right corner of figure 1; *3*, view of unweathered surface of radial in RD sector; represents a continuation at a higher magnification of the ridge in right center of figure 1; × 300; *5*, a higher magnification of the area on the upper edge, left center of figure 3; × 1000. *4*, *6*, UMMP 60498; *4*, view of unweathered surface of RD sector in another radial in approximate location to that of figures 3, 5; × 300; *6*, enlargement of right center of figure 4; × 1000; note greater roundness of surface of stereom in figures 4 and 6 when compared with figures 3 and 5; also compare unaltered surface of RB sector in plate 2, figures 1, 3, with these figures.

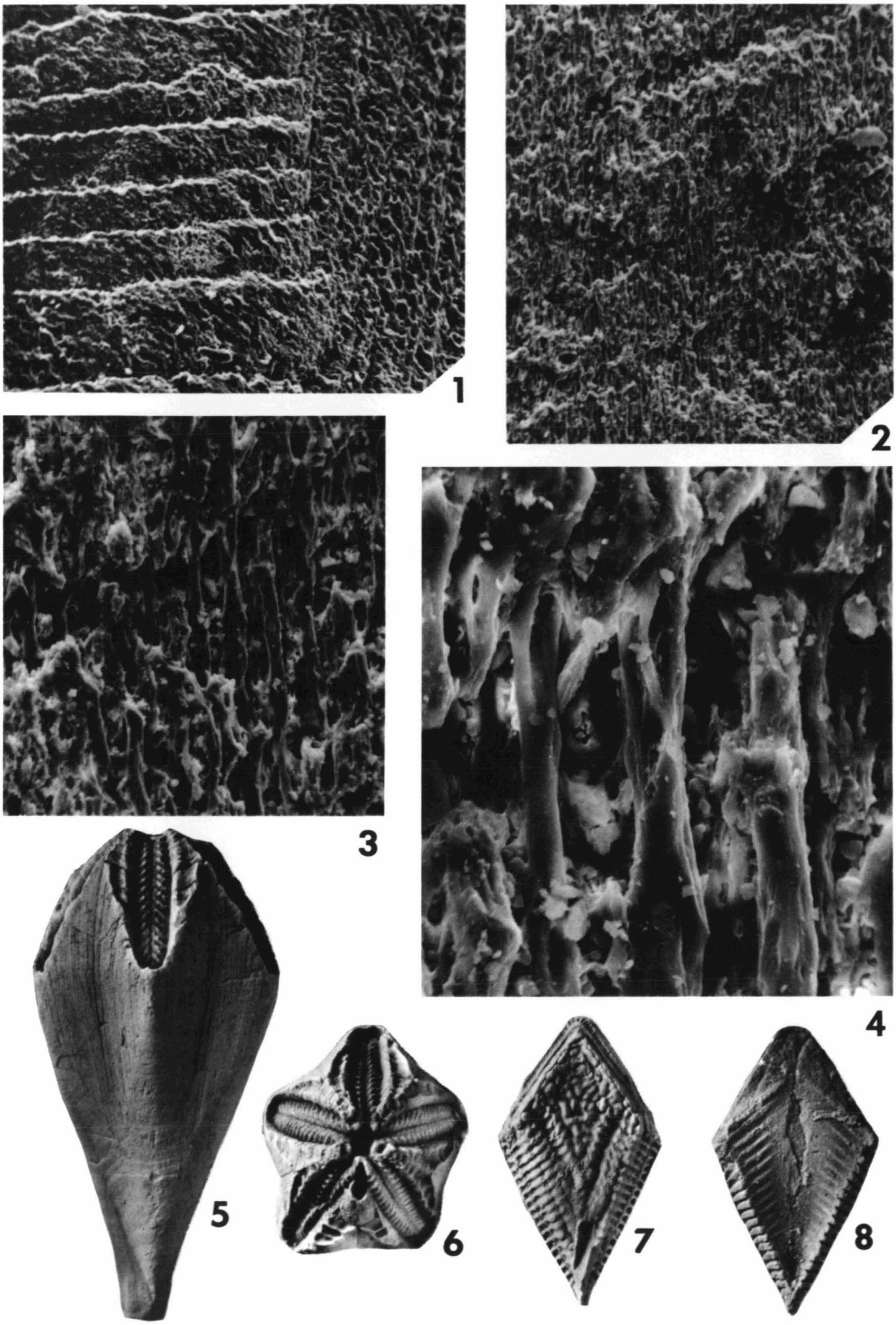


PLATE 1

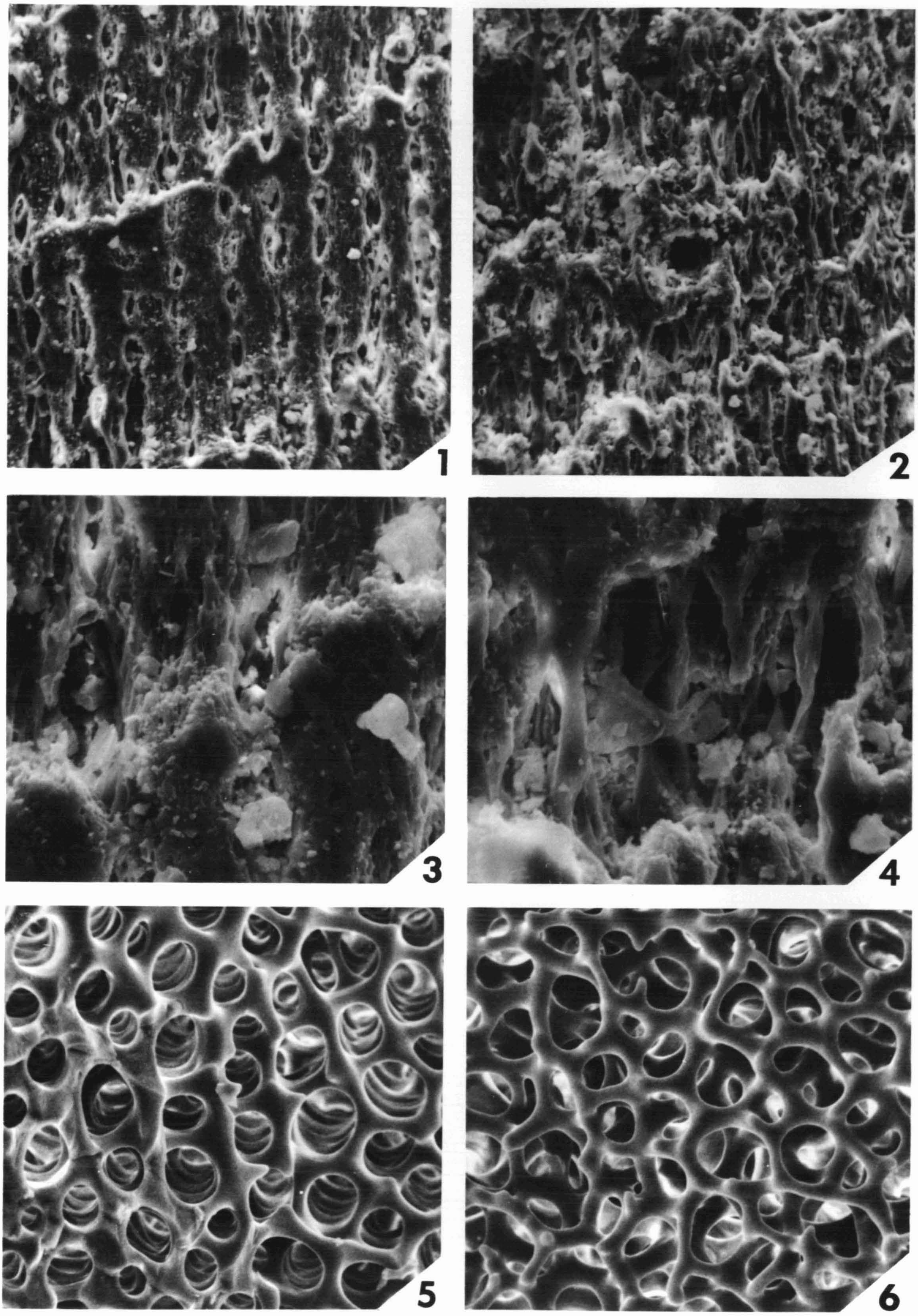


PLATE 2

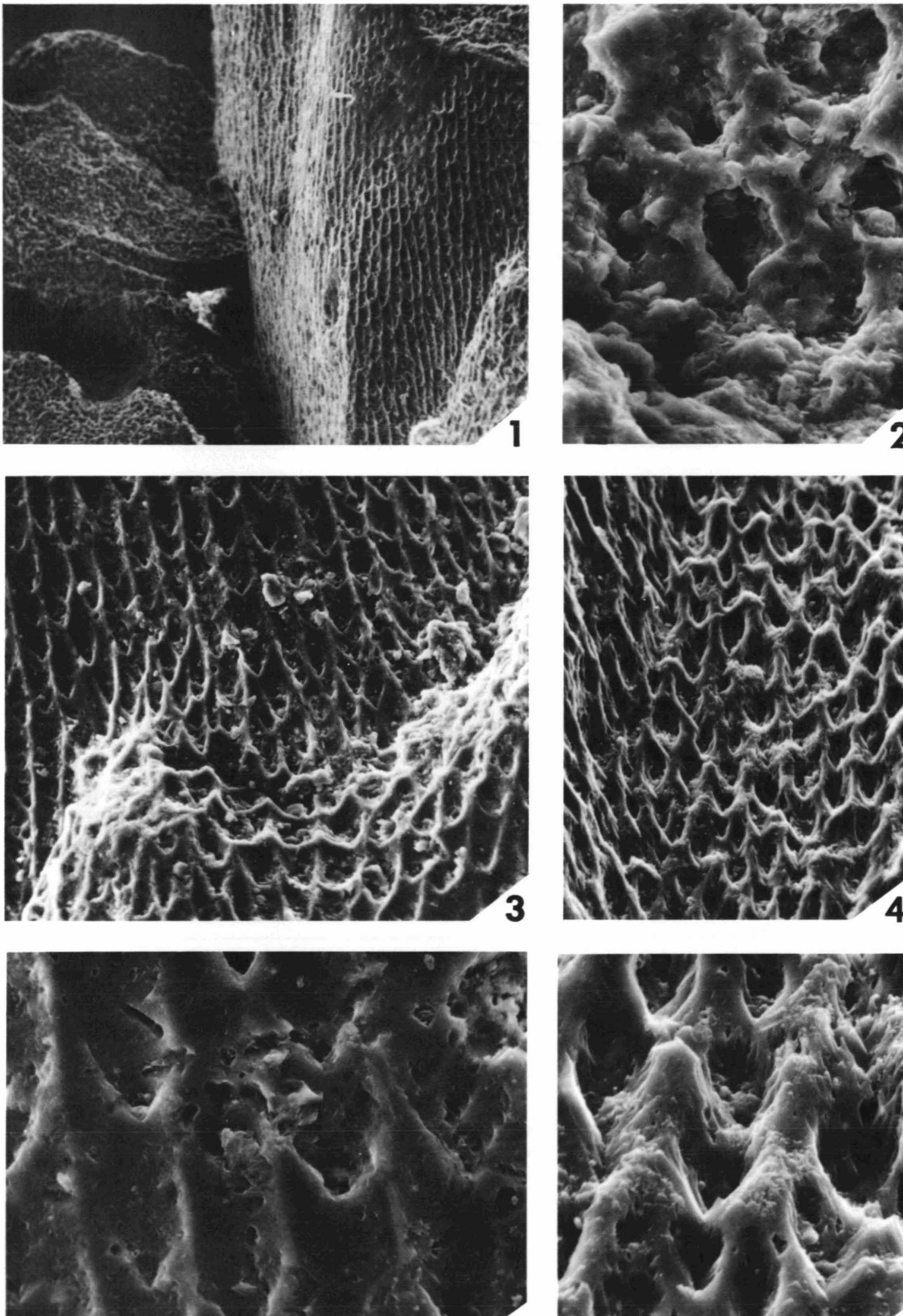


PLATE 3

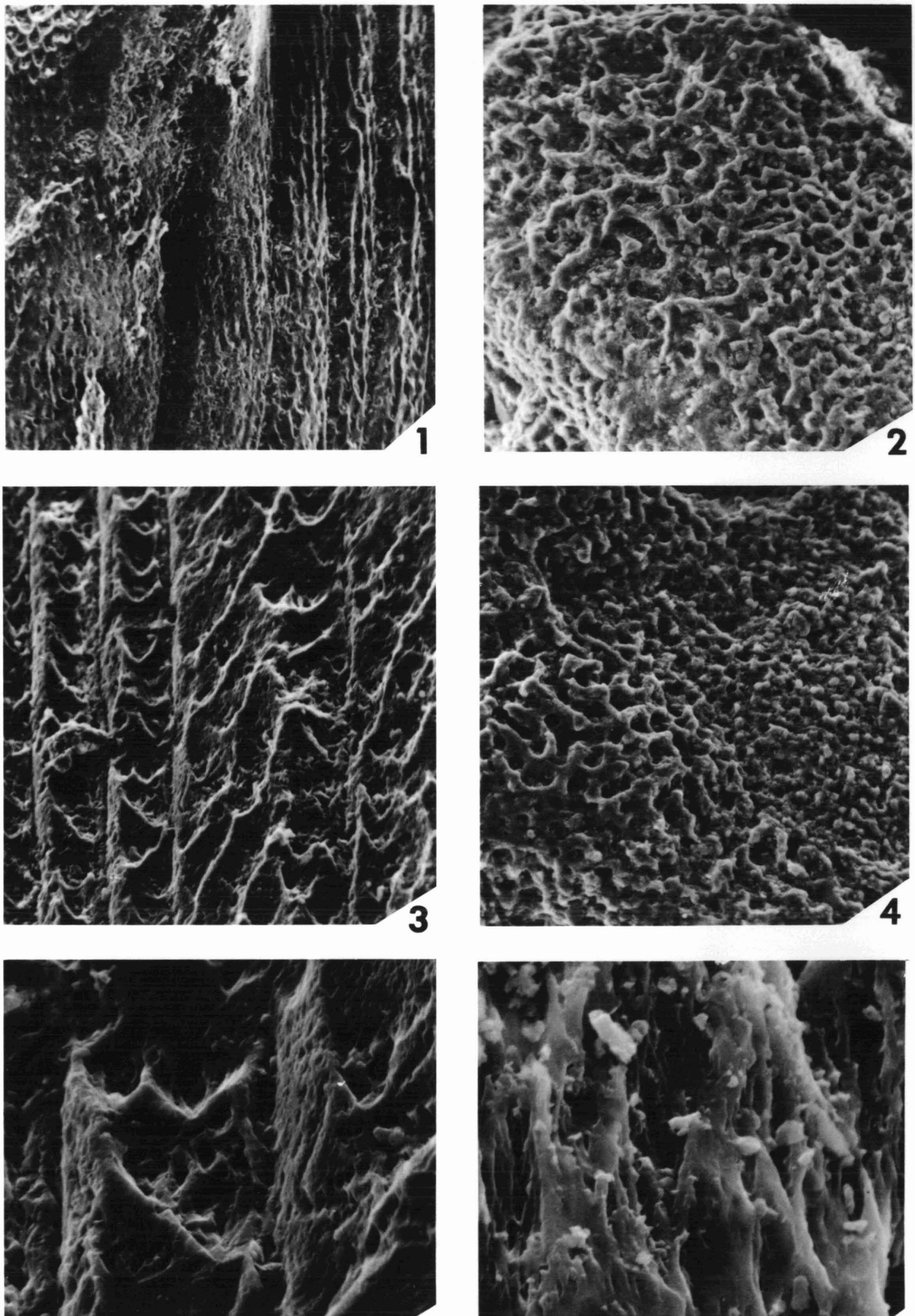


PLATE 4

those which are called the fissiculates. These are characterized by hydrospire slits which almost always communicate directly with the surrounding seawater. The hydrospire slits and traces of the points of hydrospire attachment may be seen on the isolated deltoids in plate 1, figures 7, 8. Fissiculate evolution has recently been monographed (Breimer & Macurda, 1972); these authors concluded that the spiraculate blastoids were polyphyletically derived from the fissiculates. Spiraculates are characterized by pores which border the ambulacra (pl. 3, fig. 1) and spiracles which surround the peristome (pl. 1, fig. 6). Water apparently entered the respiratory hydrospires through the pores and exited via the spiracles.

The material examined in this study represents both spiraculate and fissiculate species. Some preliminary specimens were available in 1967 for an attempt to illustrate the stereom by normal photographic means (Macurda, 1967, fig. 210, *7*, *9*). In 1968 the writer was able to visit the locality from which the earlier material came and collect the specimens which formed the basis for this study. The type section of the Permian Callytharra Formation (Artinskian) is about 500 miles north of Perth in Western Australia on the south bank of the Wooramel River at 25°52′S, 115°30′E (UMMP locality 1968/Pe-2). Here it is about 330 feet thick, consisting mainly of a crinoidal marlstone. The fauna is diverse but echinoderm material is predominant on the outcrop. The echinoderms were largely disarticulated prior to burial and the breakdown of the matrix has released countless plates which are very densely scattered over several acres. The climate is arid; differential etching has caused the stereom to be weathered into relief on a few plates, providing the three-dimensional relief necessary for study with the SEM. Three radial plates of *Rhopaloblastus* sp., a spiraculate (UMMP 60497–60499) and two deltoids of *Neoschisma australe*, a fissiculate (UMMP 60500, 60501) were selected for study. Specimens were coated with 500 angstroms of chromium and photographed at 25 KV with Polaroid PN type 55 film. The SEM used in this study was a Japan Electron Optic Laboratory Model JSM-U3 which is located in the Microprobe Laboratory, College of Engineering, The University of Michigan.

THE RADIAL STEREOM OF *RHOPALOBLASTUS*

The external surface of the radial is ornamented with prominent growth lines in the RR and RB sectors (pl. 1, fig. 1). The width of these growth lines varies but they occur with a frequency of several per mm. Each growth line appears to represent a temporary slowdown in calcification but the temporal frequency of these halts is unknown. At lower magnifications, each growth line in the RB sector appears to have a relatively smooth surface (pl. 1, fig. 1) but at higher magnifications a series of openings penetrating the outer surface of the stereom become visible (pl. 2, fig. 1). They are elliptical, with the long axis parallel to the direction of growth, and are quite regular in their spacing. The external surface in the RB sector was smooth but where weathering has breached this, the more characteristic open meshwork of the interior of the plate can be seen (pl. 2, figs. 1, 3). When the external surface has completely weathered away and the internal meshwork brought into relief, the trabeculae can be seen to consist primarily of long rods which are oriented approximately parallel to the direction of growth in the RB sector (pl. 1, figs. 2–4; pl. 2, figs. 2, 4; pl. 7, fig. 3; pl. 8, fig. 1). Narrow rods diverge irregularly from the main rods and connect between them. Examination of stereo photographs (e.g., pl. 7, fig. 3; pl. 8, fig. 1) shows a much more strongly oriented meshwork in the RB sector than that seen in some parts of modern echinoderms (pl. 2, figs. 5, 6; pl. 6, fig. 6). Pores within the meshwork of the RB sector do not show any preferred orientation. In one instance the growth line can clearly be seen in

←

Explanation of Plate 4

Rhopaloblastus sp., Permian—*1–5*, UMMP 60497; *1*, view of intersection of RD sector (left) and interradial (RR) sector (right) in upper right part of a radial; × 100; see plate 1, figure 5, for location; ornament of RD sector compares with plate 3, figure 1; vertical lines on right are growth lines of RR sector; *2*, upper surface of "mesa" between two ambulacral side grooves in ambulacrum, showing partially weathered exterior surface of stereom on upper part of a side plate; × 300; enlarged view of center of plate 7, figure 1; *3*, view of growth lines in center of the left RR sector of a radial, showing variable width of growth lines and unweathered exterior of RR sector; × 300; *4*, view showing differences in fenestration of stereom on "mesa" (lower left) and brachiolar facet (upper right) in an ambulacrum; × 300; see plate 7, figure 1, for orientation; note small fenestration openings on brachioler facet; *5*, enlargement of lower left center of figure 3; × 1000. *6*, UMMP 60499; magnified view of weathered stereom in RB sector just adjacent to junction with RR sector (boundary is light diagonal ridge in upper right); lower right side of a radial; × 3000; see plate 1, figure 5, for orientation.

the interior of the plate (pl. 1, fig. 2). Examination of such a growth line at higher magnifications (pl. 1, figs. 3, 4; pl. 8, fig. 1) suggests that the stereom is less porous just above a growth line. Perhaps as the animal temporarily discontinued forward growth of the plate, a buildup occurred internally adjacent to the edge of the plate due to excess secretory ability. As can be seen in plate 1, figures 3, 4, the earliest part of each rod is subdivided, suggesting that growth resumed at several discrete points. These growth points then merge to form a solid trabecular rod.

Growth within an RR sector of *Rhopaloblastus* sp. also resulted from the lateral secretion of calcite. The ornament on the area between two growth lines shows scallop-shaped markings which open upward on the theca. The direct elliptical openings of the RB sector are lacking (compare pl. 2, fig. 1, with pl. 4, figs. 3, 5) and the impression is given that to view stereom openings one would need to look almost parallel to the surface of the plate from an oral direction in contrast to looking from directly overhead in the RB sector. Where seen in the lowermost part of an RR sector just adjacent to the RB sector (pl. 4, fig. 6), the long rods of the trabeculae have the same orientation and configuration as those within the RB sector. This is apparently just an edge effect, as within the RR sector the long rods of the trabeculae are almost at a right angle to the interradial suture and thus oriented parallel to the primary direction of growth within that sector.

Growth within the RD sector results from both lateral accretion along the radiodeltoid suture and also from the addition of calcite to the outer surface of the plate, producing a surface with more relief (pl. 1, fig. 5). Growth

---

→

EXPLANATION OF PLATE 5

Rhopaloblastus sp., Permian—*1–5*, UMMP 60497; *1*, view of an ambulacrum from an aboral direction; main ambulacral groove runs perpendicularly in left center; ambulacral side grooves enter at an angle; minor grooves lead down from higher elevations; × 100; see plate 1, figure 5, for orientation; compare with stereo pair in plate 7, figure 1; *4*, enlarged view of stereom on upper surface of "mesa" and upper part of minor grooves; × 300; view centered on lower right center of figure 1; *2, 3, 5*, increasingly enlarged magnifications of center of figure 4, showing fenestrations of the stereom and the apparent etching (lack of a smooth surface) of the fenestrations by weathering as seen in figure 5; figure 2, × 1000; figure 3, × 2500; figure 5, × 7500.

EXPLANATION OF PLATE 6

Neoschisma australe Breimer & Macurda 1972, Permian—*1, 3, 5*, UMMP 60501; *1*, view of a posterior left lateral edge of a deltoid from a somewhat forward internal vantage point; × 100; it would correspond to a view of plate 1, figure 7, if one were to stand below the upper right apex of plate 1, figure 6, and look southeast at the lower left edge of plate 1, figure 7; the depressed areas in figure 1 represent the interior of hydrospire slits which are visible at the extreme lower left edge of plate 1, figure 8; *3, 5*, increasingly enlarged magnifications of left center of figure 1, showing stereomic microstructure in deltoid; figure 3, × 300; figure 5, × 1000. *2, 4*, UMMP 60500; *2*, view of lower inner terminus of hydrospire slit (groove in upper right) and trace on inner surface of deltoid where hydrospire fold was attached (double line from upper right to lower left); × 100; see plate 1, figure 8, and plate 8, figure 2, for orientation; *4*, enlargement of the inner surface of the deltoid, showing nature of stereom on exposed internal surface and within the area to which the hydrospire fold was attached; × 300; figure 4 corresponds in position to an enlargement of the left center of figure 2; diagonal line across lower right of figure 4 represents boundary between the two regions. (It is the next hydrospire slit to the right of that in figure 2.)

Ophiura sp., Recent—*6*, D. L. Meyer collection; stereomic microstructure of an ophiuroid arm ossicle, showing labyrinthic configuration of the mesh; × 1000.

EXPLANATION OF PLATE 7

Rhopaloblastus sp., Permian—*1, 2*, UMMP 60497; *1*, stereo pair of the right side of an ambulacrum as viewed from directly overhead, with peristome located north of figure; × 70; see plate 1, figure 5, for orientation; main ambulacral groove runs from upper left to lower left; ambulacral side grooves lead to brachiolar pit (depression right center) which is at forward terminus of brachiolar facet, the horseshoe-shaped area at the right edge which is bisected by a low median ridge (note aboral half is higher topographically); minor grooves lead down into main and side ambulacral grooves; pore furrow borders adoral edge of brachiolar facet and goes into hydrospire pore at right edge of ambulacrum (just beyond right edge of right photograph in figure 1); *2*, enlarged stereo pair of right center of figure 1, showing brachiolar pit (left center), part of surface of adoral part of brachiolar facet (lower right), and pore furrow (groove in upper portion of photograph); light spot due to surface charging; × 210. *3*, UMMP 60499; stereo pair showing configuration of internal stereom of an RB sector exposed by weathering; bottom of RB sector toward right edge of photograph; × 700; compare with plate 2, figure 4.

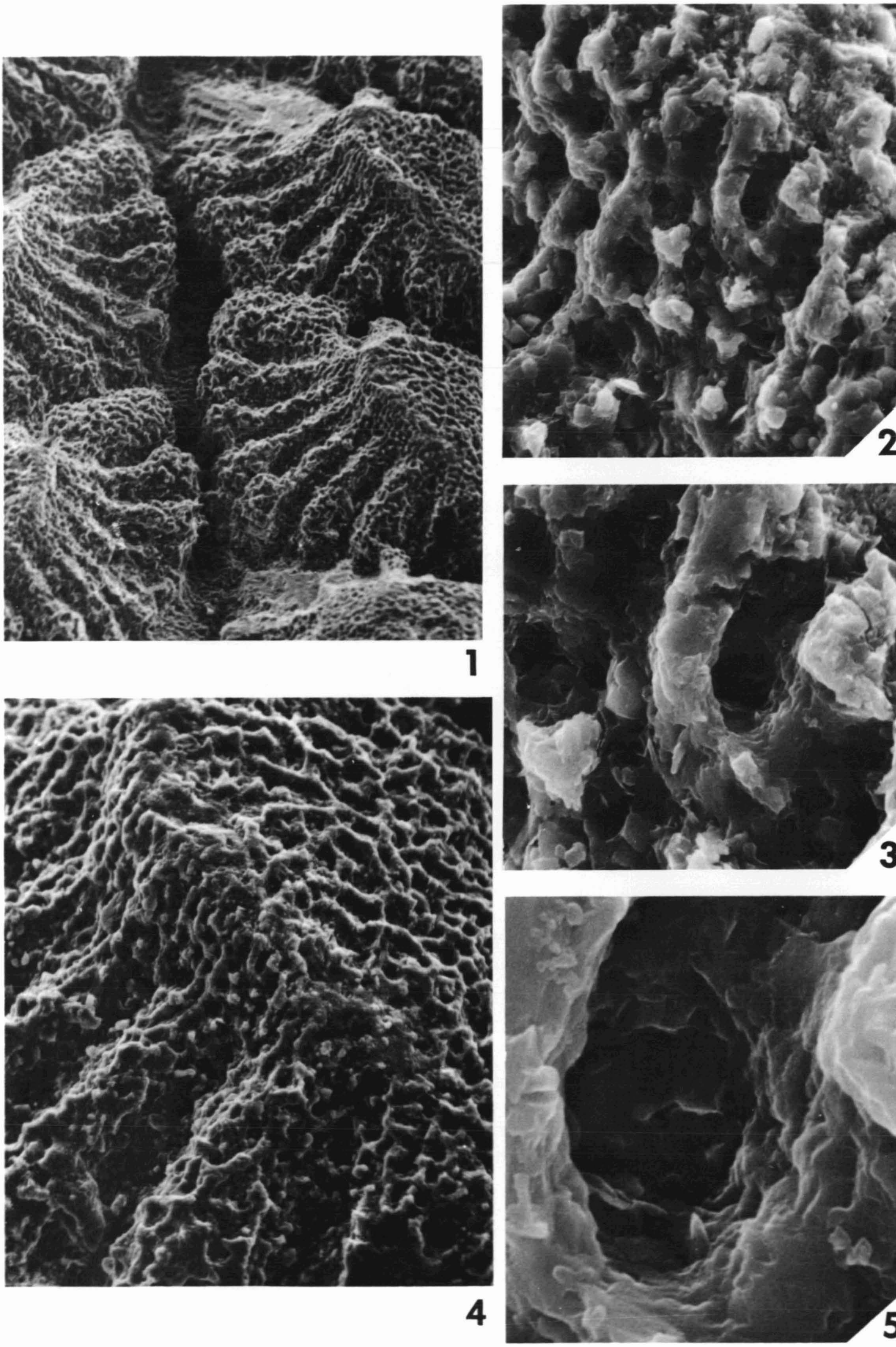


PLATE 5

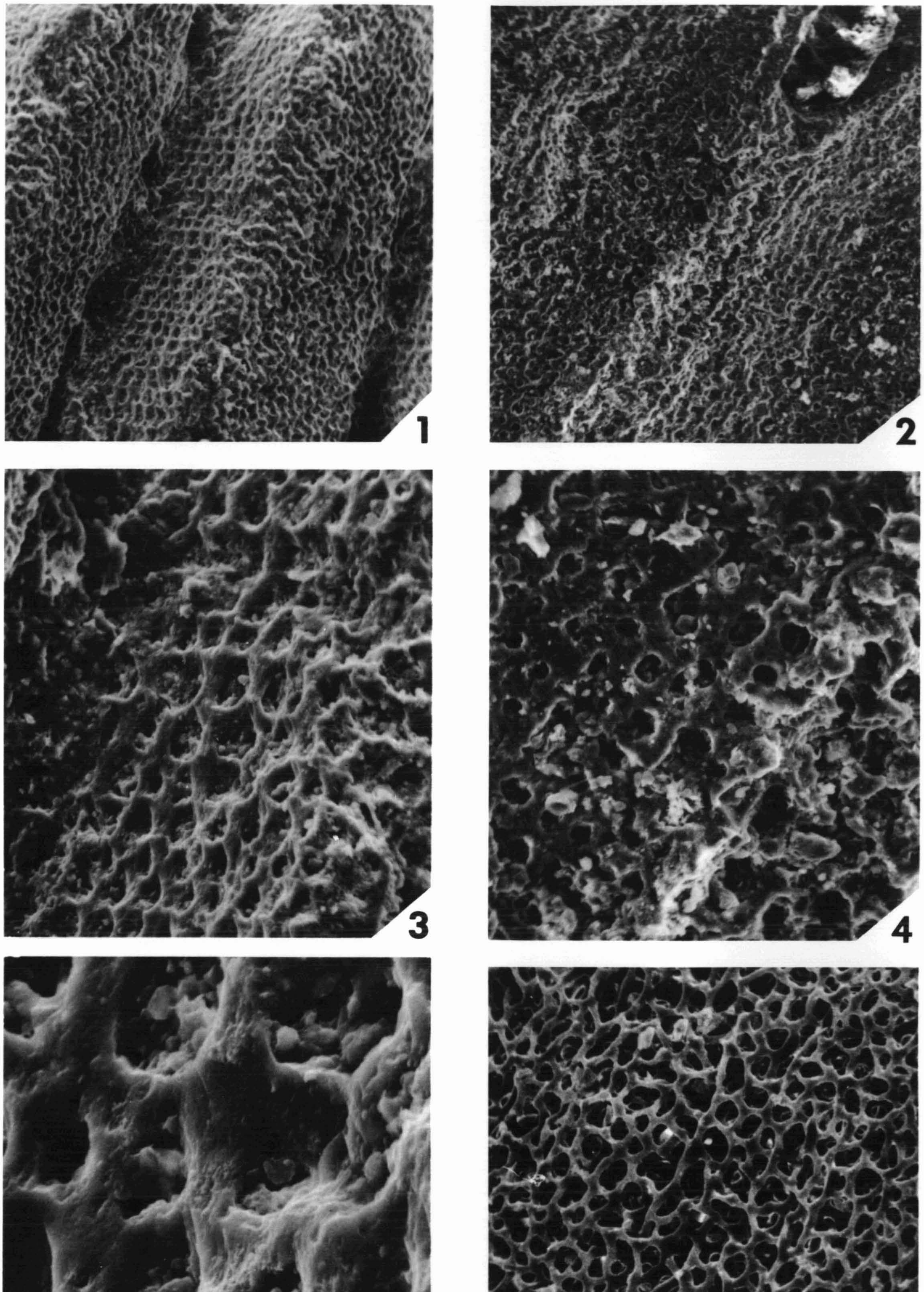
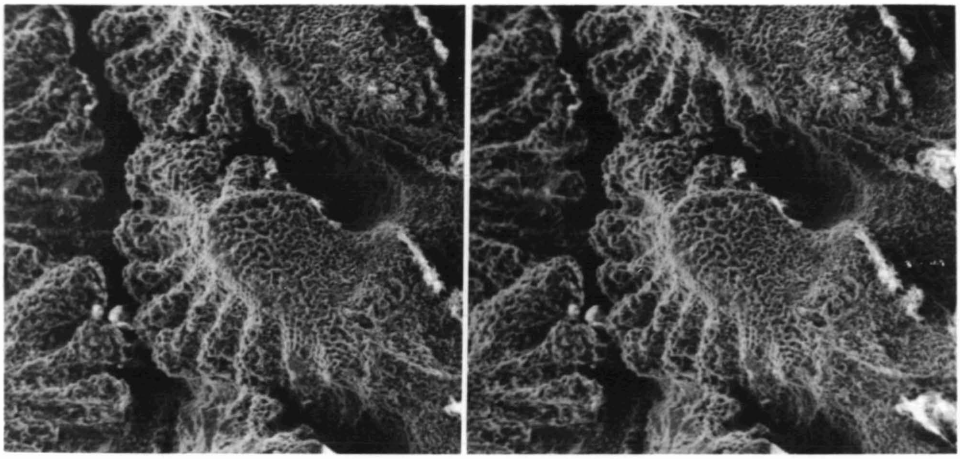
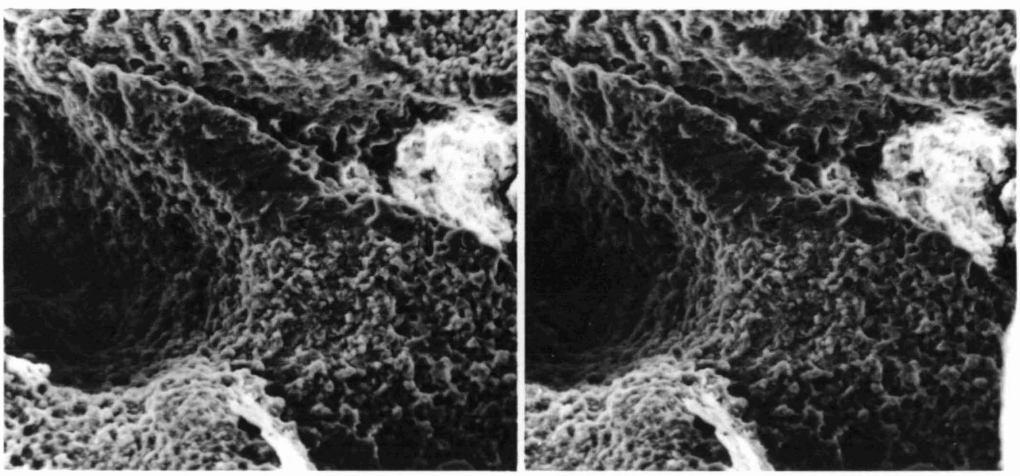


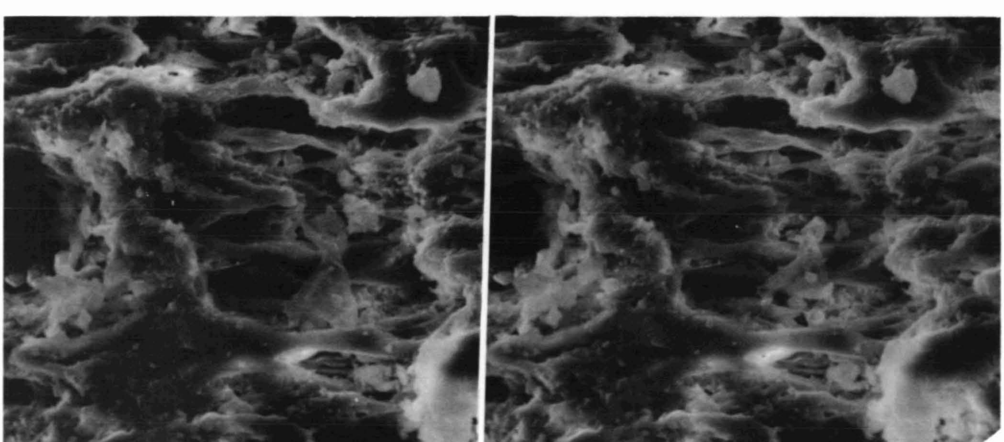
PLATE 6



1

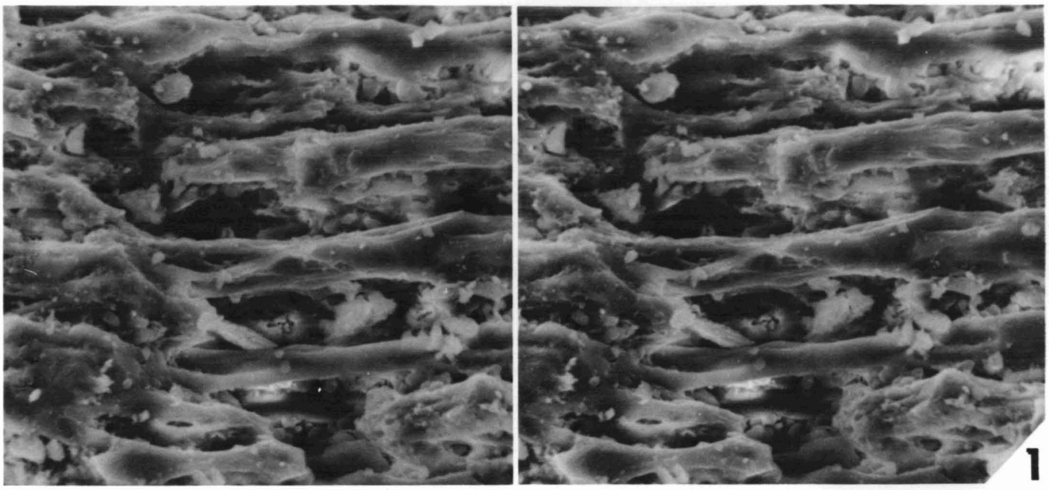


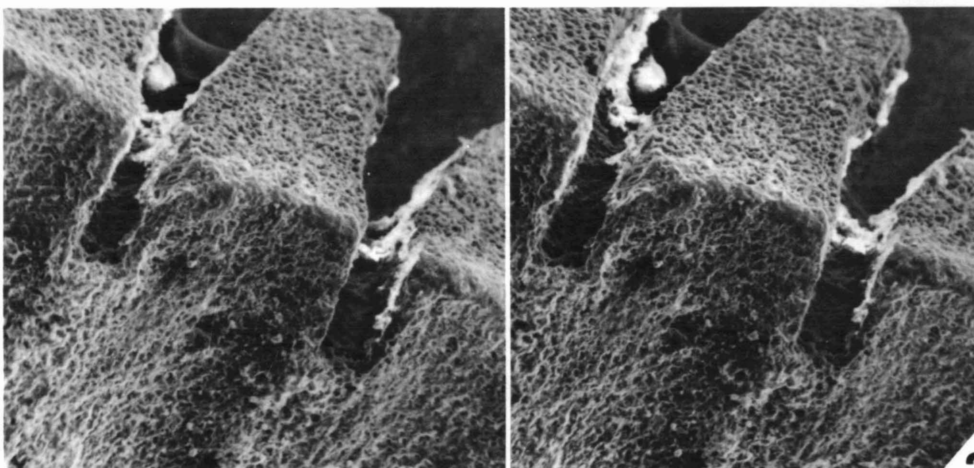
2

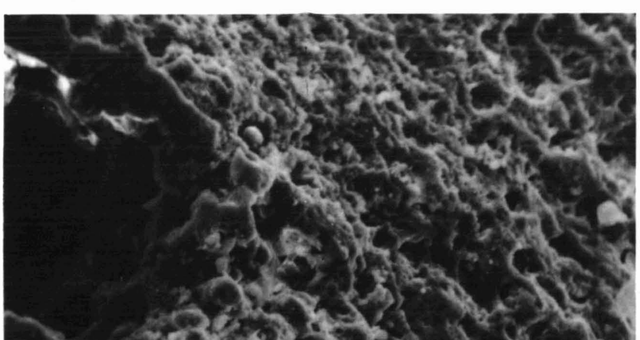


3

PLATE 7







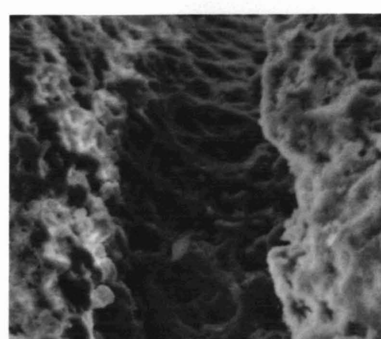


PLATE 8

lines are not evident; the ornament consists of irregular, vertically oriented rows of the scallop-shaped markings seen in the radials (pl. 3, figs. 1, 3–5). Some of the borders of these scallops are flat, others more rounded. When the external surface of the RD sector is breached by weathering, pores within the meshwork are evident (pl. 3, fig. 2) and there do not appear to be the long trabecular rods as seen in the RB sector. The transition from an RD to an RR sector can be seen in plate 4, figure 1.

AMBULACRAL STEREOM OF *RHOPALOBLASTUS*

The ambulacrum of a blastoid is one of the most complex parts of the animal. Breimer & Macurda (1972) have reinterpreted the morphology of a blastoid ambulacrum and the morphological remarks in the following paragraph are based upon that work. Examination of the stereo photographs of plate 7, figure 1, will aid in this discussion.

The deep main ambulcral groove forms the midline of the ambulacrum. Ambulacral side grooves lead off alternately to the brachiolar pits, which lie just medial to the brachiolar facet (pl. 7, fig. 2). The main and side ambulacral grooves are inferred to have lodged the radial water vessel of the water vascular system and its lateral branches. The minor grooves which descend into the main and lateral grooves are inferred to have lodged tube feet. The area above the main ambulacral groove, the side grooves, and minor grooves is known to be roofed by cover plates in some fissiculates and spiraculates and presumably such cover plates or a plated integument afforded similar protection in *Rhopaloblastus*. The top of the mesa-like area between side grooves would thus be externally exposed. The brachiolar pit represents the area where the brachiolar food groove (and inferentially the brachiolar water vessel) descended to the ambulacrum. As can be seen in plate 7, figures 1 and 2, the brachiolar facet is a heart-shaped area at the lateral edge of the ambulacrum to which the brachiole was attached. The blastoid brachioles are biserial and are offset from one another; this can be seen in the lower elevation of the adoral part of the facet to which the lowermost adoral brachiolar plate was attached. A pore furrow lies adoral to the brachiolar facet and descends into a hydrospire pore at the edge of the ambulacrum.

The stereom of the ambulacrum is illustrated at increasing magnification in a series of photographs in plate 5, figures 1–5. At lower magnifications the external surface of the stereom can be seen to be comprised of irregular wandering trabeculae with round pores which is very similar to that seen in the muscle attachment in the arm of a modern crinoid (pl. 2, fig. 6). The "porosity" of the ambulacral stereom was high. The size of the pores has been slightly enlarged by etching (see pl. 5, figs. 3, 5) and the surface of the stereom is no longer smooth as it is in modern echinoderms (pl. 2, figs. 5, 6; pl. 6, fig. 6). The meshwork on the surface of the mesa between the side grooves is open (pl. 4, fig. 2) but the mesh underlying the brachiolar facet is less porous, the pores being smaller. The two areas are comparatively illustrated in plate 4, figure 4. A similar effect can be seen in the mamelon of an echinoid tubercle. On the surface of articulation with the base of a spine, the meshwork is dense; away from this area, the meshwork is more open. This appears to be a strengthening of the mesh to accommodate the stress induced by movement of the spine. Thus the greater density of the meshwork of the brachiolar facet would also appear to be a strengthening device to reduce stress induced by brachiolar movements. In a modern crinoid where the ligament penetrates the stereom to interconnect two plates, a galleried effect is produced (pl. 2, fig. 5). No muscular facets are known in blastoid plates and presumably the brachiolar plates were held together by ligaments and held the lowermost brachiolar plates to the brachiolar facet. The internal configuration

←

EXPLANATION OF PLATE 8

Rhopaloblastus sp., Permian—*1*, UMMP 60499; stereo pair showing configuration of internal stereom of an RB sector exposed by weathering; bottom of RB sector toward right edge of photograph; × 700; compare with plate 1, figure 4.

Neoschisma australe Breimer & Macurda 1972, Permian—*2–4*, UMMP 60500; *2*, stereo pair of posterior inner edge of a deltoid, as viewed from below; hydrospire slits form notch at edge of deltoid; traces of area of hydrospire attachment forms double line leading to lower edge of photograph from hydrospire slit; × 70; orientation corresponds to being above center of plate 1, figure 8, and looking SE; *3*, enlarged view of inner edge of hydrospire slit and area of hydrospire attachment; × 300; slit is that in lower right center of figure 2 as viewed from the northwest; *4*, view of stereomic microstructure along inner surface of a hydrospire slit in a deltoid; exterior is toward top of photograph; × 300.

of the meshwork just below a facet is not known but could be similar to that of the crinoid (pl. 2, fig. 5).

STEREOM OF DELTOID OF *NEOSCHISMA*

The stereom discussed thus far has belonged to a spiraculate blastoid. The fissiculate *Neoschisma australe* is presumed to be quite removed from *Rhopaloblastus* phylogenetically. Therefore, a comparison of the meshwork should suggest whether there are fundamental differences within the stereom of the two subdivisions of the blastoids. The overall shape of the deltoid of *N. australe* is illustrated in plate 1, figures 7, 8.

The lateral surfaces of the deltoid of *N. australe* show a somewhat unorganized network of trabeculae (pl. 8, fig. 2) which is very similar to that seen on the upper surface of the ambulacrum of *Rhopaloblastus* (pl. 4, fig. 2). The relative porosity appears similar. In one of the hydrospire slits, the stereom does assume a more organized polygonal appearance (compare pattern within groove of pl. 6, fig. 1, with that outside groove) and at higher magnifications the pores can be seen to be larger than in modern echinoderms (compare pl. 6, figs. 3, 5, with pl. 6, fig. 6). The configuration of the stereom at the headwall of a hydrospire slit is illustrated in plate 8, figures 3, 4. The internal surface of a deltoid is smooth and is penetrated by pores of the stereom (pl. 6, fig. 2). There is a suggestion that the pores on the deltoid within an area bordered by the two lamellae of a hydrospire fold may be slightly larger than on the deltoid surface external to the hydrospires (pl. 6, fig. 4; pl. 8, fig. 3).

The hydrospire folds themselves were not preserved in these specimens. In some other genera, the hydrospires are preserved in clear calcite and may be seen in thin section. They are extremely thin and one gains the impression of looking at a filamentous lace curtain. As yet, suitable hydrospire material for study with the SEM has not come to the writer's attention. However, based upon the nature of the blastoid stereom revealed by this study, it is suggested that the tissue of the hydrospire wall was supported by a thin open meshwork which would have provided no barrier to the gaseous exchange between coelomic fluids and seawater.

CONCLUSIONS

The blastoids have a skeletal stereom which has many similarities to that of modern crinoids and ophiuroids. This further supports earlier suggestions that the microstructure of the echinoderm endoskeleton was differentiated very early in the history of the phylum and has been a conservative characteristic ever since. The trabeculae within the RB and RR sectors of a radial plate of *Rhopaloblastus* are composed primarily of long rods which are oriented parallel to the direction of growth. The external surface of the RB sector is characterized by small elliptical openings whereas that of the RR sector has scallop-shaped markings. The RD sector has rows of similar ornament but does not have the trabecular rods. The pattern of the meshwork on the surface of the ambulacrum is irregular and porous. It is denser at sites of plate interaction, such as the brachiolar facets. The stereom of a deltoid of a fissiculate, *Neoschisma australe*, is similar to *Rhopaloblastus* and suggests no major differences between the two blastoid subclasses. The meshwork is irregular on the lateral surface but becomes more organized within a hydrospire slit.

ACKNOWLEDGMENTS

The writer would like to thank the following individuals who contributed ideas or material to this study or aided in the collection of material in the field or its analysis in the laboratory: W. C. Bigelow, Director of Microprobe Laboratory, and Larry Allard, Research Associate, The University of Michigan (Allard operated the SEM throughout the study and the quality of the photographs and stereo effects are due to his expertise); R. L. Gilbertson, The University of Michigan; B. Ingram and J. H. Lord, Geological Survey Western Australia; D. L. Meyer, Smithsonian Tropical Research Institute; K. M. Towe, Division of Paleobiology, Smithsonian Institution.

Dr. Robert V. Kesling edited the manuscript, Mr. Karoly Kutasi prepared the figures on the plates, and Mrs. Gladys Newton typed the final draft and helped read proof. They have my sincere thanks for their kind assistance.

LITERATURE CITED

AGASSIZ, ALEXANDER, 1892, *Calamocrinus diomedae*, a new stalked crinoid, with notes on the apical system and the homologies of the echinoderms: Mem. Mus. Comp. Zoology, Harvard, v. 17, no. 2, 95 p., 32 pls.

BATHER, F. A., 1900, The Echinoderma: A Treatise on Zoology, E. R. LANKESTER, editor, Part 3, 344 p., London, Adam and Charles Black.

BREIMER, ALBERT, & MACURDA, D. B., JR., 1972, The phylogeny of the fissiculate blastoids: Kon. Ned. Akad. Wetensch., Afd. Natuurk., Amsterdam, Verh., Eerste Reeks, Deel 26, no. 3, 389 p., 34 pls.

DONNAY, GABRIELLE, & PAWSON, D. L., 1969, X-ray diffraction studies of echinoderm plates: Science, v. 166, p. 1147–1150.

DURHAM, J. W., 1966, *Camptostroma*, an early Cambrian supposed Scyphozoan, referable to Echinodermata: Jour. Paleontology, v. 40, no. 5, p. 1216–1220.

MACURDA, D. B., JR., 1967, Development and hydrodynamics of blastoids: Treatise on Invertebrate Paleontology, R. C. MOORE, editor, Part S, Echinodermata 1, p. S356–S381, New York, Geol. Soc. America, Inc.

MOORE, R. C., JEFFORDS, R. M., & MILLER, T. H., 1968, Morphological features of crinoid columns: Univ. Kans. Paleon. Contrib., Echinodermata, ser. no. 45, art. 8, 30 p., 4 pls.

NICHOLS, D., & CURREY, J. D., 1968, The secretion, structure, and strength of echinoderm calcite, *in* S. M. MCGEE-RUSSELL & K. F. A. ROSS, Cell structure and its interpretation, essays presented to John Randal Baker F. R. S., p. 251–261: London, E. Arnold (Pub.) Ltd.

NISSEN, H.-U., 1963, Röntgengefügeanalyse am Kalzit von Echinodermenskelleten: Neues Jahrbuch Geologie Paleontologie, Abh., v. 117, p. 230–234.

———, 1969, Crystal orientation and plate structure in echinoid skeletal units: Science, v. 166, p. 1150–1152.

RAUP, D. L., 1966, The endoskeleton, *in* R. A. BOOLOOTIAN, editor, Physiology of Echinodermata, p. 379–395: New York, Interscience Pub.

ROUX, MICHEL, 1970, Introduction à l'étude des microstructures des tiges des crinoïdes: Geobios, v. 3, no. 3, p. 79–98, pls. 14–16.

TOWE, K. M., 1967, Echinoderm calcite: single crystal or polycrystalline aggregate: Science, v. 157, p. 1048–1050.

WEBER, J. N., 1969, The incorporation of magnesium into the skeletal calcites of echinoderms: Am. Jour. Sci., v. 267, no. 5, p. 537–566.

———; GREER, RAYMOND; VOIGHT, BARRY; WHITE, EUGENE; & ROY, RUSTUM, 1969, Unusual strength properties of echinoderm calcite related to structure: Jour. Ultrastructure Research, v. 26, no. 5–6, p. 355–366.

MANUSCRIPT SUBMITTED May 8, 1972.