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The Imprints of Cenozoic Calcareous Nannofossils from Polymetallic Concretions: Biostratigraphic Significance for two Crusts from the Central Pacific (Line Islands Ridge and Mid-Pacific Mountains)

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With 5 Figures, 4 Tables and 4 Plates

Central Pacific
Line Islands Ridge
Mid-Pacific Mountains
Sonne-18 Cruise
Ferromanganese Crusts
Coccoliths
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Zusammenfassung

REM-Untersuchungen an aus verschiedenen ozeanischen Gebieten gebaggerten Mangankrusten und -knollen ergaben zahlreiche, von mehr als 30 känozoischen Arten herstammende Nannofossilabdrücke. In zwei kobaltreichen Krusten aus dem Zentralpazifik (Line Islands Ridge und Mid-Pacific Mountains) erlaubte die außergewöhnliche Feinkörnigkeit des Manganoxids Abdrücke von sehr kleinen Formen wie *C.* gr. *murrayi, E. huxleyi, Gephyrocapsa* ssp. und *R. claviger* zum erstenmal zu erkennen. Die beobachteten Nannofossilien zeigen, daß diese Konkretionen sich während zweier Hauptperioden zwischen älterem Pliozän und der Gegenwart entwickelt haben.

Abstract

SEM investigation of manganese nodules and crusts dredged in diverse deep-sea areas has shown many imprints of calcareous nannofossils assigned to more than 30 Cenozoic species. In two Cobalt-containing crusts from the central Pacific (Line Islands Ridge and Mid-Pacific Mountains), the exceptional grain fineness of the manganese oxide allowed to identify for the first time the molds of very small forms, such as *C.* gr. *murrayi, E. huxleyi, Gephyrocapsa* ssp. and *R. claviger*. The encountered nannofossils demonstrate that these concretions have grown during two main periods between early Pliocene and Recent.

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Résumé

L'étude au MEB de croûtes et nodules de manganèse dragués dans diverses aires océaniques a montré de nombreuses empreintes de Nannofossiles calcaires, provenant de plus de 30 espèces cénozoïques. Dans deux croûtes cobaltifères du Pacifique central (Iles de la Ligne et Chaîne Centre-Pacifique) l'exceptionelle finesse de grain des oxydes de manganèse a permis d'identifier pour la première fois les empreintes de très petites formes, telles que *C.* gr. *murrayi, E. huxleyi, Gephyrocapsa* ssp. et *R. claviger*. Les Nannofossiles observés indiquent un développement de ces concrétions durant deux périodes principales entre le Pliocène inférieur et l'Actuel.

1. Introduction

All the Calcareous Nannofossils included in the manganese oxide layers of the polymetallic concretions have been fully dissolved and appear as empty molds. Their dissolution, resulting from the growth processes of the incrustations, occurred even in samples developed far above the CCD level in well preserved calcareous sediments. The only calcitic coccoliths encountered are located either in interstices between the oxide layers or within agglutinated walls of Foraminifera (JANIN, 1981b).

The aims of this work are:

a) to record the main types of coccolith imprints observed in the ferromanganese concretions and to figure for the first time some molds of Plio-Pleistocene species identified in two crusts from the Central Pacific: DR-31 and Dr-113, cruise Midpac 81 (= Sonne-18; SCHMIDT-GRASSEGGER et al., in press) and
b) to discuss the biostratigraphic significance of the molds and to reconstruct the growth history of the concretions DR-31 and DR-113.

2. The Calcareous Nannofossil Imprints of the Polymetallic Concretions

2.1. Method of Investigation

The coccolith imprints in the polymetallic concretions can be only investigated in situ (on recent fracture faces of hand broken samples) with Scanning Electron Microscope (SEM). The characters available for the specific identification of the molds are the same as those used for calcitic individuals studied by SEM (size, number and arrangement of the elements) and comparable difficulties arise for species distinguished mainly by optical properties (cross-polarized light images). Moreover, the fracture planes of the samples randomly intersect the coccolith casts and the molds rarely display all the features requested for determination. In order to take all occurring coccoliths into account, the imprints must often be assigned to wide morphological groups rather than to narrowly defined species (JANIN, 1985b).

2.2. Main Species Recognized in the Imprint State

The molds of more than 30 Cenozoic species have been identified until now in the polymetallic concretions (Table 1). Most of them are observed in nodules and crusts dredged between 1000 and 2500 m in the Central Pacific: Tuamotu Archipelago (JANIN, 1985a,b), Line Islands Ridge and Mid-Pacific Mountains (this work, below).

The crusts recovered from comparable depth (2600–3100 m) in the Eastern Atlantic (Portuguese continental margin, JANIN, 1981a,b) provided only imprints of large placoliths (*C.* gr. *pelagicus, C.* gr. *leptoporus*), reflecting the poor Plio-Pleistocene Nannoplankton assemblages of this area (BLECHSCHMIDT, 1979). Deep-sea manganese nodules from the Clarion-Clipperton Zone (North Eastern Equatorial Pacific, 4700 –

Table 1: Main imprints of Calcareous Nannofossils identified in the polymetallic concretions.
1 = Western and Central Pacific: HARADA & NISHIDA (1976, 1979), HARADA (1978); 2 = Clarion-Clipperton Zone: JANIN (in press) and unpublished data; 3 = Portuguesean Margin: JANIN (1981a,b); 4 = Tuamotu Archipelago: BIGNOT & DANGEARD (1976a,b); Hollow triangles indicate molds not figured in the mentioned articles.

Species	Tuamotu Archipel. JANIN (1985 a, b)	Line Islands Ridge DR-31 (this work)	Mid-Pacific Mount. DR-113 (this work)	Others		
				1	2	3
Braarud. bigelowii	● (+4)					
rosa	●					
Calcid. gr. *leptoporus*	●	●△	●△	●	●△	●
Calcios. murrayi			●			
Ceratol. cristatus s.l.		●	●			
Coccol. gr. *pelagicus*	●			●	●	●
Discoa. gr. *brouweri*	(4)	●△	●		●	
gr. *deflandrei*	●		●		●	
gr. *variabilis*	●	●△	●		●	
Discosp. tubifer	●	●△	●△			
Emilian. huxleyi		●△	●			
Gephyrocapsa ssp.		●△	●			
Helicos. carteri			●			
Micrant. cf. *entaster*	●					
Neospha. coccolithomorpha			●			
Oolitho. fragilis	●	●△	●			
perplexus			●			
Pontosp. messinae	●					
gr. *discopora*			●			
Pontosp. + *Scyphosp.* ssp.	●					
P. lacunosa (*E. annula*)	●	●△	●	}●△		
(*E. ovata*)			●			
Reticul. floridana	●					
Reticul. (oval, < 6 µm)	●△	●△	●		●	
(oval, > 6 µm)	●		●			
Rhabdos. claviger			●			
Scyphos. gr. *apsteinii*	●					
pulcherrima	●					
Sphenol. gr. *abies*	●	●△	●			
Syracos. pulchra			●			
Syracosphaera ssp.	●	●△	●△			
Umbello. irregularis			●			
Umbilic. sibogae	●	●	●	●△		

5300 m), although they are now associated with red clay and biogenic siliceous sediments, occasionally show in their internal layers a few placolith and *Discoaster* imprints, indication of an initially less corrosive growth environment (JANIN, in press).

The crust DR-113 from the Mid-Pacific Mountains (and, in a lesser degree, the crust DR-31 from the Line Islands Ridge) provided exceptionally frequent and diversified imprints: up to 50 specimens/mm^2, more than 25 identified species. That results from both

1) the geographical location of the sample, dredged at relatively shallow depth in the equatorial zone, known for the diversity of its nannoflora,
 and
2) the particular fineness of the ferromanganese oxide in this crust (grain<0,05 µm), which has preserved for the first time the structural details of some Plio-Pleistocene taxa. The interpretation of these new imprint types is presented below, together with further electromicrographs for some molds precedently described (JANIN, 1985b).

Discoaster ssp.

(Pl. 1, figs. 2,3,5,6,8,9,11,12,14,15)

The abundance of the "species" described in the genus *Discoaster*, the taxonomic problems due to a diagenetic breaking (Pl. 1, fig. 12), dissolution (Pl. 1, fig. 3) and overgrowth (Pl. 1, fig. 11), together with the particular state of preservation in the polymetallic concretions prevent precise species identification. All encountered imprints are related to 6-rayed asteroliths belonging to 3 morphological groups:

D. gr. *brouweri*: delicate specimens with long sharp arms (Pl. 1, figs. 2,5,8 at left);

D. gr. *deflandrei*: massive specimens with blunt arms (Pl. 1, fig. 8, at right, 11,14);

D. gr. *variabilis*: more or less slender specimens with bifurcated arms (Pl. 1, figs. 9,12,15).

Particularly in the last group, the central area often presents radiating rhomboidal figures (depressions in the calcitic individuals: Pl. 1, fig. 3; reliefs on the imprints: Pl. 1, fig. 6) interpreted as dissolution figures (JANIN, in press).

2.3. Systematic remarks

Species identification is mainly based upon the numerous electromicrographs published by MCINTYRE & BÉ (1967), BOUDREAUX & HAY (1969), BORSETTI & CATI (1972, 1976, 1979), BRÉHÉRET (1977), OKADA & MCINTYRE (1977) and CONLEY (1979). Full taxonomic references can be found in the catalogues of LOEBLICH & TAPPAN (1966–1973), VAN HECK (1979–1982) and STEINMETZ (1983–1985).

Calciosolenia gr. *murrayi*

(Pl. 1, figs. 1,4)

Calciosolenia murrayi GRAN in MURRAY & HJORT, 1912.
Anoplosolenia brasiliensis (LOHMANN) DEFLANDRE, 1952.
Calciosolenia sinuosa SCHLAUDER, 1945.

Two scapholith types occur in the superficial calcareous sediment associated with the studied Central Pacific crusts: broad rhomboidal forms indistinctly assigned to *A. brasiliensis*, *C. murrayi* or *C. sinuosa* because of lack of information on the coccosphere (OKADA & MCINTYRE, 1977; CONLEY, 1979) and more slender ones, that are the only specimens usually named *Scapholithus fossilis* DEFLANDRE, although DEFLANDRE in DEFLANDRE & FERT (1954) created this taxon for all kinds of fossil scapholiths. The scapholith imprint encountered in the crust DR-31 belongs to the first type.

Ceratolithus cristatus KAMPTNER s.l.

(Pl. 1, figs. 7,10,13)

We follow the broad acception of the species proposed by BORSETTI & CATI (1976). The portion of horseshoe-shaped imprint in Pl. 1, fig. 7 shows close similarity with simple specimens of *C. cristatus* figured by these authors (Pl. 17, fig. 1), whereas the mold fragment in Pl. 1, fig. 13 evokes a flange part of a comb-shaped variety as *C. telesmus* NORRIS, 1965 or *C. crist. rostratus* BORSETTI & CATI, 1976.

Emilania huxleyi, *Gephyrocapsa* ssp., *Pseudoemiliania lacunosa* and related forms

(Pl. 2, figs. 1–16)

The exceptional oxide fineness in the crusts DR-31 and DR-113 allows to identify some specimens of these very small placoliths (size: 1–5 µm). The distinctive features used for calcitic population: size, shape of the shield elements (the Mn-oxide filling of the spaces between the I-shaped elements of *E. huxleyi*, *P. lacunosa* or *G.* gr. *protohuxleyi*, forms easily recognized radiating rods on the imprints), presence and direction of the bridge, are still valid for the imprints. As in the instance of the large placoliths (JANIN, 1985b) each species may give many different types of molds, particularly in *Gephyrocapsa*, where the central area filling, between the grill and the bridge (Fig. 1) can remain attached to the imprint or not (types 1+A, 2+A, 3+A, 4+A or 1–A, 2–A, 3–A, 4–A).

All the identification criteria usually appear only on the distal imprints of distal shield (types 1), while the molds of proximal shields cannot be distinguished: Table 2 gives the theoretical interpretation of each kind of imprints that may be slightly distorted because of the natural variability of the group:

1) presence of a pseudobridge in some *E. huxleyi* specimens (OKADA & MCINTYRE, 1977), that hinders discrimination between *E. huxleyi* and *G.* gr. *protohuxleyi* (see BRÉHÉRET, 1977);
2) lack of bridge in some *Gephyrocapsa* as *G. ornata* HEIMDAL, 1973 (see OKADA & MCINTYRE, 1977), that prevents discrimination between *Gephyrocapsa* and *Crenalithus*-small *Reticulofenestra* group;
3) ecophenotypic variation of the shape of proximal elements according to the latitude, at least in *E. huxleyi* (see MCINTYRE, BÉ & ROCHE, 1970; BUKRY, 1974; WINTER, REISS & LUZ, 1979) and in *G. protohuxleyi* (see MCINTYRE, 1970).

In consideration of the taxonomic problems due to

1) the natural variability and the phylogenetic relation of these species,
2) the inadequate description of some forms and the various concepts of the same species according to

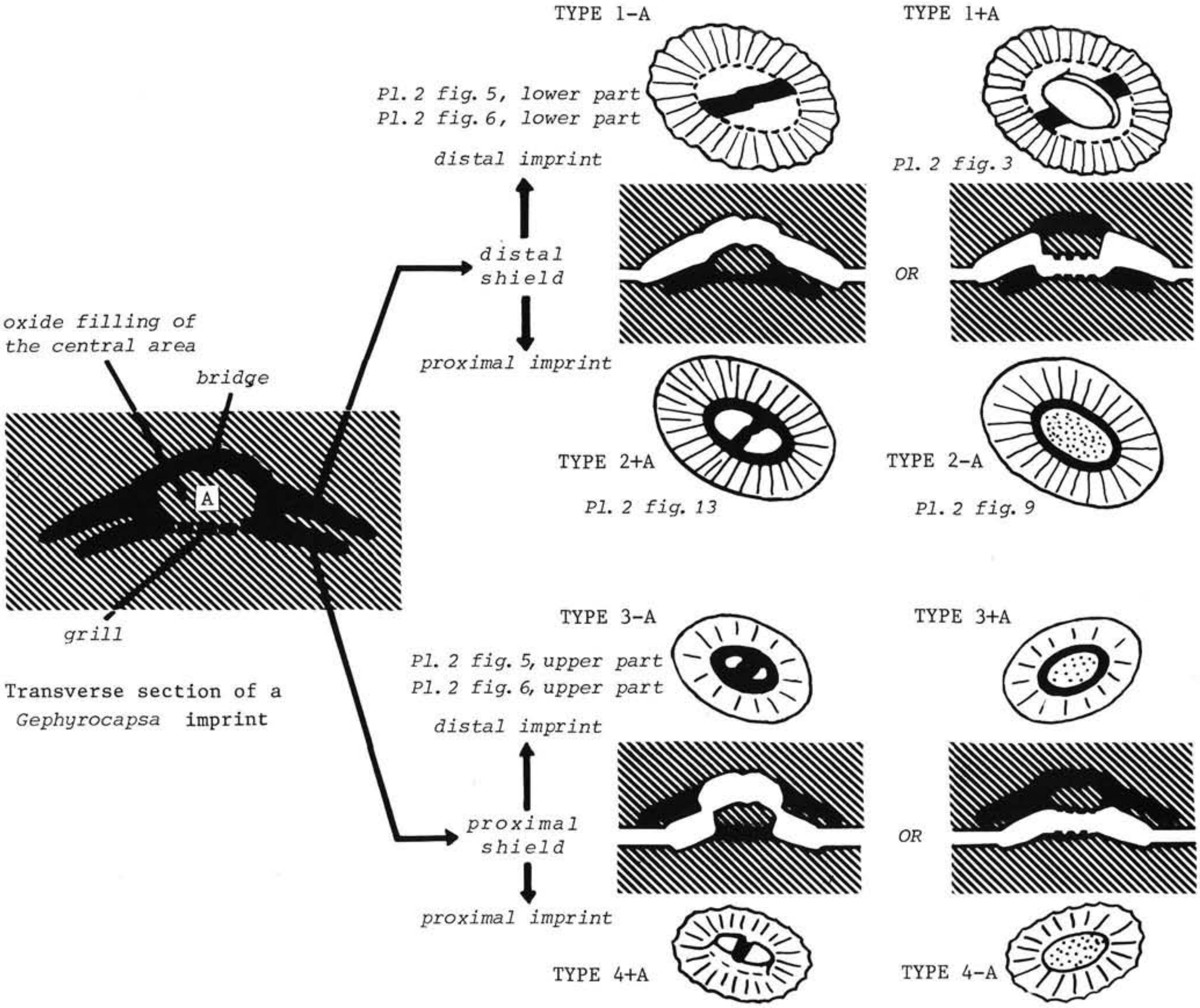

Fig. 1: The different imprint types of *Gephyrocapsa*.
A = Mn-filling of the central area; imprints of types 1+A, 2+A, 3+A, 4+A = imprints with whole filling of the central area; imprints of types 1−A, 2−A, 3−A, 4−A = imprints without central area filling.

different authors (see discussions on *Gephyrocapsa* in BRÉHÉRET(1977, 1978), SAMTLEBEN (1980), RIO (1982) and on the *Crenalithus*-small *Reticulofenestra* group in BACKMAN (1980) and BUKRY (1981), for instance),

3) the particular state of preservation of the studied nannofossils,

only the following morphological groups are distinguished:

Emiliania huxleyi (LOHMANN, 1902) HAY & MOHLER in HAY et al., 1967

(Pl. 2, figs. 1,4,7,8)

Forms with I-shaped elements in the two shields and without bridge. They are related to the warm-water variety. All the specimens with perforated distal shield but solid proximal shield displayed a bridge, and thus they were assigned to *G.* gr. *protohuxleyi*. The cold water variety of *E. huxley* was not identified.

Gephyrocapsa gr. *protohuxleyi*

(Pl. 2, figs. 2,3,5,6)

Although this morphotype includes specimens belonging to more than one biological unit (SAMTLEBEN, 1980), it is conveniently used here for specimens with bridge and perforated distal shield. Proximal elements are separated (group 1) or connected along entire suture (group 2). The first type (Pl. 2, figs. 2,5) may be related to *G. rota* SAMTLEBEN, 1980 or to the lower-latitude variety of *G. protohuxleyi* sensu McINTYRE, 1970. The second group, usually smaller sized (Pl. 2, fig. 6), may belong to *G. ericsonii* Mc INTYRE & BÉ, 1967 (see SAMTLEBEN, 1980).

Gephyrocapsa sp.

(Pl. 2, figs. 10,13,16)

No attempt was made to split up the group of forms with a bridge and 2 solid shields, because length and bridge angle are not exactly measurable on the molds. By their large size, these imprints may be assigned to

Table 2: Identification criteria of imprints from *Emiliania, Gephyrocapsa* and related forms (see fig. 1 for the definition of the imprint types).

IMPRINT TYPE	1 + A	1 - A	2 + A	2 - A	3 + A	3 - A	4 + A	4 - A
irregular I-shaped elements without bridge	*E. annula* *E. ovata*		*E. annula* *E. ovata*					
regular I-shaped elements without bridge	*E. huxleyi* (cold + warm var.)		*E. huxleyi* (cold + warm v.)	*G. protohuxl.* gr. 1, gr. 2	*E. huxleyi* (warm variety) *G. protoh.*gr.1		*E. huxleyi* (warm variety)	*G. protoh.*gr. 1
regular I-shaped elements with bridge	*G. protohuxl.* gr. 1, gr. 2	*G. protohuxl.* gr. 1, gr. 2	*G. protohuxl.* gr. 1, gr. 2			*G. protohuxl.* group 1	*G. protohuxl.* group 1	
solid shield with bridge	*Gephyro.* ssp.	*Gephyro.* ssp.	*Gephyro.* ssp.			*G. protoh.*g. 2 *Gephyro.* ssp.	*G. protoh.*g. 2 *Gephyro.* ssp.	
solid shield without bridge	small *Reticulofenestra* - *Crenalithus* group		small *Reticul.* + *Crenalit.*	*Gephyro.* ssp.	*E. annula, E. ovata* *E. huxleyi* (cold variety) small *Reticul.* + *Crenalit.* *G. protoh.*gr. 2 *Gephyro.* ssp.		*E. annula, E. ovata* *E. huxleyi* (cold variety) small *Reticul.* + *Crenalit.*	*G. protoh.*gr. 2 *Gephyro.* ssp.

G. oceanica KAMPTNER, 1943, *G. caribbeanica* BOUDREAUX & HAY in HAY et al., 1967, *G. margereli* BRÉHÉRET, 1978 or *G. muellerae* BRÉHÉRET, 1978, according to SAMTLEBEN's concepts of these 4 species.

Pseudoemiliania lacunosa (KAMPTNER, 1963) GARTNER, 1969

(Pl. 2, figs. 11,12,14,15)

Emiliania annula (COHEN, 1964) BUKRY, 1971
Emiliania ovata BUKRY, 1973

Imprints of distal shields are characterized by irregularly spaced radiating rods reflecting the incomplete connection of the elements. The crusts DR-31 and DR-113 provided many well preserved molds of large circular forms (*E. annula*: Pl. 2, figs. 11,12,15), but only few elliptical specimens (*E. ovata*: Pl. 2, fig. 14). *E. ovata, E. huxleyi* and *G.* gr. *protohuxleyi*, having comparable size and outline, are difficultly distinguished, if sutural spaces are not truly molded.

Small *Reticulofenestra* – *Crenalithus* Group

Small specimens (<6μm) with two solid shields are included here when the imprint appears unquestionably devoid of a bridge. Proximal molds of *Gephyrocapsa* are usually not differentiated from those of small Reticulofenestrids (Pl. 2, fig. 9). This group is related to living or fossil species as *C. sessilis* (LOHMANN, 1912) OKADA & MCINTYRE, 1977, *C. parvulus* OKADA & MCINTYRE, 1977, *C. punctatus* OKADA & MCINTYRE, 1977 or *R. pseudoumbilica* (GARTNER, 1967) GARTNER, 1969 and the complex of small Reticulofenestrids described by BACKMAN (1980) or BACKMAN & SHACKLETON (1983).

Helicosphaera carteri (WALLICH, 1877) KAMPTNER, 1954

(Pl. 3, figs. 1,4)

The helicoform imprint in Pl. 3, fig. 4 is asssigned to the proximal side of *H. carteri* on the basis of the well developed spiral flange and of the central relief in the proximal disc that reflects central openings arranged in a line.

Helicosphaera sp.

(Pl. 3, fig. 7)

This imprint shows the characteristic asymmetry of the helicoliths. Compare with Fig. 2.

Neosphaera coccolithomorpha LECAL-SCHLAUDER, 1950

(Pl. 3, figs. 11,14n)

The distal imprint of this species, often wrongly (but following MCINTYRE & BÉ, 1967) named *Cyclolithella annula*, is characterized by a large circular outline and a smooth shield with almost indistinct sutures, surrounding an annular groove, that represents the central collar.

Oolithotus fragilis (LOHMANN, 1912) MARTINI & MÜLLER, 1972

(Pl. 3, figs. 10,13,14o)

Discolithus antillarum COHEN, 1964.
Oolithotus fragilis fragilis OKADA & MCINTYRE, 1977.

Oolithotus fragilis cavum OKADA & MCINTYRE, 1977.

Imprints of *O. fragilis* are identified because of the asymmetrical construction of the flat distal shield. The two varieties of OKADA & MCINTYRE (1977) were encountered: specimens with straight suture lines (subsp. *fragilis*: Pl. 3, figs. 10,13) and smaller forms with curved sutures (subsp. *cavum*: Pl. 3, fig. 14 [o]).

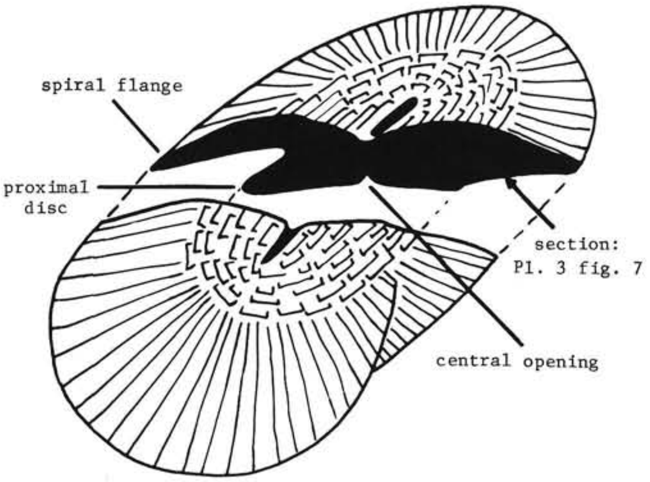

Fig. 2: Cross section of *Helicosphaera* (distal view) and related imprint.

Oolithotus perplexus (BRAMLETTE & RIEDEL, 1954) CONLEY & BURNS in CONLEY, 1979

(Pl. 3, figs. 12,15)

Imprints of *O. perplexus* differ from those of *O. fragilis* by symmetrical construction and polygonal outline of the distal shield.

Pontosphaera gr. *discopora*

(Pl. 3, figs. 5,8)

Pontosphaera discopora SCHILLER, 1925 emend. BURNS, 1973.
Pontosphaera multipora (KAMPTNER, 1948) ROTH, 1970 emend. BURNS, 1973.
Pontosphaera distincta (BRAMLETTE & SULLIVAN, 1961) BURNS, 1973.

This group includes elliptical cribriliths with large perforations evenly distributed over the entire surface. According to BURNS (1973), *P. discopora, P. multipora* and *P. distincta* differ by the number (1 to 3) of peripheral rings of perforations, but this feature can be difficultly used for imprints, that rarely display the whole cribrilith surface. However, the mold in Pl. 3, fig. 8, bearing 52 pore fillings arranged in two rings on the periphery and randomly disposed at the center, may be assigned to *P. multipora*. Since the imprint margin is surrounded by a groove indicating the flange place, it represents the mold of the inner discolith side.

Large *Reticulofenestra* Group

(Pl. 3, fig. 2)

Imprints of large *Reticulofenestra* (>6μm) and related genera (*Apertapetra* HAY, MOHLER & WADE, 1966; *Cyclicargolithus* BUKRY, 1971; *Dictyococcites* BLACK, 1967) are easily differentiated from those of other placoliths by the great number of shield elements and the complex construction of the central area (JANIN, 1985b). Central grills are well preserved in the studied samples. Specific identification requires a better knowledge of the variability of morphometric parameters in the calcitic assemblages according to age and geographical location.

Rhabdosphaera claviger MURRAY & BLACKMAN, 1898

(Pl. 4, figs. 1,4,7,8,11,14,15,16 below)

Rhabdosphaera claviger MURRAY & BLACKMAN, 1898.
Rhabdosphaera stylifer LOHMANN, 1902.
Discolithus phaseolus BLACK & BARNES, 1961.

Various kinds of rhabdolith imprints were observed: stem molds in longitudinal (Pl. 4, fig. 4,8) or cross-section (Pl. 4, fig. 7) and distal or proximal imprints of basal disc with stem (Pl. 4, fig. 11) or of unappendixed discs (Pl. 4, figs. 14,15,16). Only imprints of basal discs (Pl. 4, fig. 15,16) or stem tip (Pl. 4, fig. 4) shows the characteristic structure of *R. claviger*. As the other molds were found in the same area, they are assigned to the same species.

Sphenolithus gr. *abies*

(Pl. 4, figs. 2,5)

Sphenolithus abies DEFLANDRE in DEFLANDRE & FERT, 1954.
Sphenolithus neoabies BUKRY & BRAMLETTE, 1969.
Sphenolithus verensis BACKMAN, 1978.

Sphenolith casting provides the surprising but easily recognized figures previously described (JANIN, 1985b). The cone-shaped Mn-oxide fillings in position of the apical body reflect the net of thin walls observed by BACKMAN (1978) in *S. verensis* and also displayed by well preserved specimens of *S. abies* or *S. neoabies*. The molds rarely appear as axial section and the three species cannot be differentiated here according to their more or less elongated outline. Size measurements of 11 specimens (3–4 μm: 7 individuals; 5μm: 1; 6–7 μm: 3) indicates occurrence of both *S. neoabies* (Pl. 4, fig. 5) and *S. abies-verensis* group.

Syracosphaera pulchra LOHMANN, 1902

(Pl. 3, figs. 3,6,9)

Large elliptical imprints (length >5μm) with a wide central area bearing two concentric rings of rod-like reliefs reflecting complex grill construction are assigned to *S. pulchra*.

Umbellosphaera irregularis PAASCHE in MARKALI & PAASCHE, 1955

(Pl. 4, figs. 9,12)

The mold of a trumpet-shaped nannofossil made up of large, connected tongue-like elements was interpreted as axial section of *U. irregularis*.

Umbilicosphaera sibogae (WEBER VAN BOSSE, 1901) GAARDER, 1970

(Pl. 4, figs. 3,6,10,13,16)

Umbilicosphaera sibogae sibogae OKADA & MCINTYRE, 1977.
Umbilicosphaera sibogae foliosa (KAMPTNER, 1963) OKADA & MCINTYRE, 1977.

Distal imprints of *U. sibogae* differ from those of other placoliths by the crater-shaped central area with strongly marked suture lines. The warm-water variety (*sibogae*), with small (Pl. 4, fig. 3,6) or wide (Pl. 4, fig. 10) central area, occurs more frequently than the cold-water one (*foliosa*: Pl. 4, figs. 13,16).

2.4. Biostratigraphic Use in Growth Rate Estimating of Ferromanganese Concretions

Among the numerous methods suitable to estimate the growth rate of polymetallic concretions (FINNEY, HEATH & LYLE, 1984), the micropaleontologic datation of included microfossils (HARADA & NISHIDA, 1976; HARADA, 1978; KADKO & BURCKLE, 1980; JANIN, 1981a,b, 1985a,b; JANIN & PERSON, 1986 in press) is one of the least used (BIGNOT & DANGEARD, 1980) because of the scarcity and peculiar state of microfossil preservation in the oxide layers. However, careful and patient SEM study proves that, at least in nodules and crusts dredged between 1000 and 4000 m depth, the identifiable imprints of calcareous nannofossils may be frequent and diversified enough to authorize chronological conclusions as they are made in sedimentary sequences.

Importance of species absence in mold assemblages is lowered by the low number of identifiable forms. If all species seem to be able to give characteristic molds, only the dominant forms have some chance to be encountered as imprints: the index-species usually rare in calcitic populations are not usable and the biostratigraphic resolution is lower for polymetallic concretions than for well preserved calcareous oozes.

On the other hand, since impressions cannot undergo post-lithification reworking or contamination during sample preparation, species presence is more reliable for imprints than for calcitic specimens. For the same reason, a better record of the successively deposited assemblages may be expected in concretions than in the associated sediment columns, which are usually condensed and diagenetically modified.

3. Biostratigraphy of two Central Pacific Crusts

The studied samples (Fig. 3) are two among the Cobalt-containing crusts from Line Islands Ridge (DR-31) and Mid Pacific Mountains (DR-113) described and analysed by SCHMIDT-GRASSEGGER, MARCHIG, GUNDLACH & TUFAR (in press). Table 3 summarizes their main characteristics.Two complete sections of DR-113 and one section and a half of DR-31 were investigated with the SEM (Fig. 4).

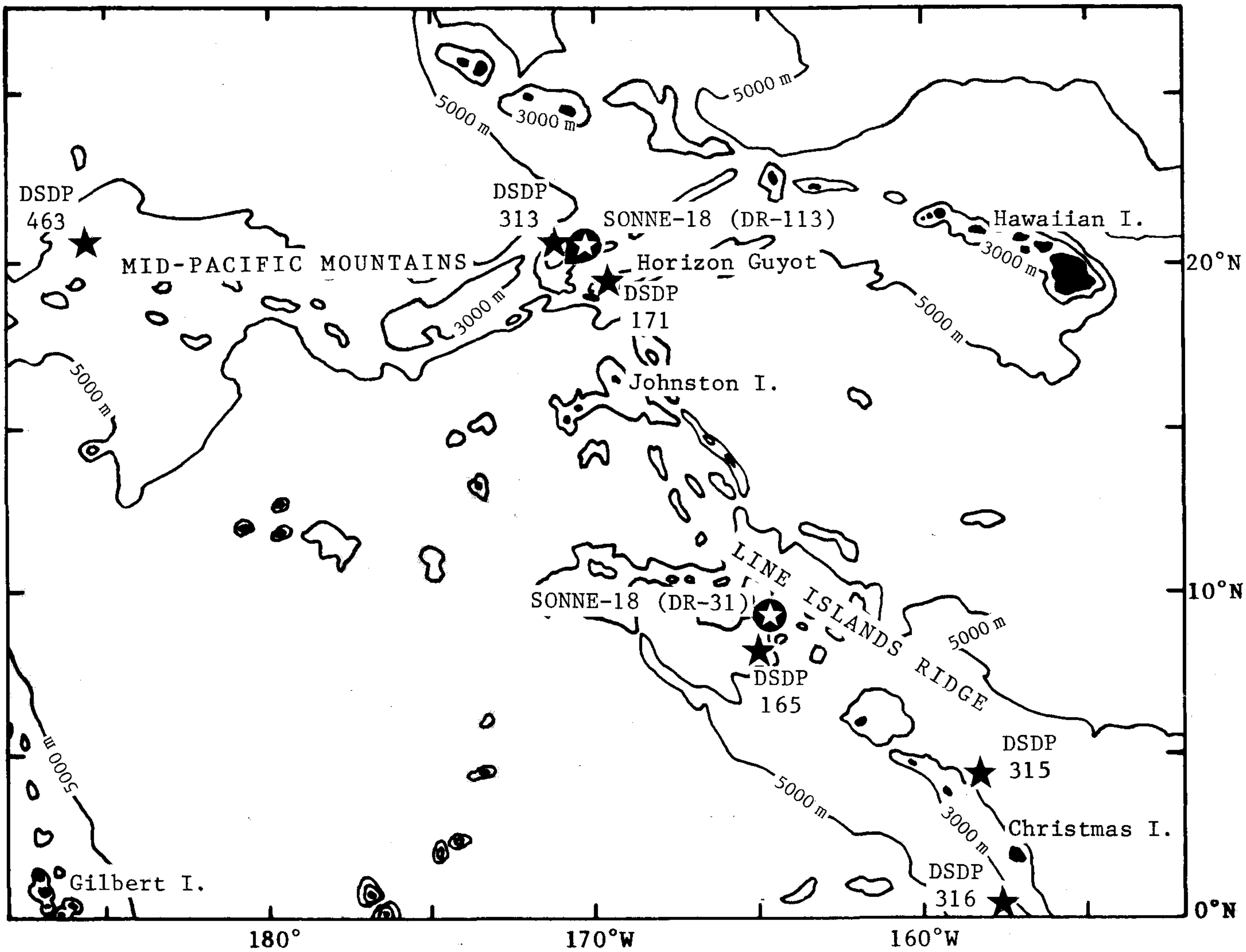

Fig. 3: Location of the studied SONNE-18 crusts.

Table 3: Characteristics of the studied SONNE-18 crusts.

SAMPLE	DR-31 e	DR-113 d
approximate coordinates	9° N 165° W	20° N 171° W
depth	2100 m	2500 m
sample size (cm)	17 x 11 x 6	20 x 14 x 6
oxide thickness	2 to 9 mm	8 to 9 mm
substratum	phosphorite	altered basalt

3.1. Micropaleontological Investigation

Table 4 shows the distribution of all identified Calcareous Nannofossils (imprints and calcitic or epigenised specimens).

a) The surface of the two crusts bears a well preserved calcitic population related to living species, with dominance of *E. huxleyi, F. profunda, U. sibogae* and *Gephyrocapsa* ssp., associated in DR-31 with a few Diatoms. Reworked specimens of extinct species rarely occur: only some *D.* gr. *brouweri* and one or two individuals of *D.* gr. *deflandrei*, large *Reticulofenestra* and *Sphenolithus* were encountered among several hundred of recent forms.

b) Oxide layers include no calcitic ooze contrary to those of some Co-rich crusts from Tuamotu Archipelago (JANIN, 1985a). Some epigenised specimens (among those *G.* gr. *protohuxleyi*, Pl. 2, fig. 2), *Gephyrocapsa* sp., *C. leptoporus, P. lacunosa* and *S. fossilis*) were recognized in an isolated interstice in the upper part of DR-31. Most nannofossils are imprints and distributed in two main assemblages: the innermost layers display often isolated large forms (*Discoaster*, large *Reticulofenestra* (>6µm), *Sphenolithus*) while the outermost part contains more delicate species (*P. lacunosa, G.* gr. *protohuxleyi, E. huxleyi, O. fragilis*) associated with many small imbricated molds generally related to *U. sibogae* and *Gephyrocapsa* or small Reticulofenestrids. Mixing of the two populations in fragment B of DR-113 (section 1, Fig. 4) may be explained by the irregular growth of the oxide, that puts layers of different ages in the same horizontal level. If the irregular distribution and the sparseness of the identifiable molds do not allow to undoubtedly recognize finer subdivisions, it is noteworthy that *P. lacunosa* and *G.* gr. *protohuxleyi* have been found neither in the superficial oxide layers nor on the crusts surface.
The boundary between the two assemblages roughly corresponds to the main morphological discontinuity observed in the middle part of the crusts (Fig. 4). Chemical investigation performed with an Electron Dispersive Analyse X (EDS II) system coupled with the SEM, indicates that, in DR-31 at least, this boundary corresponds also with the dividing line between the inner oxide layers, with low Cobalt content ("ältere Mangankrusten-Generation" of SCHMIDT-GRASSEGGER et al., in press), and the outer Co-rich layers ("jüngere Mangankrusten-Generation"). Due to the lower amount of Cobalt in the crust DR-113, the Co-content variations could not be studied by the EDS technique.

c) The deepest Mn-oxide layers of DR-113 and their basaltic substratum have provided no nannofossils in spite of careful investigation; the phosphoritic nucleus of DR-31 showed many dissolved or phosphatised specimens of *C. pelagicus, Sphenolithus* gr. *abies* and large *Reticulofenestra* (such as *R. bisecta* and *R. floridana*), together with a 6-rayed *Discoaster* sp. and one *D. tani*.

3.2. Stratigraphical Interpretation

The distribution of Calcareous Nannofossils in the crusts is consistent with the low-latitude zonations proposed by MARTINI (1971) or OKADA & BUKRY (1980), together with the data obtained from the DSDP sites cored in the same area (Fig. 3): sites 171 (ROTH, 1973), 313 (BUKRY, 1975), 463 (THIEDE, VALLIER et al., 1981) in the Mid-Pacific Mountains and 315, 316 (MARTINI, 1976) in the Line Islands.

a) The rich calcitic assemblage on the crusts surface (Fig. 5) reflects the recent nannoplankton composition recorded in the Central Pacific by ROTH & BERGER (1975), OKADA & McINTYRE (1977) and GEITZENAUER, ROCHE & McINTYRE (1977).

b) For the oxide layers, the more reliable event is the *Sphenolithus* extinction in the middle part that corresponds to the early/late Pliocene boundary (NN15/NN16 boundary of MARTINI's zonation or CN11/CN12 boundary of OKADA & BUKRY's zonation) with an estimated age of about 3.5 m.y. according to BACKMAN & SHACKLETON (1983).
In the upper part, most imprint assemblages, with dominance of *P. lacunosa* (type *E. annula*) and *Gephyrocapsa*, associated with few probably reworked *Discoaster*, belong to the early Pleistocene (NN19 or CN13–CN14a). The absence of *P. lacunosa* in some superficial areas and the local mixing of *E. huxleyi* and *P. lacunosa* may reflect sporadically younger populations (late Pleistocene – Recent: NN20–NN21 or CN14b–CN15). On the other hand, some *Discoaster* may not be reworked and the presence of late Pliocene in places cannot be excluded.
In the lower part, the presence of *Gephyrocapsa* sp., that appears about 4 m.y. ago (NN15) in the Atlantic according to SAMTLEBEN (1980), together with the absence of *C.* gr. *pelagicus*, that disappears in the early Pliocene at the DSDP site 171 cored near the station DR-113 on the Horizon Guyot (ROTH, 1973), indicates that these layers probably did not start to grow before the later part of the early Pliocene (NN15 or CN11, about 4 m.y.). Only the innermost oxide levels below the first Nannofossils encountered may be older (Figs. 4,5).

c) The age of the basaltic substratum of the crust DR-113 cannot be determined by radiochemical method because of the strong alteration of the basalt (SCHMIDT-GRASSEGGER et al., in press). For the crust DR-31, the nannofossil population identified in the phosphorite wholly differs from those of both the oxide layers and the superficial calcitic ooze: it indicates an older (late Oligocene or Miocene?) age, but more detailed investigations are needed to precise this stratigraphical interpretation.

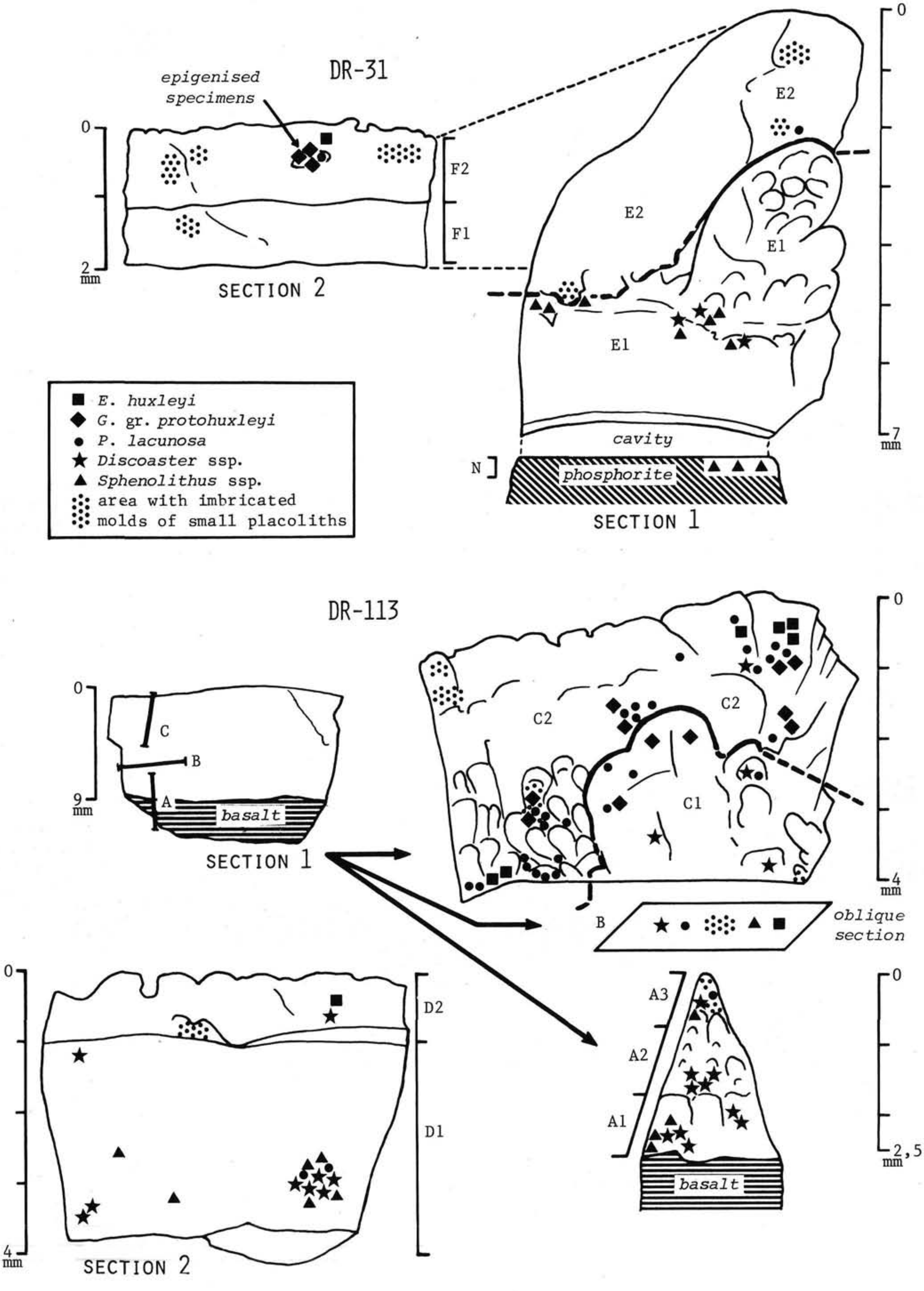

Fig. 4: Location of the stratigraphically useful imprints identified in the studied SONNE-18 crusts.

Table 4: Distribution of the Calcareous Nannofossils and their imprints in the studied SONNE-18 crusts.
E = epigenised specimen; r = probably reworked specimen.

DR-31						Species	DR-113								
NUCLEUS	SECTION 1		SECTION 2		SURFACE OOZE		SECTION 1						SECTION 2		SURFACE OOZE
N	E1	E2	F1	F2	S		A1	A2	A3	B	C1	C2	D1	D2	S
•						*C.* gr. *pelagicus*									r
•						*D. tani*									
•	•					*S.* gr. *abies*	•		•	•			•		r
•						*Reticulofenestra* (> 6 µm)	•		•	•					r
•	•					*Discoaster* sp. (6-rayed)		•		•					r
						D. gr. *deflandrei*	•		•		•		•		r
						D. gr. *variabilis*	•	•							r
	•				r	*D.* gr. *brouweri*	•	•	•	•		•	•	•	r
		•		E		*P. lacunosa*			•	•	•	•	•		r
•	•		•		•	*Retic.* (< 6 µm)- *Crenal.*			•			•			•
	•	•		• E	•	*Gephyrocapsa* sp.	?		•	•	•	•	•	•	•
				E		*G.* gr. *protohuxleyi*					•	•			
				•	•	*E. huxleyi*				•		•		•	•
	•	•	•	•	•	*U. sibogae*	•	•		•	•	•	•		•
	•		•	• E	•	*C.* gr. *leptoporus*			•	•	•	•	•	•	•
	•				•	*Syracosphaera* sp.			•	•	•	•	•	•	•
					•	*S. pulchra*				•	•	•			•
		•	•	•	•	*O. fragilis*				•	•			•	•
					•	*O. perplexus*						•			•
			•		•	*C. cristatus* s. l.						•			•
					•	*N. coccolithomorpha*				•	•				•
					•	*R. claviger*				•	•			•	•
					•	*C.* gr. *murrayi*						•			•
				E	•	*S. fossilis*									
					•	*D. tubifer*					•	•			•
					•	*H. carteri* + *Helicosph.* sp.					•	•		•	•
					•	*Pontosphaera* ssp.						•			
					•	*U. irregularis*					•				•
					•	*T. heimii*						?			
					•	*F. profunda*									•
					•	*U. tenuis*									•

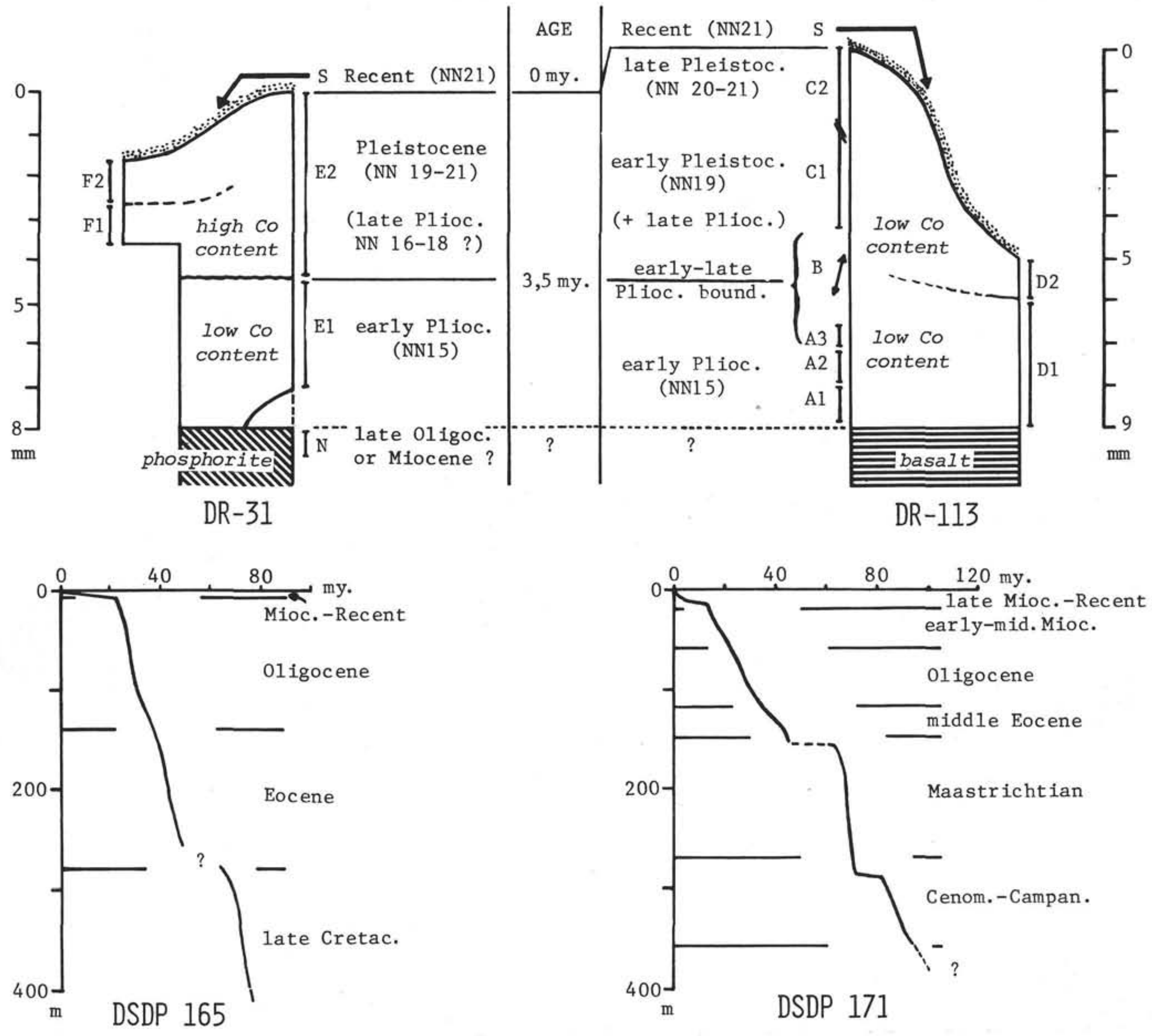

Fig. 5: Correlation between the growth phases of the SONNE-18 crusts and the sediment accumulation rates at the neighbouring DSDP sites. DSDP sites after WINTERER (1973, fig. 1); water depth: 5053 m for site 165 and 2290 m for site 171.

4. Conclusion

Detailed SEM investigation of the Calcareous Nannofossil imprints included in the SONNE-18 concretions allowed to reconstruct the history of the crust. The polymetallic oxide was deposited during two main stages: the first one in early Pliocene (NN15), the second between late Pliocene and Recent (principally NN19). These periods coincide with the abrupt decrease of the sedimentation rate measured in the Neogene of the neighbouring DSDP sites (Fig. 5), that may be explained by an increase in deep-water circulation related to late Cenozoic glaciation (WINTERER, 1973).

A correlation between Plio–Pleistocene glaciation and Mn-oxide precipitation, such as suggested by WATKINS & KENNET (1972), CONOLLY & PAYNE (1972) and GLASBY (1978), was also noted for deep-sea manganese nodules from the Clarion-Clipperton Zone associated with diatom (*Ethmodiscus*) oozes (JANIN & PERSON, 1986). A major Plio–Pleistocene growth phase was also found in other nodules from the Clarion-clipperton Zone (Von STACKELBERG, 1979; 1982), from the Western and Central Pacific (HARADA & NISHIDA, 1976; 1979; HARADA, 1978), in crusts from the Tuamotu Archipelago (JANIN, 1985a) and from the Portuguesean Margin (JANIN, 1981a,b). This time interval may be a world-wide favourable period for Mn-oxide precipitation.

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Plate 1

Figs. 1,4: *Calciosolenia* gr. *murrayi*.
 1: Calcareous specimen; surface of DR-31.
 4: Imprint; DR-113.

Figs. 2,5: *Discoaster* gr. *brouweri*.
 2: Calcareous specimen; surface of DR-113.
 5: Imprint; DR-113.

Figs. 3,6: *Discoaster* sp., displaying dissolution figures in their central area.
 3: Calcareous specimen; Trinidad (Oropuche field, NN5).
 6: Imprint; DR-113.

Figs. 7,10,13: *Ceratolithus cristatus* s.l.
 7: Imprint; DR-113.
 10: Calcareous specimen; surface of DR-31.
 13: Imprint of flange part; DR-31.

Fig. 8: *Discoaster* gr. *brouweri* (b, at left) and *D.* gr. *deflandrei* (d, at right).
 Imprints; DR-113.

Figs. 9,12,15: *Discoaster* gr. *variabilis*.
 9,15: Imprints; DR-113.
 12: Calcareous specimen; surface of DR-113.

Figs. 11,14: *Discoaster* gr. *deflandrei*.
 11: Calcareous specimen from the Marquesas Formation (Clarion-Clipperton Zone).
 14: Imprint; DR-113.

Scale bar = 2 μm.


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Fig. 13
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Plate 2

Emiliania, Gephyrocapsa and related forms (compare with text-fig. 1 and table 2).

Figs. 1,4,7,8: *Emiliania huxleyi*.
- 1: Calcareous specimens, associated with *F. profunda* (at right) and *U. sibogae* (bottom); surface of DR-31.
- 4: distal imprint of distal shield (type 1+A, lower part) and of proximal shield (type 3+A, upper part) with truly molded central grill; DR-113.
- 7: Distal imprint of distal shield (type 1+A); Dr-113.
- 8: Proximal imprint of distal shield (type 2−A, at left) and of proximal shield (type 4−A, at right); DR-113.

Figs. 2,3,5,6: *Gephyrocapsa* gr. *protohuxleyi*.
- 2: Epigenised specimen (arrow) among other unidentified small placoliths; DR-31.
- 3: Distal imprint (type 1+A); DR-113.
- 5: Distal imprint of distal shield (type 1−A, lower part) and of proximal shield (type 3−A, upper part) showing I-shaped elements; DR-113.
- 6: Similar imprint of a form with a solid proximal shield; DR-113.

Fig. 9: *Gephyrocapsa* or small Reticulofenestrid.
Proximal imprint of distal shield (type 2−A); DR-113.

Fig. 10: *Gephyrocapsa* ssp.
Two calcareous specimens illustrating the variability of the group; surface of DR-31.

Figs. 11,12,15 (at right): *Emiliania annula*.
- 11: Calcareous specimen; ooze associated with Mn-crust from Tuamotu Archipelago.
- 12,15: Distal imprints (type 1+A); DR-113.

Fig. 13: *Gephyrocapsa* cf. *oceanica*.
Proximal imprint of distal shield (type 2+A) showing the bridge mold (arrow); DR-113.

Figs. 14,15 (at left): *Emiliania ovata*.
Distal imprint (type 1+A); DR-113.

Fig. 16: *Gephyrocapsa* sp.
Oblique section, imprint; DR-113.

Scale bar = 1 μm.

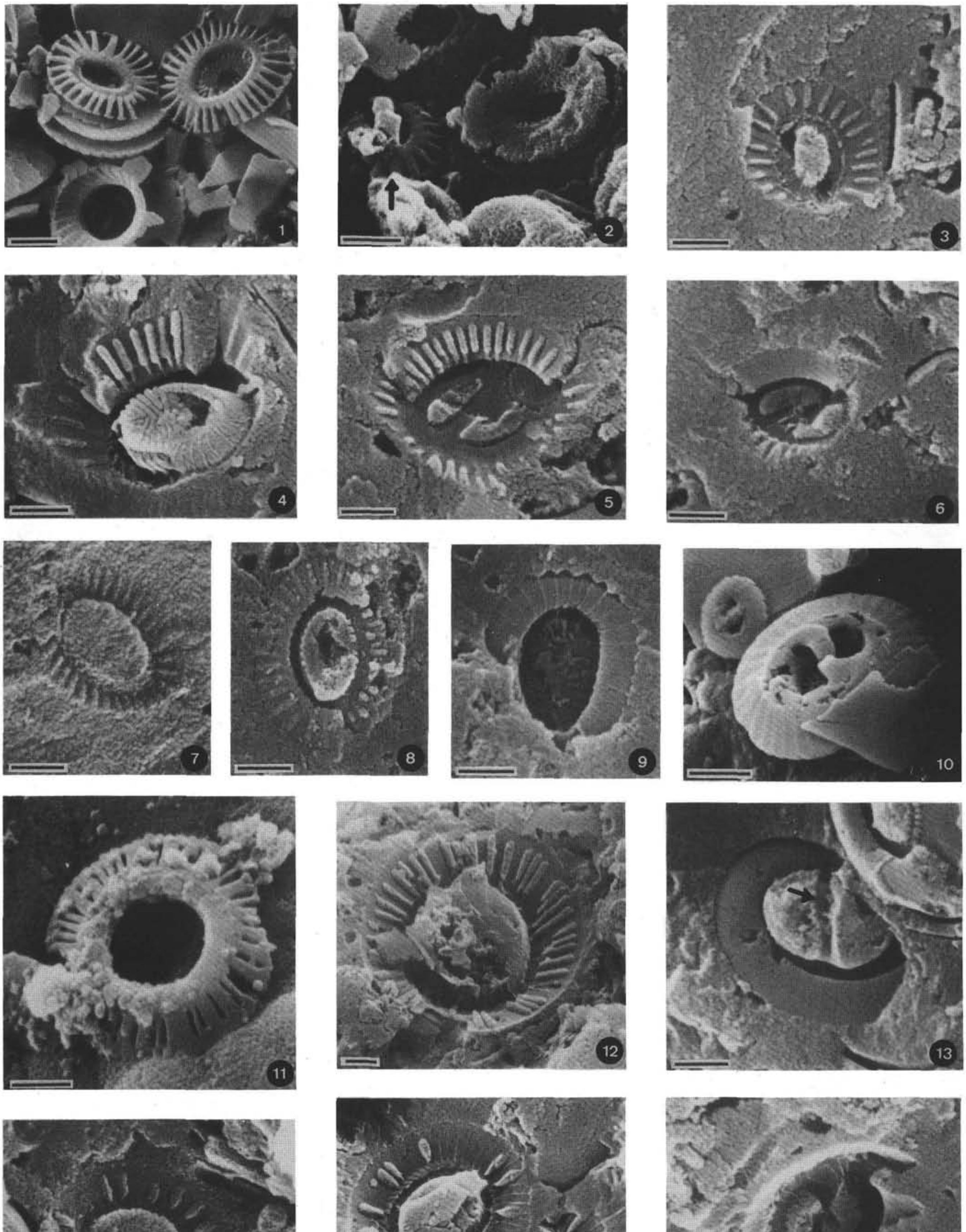
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Plate 3

Figs. 1,4: *Helicosphaera carteri.*
1: Proximal side of a calcareous specimen; surface of DR-31.
4: Proximal imprint, DR-113.

Fig. 2: *Reticulofenestra* sp. (large form).
Distal imprint, with mold of the central grill; DR-113.

Figs. 3,6,9: *Syracosphaera pulchra.*
3: Calcareous specimen, proximal side; surface of DR-31.
6: Proximal (= outer) imprint; DR-113.
9: Distal (= inner) imprint; DR-113.

Figs. 5,8: *Pontosphaera* gr. *discopora.*
5: Calcareous specimen, proximal side; surface of DR-31.
8: Distal (= inner) imprint of discolith, the arrow shows the wall place; DR-113.

Fig. 7: *Helicosphaera* sp.
Transverse section of mold (compare with text-fig. 2); DR-113.

Figs. 10,13: *Oolithotus fragilis fragilis.*
10: Calcareous specimen, distal side; surface of DR-31.
13: Distal imprints (o), associated with a mold of small placolith (p); DR-113.

Fig. 11: *Neosphaera coccolithomorpha.*
Calcareous specimen, distal side; surface of DR-31.

Figs. 12,15: *Oolithotus perplexus.*
12: Calcareous specimen, proximal side; ooze associated with crust from Tuamotu Archipelago.
15: Proximal imprint; DR-113.

Fig. 14: *Neosphaera coccolithomorpha* (n; note the trace of the central collar mold: arrow) and *Oolithotus fragilis cavum* (o).
Distal imprints; DR-113.

Scale bar = 2 μm.

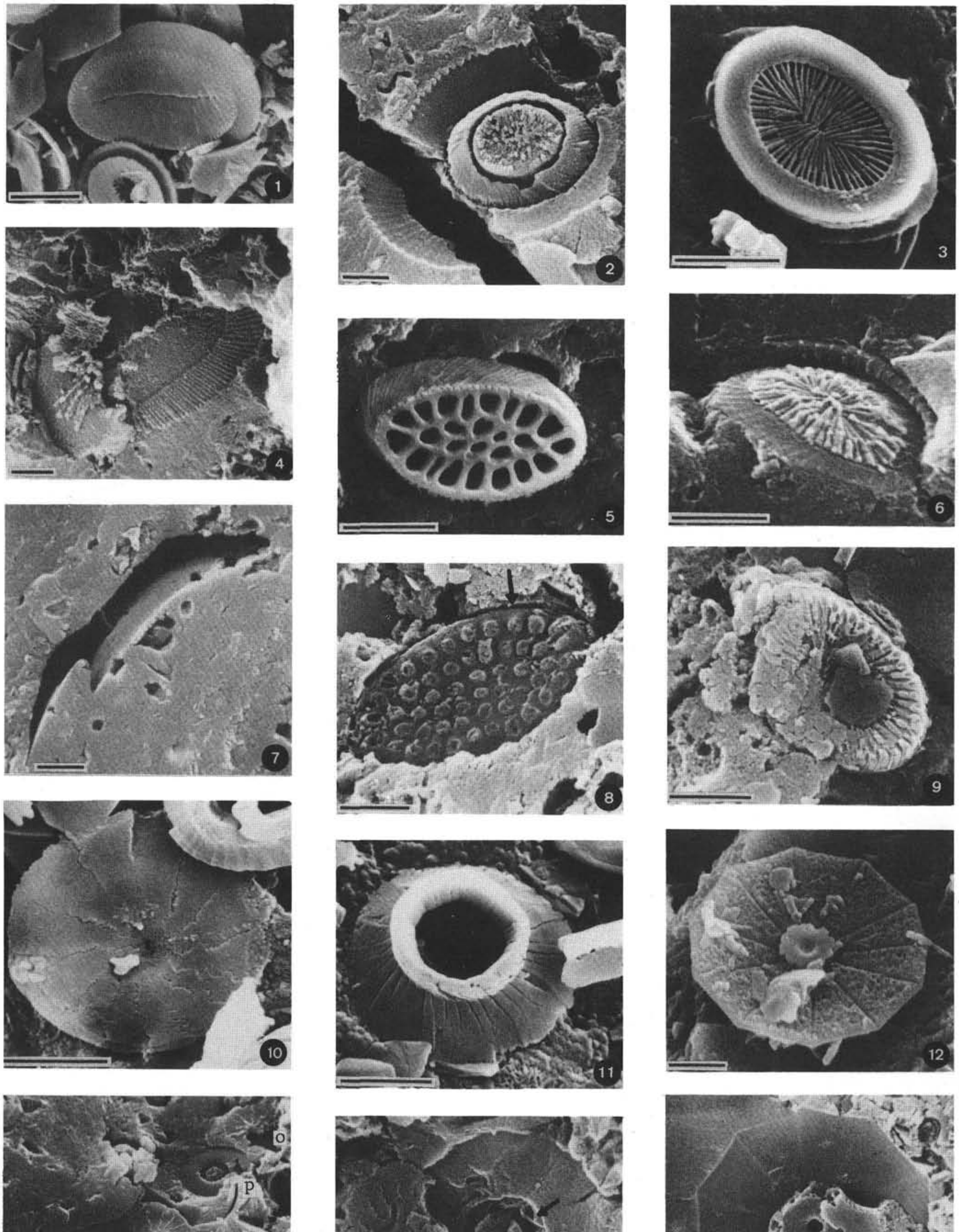
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Plate 4

Figs. 1,4,7,8,11: *Rhabdosphaera claviger*, appendixed form.
1: Calcareous specimen; surface of DR-31.
4,8,11: Longitudinal section of molds of stem (tip: 4, median part: 8, base: 11); DR-113.
7: Cross-section of stem mold; DR-113.

Figs. 2,5: *Sphenolithus neoabies*.
2: Calcareous specimen; ooze associated with Mn-crust from Tuamotu Archipelago.
5: Longitudinal section of imprint; DR-113.

Figs. 3,6,10: *Umbilicosphaera sibogae sibogae*.
Distal imprints of forms with small (3,6) or wide (10) central area; DR-113 (3,10) and DR-31 (6).

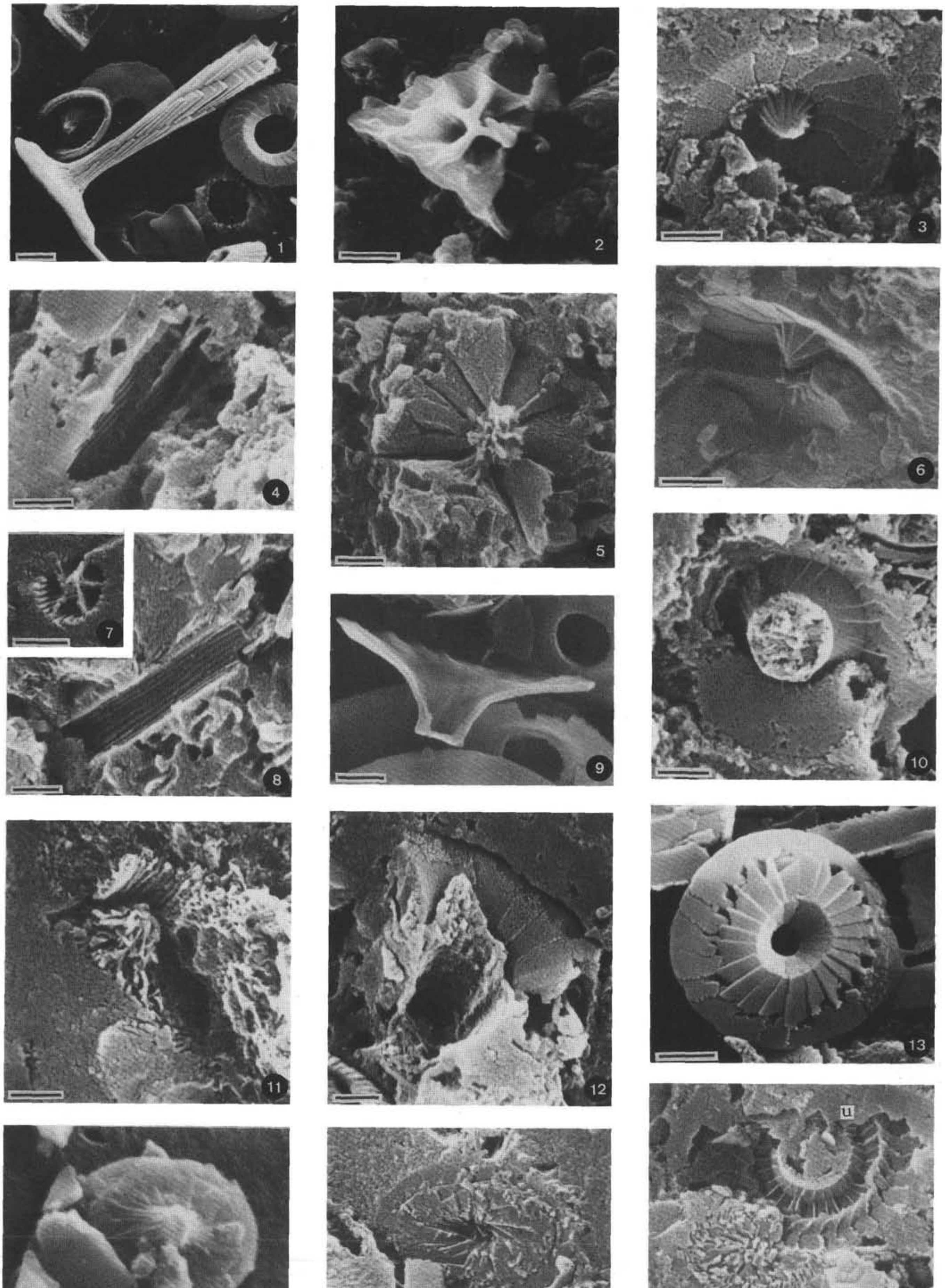
Figs. 9,12: *Umbellosphaera irregularis*.
Cross sections.
9: Calcareous specimen; surface of DR-31.
12: Imprint, DR-113.

Fig. 13: *Umbilicosphaera sibogae foliosa*.
Calcareous specimen; surface of DR-31.

Figs. 14,15: *Rhabdosphaera claviger*.
Unappendixed form.
14: Calcareous specimen, distal side. Ooze associated with crust from Tuamotu Archipelago.
15: Distal Imprint; DR-113.

Fig. 16: *Umbilicosphaera sibogae foliosa* (u, distal imprint) and *R. claviger* (r, proximal imprint); DR-113.

Scale bar = 1 μm.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