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Wall Microstructure of *Globorotalia truncatulinoides* (d'Orbigny)

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ABSTRACT

Current studies on planktonic Foraminifera indicate that the external morphology of the test and the structure of the wall are of prime importance for taxonomy, ecology and studies on their evolution. Investigations on the spatial variation of the morphology and on the microstructure of the shell wall provides sound basis for the evaluation of the chronologic morphogenesis of the planktonic Foraminifera. In the present study the well known planktonic species, *Globorotalia truncatulinoides* (d'Orbigny), was analysed as to the geographic variation of its external morphology, and the wall structure was examined with the electron microscopes.

Statistical analyses demonstrate that: 1) highly conical forms are seemingly concentrated in the lower latitudinal regions and the lower conical ones in the higher latitudes; 2) individuals with umbilical teeth and dextrally coiled shells dominate in the lower latitudes; the categories are independent of one another.

Two methods of electron microscopy were employed for the study of the wall microstructure, namely, the transmitted type and the scanning type. A complete electron micrograph of a vertical section of the test was reconstructed, and a schematic diagram showing the fundamental wall structure constructed. The wall of *G. truncatulinoides* is basically divided into the lamellar layer and crust; these are different from each other in microstructure. The lamellar layer in each chamber is distinguished into the inner and outer lamellae by structure and texture. The inner lamella, limited in each chamber, consists of minute interlocking calcite grains and is lined by basal sublamella. The outer lamella is composed of interlocking columns and wedges perpendicular to the surface and finely bumpy in texture. The boundary between these lamellae is not defined by a sharp line or "canal" in contrast to those between the consecutive outer lamellae. Textural differentiation in the bilamellar layer is considered to be related to the contact with the protoplasmic mass. The crust composed of elongate, prismatic calcite units is a layer formed after the completion of the ultimate chamber. These calcite units exhibit a microstructure supposed to be cleavage. Pore concentration in the wall is usually 7 to 9 per $25 \times 25\,\mu$ square. Protuberances developed in and on the wall are classified into *punctae* and *pustules* on the basis of site of occurrence, structure, and external morphology. Keels, umbilical teeth, and inner margins of the umbilical walls are essentially identical in structure with the usual type of the wall, though each of them assumes a peculiar feature in some respects. The characteristic features of the keel are mostly due to the thickening of the basal suite of the lamellae formed by an inflection at the periphery.

CONTENTS

INTRODUCTION

During the last two decades much attention has been paid to the planktonic Foraminifera. Most of the previous works concerning this group may be classified into the following categories of 1) taxonomy, 2) biogeographic distribution and ecology, and 3) origin and stratigraphic distribution.

As recently discussed by Towe and Cifelli (1967), the structure and mineral composition of the wall have become of prime importance in the classification of the calcareous Foraminifera. Especially in the cases of planktonic Foraminifera, the wall structure together with the external morphology have been considered as an adaptive response to the mode of life (*e.g.* Bolli *et al.*, 1957). In this respect the classification based on skeletal morphology is closely associated with the ecology of the organism. Many investigations on modern planktonic Foraminifera have been carried out by various workers, especially on their zoogeographic distribution. Accordingly, the distributions in oceanic waters and even in bottom sediments have become well known. In the field of their life activity, such as life cycles, reproduction, etc., our knowledge is still young in spite of the several observations in the field and laboratory by several authors (Le Calvez, 1936; Bé, 1960b; Bradshaw, 1959; Lee *et al.*, 1965; Christiansen, 1965; Berger and Soutar, 1967; and others). The validity of the planktonic Foraminifera as indicators of ecologic water masses has been well demonstrated by Bradshaw (*op. cit.*) and succeeding workers. In addition there are fairly good coincidences of the patterns of distributions among the populations living in the surface water masses and the dead ones in the bottom surface sediments of the oceans, so far as the conditions allow preservation of the latter (*vide* Phleger *et al.*, 1953; Bé, 1959, 1960a; Bradshaw, *op. cit.*; Belyaeva, 1964; Schott, 1966; Bé and Hamlin, 1967; Parker, 1967b). These facts strengthen the belief that the gross paleoceanographic conditions can be reconstructed on the basis of the distribution of fossil planktonic Foraminifera.

In the meantime, planktonic foraminiferal biostratigraphy of the Upper Cretaceous and Cenozoic strata have progressed in tropical to subtropical areas of the world, and the faunal zonations established there have been proved to be applicable for sediments in many temperate areas. As one of the fundamental criteria to define the planktonic foraminiferal zones the concept of evolutionary lineage has become widely recognized, and many lineages of various stocks have been pursued by authors. Leaving aside the questions of whether most of those "lineages" are true phylogenetic ones, recent progress in the microbiostratigraphy of the deep-sea sediments enables the study of such lineages in a precise manner through the continuous sequences formed under relatively unchanging environmental conditions. Thus, biostratigraphy, the most practical branch of paleontology, is to be united with paleobiology into a unified science as discussed by Glaessner (1966). More than 20 years ago he wrote (Glaessner, 1945, p. 5): "Micropaleontology, "academic" as well as "applied", is turning towards analytical methods. A detailed morphological analysis — structural, morphogenetic and variational — is becoming the basis of taxonomy. An ecological analysis of assemblages reveals facies relations. A stratigraphic analysis provides the key for the necessary evaluation of species and assemblages in stratigraphy."

In the present study the morphology of the well known planktonic species, *Globorotalia truncatulinoides* (d'Orbigny), is analysed by using the electron microscopes. Concerning the wall microstructure of this species, some contributions appeared in recent years. These works are, however, based on optical observations except for the latest works by

Pessagno (1967) and Pessagno and Miyano (1968). Although the results of the studies on thin sections by transmitted and polarized light should not be minimized, the limitations of the optical microscope have caused vague and sometimes erroneous interpretation, as mentioned by Towe and Cifelli (*op. cit.*). Our main purpose is to illustrate the wall microstructure of a young globorotaliid in a geological sense through examination of the electron micrographs. We hope that the results of the present observation will provide a cornerstone for future taxonomy and evolutionary studies on the planktonic Foraminifera.

Before going into the discussion on the electron microscopic observations, it is necessary to review the previous works concerning the taxonomy, wall structure, modern geographic and bathymetric distributions, coiling direction, and stratigraphic distribution of *G. truncatulinoides* for understanding the present circumstances.

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SYNTHETIC REVIEW OF THE PREVIOUS WORKS ON GLOBOROTALIA TRUNCATULINOIDES (D'ORBIGNY)

Taxonomy. — Designating *Globorotalia truncatulinoides* (d'Orbigny), 1839 as the type, Cushman and Bermúdez (1949) established the subgenus *Truncorotalia*. Their definition is:

> "Test planoconvex, thick, dorsal side flattened, ventral side sharply conical except for a large open umbilicus surrounded by the raised knobs of the inner ends of the chambers on the ventral side, periphery angular throughout; chambers not much increasing in size but rapidly in thickness as added, ventral face of the last-formed chamber above the aperture forming a concave surface."

Since then controversy arose concerning the relationship between *Globorotalia s.s.* and *Truncorotalia*. However, as discussed and pointed out by Luterbacher (1964), the subgenus, whether taken as of subgeneric or generic rank, is disapproved by most recent workers (Bolli *et al.*, 1957; Banner and Blow, 1959; Reiss, 1960, 1963; Luterbacher, *op. cit.*; and others).

Nevertheless, concerning the validity of another taxa related therewith, opinions are still divided on the taxonomic status of *Turborotalia* Cushman and Bermúdez, 1949, which was originally distinguished from *Globorotalia s.s.* in having a globular test with round periphery and no definite umbilicus. Aside from these arguments, the present species is currently included in the genus and/or subgenus *Globorotalia* in strict sense by almost all authors except Bermúdez (1961). According to Loeblich and Tappan (1964), *Globorotalia* is defined as follows:

> "Test free, trochospiral, periphery carinate, chamber angular, rhomboid, or angular-conical; sutures may be thickened, depressed to elevated; wall calcareous, finely perforate, but with nonporous keel or peripheral band, surface smooth to cancellate or hispid; aperture interiomarginal, an extraumbilical-umbilical arch bordered by lip, varying from narrow rim to broad spatulate or triangular flap".

Thus the *non-porous* keel or peripheral band is taken to be an essential character of *Globoro-*

talia. Furthermore, the wall character, that is non-spinose when living, both in adult and in ontogeny, but is secondarily spinose or pustulate, is emphasized to be an important attribute of the family Globorotaliidae by Parker (1962) and Lipps (1964, 1966).

Wall structure. — As stated in the earlier lines, the wall structure of foraminiferal tests has acquired a deep significance in modern taxonomy. Among the planktonic Foraminifera, the Globorotaliids have been taken as one of the important material for study by various authors, and much attention has been paid to the wall structure of *G. truncatulinoides.* At the time of establishing the superfamily Bilamellidea, in which all planktonic Foraminifera are included, Reiss (1957) gave a full acount of the wall structure of the Globorotaliidae. Although the bilamellid nature of the planktonic foraminiferal wall was disputed by Hofker (1962) and Ujiié (1963) who did not recognize the lamellar structure in this group, it was well documented by Reiss (1963a, b), Bé and Ericson (1963), and, Bé and Lott (1964). Since the wall structure of *Globorotalia* has been described by varioua authors, repetition is not necessary. The characters relevant to the present study are summarized based on Reiss' works (1957, 1958, 1963a, b, c).

By definition the bilamellid Foraminifera are distinguished from other groups by having double chamber-walls, "canal" systems, and aperture which is never terminal in position. The chamber-walls consist of an outer lamella which is formed of one per instar and covers the whole test, and an inner lining (or lamella) confined to each chamber; they coalesce in the region of the aperture (persitomal area). The outer lamella is considered to be deposited by the ectoplasm, and the inner one by the endoplasm. The "canal" system is formed by maintaining the presence of protoplasmic matter between them during and after deposition. In the Globorotallidae (in the sense of Reiss, 1957), part of the distal face of each chamber, part of each septum, apertural face, peristomal thickening, apertural lip, and keels are imperforate; scattered "pores" are present at the junction between the apertural face and peristomal "rim" and in the keels. Communications of the canal system with the main protoplasmic mass is believed to be maintained by such "pores" which are different from the normal pores of the perforate parts in size and arrangement. In photomicrographs of sections the "canals" (or "passages") are usually recognized as "dark lines" or "dots" situated between the outer lamella and the inner lining, and the interlamellar "dark lines" between the consecutive outer lamellae in thickened parts of the test represent the contact surface.

In addition to these fundamental structures of the wall, the existence of a calcite crust superimposed on the bilamellar test of mesopelagic forms of *Globorotalia truncatulinoides* was recognized by Bé and Ericson (*op. cit.*). They inferred that the crust, assuming quite distinct crystallographical features, was secreted by the organisms during slow descent to the deep water level in the later stage of their life cycle. According to the recent investigation by Orr (1967), the encrusting of this species takes place in water deeper than 350 m in the Gulf of Mexico. Pessagno (1964) distinguished three types of wall structure in the superfamily Globigerinacea including *Globorotalia.* They are microgranular hyaline structures restricted to the septal wall, macrogranular hyaline structures comprising most of the test (including septal walls), and ultragranular hyaline structures restricted to ornamental features such as spines, pustules and some carinae. His view was opposed by Lipps (1966) who maintained that the lamellae are composed of radially arranged calcite crystals with their c-axes perpendicular to the test surface. On the basis of various types of microscopic observations, Pessagno and his collaborator added comments on his previous work (Pessagno, 1967; Pessagno and Miyano, 1968). Among their statements important are: 1) the calcite crust of *G. truncatulinoides* is composed of elongate, euhedral prisms of calcite oriented normal to the test wall; 2) the lamellar layer is microgranular hyaline in character; 3) the fibrous appearance is not due to the presence of rapidally aligned, elongate

microprisms, but to the density of the radially aligned pores. With respect to this type of controversy, Towe and Cifelli (*op. cit.*) pointed out correctly that much of the confusion arises from the fact that a single crystal can be and has been interpreted in different ways. It is also agreeable with their view that no definition of a single crystal will be satisfactory if taken out of context with the material being studied and the level of resolution being attained. Some results of our electron microscopic observation will be discussed in a later section.

Modern geographic distribution. — Concerning the distributions of planktonic Foraminifera in the oceans, enormous amounts of contributions have been made since the last century, but most of the valuable works appear to be in recent years. These are grouped into two categories; the first is concerned with the living faunal distribution and the second with the distribution in the botton surface deposits. Among the first category the principal works are by Bradshaw (1959) and Parker (1960) in the Pacific; Bé (1959, 1960a), Bé and Hamlin (1967), Boltovskoy (1962, 1964, 1966a, 1966b), and Cifelli (1962, 1965, 1967) in the Atlantic; Belyeva (1964) and Ujiié (1968) in the Indian; Bé (1960b) in the Arctic; Chen (1966) in the Antarctic; and Bé (1966) in general. On the other hand, the works of the second category are by: Kustanowich (1963), Belyaeva (1966), Boltovskoy (1966c), Parker (1962, 1967b), and Lipps and Warme (1966) in the Pacific; Phleger, Parker, and Peirson (1953) and Schott (1966) in the Atlantic; Belyaeva (1963, 1964) and Oba (1967) in the Indian; and Uchio (1960) in the Antarctic. From these results it is judged that both living and dead populations of *Globorotalia truncatulinoides* are distributed within a fairly wide latitudinal range, regardless of what has been assumed as a representative of the subtropical or central-water of the oceans. It is also pointed out that there is not much difference in the limit of the geographic extent of occurrence among the living and dead, though sufficient data on dead populations in the bottom surface sediments in the North Pacific and South Atlantic are not available for comparison. The latitudinal range is about 55°N Lat. (alive and dead) to 54°S Lat. (alive) in the Atlantic; 42°N Lat. (alive) to 60°S Lat. (alive and dead) in the Pacific; and 20°N Lat. to 56°S Lat. (alive and dead) in the Indian Ocean. These features may approximately correspond with the distributions of the oceanic currents. For instance, the pole-ward limit of the Foraminifera in the southern hemisphere almost coincides with that of the Westwind Drift (=the Antarctic Convergence). Similarly in the northern hemisphere, the limit of the same foraminifer is nearly the same as the northern limit of the Kuroshio extension and of the North Pacific Current, namely the Subarctic boundary (Dodimead *et al.*, 1963) in the Pacific, and its limit corresponds with the North Atlanic Current in the Atlantic.

Bathymetric distribution. – From the O^{18} analysis of the shells of several planktonic foraminiferal species Emiliani (1954) concluded that different species occupy different depths. According to his result, the maximum density to *G. truncatulinoides* population was indicated to occur at the depth of 220 m. As to the bathymetric distribution of the present species and its seasonal change in the central North Atlantic, Bé (1960a) and Bé and Ericson (*op. cit.*) made detailed studies. Concentrations of *G. truncatulinoides* were observed in the surface waters of the mentioned region during the winter, whereas it was practically absent there between May and early November. A large number of specimens of this species was found by the authors mentioned above at depths between 500 and 1000 m during August, while they were absent in the epipelagic zone above. Similar deep habitats have been observed by Chen (1966) in the Scotia Sea and Drake Passage, despite that many other planktonic species complete their life cycle in the upper hundred meters (Berger and Soutar, 1967). According to Chen, the species is very abundant at a water depth of 200–800 m north of the Antarctic Convergence. Morphologic as well as protoplasmic changes in living individuals due to depth were noted and discussed by Bé and Ericson (*op. cit.*) and

Bé and Lott (1964).

Based upon the data cited in reference to the geographic and bathymetric distributions, it may be concluded that *G. truncatulinoides* can survive within waters ranging between 3–24°C in temperature and 34.0–36.6‰ in salinity.

Coiling direction. – Eriscon, Wollin, and Wollin (1954) were the first to recognize three geographic provinces in the North Atlantic on the basis of the coiling direction of *G. truncatulinoides* in the top layer of the deep sea cores. The northeast quadrant and most of the tropical region of the North Atlantic are represented by dominantly right-coiling populations and the central region in-between is occupied by left-coiling populations. Parker (1967b) investigated the same phenomenon in the areas not studied by the authors mentioned above, and approximately delineated the coiling direction provinces in those regions except for the South Atlantic. Generally speaking, at least at present the warm water regions are dominated by the right-coiling populations while the other regions by the left-coiling ones. The same characteristic distributional pattern may be detected in the future in living populations regardless of the opinion expressed by Ericson, Ewing and Wollin (1963). They wrote: "the areal distribution of dextral and sinistral populations of *G. truncatulinoides* is not temperature-dependent but is controlled by some other, as yet known, environmental condition." However, previous observations by Boltovskoy (1966a, 1966c), Chen (*op. cit.*), and Bé and Hamlin (*op. cit.*) in the Atlantic and South Pacific are considered to confirm our statement. In a later section the coiling direction of the samples used in this study will be discussed.

Aside from the question about the cause of change in coiling direction, the percentages of dominant coiling direction in the total test count of *G. truncatulinoides* has been proved useful for correlation among deep sea cores by Ericson and his collaborators (Ericson, Wollin, and Wollin, 1954; Ericson and Wollin, 1956; Ericson, Ewing, Wollin, and Heezen, 1961; Ericson, Ewing, and Wollin, 1963; and others).

Stratigraphic distribution. – Since the species was originally described from the bottom sediment off the Canary Islands in the eastern Atlantic by d'Orbigny (1839), it has been recorded from Recent marine sediments as well as from the younger Cenozoic strata of various parts of the world. Ericson, Ewing and Wollin (*op. cit.*) were the first to propose five paleontologic criteria for defining the Pliocene-Pleistocene boundary in the biostratigraphy of pelagic sediments. Among these criteria, the appearance of *G. truncatulinoides* in abundance above the boundary was regarded as an important marker. As to the stratigraphic range of the species opinions were independently expressed by Bandy (1963a, b, 1964), Bolli and Bermûdez (1965), Bolli (1966), Jenkins (1964, 1966, 1967), McTavish (1966), Huang 1967), Poag and Akers (1967), and Ingle (1967), on the basis of the planktonic foraminiferal sequences in areas as the Philippines, Venezuela, Jamaica, Java, New Zealand, British Solomon Islands, Taiwan, Gulf Coast, and Southern California. These authors assume that the species made its first appearance at or near the base of the Pliocene. On the other hand, in 1965 Banner and Blow published a new scheme of planktonic foraminiferal zonation for the Miocene to Recent interval. Of their total 23 zones, Zone N. 22 is defined by that part of the range of *G. truncatulinoides* prior to the first appearance of the Zone N. 23 foraminiferal assemblage, while the subjacent Zone N. 21 is defined by that part of the range of *G. tosaensis* Takayanagi and Saito prior to the first appearance of its immediate descendant, *G. truncatulinoides*. It is noteworthy that they recognized at the same time the occurrence of Zone N. 22 near the base of the stratotype Calabrian at Santa Maria di Catanzaro, the basal Pleistocene. Later they gave a full account of their upper zones (Zone N. 16 to Zone N. 23) with a range chart (Banner and Blow, 1967). The same evolutionary lineage has been consecutively recognized in some deep-sea cores of the Pacific and Indian Oceans (Parker, 1967) and some of the Atlantic (Hays and Berggren, 1967; Berggren *et al.*,

1967). Further remarkable is that the latter authors have found that this evolutionary transition occurred within the Olduvai Normal Magnetic Event, which ranges between 1.75 and 1.95 million years ago. These facts make clear that the Pliocene-Pleistocene boundary can be placed between Banner and Blow's Zones N. 21 and N. 22, and corraborate the evidence of the level at which *G. truncatulinoides* first appeared. As Jenkins (1964) discussed, there still remains a possibility that the species appeared earlier at higher latitudes than it did in lower latitudes, the same may be said for *G. tosaensis* as stated by Parker (1967). It is highly probable, however, that contradictory views of authors about this level are caused in part by difference in taxonomic concepts on the relationship between *G. tosaensis* and *G. truncatulinoides*. Because they are so closely related and the evolutionary process may have happened within a fairly short interval.

MATERIAL

The mterials examined in the present study are all from Recent deep-sea cores taken in the Atlantic, Pacific and Indian oceans. They were collected by the surveying ships of the Lamont Geological Observatory, Columbia University, and of the Scripps Institution of Oceanography, University of California. Samples mostly from the top of the cores or trigger cores were selected to represent the various latitudes in the oceans. However, the samples from the North Pacific were omitted, because of the majority being affected by calcium carbonate solution. Thus their preservations were inadequate for analysis of wall structure. The locations of the cores, depths, and level of the samples in the respective cores are listed in table 1.

Table 1. Locations and depths of cores and depths of samples in cores

Core		Location	Depth (m)	Sample level from top of core (cm)
Atlantic	V16-206	23°20′N. 46°29′W.	3733	0-1
	V18-24	02°25′N. 35°50′W.	3684	0-1
	V16-34	17°02′S. 16°13′W.	3530	0-1
	V16-36	19°22.5′S. 11°26.5′W.	3329	0-1
	V18-169	30°30′S. 16°15.5′W	3319	0-1
	V12-53	40°54.3′S 20°22.9′W	3798	0-1
	V18-120	48°36′S. 54°36′W.	3411	0-1
Pacific	DWBG-120	27°56′S. 106°55′W.	3060	0-4
	DWBG-75	43°33′S. 108°18′W.	3650	0-4
	DWBG 83	44°04′S 95°42′W.	4660	0-3
	DWBG 60	45°27′S. 124°01′W.	4040	0-6
	DWBG-64	46°43′S. 118°20′W.	3480	0-4
	DWBG-70	48°29′S. 113°17′W.	2580	0-4
Indian	MSN-53G	17°48′S. 60°02′E.	3700	10-12

TEST MORPHOLOGY AND GEOGRAPHIC VARIATION

Globorotalia truncatulinoides is characterized by its umbilico-convex trochospiral test with five chambers in the last whorl. The periphery is keeled throughout, and subacute in edge view especially of the final chamber but is obliterated with thick calcium carbonate deposition on the earlier chambers of the adult specimens. The aperture is a narrow slit, interiomarginal, extraumbilical-umbilical in position, and usually accompanied with a narrow bordering lip. The umbilicus is distinct and deep. Protuberances of various size

are distributed over the surface but are heavily concentrated around the umbilical region and the umbilical surface of the earlier chambers.

As was first noticed by Cushman and Bermúdez (1949), the apertural face of the last chamber forms a concave surface. Similar folds are recognized at the septa (apertural faces of the preceding chambers) of the last whorl in the soft X-ray contact radiomicrograph (pl. 20, fig. 2). In this micrograph it is clearly shown that the septal sutures on the spiral side are inclined forward near the peripheral margin ("tectum" of Brotzen, 1948) while the ones on the umbilical side are gently curved backward at the periphery, though both kinds of sutures are almost radial. The fold of the septal face forming a shallow hollow parallel to the tectum has been named as "scrobis septalis" by Brotzen (*op. cit.*). Both "tectum" and "scrobis septalis" are represented on the umbilical-side of *G. truncatulinoides* (pl. 30, fig. 1).

In general outline the juveniles have lower conical shape with smaller umbilical opening, compared with the adult specimens. Similr morphologic contrast may be noticed between the specimens from the lower and higher latitudinal areas. Further, on most of specimens examined there is developed a narrow lip just above the aperture. As an umbilicalward extension of the lip, a toothlike structure is formed on the chambers surrounding the umbilicus. The presence of such umbilical teeth was first referred to by Cifelli (1965), though Parker had already shown this structure in her illustration (1962, p. 241, pl. 6, fig. 7b). The teeth are usually developed on the last two or three chambers in the final whorl, and are thin and roughly triangular in shape. Although the development of the teeth are independent of the coiling direction of the tests, the teeth-bearing specimens appear to be rather concentrated in the lower latitudes.

Under the circumstances mentioned above some statistical tests were made concerning the ratio of height to diameter, the ratio of number of specimens with umbilical teeth to the total population, and the ratio of number of specimens with preferred coiling direction to the total population.

H/D of Globorotalia truncatulinoides

For the purpose of statistical analysis more than 35 specimens were picked from the respective samples, and the maximum diameter (D) and height (H) of the test of each specimen were measured under a binocular microscope. The maximum diameter ranges approximately from 940μ to 120μ, height from 620μ to 70μ , and their ratio H/D from 0.907 to 0.500.

As already stated, the higher conical forms appear to be concentrated in the lower latitudinal stations. To examine this tendency, statistical tests were made on: (1) whether the distribution of the ratio H/D changes by stations; and (2) whether the ratio H/D increases from higher to lower latitudinal stations.

To test whether the distribution of the ratio H/D changes by stations, the following condition is required. If the H/D is not constant with change of the diameter, namely, if there is no linear relation between the changes of the diameter and height, the distribution of H/D may change by the mode of distribution of the diameter. Consequently, it is necessary that the distribution of the diameter in each station be homologous.

As the first step, it was tested whether the relation of regression of the height to diameter is linear. Let N be the size of the sample; k the number of class of the diameter; and n the correlation ratio of height to diameter, respectively. The statistics can be formulated as

$$F = \frac{\eta^2 - r^2}{1 - \eta^2} \cdot \frac{N - k}{k - 2}$$

where as shown possesses F-distribution with $n_1=k-2$ and $n_2=N-k$ degrees of freedom. Moreover, $(1-\eta^2)/(N-k)$ indicates fluctuation due to density of distribution, regardless of whether regression is linear. On the other hand, $(\eta^2-r^2)/(k-2)$ indicates flucutation due to difference between the linear and curved regressions. Using this formula, the linear relation of regression of height to diameter can be tested.

In the total 380 specimens of Pacific samples, $r=0.855$, $\eta=0.870$, $N=380$, and $k=40$. Since

$$F=\frac{(0.870)^2-(0.855)^2}{1-(0.870)^2}\cdot\frac{340}{38}=0.953<1$$

$(\eta^2-r^2)/(k-2)$ is not so significant compared with $(1-\eta^2)/(N-k)$ caused simply by a contingent error. Accordingly the hypothesis that the relation of regression is linear will not be rejected. In short the ratio H/D can be assumed as constant with the change of the diameter.

The numbers of specimens measured, mean value of H/D, and the standard deviation of each station is shown in tables 2 and 3.

Table 2. Statistics of the specimens from the Atlantic stations

Station	Mean H/D	Number of specimens	Standard deviation ($\times10^{-2}$)
V16-206	0.746	39	5.73
V18-24	0.705	63	7.31
V16-34	0.706	61	5.71
V16-36	0.690	65	5.48
V18-169	0.696	66	4.29
V12-53	0.721	58	6.49
V18-120	0.684	35	6.76
Total	0.706	387	

Table 3. Statistics of the specimens from the Pacific stations

Station	Mean H/D	Number of specimens	Standard deviation ($\times10^{-2}$)
DWBG-120	0.757	58	7.50
DWBG-75	0.683	64	6.21
DWBG-83	0.701	60	5.80
DWBG-60	0.695	62	6.18
DWBG-64	0.704	52	4.97
DWBG-70	0.701	84	6.95
Total	0.706	380	

The mean value of H/D changes by stations. It is markedly large at the station DWBG-120, located in the lowest latitude among the Pacific stations examined, and it is also largest at station V16-206, which is the northernmost one in the Atlantic stations studied. There is, however, no evident tendency of increase of the value towards the lower latitudes.

In the case of standard deviation the maximum appears in the lowest latitudinal

stations in both the Pacific and Atlantic Oceans; they are DWBG-120 and V18-24, respectively. It becomes reduced from the lower to middle latitudes and again increased in the higher latitude in the Atlantic. But, no distinct regularity is recognized among the Pacific stations.

Concerning the standard deviation, it was tested whether there is any significant difference among the variances, square of deviations, of the respective stations. Let N_1 and N_2 be sizes and s_1^2 and s_2^2 variances of two respective samples drawn from the normal populations with the same variance σ^2. Statistics $N_1 s_1^2/\sigma^2$ and $N_2 s_2^2/\sigma^2$ possess independent χ^2-distribution with N_1-1 and N_2-1 degrees of freedom. Further let v_1^2 and v_2^2 be unbiased estimates of variances, respectively. They are given by

$$v_1^2 = \frac{N_1 s_1^2}{N_1 - 1}, \qquad v_2^2 = \frac{N_2 s_2^2}{N_2 - 1}$$

Then the statistics can be formulated as,

$$F = \frac{v_1^2}{v_2^2} = \frac{\dfrac{N_1 s_1^2/\sigma^2}{N_1 - 1}}{\dfrac{N_2 s_2^2/\sigma^2}{N_2 - 1}}$$

where as shown possesses F-distribution with $n_1=N_1-1$ and $n_2=N_2-1$ degrees of freedom. Although the samples should be ascertained to be normally distributed at first, by means of this relationship the homogeneity of the variances can be tested on the hypothesis that variances are homogeneous.

If we assume the difference as significant with the level of signfiicance $\alpha_1=0.01$ and as insignificant with the level of significance $\alpha_2=0.05$, the significance of difference among the variances of the respective stations may be as shown in tables 4 and 5. In the present study the distribution of specimens of each station was confirmed to be close to a normal distribution by using probability papers, though its goodness of fit was not tested.

Table 4. Significance of difference among the variances of the Atlantic stations

V16-206							
V18-24	−						
V16-34	−	±					
V16-36	−	±	−				
V18-169	±	+	±	±			
V12-53	−	−	−	−	+		
V18-120	−	−	−	−	+	−	
	V16-206	V18-24	V16-34	V16-36	V18-169	V12-53	V18-120

Table 5. Significance of difference among the variances of the Pacific stations

DWBG-120						
DWBG-75	−					
DWBG-83	±	−				
DWBG-60	−	−	−			
DWBG-64	+	−	−	−		
DWBG-70	−	−	−	−	+	
	DWBG -120	DWBG -75	DWBG -83	DWBG -60	DWBG -64	DWBG -70

The next question is whether the mean H/D differs significantly from each other. When two random samples are taken independently from the normal population with the mean m and variance σ^2, let x_1 and x_2 be the means and N_1 and N_2 the sizes of the samples, respectively. Then since $\bar{x}_1$ and $\bar{x}_2$ possess normal distributions about m with the standard deviations $\sigma\sqrt{N_1}$ and $\sigma\sqrt{N_2}$, respectively, the statistic $\bar{x}_1-\bar{x}_2$ possesses normal distribution about 0 with the standard deviation $\sigma\sqrt{1/N_1 + 1/N_2}$. Hence the formula

$$\chi_1^2 = \frac{(\bar{x}_1 - \bar{x}_2)^2}{\sigma^2\left(\frac{1}{N_1} + \frac{1}{N_2}\right)}$$

posseses χ^2-distribution with 1 degree of freedom.

Further let s_1^2 and s_2^2 be variances of the samples, respectively. Since $N_1 s_1^2/\sigma$ and $N_2 s_2/\sigma$ possess χ^2-distribution with N_1-1 and N_2-1, the formula

$$\chi_2^2 = \frac{N_1 s_1^2 + N_2 s_2^2}{\sigma^2}$$

possesses χ^2-distribution with N_1+N_2-2 degree of freedom.

Consequently, the formula

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{1}{N_1} + \frac{1}{N_2}}} \Big/ \frac{\sqrt{N_1 s_1^2 + N_2 s_2^2}}{\sqrt{N_1 + N_2 - 2}}$$

possesses t-distribution with N_1+N_2-2 degree of freedom.

If it is confirmed that the distributions are normal and that the standard deviations are the same, we can test the difference between the means on the hypothesis that the respective means of the universe are the same. It was already tested whether the standard deviations are same, *viz.*, whether the variances are homogeneous. Accordingly, if we set the condition for levels of significance in the same manner as the test on variances, the significance of difference between the mean values of H/D of each station may be as shown in tables 6 and 7.

As has been discussed in the foregoing lines, there are significant differences among the standard deviations and also the mean values of H/D of the stations. Therefore it is pressumed that these distributions are biased by physico-chemical and/or biologic factors. In other words, the contour patterns of deviation may be delineated on the basis of the size of these values, and the mode of distributions are significant in the physico-chemical and/or biologic sense. In the Atlantic Ocean the standard deviations exhibit tendency related to the latitudinal position of the stations. Although a similar tendency is hardly recognized in the Pacific, this may be probably due to the biased distribution of the stations.

Assuming that the latitudinal change bears direct relation with the change in water

Table 6. Significance of difference between the mean H/D of the Atlantic stations

V16-206							
V18-24	+						
V16-34	+	−					
V16-36	+	−	−				
V18-169	+	*	−	−			
V12-53	±	−	−	+	*		
V18-120	+	−	−	−	*	±	
	V16-206	V18-24	V16-34	V16-36	V18-169	V12-53	V18-120

Table 7. Significance of difference between the mean H/D of the Pacific stations

DWBG-120						
DWBG-75	+					
DWBG-83	+	−				
DWBG-60	+	−	−			
DWBG-64	*	±	−	−		
DWBG-70	+	−	−	−	*	
	DWBG -120	DWBG -75	DWBG -83	DWBG -60	DWBG -64	DWBG -70

*) Because of the significant difference between the variances, tests could not be carried out on the samples from the following stations: between DWBG-64 to either of DWBG-120 or DWBG-70, and between V18-169 to either of V18-24, V12-53, or V18-120.

temperature, the latter may be one of the basic contributing factors to the changes mentioned above. Moreover, if these changes are directly attributed to the change in temperature, it may be concluded that *G. truncatulinoides* has greater variances of H/D – increases in individual variations on H/D — at higher and lower temperatures. Except for the location of the stations, the data on the environmental conditions are insufficient and do not allow us to proceed on further inference. Kennett (1968) demonstrated that an interdependance exists between the temperatures of the surface water and such form ratios of this species as mean ratios of width to height (=D/H). It is thus highly possible that correlation between the mean H/D and latitude will become more positive as data are added, though the available data suggests only the existence of some biased distributions at present.

Further tests were made on whether the distribution of H/D changes by the coiling direction of the specimens at the following stations: V16–206, V16–34, V16–36, V18–169, and DWBG–120. At any station no significant differences were present among the variances. Concerning the mean H/D, only one station (V18–169) was recognized where dextrally coiled specimens have greater means than the sinistrally coiled ones (table 8).

Table 8. Significance of difference between the mean H/D of dextrally and sinistrally coiled specimens

Station	Coiling direction	Mean H/D	Number of specimens	Standard deviation ($\times 10^{-2}$)	Significance	Remarks
V16-206	D*	0.751	18	4.65	−	D>S
	S*	0.743	21	6.67		
V16-34	D	0.697	46	5.38	±	D<S
	S	0.732	15	5.45		
V16-36	D	0.686	51	5.62	−	D<S
	S	0.705	14	5.89		
V18-169	D	0.740	14	4.10	+	D>S
	S	0.684	52	3.61		
DWBG-120	D	0.766	39	7.11	−	D>S
	S	0.738	19	7.78		

*) D=dextral, S=sinistral

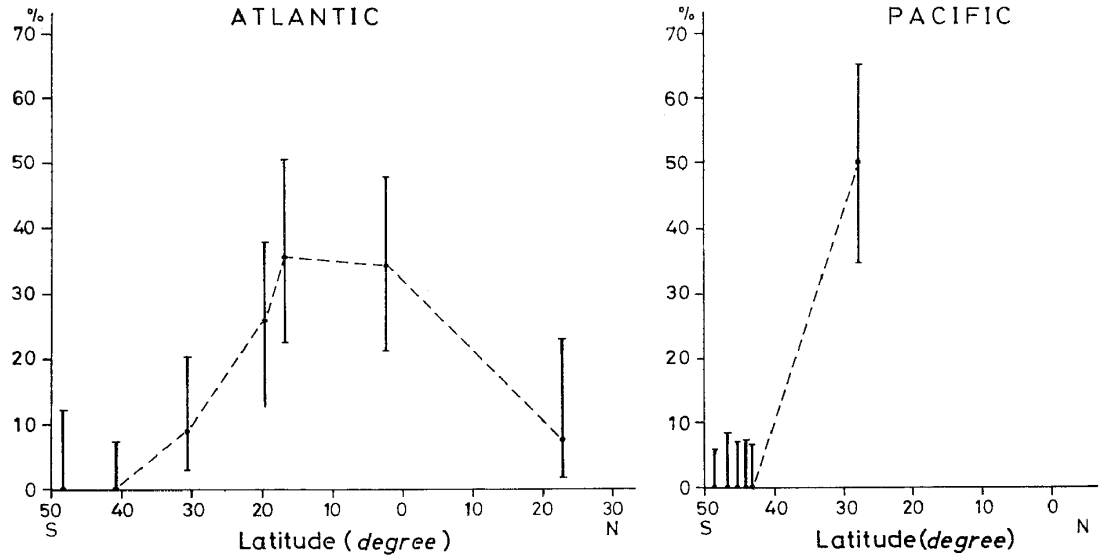

Fig. 1. Ratios of specimens with umbilcial teeth to the total populations in terms of their latitudinal position with 98 percent confidence interval.

Therefore the distribution of H/D is considered to be not effected by the coiling direction of the specimens in general.

Ratio of specimens with umbilical teeth

The ratio of the specimens with umbilical teeth to the total population was tested in terms of their latitudinal position. When the same condition with the previous tests is given for the level of significance, the ratio and their confidence limits at 98 percent confidence coefficient are as shown in fig. 1. Based upon the significant difference between the ratios and their greater values in the lower latitudes, it is accepted that the individuals with umbilical teeth flourish in the lower latitudinal, *i.e.* warmer water regions.

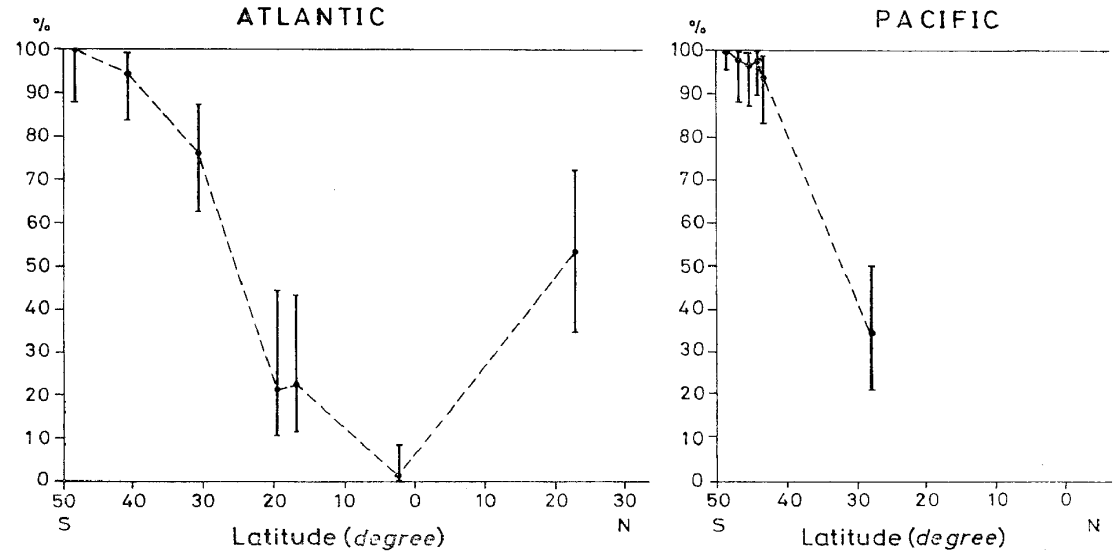

Fig. 2. Ratios of sinistrally coiled specimens to the total populations in terms of their latitudinal position with 98 percent confidence interval.

Coiling direction

The ratio of the sinistrally coiled specimens to the total population was tested in the same way as already undertaken. The ratios and their confidence limits at 98 percent confidence coefficient are shown in fig. 2. It shows that the sinistrally coiled specimens become dominant towards higher latitudes. The exact reverse is the case of the dextrally coiled specimens. Dextrally coiled individuals predominate in populations of the lower latitudes just as in the case of the individuals with umbilical teeth.

WALL MICROSTRUCTURE

METHOD OF STUDY

In the study of the wall microstructure of *Globorotalia truncatulinoides* two methods of electron microscopy were employed, namely, the transmitted type and the scanning type.

For the transmitted electron microscope work, the two-stage carbon replica method was used. The procedure adopted followed principally the methods described by Honjo (1963), Honjo and Fischer (1965), and Fischer, Honjo, and Garrison (1967). Hereunder the steps in the procedure are described briefly:

1) Clean the specimens by placing them in an ultrasonic vibrator.
2) Place the cleaned specimen on a glass slide and orient it using a small amount of glue (tragacanth gum).
3) Fix a short vinyl tube to the glass slide with the specimen as the center.
4) Pour a mixed epoxy resin into the vinyl cyclinder and heat to 60°C to gain fluidity.
5) Place the cylinder with the impregnated specimen in a vacuum desiccator to avoid air bubbles.
6) Cure the mix at 70°C for about 12 hours.
7) Remove the vinyl tube and grind the polymerized plug with the following steps: i) grind by grinder until the specimen appears near the surface; ii) grind manually on a steel plate with No. 500 carborundum until the desired cross section of the specimen becomes exposed; iii) grind on a finely frosted glass plate with No. 3000 carborundum.
8) Polish the surface on a synthetic cloth with alumina suspended in ethylene glycol.
9) Etch the polished surface for two to ten minutes in 5 percent ammonium chloride aqueous solution.
10) Replicate the etched surface with acetylcellulose film several times.
11) Shadow the films with chromimum at an angle of about 45° and back this with a carbon layer in a vacuum evaporator.
12) Cut the replica sandwich, and under a binocular microscope, fix it to an electron microscope mesh with epoxy mix at 70° for three hours.
13) Reinforce the side of the mesh with parafin, excluding the air bubbles from the mesh.
14) Remove the acetylceullulose film in a methyl acetate bath, and then remove the parafin in a hot methyl acetate bath (50°C).
15) Dry the mesh with chromimum-carbon replica in the air.

In the course of the study the JEM-30B electron microscope (superscope) was used for observation and photography, and all electron micrographs were taken on 35 mm film. Checking the chromimum-carbon replica through a binocular microscope, the parts necessary for electron microscopic examination could be located. A complete electron micrograph of a vertical section (pl. 20, fig. 1) was reconstructed by assembling such micrographs, though quite laborious. In addition a schematic profile of a vertical section (fig. 3) was accomplished by tracing this micrograph.

Peels of the acetylcellulose film made through the step (10) were also examined under

the optical microscope. The general features of the internal structure are well recognized on these peel replicas of vertical and horizontal sections under the optical microscope (pl. 20, figs. 3–5), as demonstrated already by Bé and his collaborators (Bé and Lott, 1964; Krinsely and Bé, 1965; Bé, McIntyre, and Breger, 1966).

All scanning photomicrographs were taken by JEOL-JSM-2 scanning electron microscope at the laboratory of the Japan Electron Optics Laboratory Co., Tokyo. As to the scanning electron microscopy including preparation techniques the readers are referred to Honjo, Minoura, and Okada (1967), Sandberg and Hay (1967), Honjo and Berggren (1967), Hay and Sandberg (1967), Kimoto and Honjo (1968), and Honjo and Okada (1968).

MICROSTRUCTURE IN SECTION

In section the wall consists usually of lamellar layers and a crust which is superimposed on the former of the last whorl alone (fig. 3; pl. 20, figs. 3, 5). Pores are evenly distributed but not of regular pattern; they pierce both lamellar layers and crust, though they reduce in number and assume different features at the keeled portions and septa. Small protuberances develop in various parts of the wall but change in their mode of growth by portion. In the following lines the microstructures of the lamellar layers, crust, pores, protuberances, keel and umbilical teeth are described. A schematic diagram showing the fundamental wall structure constructed on the basis of the electron micrographs is shown in fig. 4. The terms used in the description of the wall are referred to this figure.

Lamellar layers. — As is usual with the bilamellid Foraminifera, each chamber wall consists basically of two layers. Hitherto, however, various terminology have been applied to them, though most of them are not semantically different. In the present study the terms, inner and outer lamella, are adopted for these layers.

Fig. 3. Vertical section of *Globorotalia truncatulinoides* (section same as the one shown in pl. 20, fig. 1), × 225.

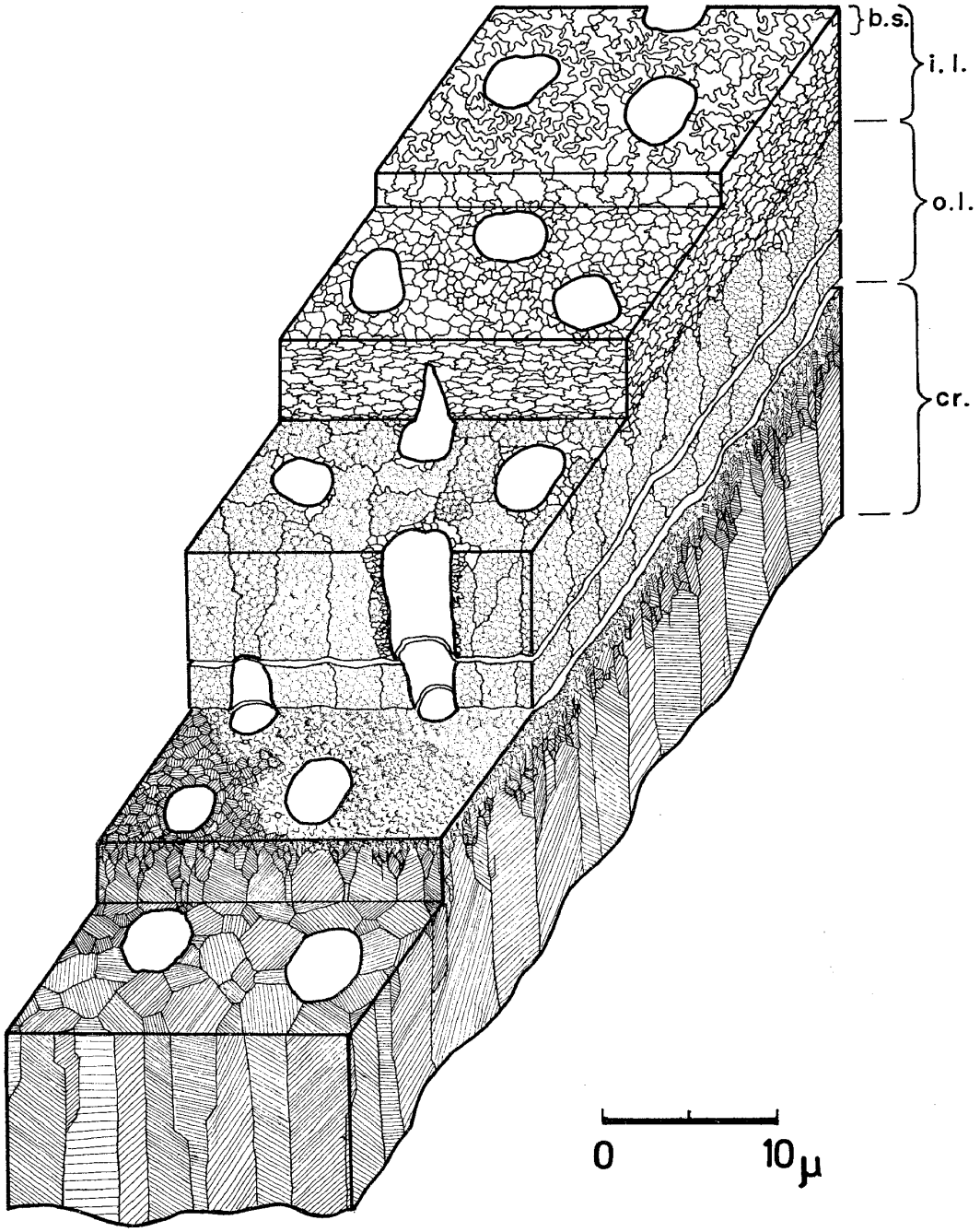

Fig. 4. Schematic block diagram showing the wall microstructure of an encrusted specimen of *Globorotalia truncatulinoides*.
b.s., basal sublamella; i.l., inner lamella; o.l., outer lamellae; cr.,crust

In sections through the wall normal to the surface, the lamellar layer is divided by a dark partition into the inner and outer lamella. Compared with the one recognized in the micrograph of a peel replica, this boundary is not always defined by a sharp line, though it is traceable for the most part of the test in the electron micrographs (fig. 3). The inner lamella is characterized by its irregularly microgranular structure, in which calcite grains range in size from 0.2 to 2.0μ. Irregularly shaped grains are interlocking in both vertical and nearly horizontal sections (pl. 21, fig. 1; pl. 22, fig. 1). In these micrographs most of

these grains appear to have preferred orientation with their longer axes parallel to the surface. The thickness of the inner lamella increases very gradually in ontogeny, and attains about 5 μ at the last few chambers except for the keeled portions. There is a thin layer at the innermost side of the inner lamella (inner surface of the lamellar layer). This is distinguished from the main inner lamella by the compact nature of morphologic array in surface view (pl. 25, fig. 1). It shows irregularly shaped grains (0.2–2.5 μ) interlocking and bounded by very fine depressed sutures. To this type of fabric the term, *amoeboid mosaic*, may be applied, which was originally introduced for a peculiar pattern present in limestone (Fischer, Honjo, and Garrison, 1967, p. 17). Fabric and grain size similar to the present species were illustrated from surfaces of some benthonic Foraminifera (Towe and Cifelli, 1967, pl. 91, fig. 1; pl. 96, fig. 3). The structure is indiscriminable in vertical sections and is not retained on the whole inner surface. It is considered a part of the inner lamella, and is named as basal sublamella.

As compared with the inner lamella, the outer lamella appears to withstand the etching. Electron micrographs of cross-section (pl. 21, fig. 1) and horizontal section (slightly oblique to the surface; pl. 22, fig. 1) show finely bumpy and compact texture comparable to that of crepe. This lamella is partitioned into columns and wedges nearly parallel with the pores vertically piercing the wall (fig. 4). Each unit varies in diameter between approximately 2 and 10 μ in horizontal section. The difference between the inner and outer lamellae appears to depend on the size of the calcite* units rather than on their behavior. As already stated, their boundary is fairly distinct especially in the spiral-side wall. In some cases, however, the lamellae do not change their fabric abruptly at the boundary but gradually across the boundary. A typical transition from the inner to outer lamellae is represented in a portion of a spiral-side wall (pl. 21, fig. 1). This shows that the microgranular structure of the former merges into the latter and grades finally into the vertical filamental partitions in a short distance. It is also noticable that fine grains (~ 1 μ) are aligned along the partitions and the side wall of the pores of the outer lamella in vertical section, and that these grains are irregularly shaped and have appearance similar to the fine grains of the inner lamella. Contrary to the previous observations under the optical microscope (*e.g.* Reiss, 1960), the boundary is in any case not represented by a sharp line or "canal" but by more or less a transitional zone between the microgranular portion and the finely bumpy, portion composed of radially aligned columns and wedges. Among the consecutive outer lamellae superimposed on the preceding ones the partitions are usually indicated by two lines respectively in vertical section. The two lines are no more than contact surfaces of the adjacent outer lamellae and are crossed by pores. The interval between these lines is variable especially at the keeled portion, but is mostly within less than 1 μ.

Crust. — Separated by a similar but commonly wider interspace, the crust layer is superimposed on the outer lamella. It covers the latter discordantly to bury its uneven surface and to adjust its acute peripheral keel. The crust layer in general reduces its thickness from the oldest to youngest chamber of the last whorl (fig. 3; pl. 20, figs. 1, 3). The crust is fundamentally different in structure from the lamellar layers. It consists of elongate columns and wedges oriented perpendicular to the wall (fig. 4; pl. 21, fig. 1). These calcite units are various in size, ranging from about 10μ to 30μ in length, and 1 μ to 6μ in width. At the basal part of the crust (part adjacent to the outer lamella) is developed microgranular structure analogous to that of the inner lamella. Towards the outer surface, the calcite grains in this structure are tightly interlocking with slightly elongate calcite units oriented perpendicular to the wall. In the same way the outer units increase in their

* In the present study the mineralogical composition of the test was not analysed and therefore the current view was accepted.

length, and finally large columns and wedges appear. Such transformation of the calcite units occur within one-third to two-thirds thickness of the crust (10 to 20 μ from the base), as observed in comparison between the vertical sections of heavily etched (pl. 21, fig. 1) and lightly etched (pl. 21, fig. 2) parts. In the deeply etched section additional structures appear in the columns and wedges. They are individually composed of a pile of thin plates with some inclination towards the wall surface. Same type of fine structure has been recorded in *Globorotalia menardii* (d'Orbigny) (Bé, McIntyre, and Breger, 1966, pl. 17, fig. 2) and *Lenticulina calcar* (Linné) (Towe and Cifelli, 1967, pl. 92, fig. 2).

Pores. — As was discussed by some authors, the concentration, pattern, and diameters of the pores are considered as not only important of the wall structure but also significant in taxonomy (*i.e.* Berggren, 1960). For investigation on the pore characters soft X-ray contact radiomicrographs may be useful. Because of the difficulty in preparation of a large number of suitable specimens, the radiomicrographic study of pores has been reserved for another occasion. Hereunder described are mainly the nature of the pores in vertical sections.

In plan view the pores are nearly circular, oval, or elliptical but sometimes subangular in general outline, and penetrate the wall vertically in principle. Speaking strictly, each pore canal changes its shape and diameter according to place and bends more or less in various directions. These canals may connect together or branch. The inner surface of the spiral-side wall of the last chamber (surface of the basal sublamella) is shown in pl. 25, fig. 1, the pores average 4.5 μ in maximum diameter and are open. There are about 8 pores per 25 $\times$ 25 μ square; they have funnel-shape, opening to the surface, suggesting their reduction in diameter at the underlying inner lamella. On the section made through the inner to outer lamellae (pl. 22, fig. 1) and the section through the outer lamella to crust (pl. 22, fig. 2) the pores with the corresponding respective lamellae are well established. There are about 9 pores per 25 $\times$ 25μ square consistently throughout the consecutive lamellae and crust. The maximum diameters average 2.5 μ in the inner lamella, 4.0 μ in the outer ones, and 5.4 μ in the basal part of the crust. It is evident that the diameters of the pores gradually increase towards the basal crust, though their behavior is not ascertained in sections near and on the surface on the crust.

The apparent choking off of the pores may probably be due to the bending of the pore canals at or near the boundaries between the adjacent layers. Such a bending is typically shown in the keeled portion (pl. 23, fig. 1), where the pores often tend to develop features uncommon to the usual type of wall. A pore appearing in the innermost layer (a suite of inner and outer lamellae) bends at the interlamellar boundary, and becomes connected with another pore situated at the keel by a narrow canal running obliquely to the lamellae. In the latter pore the extension again branches into two pore canals, both of which are open to the interior of the later formed chamber. Another example for connection of pores at the keeled portion is shown in pl. 23, fig. 2 (left side of the penultimate whorl).

Besides these features, it may again be mentioned that the fine grains with appearance similar to those of the inner lamella are commonly present around the pore wall in the outer lamellae; close relationship in occurrence is frequently marked between the pores and the filamental vertical partitions among the outer lamellae; the pores are represented at the keeled portion even though they are reduced in number and diameter; and they are very rare or almost absent in the apertural lip.

Protuberances. — In various parts of the wall protuberances are developed rather unevenly. They are principally classified into two categories by their structure and site of occurrence. The first one, termed *puncta* in this paper, is confined within the consecutive outer lamellae. There are two kinds of growth of the *punctae*: one is distributed over the test and the other is restricted to the side-walls facing the umbilicus only. In the latter case,

when a *puncta* is formed in an outer lamella, successive lamellae cover it in a conformable manner to form a cone normal to the wall. A typical *puncta* formed on the spiral side is shown in the right side of pl. 25, fig. 2. Centered around a vertical partition, an initial *puncta* is formed at the first lamella. Within the small protruded cone there is developed a microgranular texture comparable to the inner lamella. The superjacent part of the second lamella is filled with small elongate calcite units, most of which are oriented normal to the wall. Central portions of the superposing parts of the third and fourth lamellae are composed of slender columns as long as the thickness of each layer. Although the texture of the flanks of the *puncta* are rather obscure, these are seemingly transitional between the normal outer lamella and the columnar structure. In the middle of the same figure (pl. 25, fig. 2) another *puncta* is present. Although it assumes features somewhat different from the former *puncta*, such difference is probably due to biased sectioning of the latter cone. In either case the *puncta* is formed centering around the vertical partition, and is accentuated by being conformably covered with successive lamellae. One more example belonging to this category is exhibited at the keeled periphery (pl. 26). In the light of such developmental process, it seems natural that the *punctae* are almost underdeveloped in the last few chambers, as seen in the contact radiomicrograph of a non-crusted specimen (pl. 20, fig. 2).

On the contrary, the *punctae* situated on the side-walls facing the umbilicus are different in their developmental steps (pl. 24, fig. 1). They are initially formed in a way similar to the former case, but are succeedingly displaced at random.

The protubercances formed in the crust layer are of the second category, and herein called the *pustule*. The *pustules* are varied in size and shape, and distributed on the top of the crust (pl. 24, fig. 2). Although the detailed structure of the *pustules* is not clear because of the complexity of the texture underneath, each *pustule* consists of a single crystal unit rooted in the crust. In some larger crystals thin-plate-pile structure common to the usual crust is seen. As a rule these *pustules* occur commonly in the portions of the test where the thick crust is developed. In addition, they are thickly concentrated in the umbilical region and earlier chamber surfaces of the last whorl, which are close to the aperture. At the side-walls facing the umbilicus the crust thins out towards the umbilicus, thus both *pustules* and *punctae* become exposed on the wall surface.

The two types of protuberances can readily by distinguished from one another by structure and size. The *pustule* exceeds frequently more than 20μ in diameter at the base.

Keel. – The structure of the keel is essentially identical with that of the usual type of the wall, which consists of inner and outer lamellae and with crust in the case of the last whorl. As has been schematically illustrated by Reiss (1957), the outer lamella is added to the wall of every new chamber. Thus it is possible to count the number of chambers of a test in the vertical section of the first-formed chamber. In this way the ontogenetic development of the keel can be traced on the vertical section. In ontogeny the earlier chambers are globigerine without any indication of a keel. An incipient keel appears generally on the periphery of the sixth or seventh chamber, where the lamellar layer becomes slightly bended outward and thickened. Then, becoming gradually prominent outward as chambers are added; it assumes morphologically one-half to one-third concentric circles in section. Detailed structures of the keels are displayed on pl. 26 (last whorl) and pl. 23, figs. 1 and 2 (both penultimate whorl). In the first case, three successive outer lamellae and the crust are superimposed on a basal coupled layer composed of inner and outer lamellae. At the fold both lamellae of the basal layer are thickened, but not with the succeeding outer lamellae, which retain nearly the same thickness as the unfolded portion. On the other hand, the crust has a tendency to become thin over the keel, so as to "obscure the prominent keel by tapering over the bulging outline of the keel" (Bé and Ericson, 1963, p. 75). In this

micrograph (pl. 26) the basal layer is somewhat obscured in texture by the presence of two punctae around the keel, though the textures proper to the respective lamellae are still retained. The bulk of the layer (except for the upper half of the outer lamella) is occupied by an amorphous calcite mass of indeterminable texture at the axial surface of the fold. There are two distinct filamental partitions radially aligned in the folded outer lamella of the basal layer as well as the second outer lamella. Most noticeable is that they are developed into *narrow spaces* in the third and fourth outer lamellae. Although precise nature of these spaces are indeterminable without tangential section, they are judged to be a kind of pores as compared with the usual pores penetrating the remaining part of the test. The only difference between them may be the size. Widening of the interlamellar spaces among the consecutive outer lamellae and growth of the punctae are frequent in the keeled portion. Even in the penultimate whorl (pl. 23, figs. 1, 2) basically a similar aspect is shown at the keel.

Umbilicial teeth and inner margin of umbilicial wall of chamber. – As already described in earlier pages the apertural lips are well developed to form umbilical teeth at the base of the chamber walls surrounding the umbilicus of the specimens inhabiting warm water. To detect the nature of the teeth and the umbilical walls as the substratum, a vertical section was made and compared with the corresponding part of *Globorotalia menardii* (pl. 27, figs. 1, 2).

A section of the antepenultimate chamber wall of *G. truncatulinoides* is shown in pl. 27, fig. 1. Basic construction of the wall coincides almost with that of the normal one. It consists of the inner lamella and three outer lamellae partially overlain with the terminal extension of the crust. The boundary separating the inner and outer lamellae is marked for the most part. However, these layers are not so distinctly specified in texture in contrast to the normal one. Except for the toothed portion, the inner and the first outer lamellae are practically of the same texture which is microgranular as in the usual inner lamella. The second and third outer lamellae closely resemble the usual outer lamella, and the very finely microgranular texture occupies more than half of the whole. Within these lamellae finely bumpy textural units proper to the outer lamella alternate laterally with very finely microgranular ones. Similarly, the very finely microgranular texture appears in the crust and dominates especially near its base, though the calcite units tend to increase gradually in size and to become elongate outwards. The successive lamellae (second and third ones) appear to thin out once in the midst of the section and again develop in the toothed portion, so far as the present section is concerned. It was not clarified whether such apparent discontinuity is due to the primary lack or loss during the course of replication. In addition, a short streak is visible in the first outer lamella at the midway of the section, but is uncertain in origin. Nevertheless, all lamellae are thickened in the toothed portion: for instance, the inner lamellae thickens from about 5 μ to 15 μ, and the first outer lamella from 10μ to 20 μ.

In contrast to the main part, the toothed portion exhibits a coarser granular texture, in which large granules ($>2\,\mu$) are frequently included. Moreover, the boundaries between the lamellae are not represented by narrow interspaces but by obscure lines. Under these circumstances, it is rather difficult to elucidate the structure of the teeth. Incipient growth of the teeth may be indicated by the coarse granular texture near the tip of the first outer lamella. The second outer lamella shows a small bulge extending from the tip towards the umbilicus. The third one accomplishes a tooth-form through thick deposition of calcium carbonate at the tip. There is no marked preference in alignment of the granules in the tooth.

The pores are fairly common in the part covered with the crust, but very rare or absent in the remaining part.

In the course of development of tooth structure, similar steps are followed in *G. menardii*. Pl. 27, fig .2 is a section of the toothed portion of the antepenultimate chamber. The basal layer represents a set of the inner and first outer lamellae, though they are here indistinguishable. The layer shows an inflection with the appearance of reversed S-shape. The second outer lamella, which is restricted only in the lower half of the basal layer, superimposes in a conformable manner. A long tooth structure is first built in the third outer lamella in pedal form, and finally these lamellae are covered with the crust. The toothed portion is also characterized by the increase in thickness of the lamellae as well as of the coarser texture. In spite of their general morphologic difference, both species present considerable similarity in character of the teeth.

SURFACE MICROTOPOGRAPHY

In the present study a specimen was chosen from the sample V16-36 and its pictures are given in pls. 28 to 31.

Lately much attention has become directed to the pore pattern or "fabric" of the wall of planktonic Foraminifera. The pore pattern is now considered as an important character in their taxonomy as well as ecology (*e.g.* Berggren, 1960; Wiles, 1967). The surface texture is also one of the fundamental criteria for taxonomy of planktonic Foraminifera (Parker, 1962; Lipps, 1964, 1966). Thus the surface microtopography observed by means of the scanning electron microscope will supply valuable informations on the Foraminifera, as discussed by Honjo and Berggren (1967).

As a rule the surface microtopography of the wall varies progressively from the later- to earlier-formed chambers as typically shown in spiral side view (pl. 28, fig. 1). The microgranular texure is typically developed on the smooth surface of the last chamber, where there are about 7 to 8 large pores per $25 \times 25\ \mu$ square (pl. 28, figs. 2–4). Although no textural change in recognized so far as judged on these pictures, the pore "fabric" changes at places within the last chamber. The pore diameters vary locally from about 5.4 to less than $1.6\ \mu$ in the central area.

Compared with the last chamber, the penultimate chamber shows prominent relief on the surface (pl. 28, fig. 2; pl. 29, figs. 1, 2). There is no distinct difference in the degree of pore concentration between those chambers, but the latter has coarser granular texture. The grains are generally $1–3\ \mu$ in diameter, with various polyhedral subangaular outlines; while those in the last chamber are mostly less than $1\ \mu$ in diameter. The reduction of number of pore at the radial suture (=former anterior keeled margin) is clear in pl. 28, fig. 2.

On the antepenultimate chamber a small number of larger crystals make their appearance among the microtopography similar to that of the penultimate chamber (pl. 28, fig. 1). The larger crystals become predominant over the entire surface of the forth chamber from the last. Among the chambers preceding the antepenultimate one there is no distinct change in surface microtopography, though such crystals appear to attain the largest size at the surface of the very early whorl.

Sutures are not visible on the surface in forms thickly covered with a crust. Nevertheless, the sutures are rather easily located as shown in pl. 29, fig. 3. Here displayed is an area across the spiral suture between the penultimate chamber and sixth or seventh one from the last. The thick growth of calcite crystals of the crust is characteristic of the earlier chamber surface. As to the nature of the crystalline aggregates of the crust surface further study is necessary. The pores are considerably obscured by the development of the crust, but are still recognizable at the base of the crystals (pl. 29, fig. 4).

There are many needles scattered mainly over a part of the penultimate chamber

surface (pl. 29, fig. 1). They are random in arrangment, and their longer axes are nearly parallel with the relief of the surface. Although their true character was not determined, it is difficult to consider them to be a part of the crust layer, because: 1) there is no comparable material for the random array of the needles in the vertical sections of the wall, especially of the crust; 2) the same type of needle is found on the surfaces of other chambers, though rare; 3) there are many secondarily adhered materials on the surface (*e.g.* coccoliths). These observations seem to favour that the needles are secondary or exotic in origin.

In umbilicial side view the last chamber shows a smooth surface with fine perforation as already recognized on the other side (pl. 30, figs. 1–4). The surficial feature of the pores are clearly observed in oblique view. Most of the pores are approximately 5 μ in diameter on an average, and furnished with funnel-shaped openings flaring towards the surface. In addition, smaller pores (about 2 μ in diameter) are rarely seen.

Numerous round protuberances (*punctae*) are typically developed along the peripheral keel and umbilical shoulder of the last chamber. On the apertural face of the last chamber smaller *punctae* are present though they are rather limited in number (pl. 31, fig. 1). Another type of protuberances, *pustules*, are found on the surface of the earliest chamber, which is adjacent to the aperture (pl. 31, figs. 1, 2). They are conical in outline, and consist of thin-plate-pile structure. Smooth faces of euhedral crystals are presented on the top of grown pustules, which often attain nearly 30 μ in diameter at their bases.

Crystalline growth in the crust layer takes place on the umbilical side in the same manner as on the spiral side. Steps in crystal growth by chambers are displayed around the umbilical region (pl. 31, fig. 4). Ultimate crystal growth appears to be almost attained on the fourth chamber from the last. The surface microtopography of that chamber is shown in pl. 31, fig. 3, where euhedral, rhombic crystals cover its entire surface, though some pores are still open among the crystals.

In summary, the microgranular texture of the outer lamella is retained in only the last chamber, so far as the present specimen is concerned. Compared with the umbilical side, the spiral side of the last chamber shows slight signs of incipient growth of the crust. Growth of the crust changes the surface texture as well as pore "fabric" progressively. Two kinds of protuberances, *punctae* and *pustules*, are distinguishable in microtopography.

DISCUSSION

Observations by the electron micrographs confirms the previous results obtained by optical microscopic observations that the lamellar layers and crust are of distinctly different calcite texture in the wall of *Globorotalia truncatulinoides*. In addition, the electron micrographs reveal several new facts, some of which conflict the previous views concerning the structure of the shell. With respect to these problems discussions are given in the following lines.

The bilamellar nature of the chamber wall is well illustrated in the usual micrographs as well as by the electron micrographs. The inner lamella, limited in each chamber, consists of minute interlocking calcite grains and lined by basal sublamella. This sublamella of thin veneer nature is more acid resistant compared with the main part of the inner lamella. Its close resemblance in fabric pattern to the surfaces of genetically distant, benthonic species as *Lenticulina calcar* suggests similarity in the mode of wall calcification. Separated by a dark line of demarcation from the inner one, the outer lamella is composed of interlocking columns and wedges with orientation normal to the wall surface. These units are finely bumpy in texture and acid resistant like the basal sublamella. Distinction in texture between the two lamellae is, however, not definite but is rather statistical especially at their boundary. At present we have no sound basis nor data to clarify the

cause of such textural differentiation for all the previous assumptions attributed to plasmatic difference (Reiss, 1957, p. 128). Nevertheless, according to the following facts, it is suggested that the microgranular texture of the inner lamella is a product through close contact with the protoplasmic mass. These are, 1) the inner lamella is the innermost layer of the wall, and thus is supposed to have been in intimate contact with the protoplasmic mass during life; 2) the microgranular texture of the inner lamella is usually wedged into the superjacent outer lamella and disappears in the subsequent ones; 3) fine calcite grains with appearance similar to the microgranular texture of the inner lamella are found in areas such as the walls of the pores, which function as communicative passages for protoplasmic matter, and vertical partitions of the outer lamellae; 4) the microgranular textures developed in the basal part of the *punctae* are always associated with the vertical partitions directly underneath them; 5) at the inner margin of the umbilical wall which is supposedly exposed to intense protoplasmic activity the outer lamellae including the umbilical teeth also show the same microgranular texture as the inner lamella. It may be also emphasized that the features referred in (3) and (4) are an indication of the close relationship between the pores and vertical partitions.

As has been described in the early lines, there is no indication of canals or any kind of passages along the boundary between the inner and outer lamellae. In the electron micrographs this boundary is usually represented by a dark line or dots or sometimes indistinct line bordering the calcite grains comprising the respective lamellae. Further study is necessary to clarify the nature of such dark line or dots. As contrasted with such boundary, the ones between the successive outer lamellae (referred to as "interlamellar boundary") and between the final outer lamella and the crust are quite distinct. Interlamellar boundaries are narrowly but clearly spaced almost throughout the test, and exhibit considerable variations at the keels and protuberances. In the vertical sections where the pores cross the boundaries there are many cases suggesting communications between them. Further, the apparent terminations of the pores recognized frequently at the boundaries are probably due to the bending of the pore canals there. Commonly observed in the sequence of the outer lamellae is the widening of the interlamellar spaces at the keel in the same manner as the basal suite of the lamellae. Lack of direct observation of the very surfaces of the boundary planes makes it more difficult to infer whether these spaces were originally hollow or filled with organic matter. Concerning the calcification and growth of the lamellar wall of benthonic Foraminifera, Towe and Cifelli (*op. cit.*) wrote: "Crystal "seeds" develop epitaxially on an active-passive template, grow and coalesce laterally into larger grains. A new sheet of organic matrix produces the lamellar wall" (p. 755). They also stated: "The process of calcification can be stopped by a change in the concentration of the ambient crystallizing solution or by the secretion of additional organic matrices, or both" (p. 752). Similar hypothesis may be tenable in the case of *G. truncatulinoides*, and these interlamellar spaces are supposed to have been primarily filled with organic matter.

Incipient growth of the keel is usually recognized on the sixth or seventh chamber, *viz.*, the second whorl in ontogeny, and it becomes progressively prominent as a chamber is added. For this type of keel structure Brönnimann and Brown once offered a possible explanation (1965, p. 512). Briefly, as the peripheral portion of a flattened form is strongly affected by axial compression, it is reinforced with concentration of dense shell material deposited as an imperforate keel in the fully developed chamber. This explanation seems not necessarily consonant with the results of observations on *G. truncatulinoides* is concerned. In the first place, the thickening of the lamellar layers at the keel is limited to the basal coupled lamellae. In other words, the shape of the keel is primarily accomplished by the deposit of thick material at the inner and the first outer lamellae. Secondly, the pores are developed in the keel, though they are reduced in number and

size as compared with the usual wall. Accordingly, such reinforcement is considered to be almost achieved at the first step in the course of development. The pores in the keeled portion were specified by Reiss (1958) as "canalicules" and distinguished from the usual pores by their location, distribution and size. The present electron microscopic study affords no additional specification to these pores, as stated repeatedly. It is only supposed that such nature of these pores would be effective for reinforcement if necessary. Taking the "*Globorotalia fohsi* lineage" as an example, Banner and Blow (1959) introduced the terms, pseudocarina and carina, for the perforate peripheral thickening and keel composed of imperforate shell material, respectively. According to their definition, the keel of *G. truncatulinoides* will naturally come in the category of carina. Apart from the problem concerning the pores in the keel which may be difficult to recognize under a light microscope, there is no much difference in the structure as well as texture between the carina and normal type of wall. Under these circumstances, the characteristic features of the keel are considered as mostly due to the thickening of the basal suite of the lamellae formed by an inflection at the periphery.

The crust is basically different from the lamellar layers in consisting largely of elongate, prismatic calcite units. The crust is also distinguished from the lamellar layers in horizontal sections parallel to the wall surface, where these calcite units form a pavement mosaic pattern instead of amoeboid mosaic such as seen in the latter. As already described, the shape and structure of the units are complicated surficially and internally. They also change their morphology and size during the course of development. Thin-plate-pile structure of the calcite units is most likely a cleavage phenomenon as interpreted by Towe and Cifelli (*op. cit.*) in the case of radial-walled benthonic Foraminifera. The fibrous appearance of the wall was attributed to the density of the radially aligned pores by Pessagno (1967) and Pessagno and Miyano (1967). For such appearance, the vertical partitions in the outer lamellae may be also responsible.

Concerning the time of encrusting, it was well documented that the crust deposition occurs at the terminal phase of the individual life cycle (Bé and Ericson, *op. cit.* ;Bé and Lott, *op. cit.*). Their view is also supported by the present observations that the lamellar layers never cover the crust. In the light of distinct structural contrast between them, some changes are supposed to have taken place during the physiological mechanism for calcification parallel with the individual descent to deeper waters probably of more than 350 m. In this respect, it seems necessary to refer to the latest results of investigation carried out by Horibe, Niitsuma, and Sakai (in preparation). Their results are as follows: 1) electron-probe X-ray microanalysis indicates that there is no marked difference in Ca and Mg contents between the lamellar layers and crust of *G. truncatulinoides*; 2) Oxygen isotopic analysis proves the presence of a considerable difference in the ratios $0^{18}/0^{16}$, between the encrusted and non-crusted specimens. In other words, the crust is judged to be secreted in water colder than that for the lamellar layers. Although we are too little acquainted with mechanism of calcification at present, much can be expected from future investigations on the biology and biomineralogy of planktonic Foraminifera.

SUMMARY

The results of the present study on statistical tests of morphologic variations, and electron microscopy of the wall microstructure of *Globorotalia truncatulinoides* are summarized as follows:

1) Some biased distributions are present among the mean value of H/D (ratio of height to maximum diameter of test) of the samples from various latitudes. In other words, it is possible that highly conical forms are concentrated in the lower latitudinal regions

while lower conical ones in the higher latitudes.

2) Distribution of the H/D ratio is generally not affected by the coiling direction of the specimens.

3) Individuals with umbilical teeth dominate in the lower latitudes.

4) Dextrally coiled individuals predominate in the lower latitudes.

5) Wall of *G. truncatulinoides* is principally divided into two layers, namely, lamellar layer and crust. Although they assume quite different features in microstructure, it is evident in every respect that they are biogenetic in origin.

6) Lamellar layer consists of inner and outer lamellae in each chamber. Inner lamella is characterized by its microgranular structure, and is lined at the inner surface with a thin layer, called basal sublamella. Outer lamella has finely bumpy and compact texture, and is partitioned into columns and wedges normal to the surface. Their boundary is not represented by a sharp line or "canal" but is gradational. On the contrary, the boundaries between the consecutive outer lamellae are indicated by distinct lines.

7) Crust is a layer superimposed on the lamellar layers of the test after formation of the last chamber. It is composed of elongate columns and wedges of calcite, which are oriented perpendicular to the surface. Each component unit exhibits thin-plate-pile structure, which is interpreted as cleavage.

8) Pore concentration fluctuates place by place, but is usually 7 to 9 pores per $25 \times 25\,\mu$ square. There is also a fairly wide variation in pore diameter, but is about $5\,\mu$ on an average at the outer surface of outer lamella.

9) Protuberances developed in and on the wall are classified into two categories: *punctae* and *pustules*. *Puncata* is confined to the consecutive outer lamellae, while *pustule* is distributed on the top of the crust. They are clearly distinguished from each other in structure and external morphology besides occurrence.

10) Keels are essentially identical in structure with the usual type of the wall. Incipient keel appears usually on the peripheral margin of the sixth or seventh chamber. General plan of keel is outlined by a basal coupled layer of inner and outer lamellae, and the successive outer lamellae develop bulge of keel by conformably overlying. Pores exist in the keeled portion, though they are reduced in number and size in comparison with usual type of the wall.

11) Umbilical teeth and inner margins of the umbilical walls of the chambers are essentially the same in layering construction with the usual type of the wall. Compared with the latter, however, the layers of these portions are predominated by microgranular texture comparable to that of the inner lamella. Consecutive outer lamellae build up tooth-form, in which coarsely granular texture is displayed.

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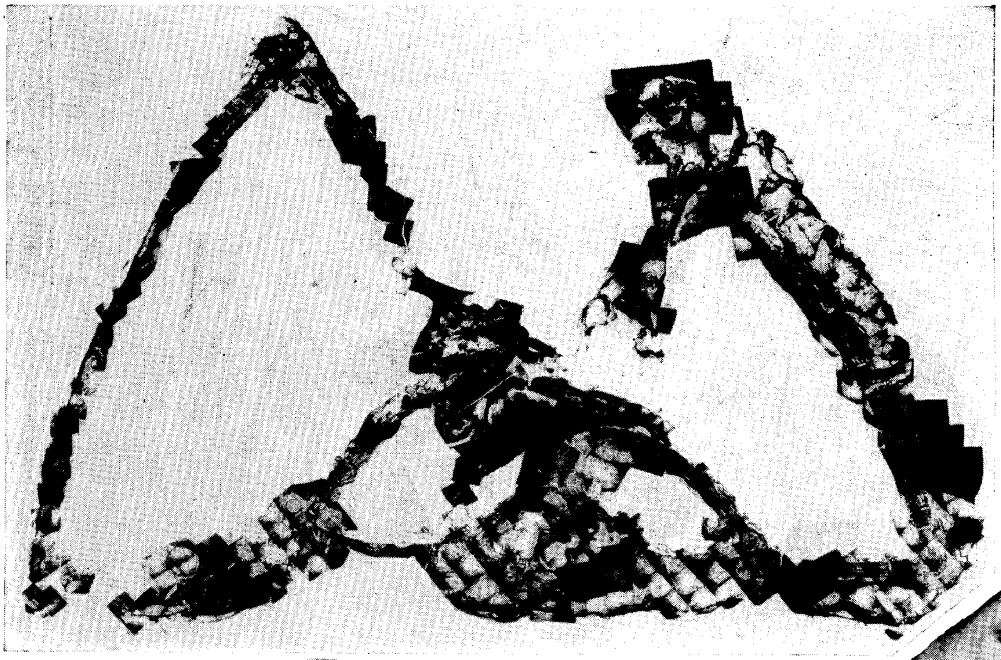
Plate 20

Fig. 1. Mosaic of a vertical section of *Globorotalia truncatulinoides*, made by patching up serial electron micrographs of replicas of the section; approximately ×170. Compare with Fig. 3 in text (traced line drawing of the same section) and pl. 20, fig. 3. Specimen from the core MSN -53G.

Fig. 2. Soft X-ray contact microradiograph of a non-crusted specimen from the core V16–34, ×145. Radial sutures on the umbilical side are concave towards direction of growth, while the ones on the spiral side are convex. Perforation is of the spiral side. White spots mainly distributed over the antepenultimate chamber and its preceders are *punctae*.

Figs. 3, 4. Vertical sections through umbilicus; both specimens from the core MSN-53G.
3, same specimen but of different section from the one shown in pl. 20, fig. 1, ×150. 4, ×115. Note that the umbilical teeth are well developed on both specimens.

Fig. 5. Horizontal section of a specimen from the core DWBG-60, ×140. Progressive thickening of the wall by addition of crust layer is traceable from the younger to older chambers.



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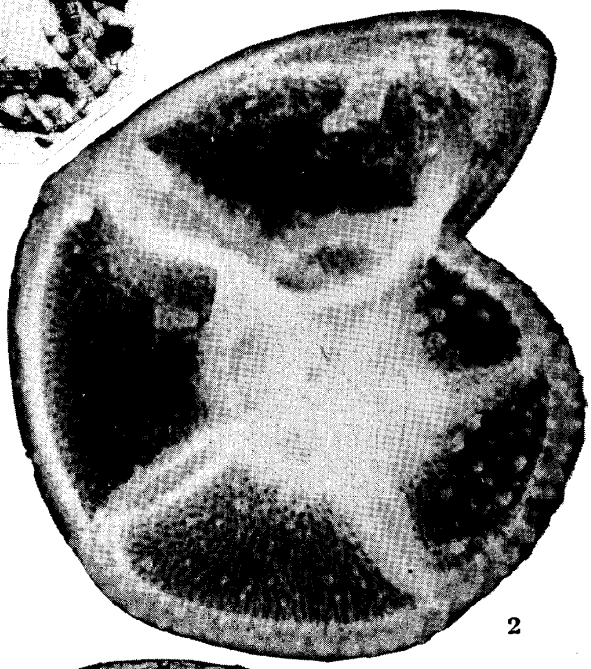

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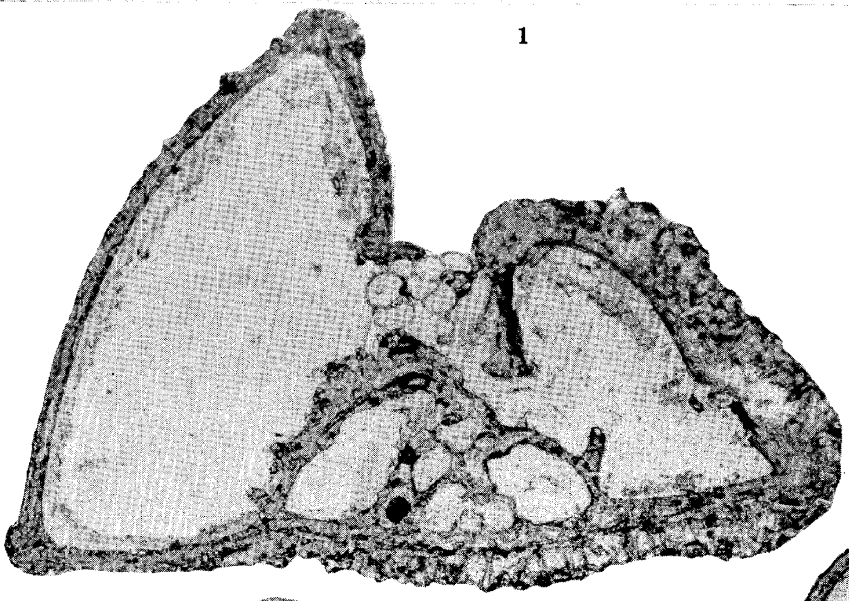

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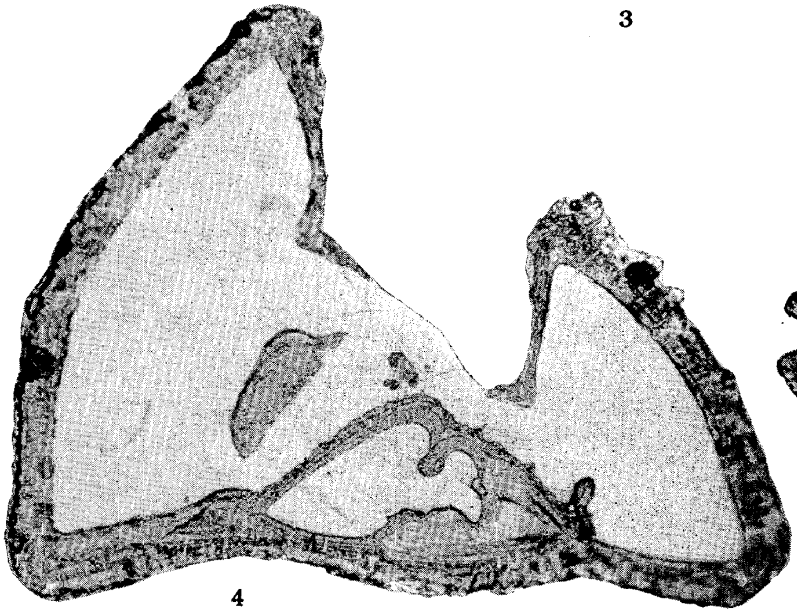

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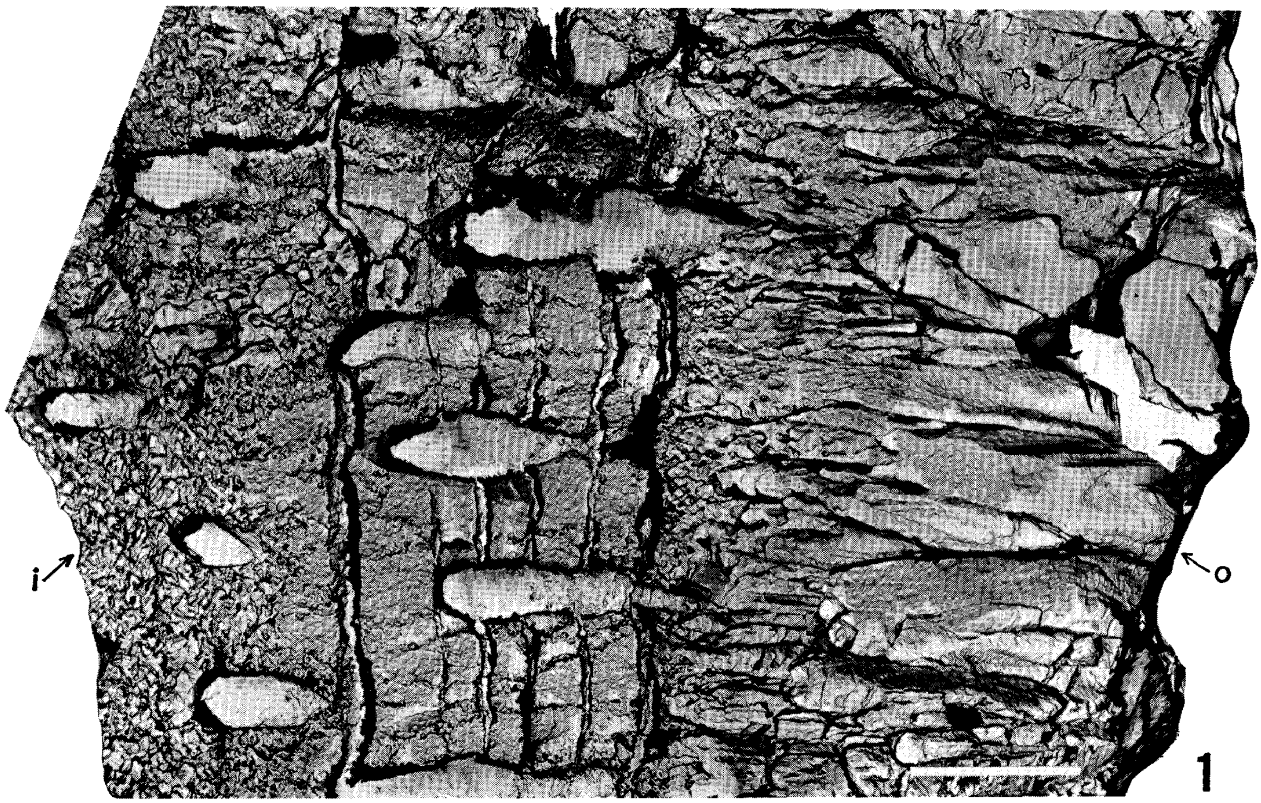

i
o
1

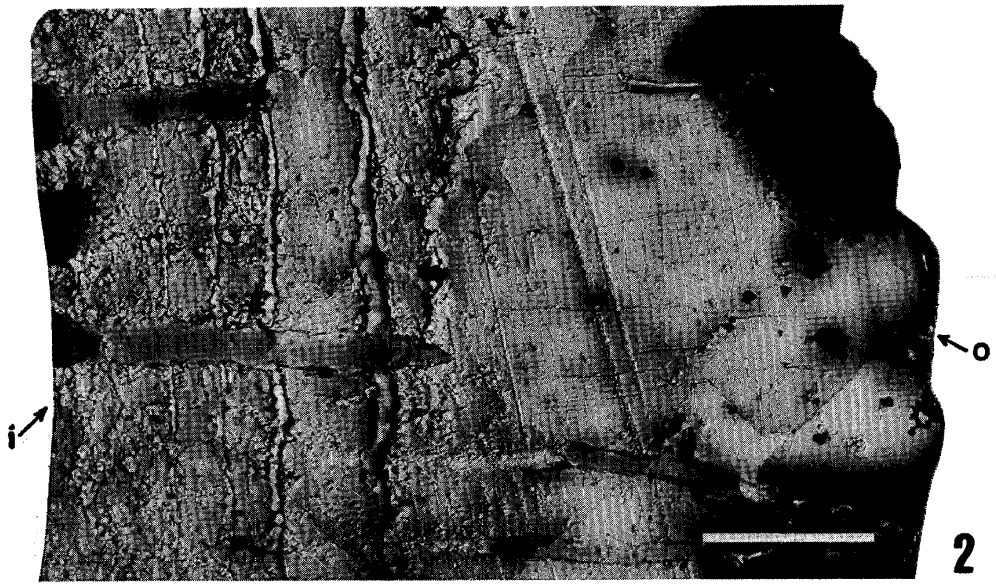

i
o
2

Plate 21

Fig. 1. Cross section of test wall (spiral side), showing inner lamella, outer lamellae and crust in a sequence, ×1850. Specimen from the core MSN-53G. [Scale bar 10μ]

Fig. 2. Cross section of test wall (spiral side), ×1850.
It is lightly etched compared with the section shown in fig. 1. Specimen from the core MSN-53G. [Scale bar 10μ]

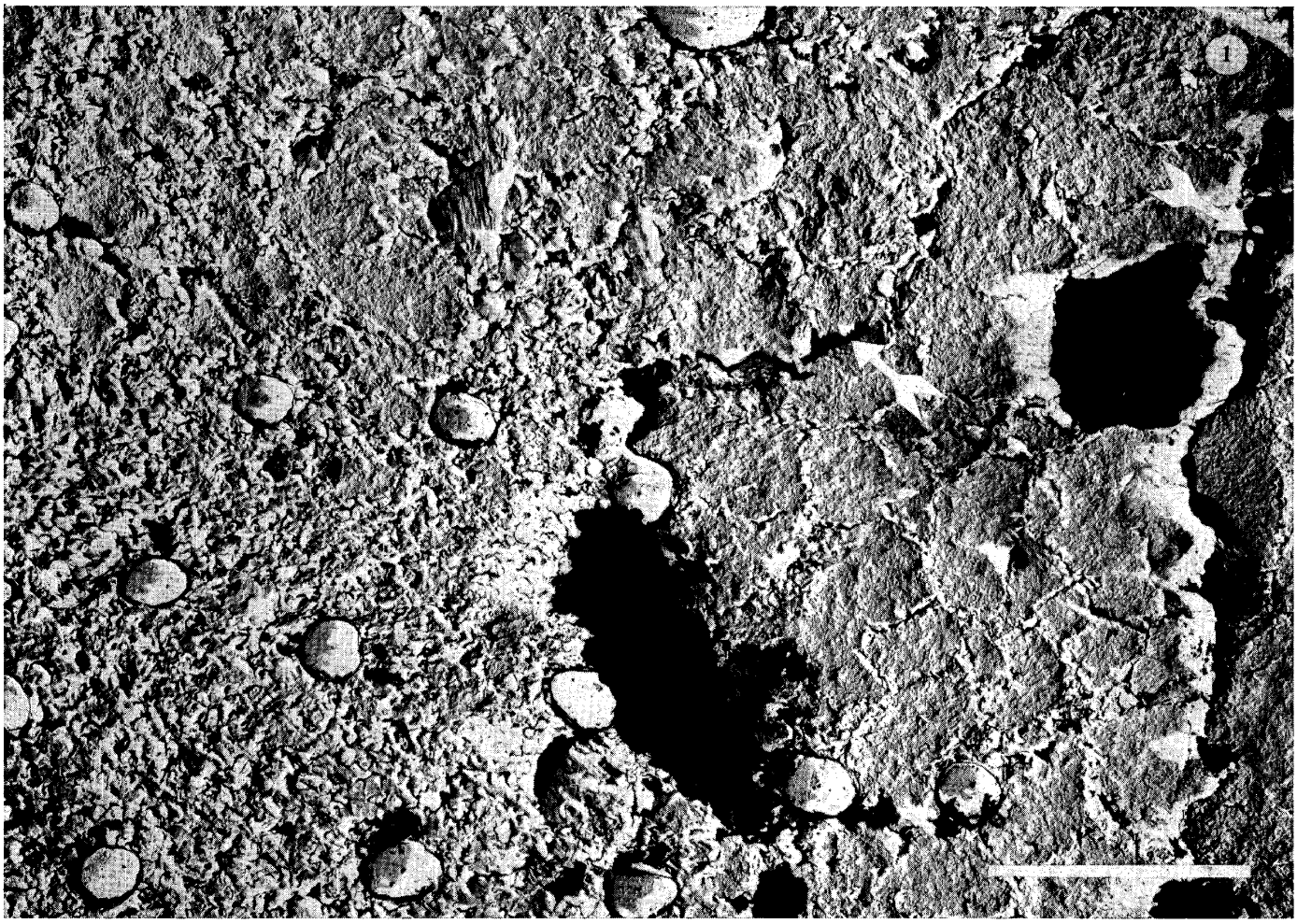
i, inner surface; o, outer surface

Plate 22

Nearly horizontal sections of test wall (spiral side), ×3000. Specimen from the core DWBG-60. [Scale bar 10μ]

Fig. 1. Section through inner lamella to the second outer lamella (from the left- to right-hand part of the photograph). Two interlamellar boundaries (marked by arrows) are represented by irregular dark lines.

Fig. 2. Section through the outer lamella to crust (from the left- to right-hand part of the photograph). The boundary between these layers is indicated by an arrow.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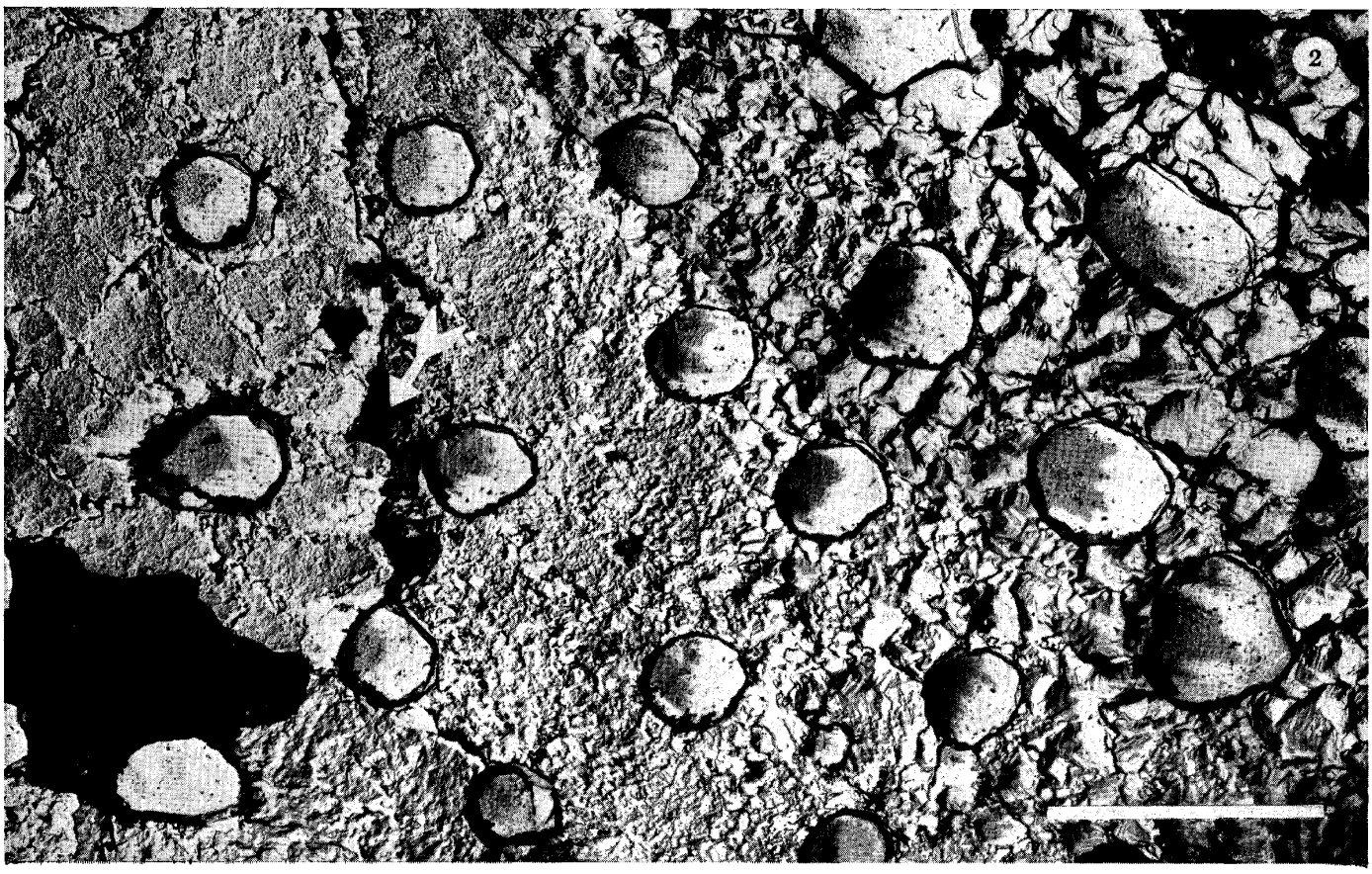
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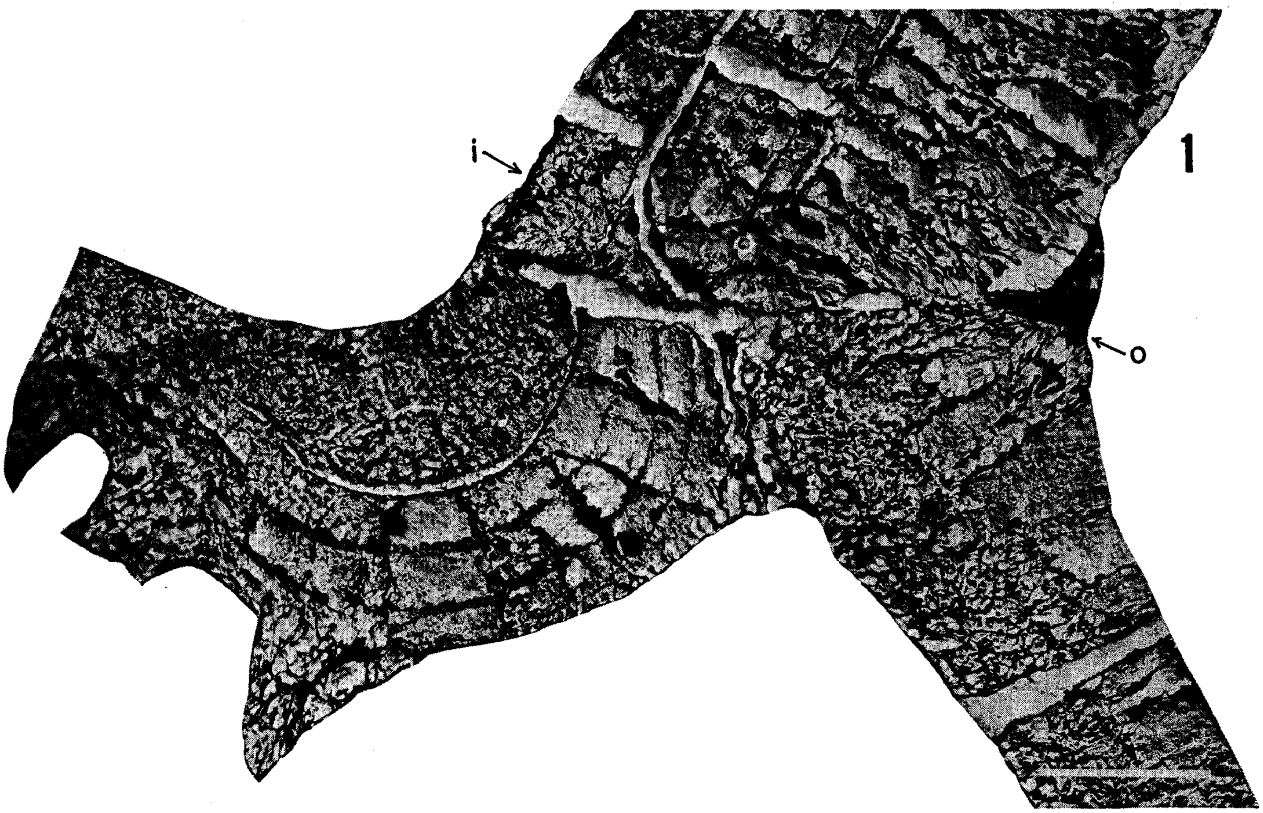

i
o
1

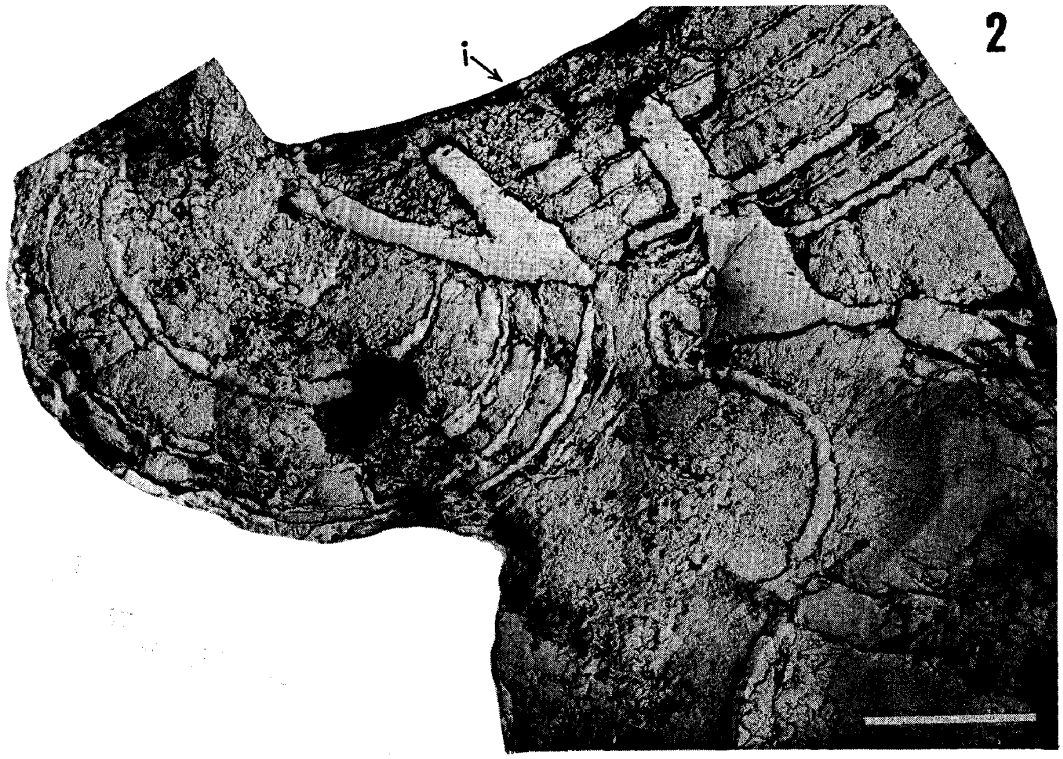

i
2

Plate 23

Fig. 1. Keel of the penultimate whorl, showing composition of the wall and pore canals; ×1850. Specimen from the core V16-34. [Scale bar 10μ]

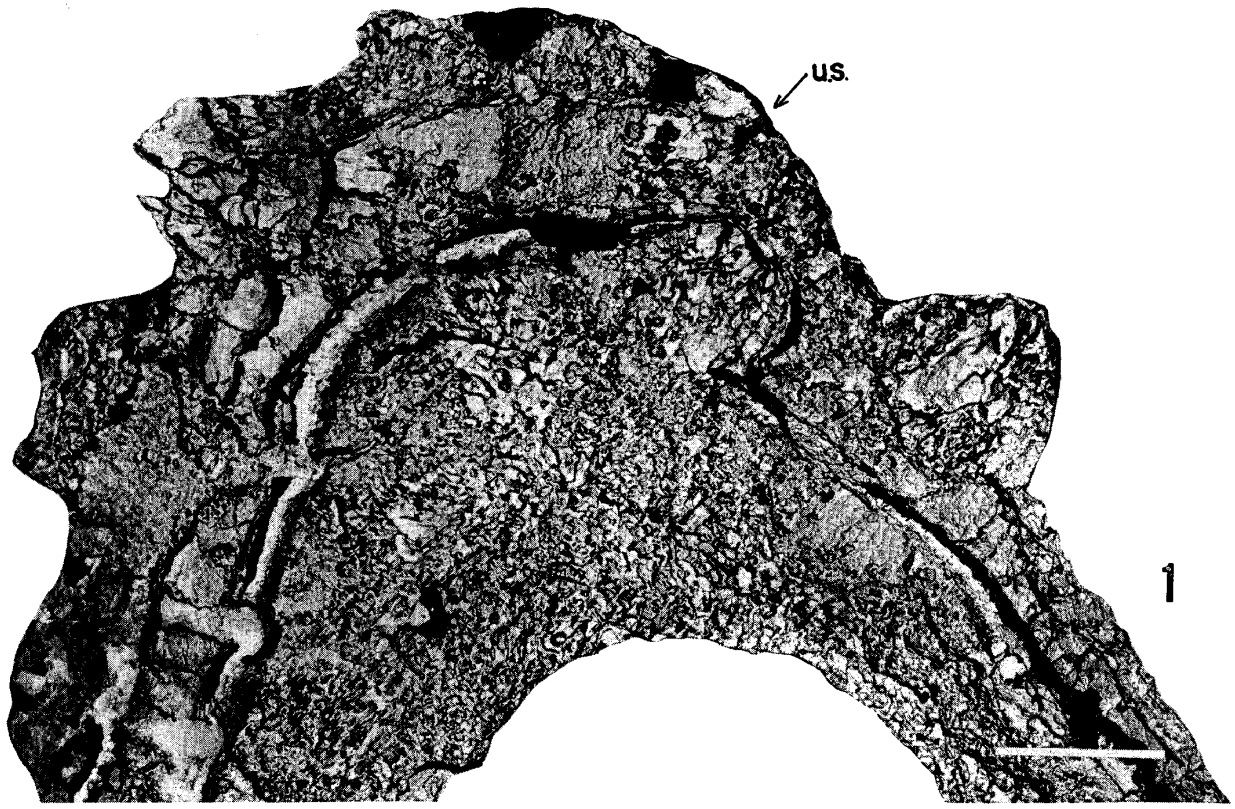
Fig. 2. Keel of the penultimate whorl, showing composition of the wall and pore canals; ×1850. Specimen from the core MSN-53G. [Scale bar 10μ]

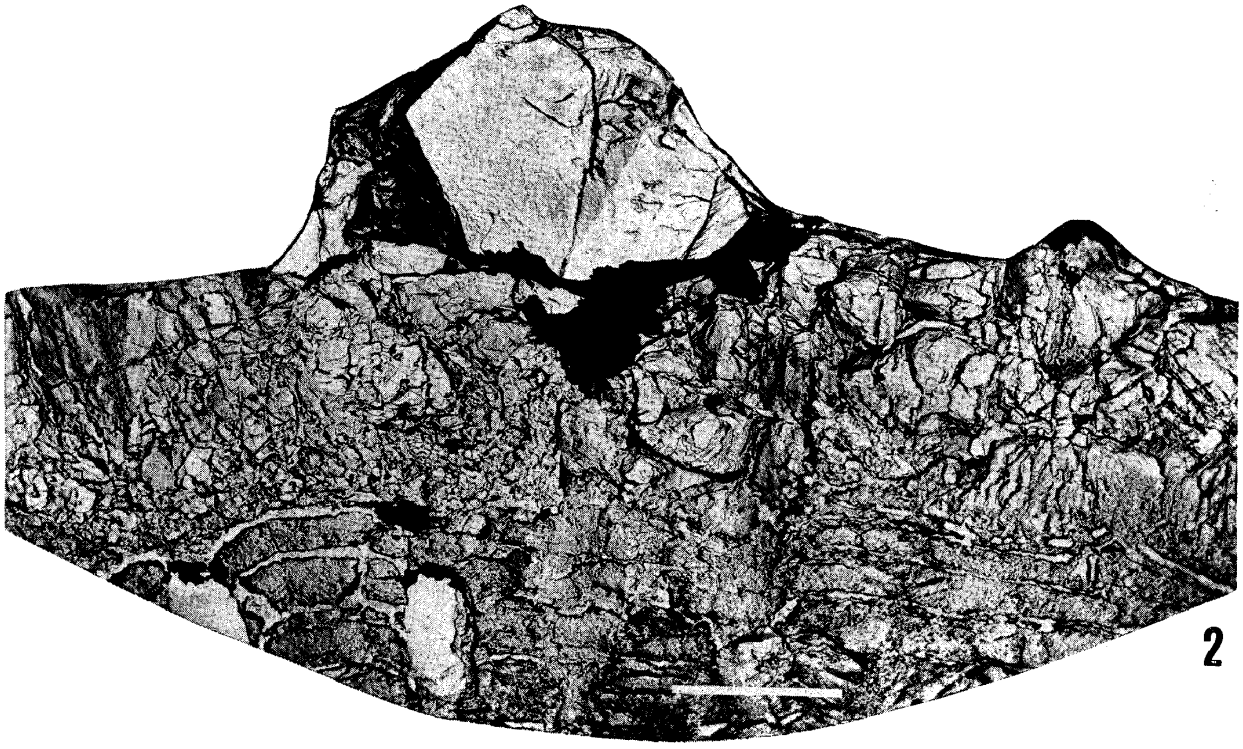
i, inner surface; o, outer surface

Plate 24

Fig. 1. *Punctae* formed at the side wall facing the umbilicus, ×1850. Note that the primary *puncta* formed at the umbilical shoulder (u.s.) of the first outer lamella is not accentuated but covered by the following lamella. There is no direct relation between the *punctae* formed in the two adjacent lamellae. Specimen from the core MSN-53G. [Scale bar 10μ]

Fig. 2. *Pustule* developed on top of the crust (spiral side), ×1850. Specimen from the core MSN -53G. [Scale bar 10μ]


u.s.
1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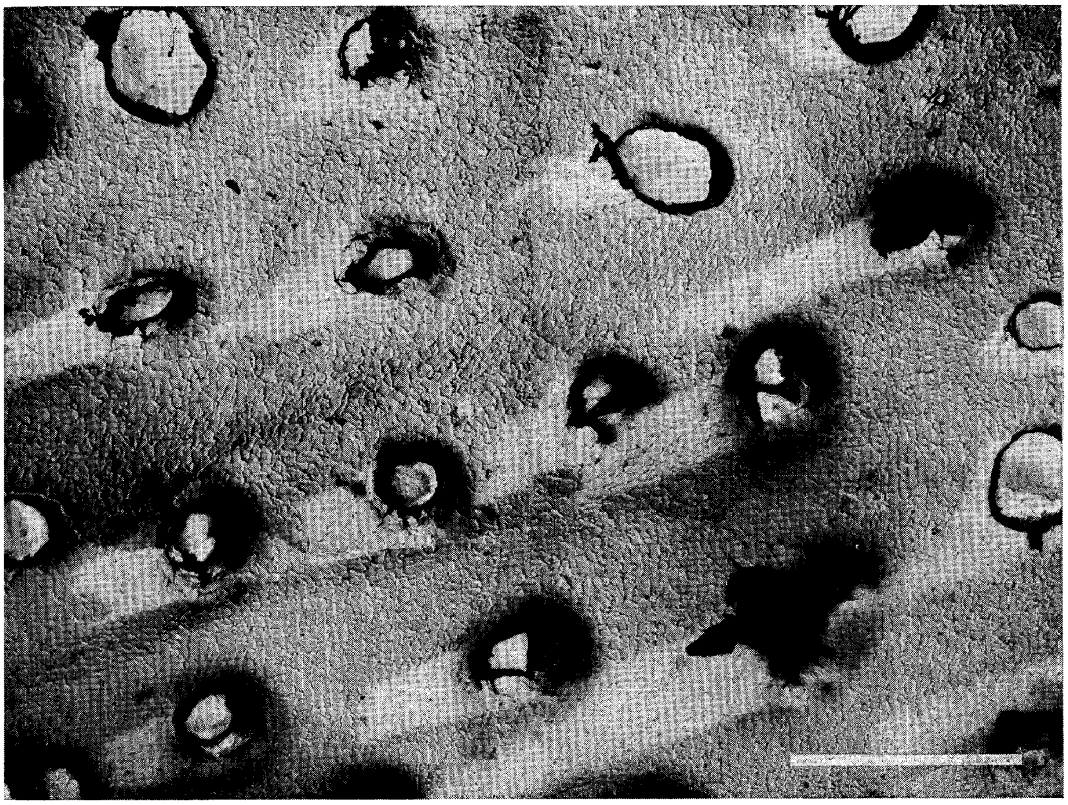
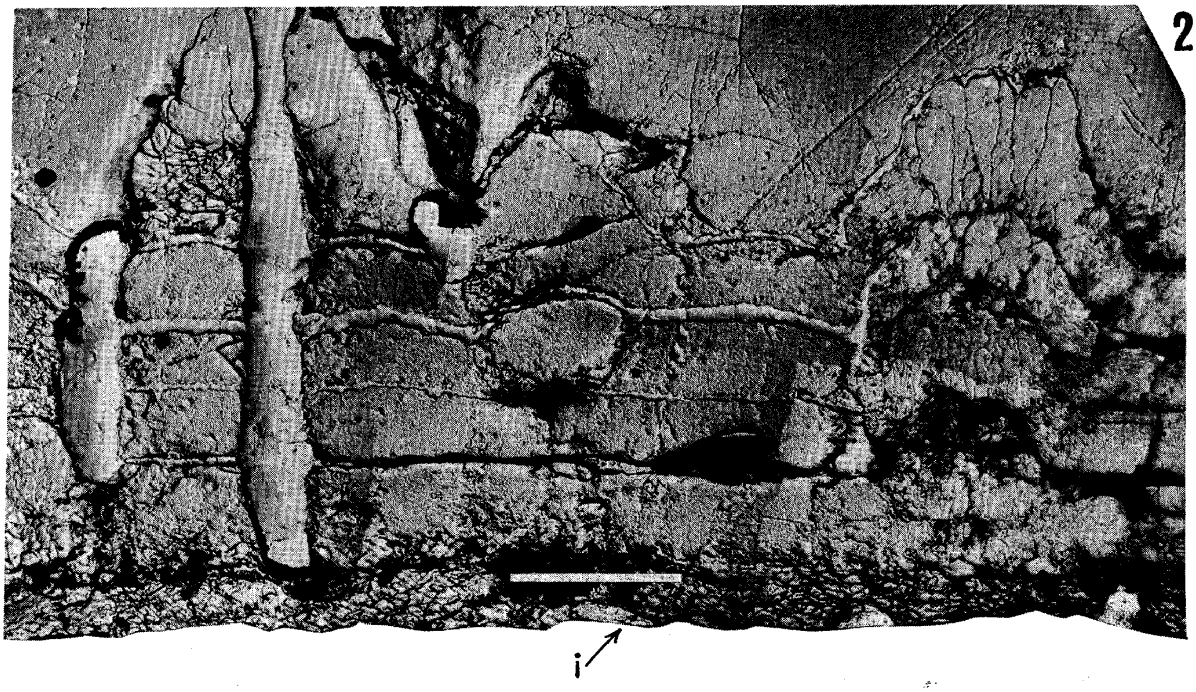


1



2

Plate 25

Fig. 1. Surface of the basal sublamella, inner surface of the inner lamella, showing pores and amoeboid mosaic type of fabric, ×2500. Specimen from the core DWBG-60. [Scale bar 10μ]

Fig. 2. *Puncta* formed at the wall of the spiral side, ×1850. Note successive change in texture of the outer lamellae within the *puncta*. Specimen from the core MSN-53G. [Scale bar 10μ]

i, inner surface

Plate 26

Keeled portion of the last whorl, showing thickening of basal coupled lamellae (inner lamella and the first outer laemlla) and the crust with a tendency to become thin towards the keel, ×1320. Compare the pores at the keel with those of the usual type of the wall. Specimen from the core MSN -53G. [Scale bar 20μ]

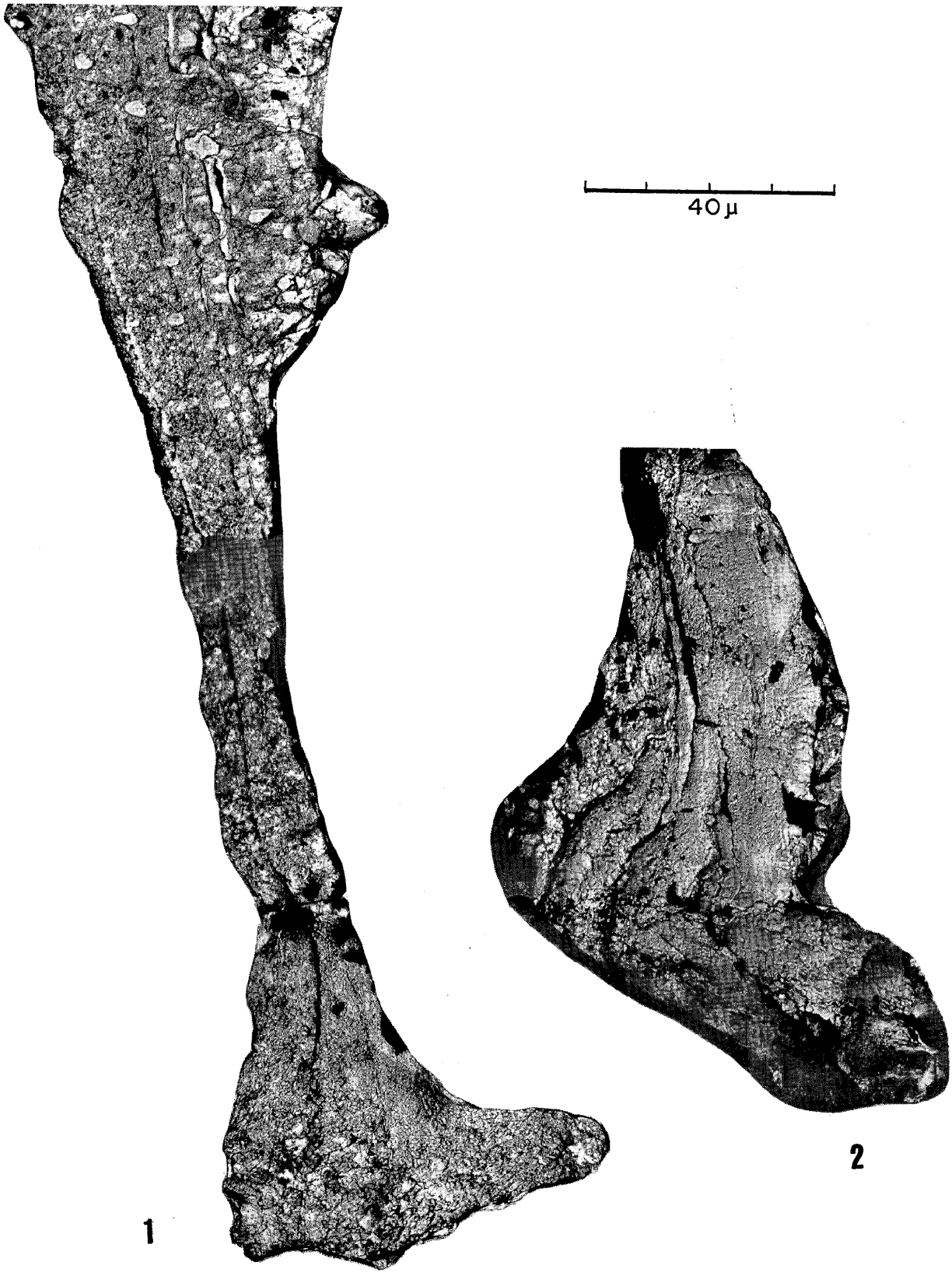

40μ
1
2

Plate 27

Umbilical tooth and the wall facing the umbilicus, ×850. [Scale bar 40μ]

Fig. 1. *Globorotalia truncatulinoides* (d'Orbigny)
Fig. 2. *Globorotalia menardii* (d'Orbigny)
Both specimens from the core MSN-53G.

All photographs on pls. 28 to 31 are of a single specimen from the core V 16-36 in the Atlantic.

Plate 28

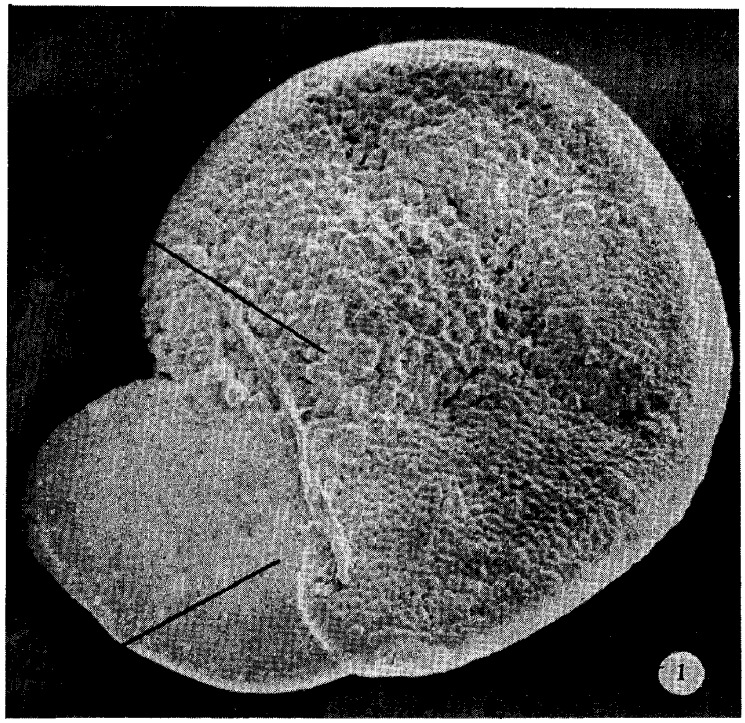
Scanning photomicrographs of *Globorotalia truncatulinoides* (d'Orbigny)-1(all spiral side veiws)

Fig. 1. Whole umbilical side view of a specimen, ×100. Fibrous matter is of tragacanth gum adhered during mounting of the specimen. Note progressive change in microtopography of the outer surface from the earlier to later chambers. (Numbers 28·2 and 29·3 refer to enlarged areas shown in pl. 28, fig. 2, and pl. 29, fig. 3, respectively).

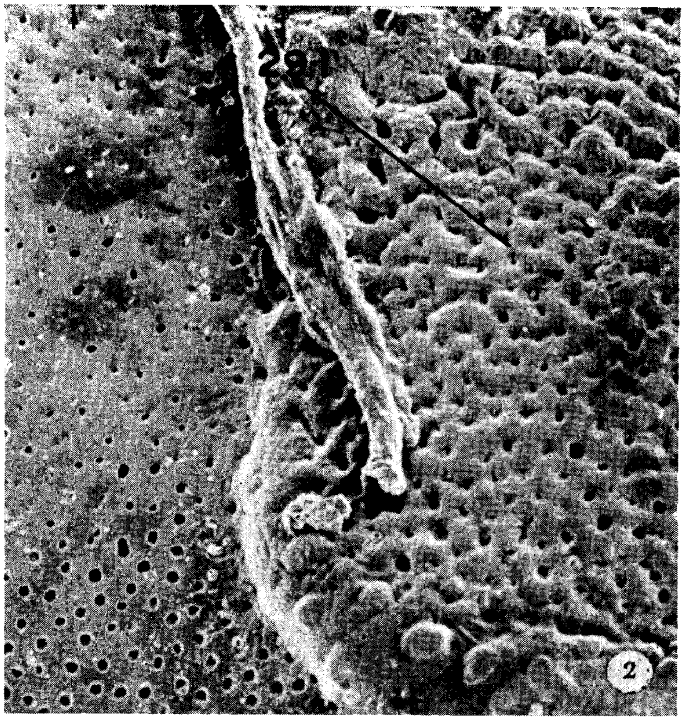
Fig. 2. Boundary area between the final and penultimate chambers, × 300. Considerable variation in the pore fabric is shown on both chambers. Anastomosis of adjacent pores is also visible on the final chamber. (Area adjacent to the left-hand side of the photograph is enlarged in pl. 28, fig. 3, though their extents are somewhat overlapped. Number 29·1 refers to the enlarged area shown in pl. 29, fig. 1).

Fig. 3. Magnified portion of the final chamber, × 1000. Pores of various sizes and shapes are shown.

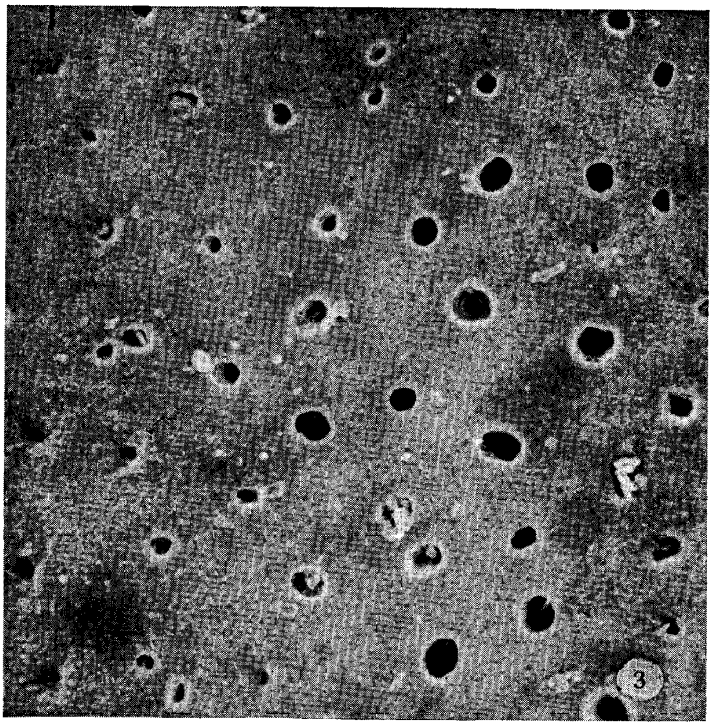
Fig. 4. Detail of the central portion of pl. 28, fig. 3, × 3000. Surface texture is finely bumpy as shown also in pl. 30, fig. 4.



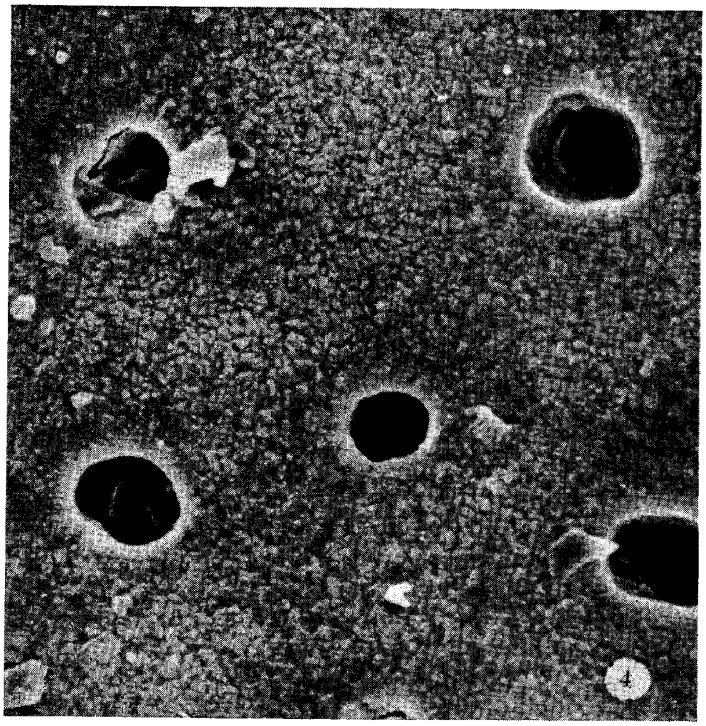
300μ



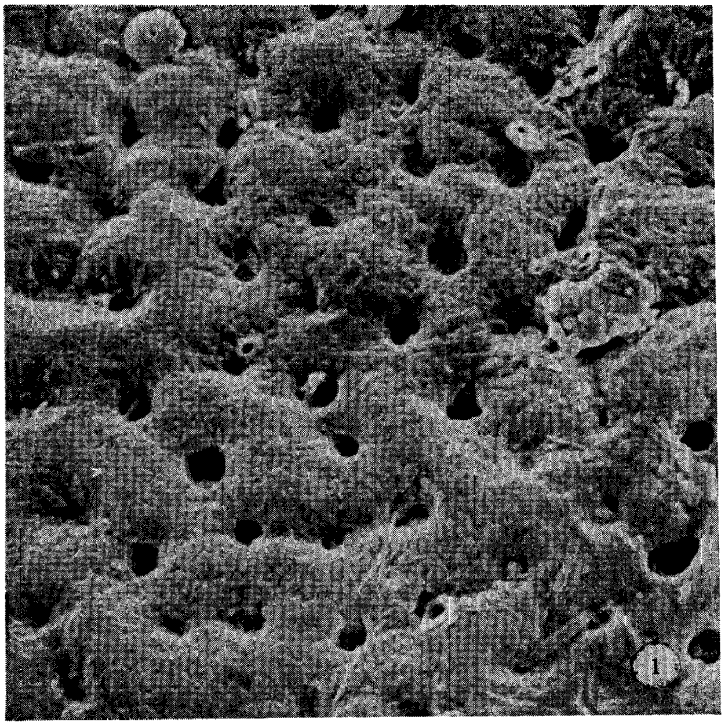
100μ

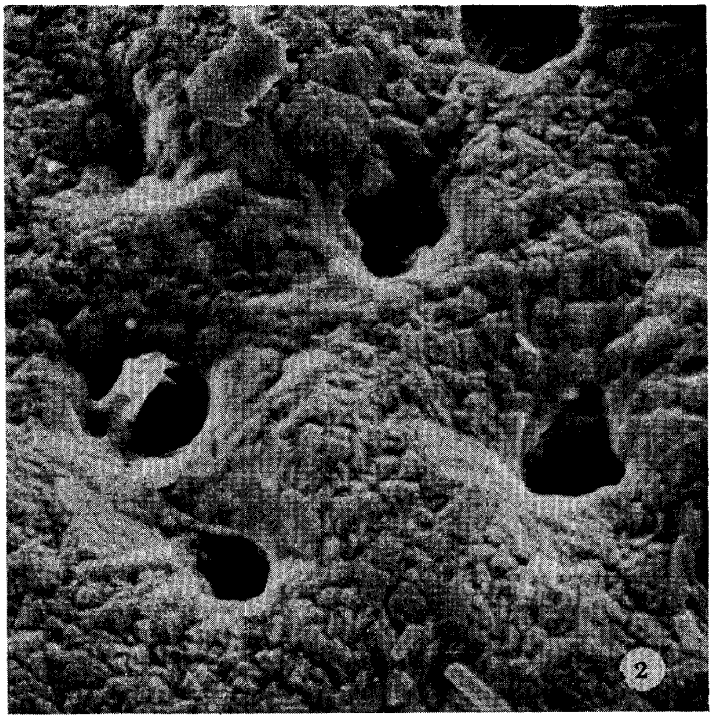


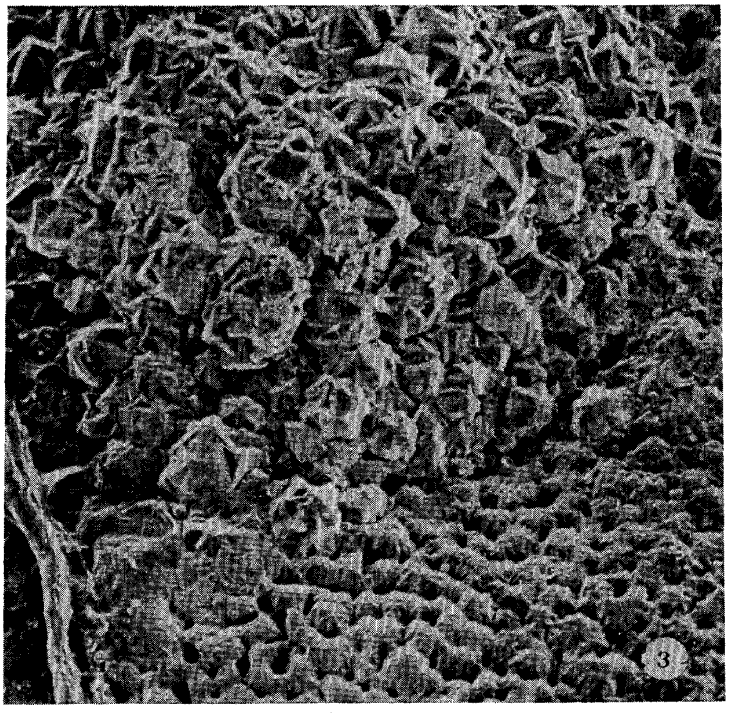
30μ



10μ


1
30μ


2
10μ


3
100μ

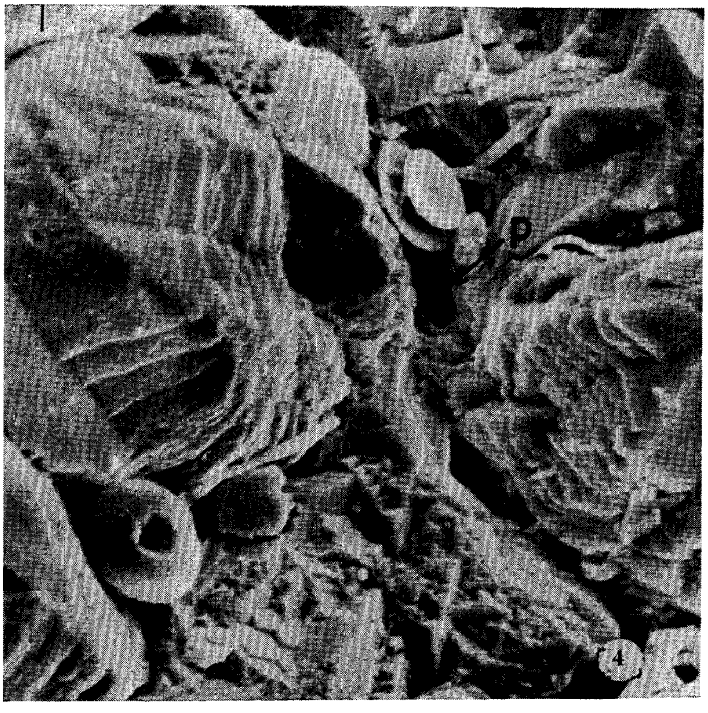

P
4
10μ

Plate 29

Scanning photomicrograph of *Globorotalia truncatulinoides* (d'Orbigny)-2 (all spiral side views)

Fig. 1. Magnified portion of the penultimate chamber, × 1000. Compared with the corresponding portion of the final chamber (pl. 28, fig. 3), the surface texture of the penultimate chamber is much coarser than the former. Note that the needles of presumably secondary and/or exotic origin and coccoliths adhere to the surface.

Fig. 2. Detail of the central portion of fig. 1, × 3000. A coccolith is trapped in a pore.

Fig. 3. Boundary area between the final whorl (penultimate chamber) and the penultimate whorl (area across the spiral suture), × 300. Lower one fourth of the photograph is overlapped with the upper part of the area shown in pl. 28, fig. 2. Although the spiral suture is indistinct, the contrast in surface topography between the final and penultimate whorls is distinct. The surface of the final whorl (penultimate chamber) with shaggy appearance is the part covered with the needles, as is illustrated in fig. 1. Heavy concentration of large crystals obscures distinction of chambers in the earlier whorls.

Fig. 4. Detail of the central portion of fig. 3, × 3000. Each crystal unit displays numerous growth steps on its surface. A pore (p) is visible among the crystals. The coccoliths are *Umbilicosphaera mirabilis* Lohmann, *Cyclococcolithus leptoporus* (Murray and Blackman), and *Coccolithus huxleyi* (Lohmann); (Identified by T. Takayama).

Plate 30

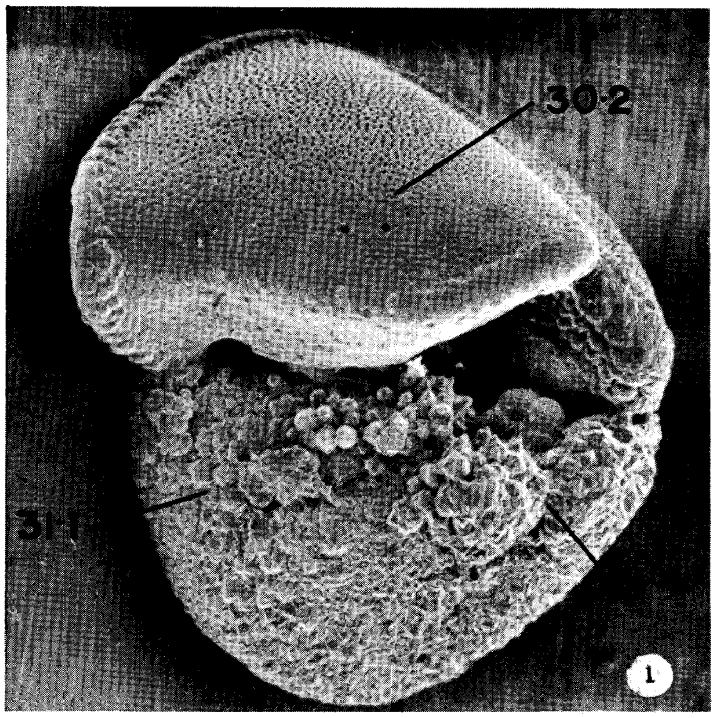
Scanning photomicrograph of *Globorotalia truncatulinoides* (d'Orbigny)-3 (all umbilical side views)

Fig. 1. Oblique view of a specimen showing the final earlier chambers in the last whorl, × 100. Note concave surface of the apertural face ("scrobis septalis"), fine perforation of the final chamber, and encrusted surface of the earlier chambers. Different types of protuberances are exhibited at keeled portions and surfaces of the earlier chambers. (Numbers 30·2, 31·1, and 31·4 refer to enlarged areas shown in pl. 30, fig. 2, pl. 31, figs. 1 and 4, respectively).

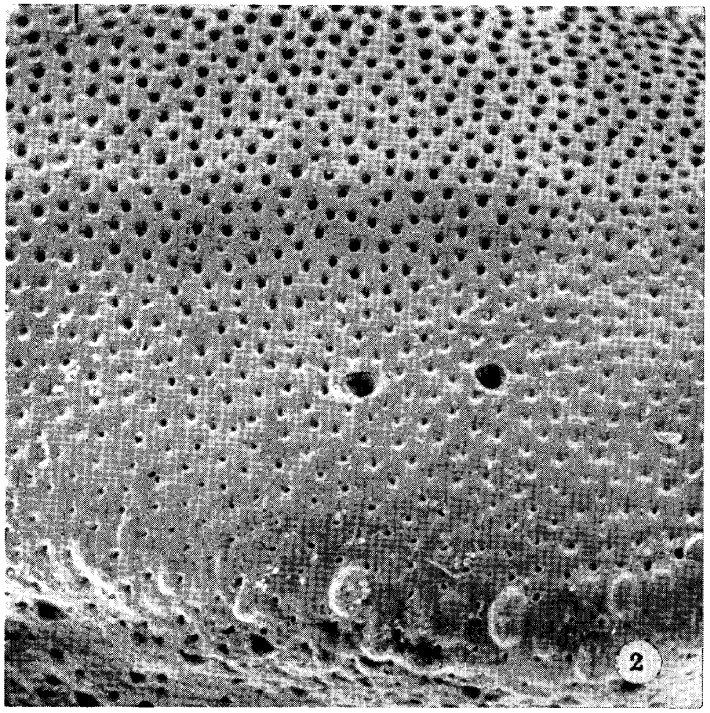
Fig. 2. Marginal portion of the final chamber showing distribution of pores, × 300. Note that the pores reduce in number at the umbilical shoulder where small *punctae* are shown.

Fig. 3. Magnified portion of the final chamber showing the pores of different sizes, × 1000. Most of the pores are medium in size and furnished with funnel-shaped openings flaring to the surface; a few smaller pores are also present. Two large pores do not seem to represent their original feature.

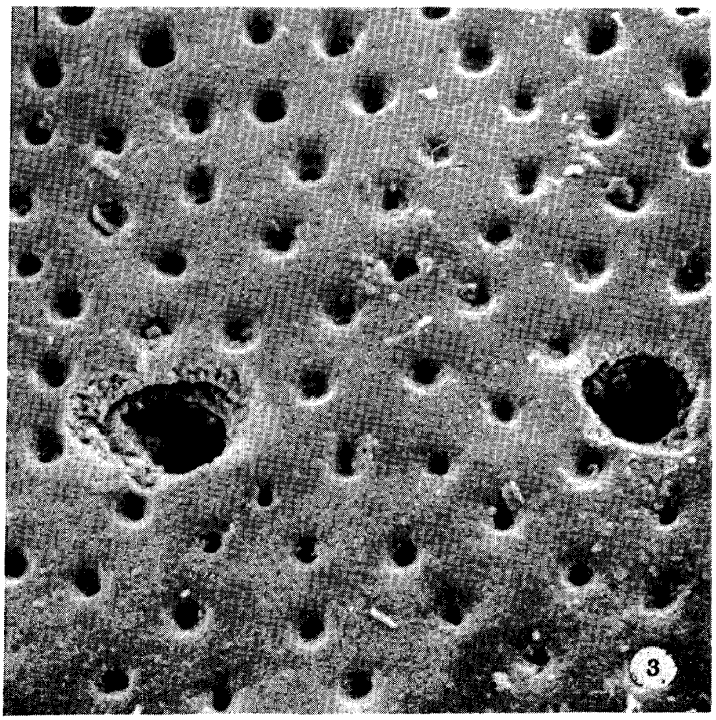
Fig. 4. Detail of fig. 3 showing a large pore and its adjacent area, × 3000. Roughened texture around the opening suggests that the part was affected by some secondary action unknown in origin. Two layers, outer and inner lamellae, are shown inside the pore. Surface assumes finely bumpy texture characteristic to the outer lamella.



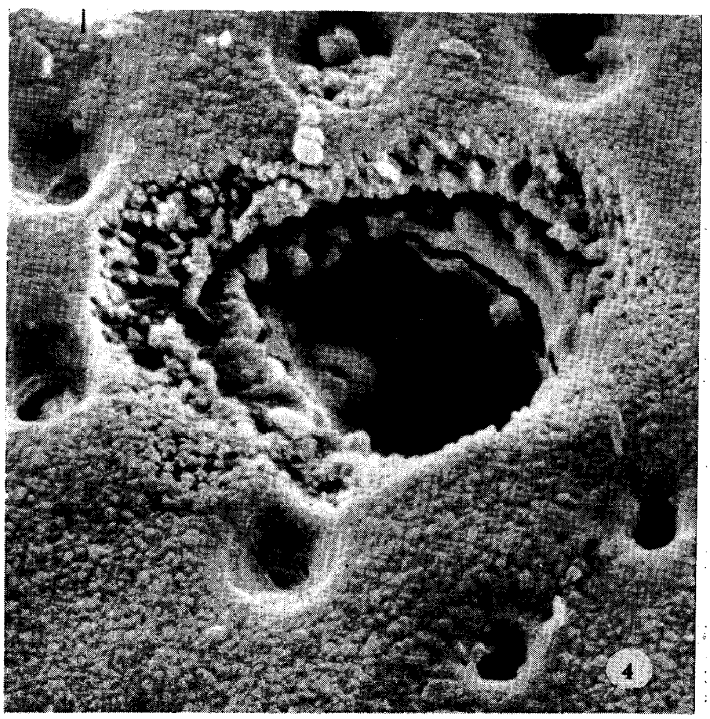
300μ



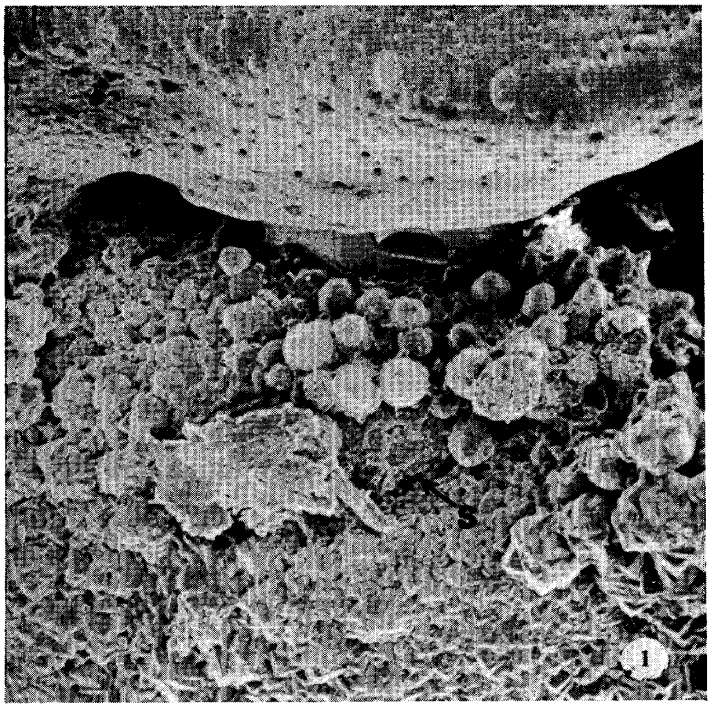
100μ



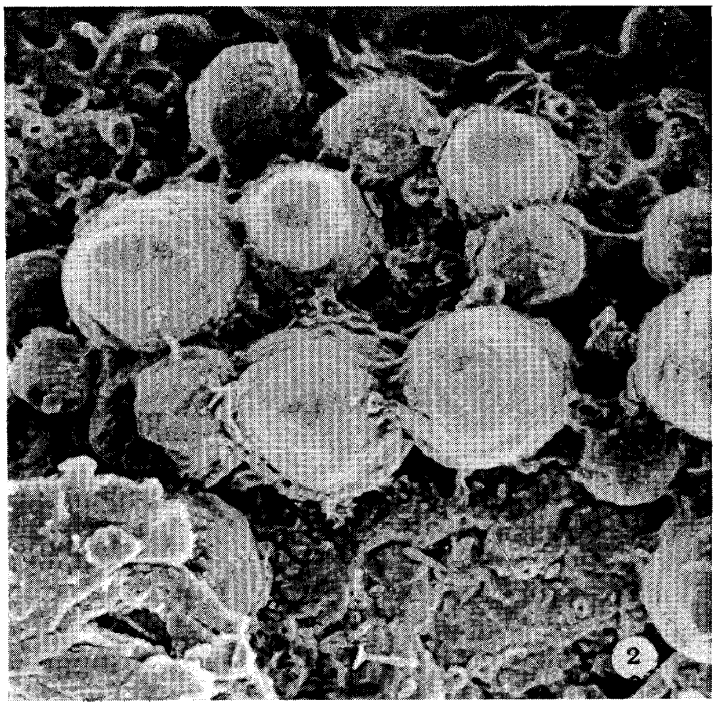
30μ



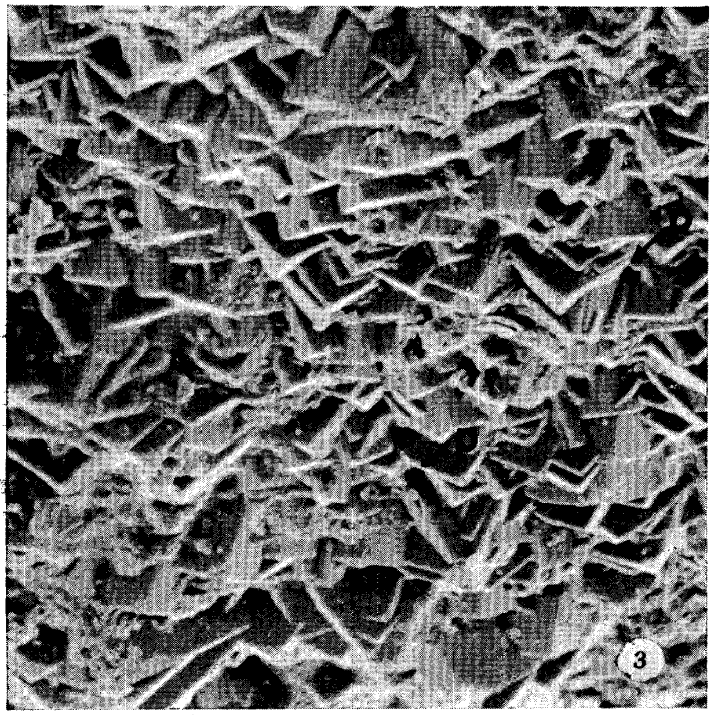
10μ



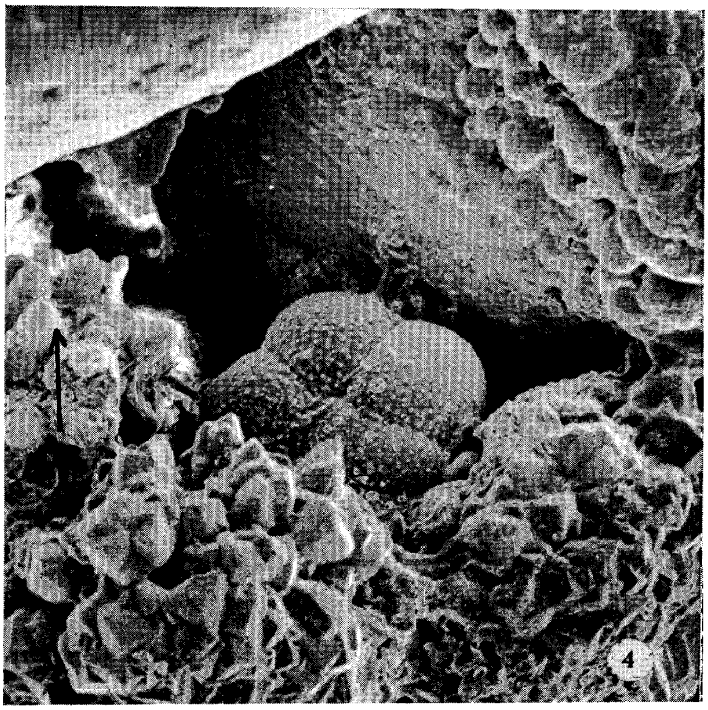
100μ



50μ



50μ



100μ

Plate 31

Scanning photomicrograph of *Globorotalia truncatulinoides* (d'Orbigny)-4 (all umbilical side views)

Fig. 1. Magnified portion of the apertural face of the final chamber and the earlier chambers in the last whorl, × 225. Note remarkable contrast between topography of the outer surface of the final chamber and those of the earlier chambers. Large *pustules* are concentrated near the aperture. Suture between the earlier chambers (s) is obliterated by the growth of crystals.

Fig. 2. Detail of the *pustules*, × 750. Note euhedral crystal faces on the top of each *pustules* composed of thin-plate-pile structure.

Fig. 3. Detail of oblique view of the encrusted outer surface of the second chamber from the earliest in the last whorl, × 750. Growth of euhedral and rhombic crystals obscure the pores (p).

Fig. 4. Oblique view of umbilical region, × 300. Larger crystals are usually concentrated around the umbilical shoulder of each chamber. Attention is drawn to progressive growth of the crystals (crust) from the younger to older chambers, though the cone-shaped ones on the earlier chamber are *pustules* (ps). A juvenile globigerinid form is embedded in the umbilicus. Only one umbilical tooth (t) is present beneath the umbilical shoulder of the final chamber.