

FORAMINIFERAL BIOSTRATIGRAPHY OF THE OLIGOCENE-MIOCENE LIMESTONES OF CHRISTMAS ISLAND (INDIAN OCEAN)

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ABSTRACT. Foraminifera indicative of the Tertiary Lower *e*, Upper *e*, and Lower *f* 'Stages' of the East Indian Letter Classification are recognized in the post-Eocene limestones of Christmas Island. The local ranges of *Spiroclypeus globulus* Nuttall (here regarded as a junior synonym of *S. margaritatus*), *Miogypsina neodispansa* (Jones and Chapman), *Lepidocyclina (Eulepidina) ephippioides* (J. and C.), and *L. (E.) andrewsiana* (J. and C.)—for all of which this small island is the type area—are determined. Five faunal assemblages are recognized, and one new species, *Heterostegina barriei*, described.

CHRISTMAS ISLAND lies almost 320 km south of Java and has an area of about 140 km². It is basically a truncated volcanic cone, capped with about 190 m of mainly flat-lying Cenozoic limestones, rising some 2450 m from the floor of the eastern part of the Indian Ocean. The island is heavily forested, the best natural exposures of limestone being in the steep inland cliffs. The area was active tectonically throughout Tertiary times, and the sedimentary succession is much affected by faulting. The geology was originally described by Andrews (1900), the only recent accounts being a paper by Trueman (1965) and an unpublished report by Barrie (1967) for the British Phosphate Commissioners.

The Tertiary foraminifera of the island were first described by Jones and Chapman (*in* Andrews 1900) on the basis of 58 poorly localized rock samples which failed to yield a recognizable faunal sequence owing to the uncertainty of their stratigraphical relationships. However, a number of new species were described, the most important being *Lepidocyclina (E.) andrewsiana*, *L. (E.) ephippioides*, *L. (E.) murrayana*, *L. insulaenatalis*, and *Orbitoides (Lepidocyclina) neodispansa*; some of these names subsequently came into general use throughout the region. The main part of the limestone was thought to be of early Miocene age, but of the few samples which appeared to have been taken from at or near the base of the succession in the area of Flying Fish Cove, no. 595 contained planktonic foraminifera (including *Orbulina*) now known not to occur below Blow's zone N. 9 (approximately base of Lower *f*), while samples 924 and 220 yielded *Miogypsina*, a genus which appears first in strata of Upper *e* age in Indonesia. The faunas from these three samples therefore conflicted with the evidence for the age (Lower *e*) of the overlying beds. Nuttall (1926) revised the orbitoids with the aid of additional sections cut from Andrews's samples, and cleared up some of the confusion caused by the poor original descriptions. However, Tan (1936) noted that the published descriptions of *Miogypsina neodispansa* were still inadequate for the satisfactory establishment of its systematic position. Ludbrook (1965) described the fauna from 22 isolated samples collected from different parts of the island. Although Nuttall and Ludbrook both contributed to our knowledge of the faunas, neither had access to material which would have enabled them to solve

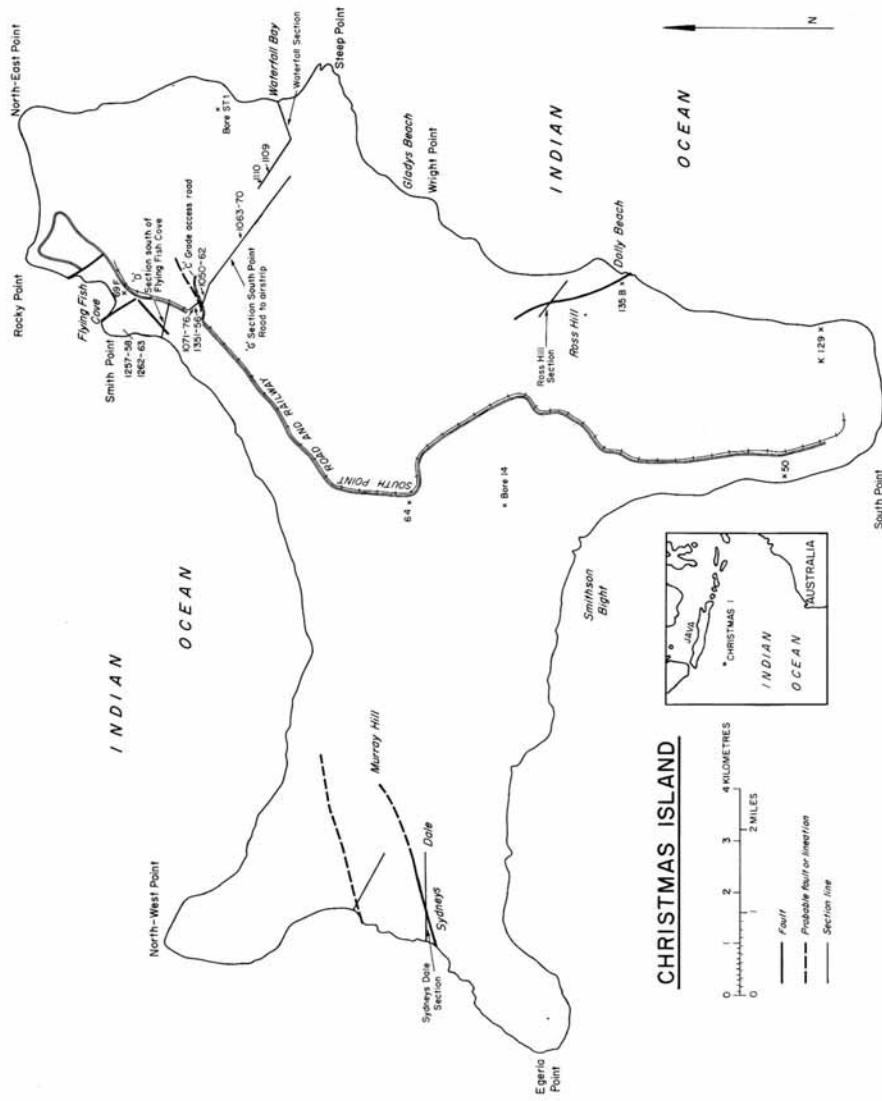
the basic stratigraphical problems. In 1965 Mr. J. M. Barrie, then with the Commonwealth Bureau of Mineral Resources, carried out a geological survey of the island for the British Phosphate Commissioners; material collected by him showed conclusively that the base of the 'Miocene' limestones was older than *insueta* Zone, but otherwise added little to our knowledge of the island's stratigraphy. One of us (D. J. B.) therefore visited the island in 1967 and collected more than 200 samples in stratigraphical order along the five traverses shown on text-fig. 1. Although the results presented here are based primarily on this material, all the previous collections have been re-examined and evaluated in interpreting the biostratigraphy.

Of the three anomalous samples collected by Andrews and referred to earlier, that containing *Orbulina* (595) was undoubtedly obtained from one of the plankton-rich fissure infillings which occur in Flying Fish Cove. The occurrence of *Miogypsina neodispansa* in samples 220 and 924 is more difficult to explain. Mr. P. J. Barrett and Mr. D. A. Powell recently collected further material (G. 840; G. 852-860) from a poorly exposed yellowish limestone in contact with the basalt at the point where Andrews obtained rock no. 924. Nine of these samples yielded *M. neodispansa*; the fauna of the yellowish limestone cannot be traced laterally, and two samples collected immediately above (G. 861-862) contain a Lower *e* stage fauna. Mr. Barrett considers the yellowish limestone to be different from others in the area, and regards it as being formed also as a result of fracture filling, perhaps of a tension fracture which was gradually opening as the island underwent adjustment. This seems to be the only explanation for a younger limestone directly against the basalt with an older limestone at a higher level. It is unfortunate that the limestone occurs at the northern end of a fault zone where the succession is obscure. Sample 220 is probably from the same locality.

Throughout this paper the East Indian Letter Stages are used in the sense of Adams (1970). Table 1 equates the Oligocene and early Miocene parts of this classification with the current European terminology.

Epoch	European Stage	Letter Stage
MIOCENE	M — Serravallian —	f
	— Langhian —	
	E — Burdigalian —	Upper e (=e5)
	— Aquitanian —	
OLIGOCENE	L — Chattian —	Lower e (=e1-4)
	M — Rupelian —	d
	E — Lattorian —	c

TABLE 1. Approximate correlation of the mid-Tertiary Letter Stages with the conventional stage terminology of Europe. (Only part of the *f* stage is shown here.)



TEXT-FIG. 1. Map of Christmas Island showing principal traverses and other important sample localities.

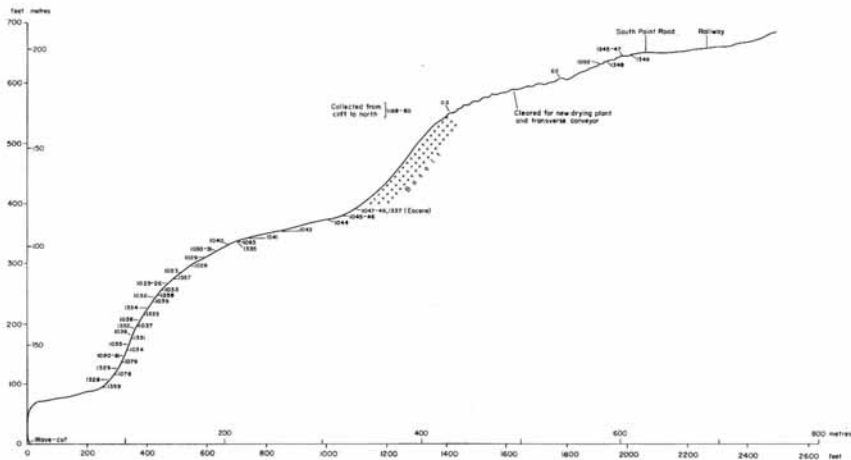
LITHOLOGY, STRATIGRAPHY, AND FAUNAL SUCCESSION

The greater part of the succession is made up of foraminiferal and algal debris in a matrix of carbonate mud. Molluscs, corals, and coral debris are present in many samples, but only in 'G' Traverse is there direct evidence for a coral reef. The limestone contains few planktonic foraminifera except in fissure infillings. Assemblages of miliolids and peneroplids known to be characteristic of shallow-water sheltered environments (e.g. lagoons) occur at many levels, whereas foraminifera believed to be typical of higher energy environments are virtually restricted to Assemblage 1. The post-Eocene limestones are seen to rest on basalt or tuff wherever they are exposed, although the contact is usually obscure; in some places it is certainly a fault plane but in others may be an erosion surface with a limestone breccia or conglomerate above. In the traverses detailed below, the base of the limestone rests on basalt. Some traverses have been named after localities in which they occur; others are differentiated by letters assigned by Barrie (1967). The discontinuity of sample numbers in the traverses resulted either from difficulty of access, particularly in 'D' Traverse, so that several visits were necessary at different times, or from further collecting in order to check particular parts of traverses after preliminary examination of samples on the island.

On discovering that the faunal sequence was difficult to interpret, we decided to take no risks with the identification of species thought to be of age-diagnostic value. The distribution charts (text-figs. 3, 5, 7, 9, 10) are, therefore, more complex than usual. Whenever we have been unable to see the diagnostic characters of a species (a common situation when random thin sections of limestone are studied), we have recorded it simply as 'X' sp. Thus, in 'D' Traverse (text-fig. 3) we recognize *Miogypsina (Miogypsinoides) bantamensis*, *M. (Miogypsinoides) complanata*, *M. (Miogypsinoides) cf. complanata*, and *M. (Miogypsinoides) sp.* This, we believe, fairly reflects the difficulties encountered in distinguishing individual species when the critical characters vary in the degree to which they are visible.

'D' Traverse (text-fig. 2). A stream traverse on the north side of the island immediately south-west of Flying Fish Cove. Fifty samples were available from the south side of the stream and nine from the north side. A further 15 samples had been collected previously by Barrie. The sequence here has a vertical thickness of about 165 m. The lower part of the sequence is composed entirely of skeletal calcarenites and limestone breccias, the faunas of which show no signs of reworking. Above sample 1170 the limestones are calcarenitic micrites or true skeletal calcarenites. Calcareous algae are common throughout.

The lowermost 73 m of rock contains a fauna which includes *Lepidocyclina (Eulepidina) spp.*, *Miogypsina (Miogypsinoides) bantamensis*, *Spiroclypeus margaritatus*, *Sorites cf. orbiculus*, *Borelis spp.*, and rare specimens of *Austrotrillina striata*. From about 122 m the hillside is covered with limestone boulders and basalt rubble, no exposure of solid rock being visible. Thin sections cut from several of the boulders revealed a fauna similar to that occurring at higher levels in the succession, and it seems probable that the rocks have fallen more than 45 m to their present positions. At about 114 m the sequence is faulted, about 4.5 m of Eocene limestone being introduced at this level. These Eocene beds are terminated abruptly by basalt, which



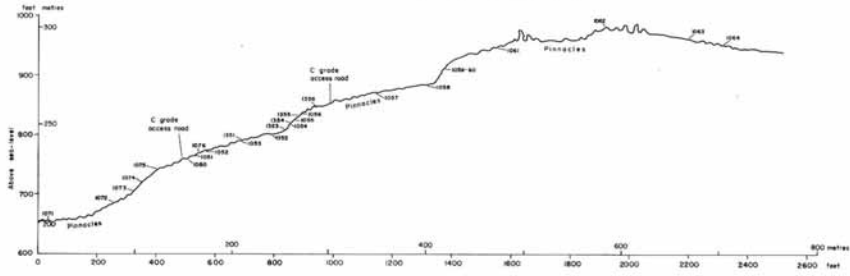
TEXT-FIG. 2. Profile of 'D' Traverse.

LEGEND
P = Present
X = Rare (< 3 specimens)
O = Few (3-10 "
● = Common (10-25 "
■ = Abundant (> 25 "

TRaverse	SAMPLE NO.																																			
		50p	1019	1020	1021	1022	1023	1024	1025	1026	1027	1028	1029	1030	1031	1032	1033	1034	1035	1036	1037	1038	1039	1040	1041	1042	1043	1044	1045	1046	1047	1048				
<i>ACERVELLINA</i> , <i>BORQUINIA</i> , <i>KANAKAIYA</i>	P	P																																		
<i>CARPENTERIA</i> , <i>SPORADOTREMA</i> spp																																				
<i>OPERCULINA</i> sp																																				
<i>LEPIDOCYCLINA</i> (E) sp				X																																
<i>CYCLOCYPRUS</i> cf. <i>EIDAE</i>																																				
<i>MILIOLIDS</i>			●	●																																
<i>AMPHISTEGINA</i> spp																																				
<i>GYPSSINA GLOBULA</i>			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
<i>BORELIS PYGMAEUS</i>						X																														
<i>BORELIS</i> spp			X						X																											
<i>SORITES</i> cf. <i>ORBICULUS</i>			X	X		O																														
<i>HETEROSTEGINA BARRIETI</i>			●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
<i>HETEROSTEGINA</i> sp																																				
<i>SPINDOCYPRUS MARGARITATUS</i>																																				
<i>M. (MIDGYPSINOIDES) BANTAMENSIS</i>																																				
<i>LEPIDOCYCLINA (E) OPHIOPHOIDES</i>																																				
<i>LEPIDOCYCLINA</i> sp. (B form)																																				
<i>M. (MIDGYPSINOIDES) cf. COMPLANATA</i>																																				
<i>SPINDOCYPRUS MARGARITATUS (BOBULUS) type</i>			●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
<i>AUSTROTRILLINA STRIATA</i>			X	X																																
<i>GYPSSINA DISCA</i>																																				
<i>LEPIDOCYCLINA (N) sp</i>																																				
<i>SPINDOCYPRUS</i> sp																																				
<i>M. (MIDGYPSINOIDES) COMPLANATA</i>																																				
<i>M. (MIDGYPSINOIDES) sp</i>																																				

ASSEMBLAGE 1 2 1

TEXT-FIG. 3. Foraminiferal distribution chart for 'D' Traverse. See text-fig. 2 for sample order.



TEXT-FIG. 4. Profile of 'G' Traverse.

produces a steep slope about 43 m high. The nature of the contact between the limestone and basalt is unknown. Immediately above the basalt the slope has been graded for the construction of a pilot washing and screening plant, and new 'C' grade calcination plant. The nearest continuous limestone exposure at this level is in a cliff about 10 m high beginning near Flying Fish Cove some 380 m to the north. This may be Andrews's locality 'at 500 feet running south from Flying Fish Cove'. If so, his sample 549 (containing *Borelis* and *Eulepidina*) must have been taken somewhere in this vicinity. The fauna in this small outcrop is dominated by *Heterostegina barriei* sp. nov. and *Spiroclypeus*; many of the foraminifera appear to be rolled and abraded. Barrie's sample D. 2 collected from the site of the washing and screening plant contains the same fauna, as do several samples collected between 189 and 195 m (i.e. just below the South Point Road).

'G' Traverse (text-fig. 4). This, in effect, is a continuation of 'D' Traverse to the top of the island, but offset a little to the south. Twenty-seven samples were collected by

'G' TRAVERSE	LEGEND																										
	SAMPLE NO.	1063	1064	1061	1059	1060	1058	1057	1056	1055	1055	1054	1054	1053	1052	1051	1053	1052	1051	1050	1075	1074	1073	1072	1071		
<i>SPIROCLYPEUS MARGARITATUS</i>																	●	○	●		○		●	●	●	■	
<i>MILIOLIDS</i>									■		■	X	X	X	X	○	○		○	X	○	○	○	○	○	○	
<i>SORITES cf. ORBICULUS</i>	X	○						?	●	X		X	X	X				X				X	X				
<i>AUSTROTROLLINA STRIATA</i>								X	○	X								X	X						?		
<i>HETEROSTEGINA</i> sp.																		X	X						X		
<i>CARPENTERIA, SPORADOTREMA</i> spp.	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P		
<i>BORELIS</i> spp.									○	X													X				
<i>ACERVULINA, BORDONIA, KENAKAJA</i> spp.	P	P									P	P	P	P	P	P											
<i>AMPHISTEGINA</i> spp.	■	■	X	X	X	○					○		X														
<i>SPIROCLYPEUS</i> sp.													○														
<i>M(MIDGYPSINOIDES) DENAARTI</i>			■	■	?	■																					
<i>TAYAMAIA MARIANENSIS</i>					?																						
<i>AUSTROTROLLINA</i> sp.	X																										
ASSEMBLAGE																											

TEXT-FIG. 5. Distribution chart for 'G' Traverse. See text-fig. 4 for sample order.

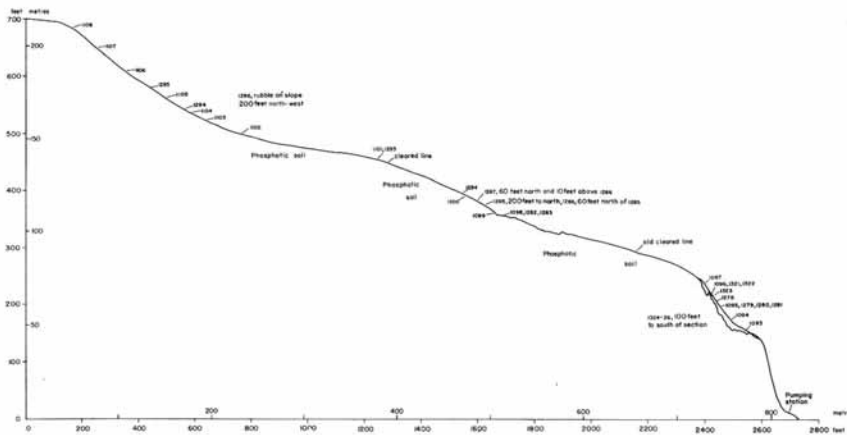
Belford and seventeen by Barrie, through a vertical distance of 100 m. The succession is relatively well exposed between the railway line and the 'C' Grade access road, but is then rather poorly exposed up to the level of *M. dehaarti*. At higher levels the outcrop is fairly continuous. The lower and upper parts of the sequence are formed of skeletal calcarenites, but between 220 and 250 m corals and calcareous algae are well developed and may represent a true reef.

The microfauna of the lower part of the section is characterized mainly by the presence of *Sorites*, *Austrorillina striata*, and *Spiroclypeus margaritatus*. *Eulepidina* and *Miogypsina* (*Miogypsinoides*) are absent. At about 270 m there is a facies change and *M. (Miogypsinoides) dehaarti* occurs in abundance, accompanied by *Carpen-teria* and *Amphistegina*. At this level the rock becomes a true foraminiferal coquina for the first time.

The combined thicknesses of 'D' and 'G' Traverses total about 270 m, of which at least 4.5 m is Eocene limestone and 44 m basalt.

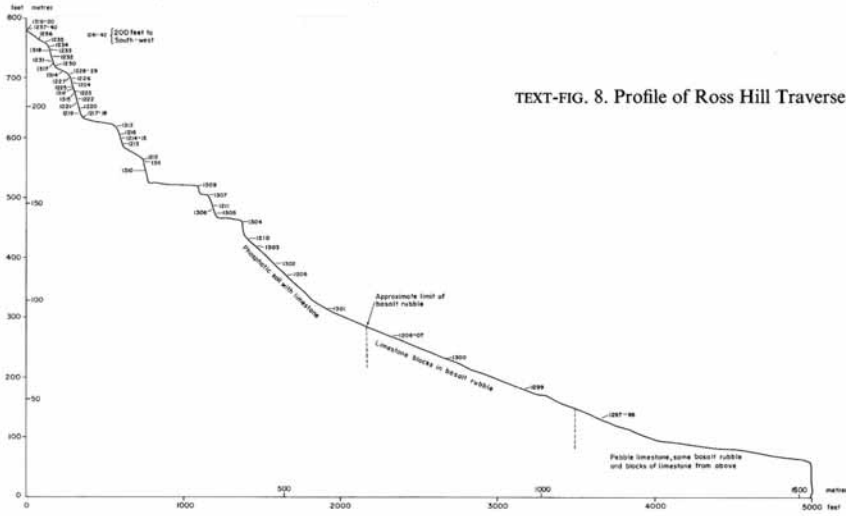
Waterfall Traverse (text-fig. 6). Thirty-seven samples were collected by Belford and Barrie from about 161 m of strata exposed in this traverse on the eastern side of the island. The lithology is remarkably uniform throughout the traverse, the limestone consisting essentially of calcilitic skeletal calcarenites.

Six samples from the lowest 15 m yielded no species of age-diagnostic value. *Heterostegina barriei* appears in sample 1095 and continues up to the 121 m level (sample 1284). The upper part of the traverse is characterized by the occurrence of *Tayamaia marianensis*, a species which has not been found *in situ* on the western side. *Miogypsina (Miogypsinoides)* is fairly common throughout the section. A single specimen of *Lepidocyclina* in 1095 is clearly redeposited. The Waterfall Traverse thus seems to be equivalent to 'G' Traverse plus the top of 'D' Traverse (Eocene beds excluded) on the north-west side of the island.



TEXT-FIG. 6. Profile of Waterfall Traverse.

TEXT-FIG. 8. Profile of Ross Hill Traverse.



ROSS HILL TRAVERSE	LEGEND		SAMPLE NO.																																		
	P Present	X Rare (<3 specimens)	1-129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160			
<i>CAMPENTERA, SPORADOTREMA</i> spp.			P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P		
<i>AMPHISTEGINA</i> spp.			X																																		
<i>MIMODIPSYNDOS</i> sp.																																					
<i>HEROSTEGINA BARRIETI</i>																																					
<i>MILICULUS</i>																																					
<i>SPIROCLYPELUS MARGARITATUS</i> (<i>SCORILLUS</i>) type																																					
<i>MIMODIPSYNDOS</i> BANTAMENSIS																																					
<i>MIMODIPSYNDOS</i> DENHAARTI																																					
<i>ACERVULINA, BORDONIA, KANAKAIA</i> spp.			P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P		
<i>GYPSINA GLOBULA</i>																																					
<i>BORELIS</i> spp.			X	X	X	X																															
<i>SORITES</i> cf. <i>ORBICULUS</i>			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
<i>SPIROCLYPELUS</i> sp.																																					
<i>NOTALIA</i> sp.																																					
<i>AUSTROTRELLINA STRIATA</i>																																					
<i>MIMODIPSYNDOS</i> COMPLANATA																																					
<i>BORELIS PYGMAEUS</i>			X	X	X																																
<i>TAYAMIA MARIANENSIS</i>			X																																		
<i>PENEROPLIS</i>																																					
<i>MARGINOPORA VENTRALIS</i>																																					
<i>OPERCULINA</i> sp.																																					
<i>MIMODIPSYNDOS</i> cf. <i>NEOISPANSA</i>																																					
<i>AUSTROTRELLINA HOWCHINI</i>																																					
<i>FLOSCULINELLA BONTANGENSIS</i>																																					
<i>P. ARCHIALES</i> sp.																																					
ASSEMBLAGE			5					4					3					2																			

TEXT-FIG. 9. Foraminiferal distribution chart for Ross Hill Traverse. See text-fig. 8 for sample order.

SYDNEY'S DALE TRAVERSE	LEGEND																				
	SAMPLE No	1136	1134	1133	1132	1130	1129	1128	1127	1246	1126	1125	1245	1124	1123	1122	1121	1120	1119	1244	
<i>CARPENTERIA, SPORADOTREMA</i> spp				P	P	P	P	P							P	P	P	P	P	P	P
<i>AMPHISTEGINA</i> spp		●			●	○									X	○					○
<i>OPERCULINA</i> sp.									X		X					X					X
<i>SORITES</i> cf. <i>ORBICULUS</i>				X	●													X	○	X	
<i>M. (MIOGYPSINOIDES)</i> cf. <i>BANTAMENSIS</i>								X	X						○			X		○	
<i>AUSTROTROLLINA STRIATA</i>					X															X	X
<i>M. (MIOGYPSINOIDES)</i> <i>DEHAARTI</i>															■			○		●	
<i>TAYAMAIA MARIANENSIS</i>				X		X	X	X													○
<i>DISCOCYCLINA</i> spp										X	X		X								X
" <i>ROTALIA</i> " spp	■			■	X	○	●		■	○	●	○	○		■		●		■		■
<i>BORELIS</i> spp				?	X												X	X			
<i>SPIROCLYPEUS</i> sp.			X	X	X		X	X													○
<i>MILIOLIDS</i>				○				●													■
<i>GYPSINA GLOBULA</i>		X		?	X	X	X	X	●	X	X	●	■			○	X				
<i>LEPIDOCYCLINA (E.)</i> sp.															○						
<i>HETEROSTEGINA</i> cf. <i>SAIPANENSIS</i>												?	X	○							
<i>GYPSINA DISCA</i>										X											
<i>ACERVULINA, BORODINIA, KANAKAIA</i> spp				P	P	P		P													
<i>LEPIDOCYCLINA (N.)</i> sp.								X													
<i>M. (MIOGYPSINOIDES)</i> cf. <i>DEHAARTI</i>				○	X	X		X													
<i>M. (MIOGYPSINA)</i> cf. <i>NEDDISPANSA</i>					X		X														
<i>BORELIS PYGMAEUS</i>			X		X	X															
<i>M. (MIOGYPSINA)</i> sp.				X		X															

TEXT-FIG. 10. Foraminiferal distribution chart for Sydney's Dale Traverse. Topographically highest sample on the left, lowest on the right.

text-fig. 10) contain reworked Eocene foraminifera. These, however, are never numerous. The occurrence of *Miogypsina (Miogypsinoides) dehaarti* and *Tayamaia marianensis* in the lowest sample (1244) indicates that no part of the sequence is older than Assemblage 3.

The frequency of occurrence of each species on the distribution charts (text-figs. 3, 5, 7, 9, 10) has been determined as the maximum number observed in any one thin section from a sample. Because of their large size, B forms of *Lepidocyclina (Eulepidina)* in the 'D' Traverse are recorded only as present. Encrusting genera are similarly treated since individual specimens tend to be badly fragmented, rendering counts meaningless.

AGE OF THE FAUNAS

Five faunal assemblages have been recognized within the post-Eocene limestones, Assemblages 1 and 2 probably being in part laterally equivalent (see below):

1. *Lepidocyclina* (*Eulepidina*) *ephippioides*/*M. (Miogypsinoidea) bantamensis*/*Spiroclypeus margaritatus* Assemblage. These species form the bulk of this Assemblage which is seen only in 'D' Traverse. Age: Lower *e*.

2. *Heterostegina barriei*/*Spiroclypeus margaritatus* Assemblage. Well developed in 'D' Traverse and also seen in the Waterfall Traverse. Age: Lower *e*, on the presence of *M. (Miogypsinoidea) complanata* in a few samples.

3. *M. (Miogypsinoidea) dehaarti*/*Tayamaia marianensis* Assemblage. Seen in the Waterfall and Ross Hill Traverses where it is well developed; also occurs in Sydney's Dale. Age: Upper *e*.

4. *Miogypsina*/*A. howchini* Assemblage. Seen in stratigraphical sequence only in the Ross Hill Traverse, although isolated samples are known from the vicinity of Flying Fish Cove and Sydney's Dale. Age: Upper *e*.

5. *Austrotrillina howchini*/*Flosculinella bontangensis* Assemblage. Believed to be restricted to a thin zone at the top of the succession and so far observed only in the upper part of the Ross Hill Traverse. Age: Lower *f*.

These faunas tend to grade into one another and their constituent species are not necessarily mutually exclusive. Hence, *M. (M.) bantamensis* and *Spiroclypeus margaritatus* may be found in Assemblage 3, as may *Austrotrillina howchini*. Long-ranging species such as *Gypsina globula* (Reuss), *Borelis pygmaeus* Hanzawa, and *Sorites* cf. *orbiculus* (Forskål) occur throughout the greater part of the succession.

The faunal sequence shows certain peculiarities. Occurrences of *M. (Miogypsinoidea) complanata* in sample 64 (near Jedda Cave), samples 1302 and 1303 (Ross Hill Traverse), and D. 3 in the 'D' Traverse, either within or above the range of *M. (M.) bantamensis*, are anomalous. In each sample, all the numerous specimens of miogypsinids appear to have long nepionic spires, thus ruling out the possibility that we are dealing merely with a few reworked individuals. It might be argued that sample 64 has been raised to its present high position by faulting, but this explanation will not suffice for samples 1302 and 1303, sample D. 3, and 135B (Dolly Beach), in each of which *M. (M.) complanata* occurs with foraminifera typical of Assemblage 2.

Although the oldest Tertiary *e* limestones appear to be those in the lower part of 'D' Traverse on the north-west side of the island, they have evidently reached their present position by faulting. They are nowhere seen immediately beneath the Assemblage 2 faunas in a continuous section. There is, therefore, a definite possibility that Assemblage 1 may be partly or entirely the lateral equivalent of Assemblage 2, the composition of the faunas reflecting differences in the local environment of deposition rather than any significant stratigraphical change. However, the occurrence of *M. (M.) complanata* with *Spiroclypeus* and *Heterostegina barriei* at Dolly Beach, Ross Hill, and in the 'D' Traverse strongly suggests that the lower part of Assemblage 2 is slightly older than the lowest beds yielding Assemblage 1 in 'D' Traverse. This interpretation would explain the occurrence of rolled and abraded specimens of *Eulepidina* (nearly always microspheric forms) in Assemblage 2, and the absence or rarity of encrusting genera in Assemblage 1.

Lower *e* is now believed (Adams 1970) to be equivalent to the upper Oligocene (Chattian) of Europe, Upper *e* to the lower Miocene (Aquitanian and Burdigalian in the type areas), and Lower *f* to the early middle Miocene.

The minimum thickness of post-Eocene limestone on the island (assuming that Assemblages 1 and 2 are laterally equivalent) is about 190 m. If they are not equivalent, the figure increases to 265 m. In this connection, it may be noted that a borehole in the South Point area was abandoned while still in limestone at 244 m (pers. comm., D. A. Powell), whereas another hole (no. 14) on the plateau north-east of Smith Point reached basalt at 167 m. A stratigraphic bore ST. 1, Jones Spring, north of the Waterfall Traverse, passed through 23 m of Tertiary *e* limestone and 55.5 m of basalt before entering an upper Eocene (Tertiary *b*) limestone.

SYSTEMATIC PALAEOLOGY

The limestones of Christmas Island are rich in microfossils, which, unfortunately, have had to be examined mainly by means of random thin sections. Only a few oriented sections could be prepared owing to the difficulty of freeing individual specimens from the hard rock matrix. This rendered specific determinations difficult, especially for genera such as *Miogypsina*, *Cyclocypeus*, and *Lepidocyclina*, in all of which the nature of the embryonic apparatus is of critical importance.

It is usually impossible to determine the range of variation of species seen only in random sections, since two or more species of the same genus may be present in the rock. For this reason no serious taxonomic revisions are attempted here. Synonymies are restricted to the original description, to previous records from Christmas Island and, where appropriate, to important recent redescriptions.

Special mention must be made of the work of Jones and Chapman (1900). These authors based their descriptions on a very small number of thin sections (one or two per sample) and misinterpreted many of the specimens. Not only did they mistake *Miogypsina* (*Miogypsinoides*) for *Heterostegina*, and *Miogypsina* (*Miogypsina*) for *Orbitoides* (*Lepidocyclina*), but they failed to distinguish between specimens now referred to *Spirocypeus* and *Lepidocyclina*. They also erected new species on shape and size alone, disregarding the possibility that these characters might be highly variable. Nuttall (1926), in revising the orbitoids, corrected most of their taxonomic errors.

Figured specimens prefixed CPC are deposited in the Commonwealth Palaeontological Collection, Bureau of Mineral Resources, Canberra, Australia; those prefixed P are deposited in the Palaeontology Department, British Museum (Natural History), London, England. Thin sections representative of the samples referred to in this paper are deposited in both Canberra and London.

Family MILIOLIDAE Ehrenberg, 1839

Genus AUSTROTRILLINA Part, 1942

This genus was revised by Adams (1968) and nothing new can be added here. The commonly occurring species on Christmas Island is *A. striata*, but at high levels in the succession it is replaced by forms transitional to *A. howchini*.

Austrorillina howchini (Schlumberger)

Plate 73, fig. 7

- 1893 *Trillina howchini* Schlumberger, p. 119, text-fig. 1, pl. 3, fig. 6.
 1968 *Austrorillina howchini* (Schlumberger); Adams, p. 86, pl. 2, figs. 1-7; pl. 6, figs. 1-5, 7.

Remarks. Associated with *Miogypsina* in the upper part of the Ross Hill Traverse. Ludbrook's record (1965, p. 291) of *A. howchini* in association with *Flosculinella bontangensis* was an error; these species have not been observed together either in the original slides from sample P. 33 or in material subsequently obtained from this locality. There is, however, no reason why *A. howchini* should not be found with *F. bontangensis*, since their ranges are known to overlap elsewhere in the region (e.g. Australia; Crespin 1955). All the individuals seen so far are fairly primitive forms lacking the greatly thickened wall so characteristic of the end members of the lineage.

Austrorillina striata Todd and Post

Plate 73, fig. 6

- 1954 *Austrorillina striata* Todd and Post, p. 555, pl. 198, fig. 9.
 1965 *Austrorillina howchini* (Schlumberger); Ludbrook, p. 292, pl. 21, figs. 4-6.
 1968 *Austrorillina striata* Todd and Post; Adams, p. 92, pl. 4, figs. 1-13; pl. 6, fig. 9.

Remarks. *A. striata* occurs at intervals throughout the Tertiary *e* limestones. Its first occurrence is in sample 1334 ('D' Traverse); its last, in sample 1228 (Ross Hill Traverse). At higher levels it is replaced by fairly primitive forms of *A. howchini*.

Family SORITIDAE Ehrenberg, 1839

Genus SORITES Ehrenberg, 1839

Type species. *Sorites dominicensis* Ehrenberg = *Nautilus orbiculus* Forskål.

Sorites cf. orbiculus (Forskål)

Plate 74, figs. 2, 10

- 1775 *Nautilus orbiculus* Forskål, p. 125.
 1965 *Sorites martini* (Verbeek); Ludbrook, pp. 290-292.
 1965 *Sorites orbiculus* (Forskål); Cole, p. 20, pl. 6, figs. 1-5, 7, 9; pl. 7, figs. 1-8, 10-12; pl. 8, figs. 7-9.
 1969 *Sorites orbiculus* (Forskål); Cole, p. C5, pl. 3, figs. 7, 8, 16; pl. 4, figs. 3-7.

Remarks. This long-ranging species occurs throughout the entire Oligocene-Miocene sequence. It is never abundant, random sections usually showing one or two individuals only. Cole (1969) gave reasons for regarding this form as *S. orbiculus* rather than *S. martini*, the name applied by most previous authors to Tertiary *e* specimens. In the absence of good equatorial sections it is impossible to be certain that some specimens do not belong to *S. marginalis* (Lamarck).

Genus MARGINOPORA Blainville, 1830

Type species. *Marginopora vertebralis* Blainville.

Marginopora vertebralis Blainville

Plate 74, fig. 11

1830 *Marginopora vertebralis* Blainville, p. 377.

Remarks. Individuals referable to this species occur in a few samples from the upper part of the Ross Hill Traverse in Assemblages 3–5. Unfortunately, they are not numerous and no well oriented sections have been obtained.

Family ALVEOLINIDAE Ehrenberg, 1839

Genus BORELIS de Montfort, 1808

Type species. *Nautilus melo* var. B Fichtel and Moll, 1798.

Borelis pygmaeus Hanzawa

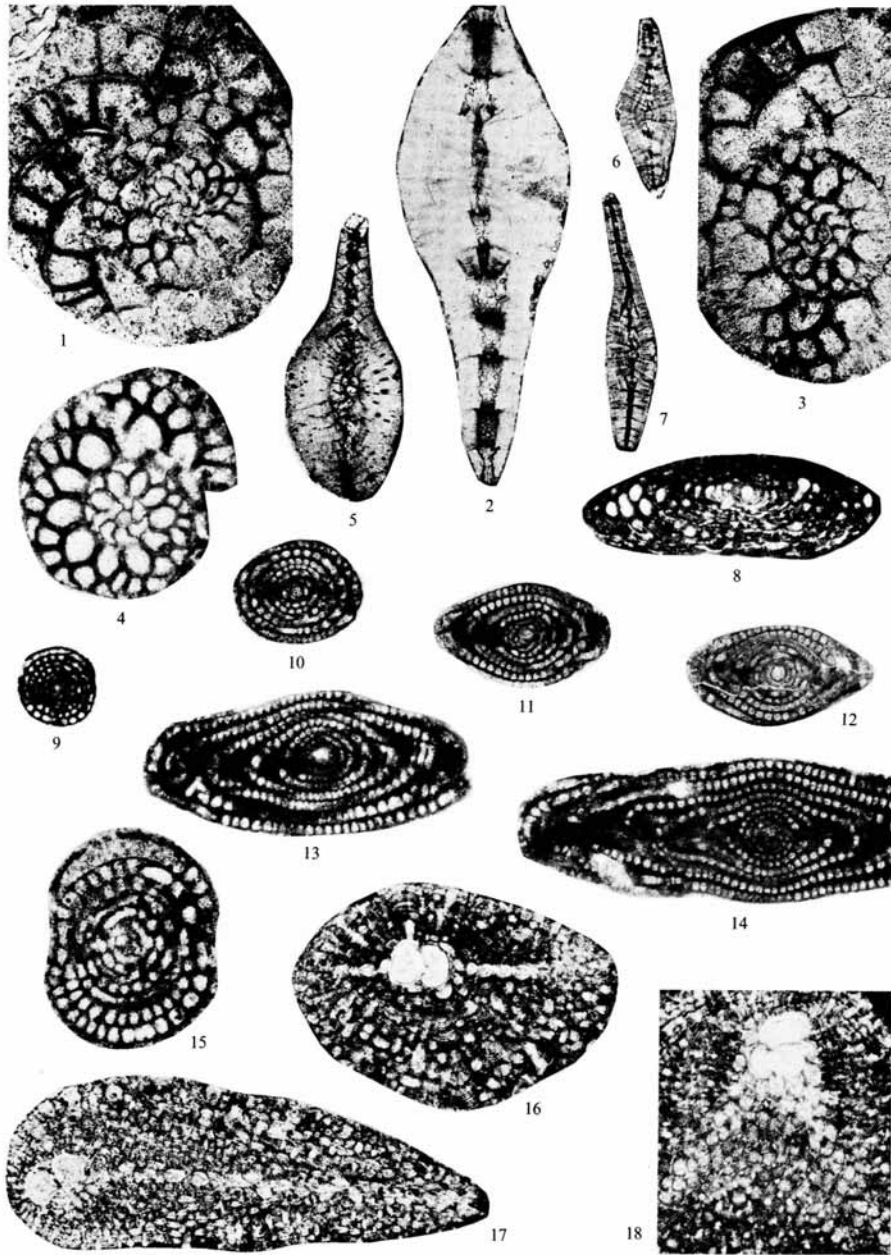
Plate 71, figs. 9–14

1900 *Alveolina melo* (Fichtel and Moll); Jones and Chapman, p. 255.1930 *Borelis (Fasciolites) pygmaeus* Hanzawa, p. 94, pl. 26, figs. 14 and 15.1965 *Borelis pygmaeus* Hanzawa; Ludbrook, p. 292, pl. 21, figs. 7 and 8.

Remarks. This well-known species is common in Assemblages 1 to 3. Small inflated forms of *Borelis*, very like the Recent *B. pulchrus*, also occur at some horizons and seem to grade into *B. pygmaeus*. Cole (1969) referred all such specimens from Midway to *B. melo*. However, the typical *B. melo*, from the middle Miocene of the Mediterranean region and the Middle East, is a strongly inflated form (usually higher than wide) which shows no axial thickening and tends to develop supplementary chamberlets (*B. melo curdica*). *B. pulchrus* and *B. pygmaeus* always show a tendency towards axial thickening, are rarely, if ever, higher than wide, and do not develop supplementary chamberlets. This is not the place, nor is the present material appropriate, for a

EXPLANATION OF PLATE 71

- Figs. 1–4. *Heterostegina barriei* sp. nov. From 'D' Traverse; all $\times 60$. 1, paratype A, CPC. 13734, median section, sample 1173. 2, paratype B, CPC. 13735, transverse section, sample 1180. 3, holotype, CPC. 13733, slightly oblique median section, sample 1168. 4, paratype C, CPC. 13736, median section, sample 1170.
- Figs. 5–7. *Heterostegina* cf. *borneensis* van der Vlerk. All transverse sections, $\times 10$. 5, CPC. 13737, oblique transverse section, sample G837, Flying Fish Cove. 6, CPC. 13738, transverse section, sample G838, Flying Fish Cove. 7, CPC. 13739, transverse section, sample G837, Flying Fish Cove.
- Fig. 8. *Tayamaia marianensis* (Hanzawa), CPC. 13740, sample 1216, Ross Hill Traverse, $\times 30$.
- Figs. 9–14. *Borelis pygmaeus* Hanzawa. Specimens from 'D' Traverse showing variation in shell size and form. 9, CPC. 13741, sample 1356, off-centre, slightly oblique section, $\times 40$. 10, CPC. 13742, sample 1334, slightly off-centre axial section, $\times 40$. 11, CPC. 13743, sample 1334, slightly off-centre axial section, $\times 40$. 12, CPC. 13744, sample 1037, axial section, $\times 48$. 13, CPC. 13745, sample 1333, slightly off-centre axial section, $\times 40$. 14, CPC. 13746, sample 1080, off-centre axial section, $\times 40$.
- Fig. 15. *Borelis melo* (Fichtel and Moll). Axial section P. 49087, from the Miocene of Turkey, $\times 50$, introduced for comparison with *B. pygmaeus*.
- Figs. 16–18. *Miogypsina (Miogypsina) neodispansa* (Jones and Chapman). All from Andrews's sample no. 220, south side of Flying Fish Cove. 16, P. 49088, transverse section, $\times 30$. 17, P. 49089, oblique transverse section, $\times 24$. 18, P. 49090, slightly oblique median section showing embryonic apparatus, $\times 30$.



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revision of the genus *Borelis*. We are therefore retaining Hanzawa's specific name, while drawing attention to the similarity between these specimens and the Recent *B. pulchrus* and *B. pulchrus schlumbergeri*. The difference between *B. pulchrus schlumbergeri* and *B. melo* is very well illustrated by Reiss and Gvirtzman (1966, pls. 1 and 2).

Genus FLOSCULINELLA Schubert, 1910

Type species. Alveolinella bontangensis Rutten, 1913.

Flosculinella bontangensis (Rutten)

Plate 74, fig. 3

1913 *Alveolinella bontangensis* Rutten, p. 221, pl. 14, figs. 1-3.

1965 *Flosculinella bontangensis* (Rutten); Ludbrook, p. 292, pl. 21, fig. 13.

Remarks. This species is known only from the uppermost beds in the Ross Hill Traverse. It has been found associated with *Amphistegina*, *Sorites* and encrusting genera. However, *Austrotrillina howchini* occurs at about the same level and is known to have co-existed with *F. bontangensis* elsewhere in the region.

Flosculinella sp.

Remarks. A single individual was seen in Barrie's sample 69F (Batu Merah, Flying Fish Cove). It is impossible to decide whether this specimen should be referred to *F. reicheli* Mohler or to *F. globulosa* (Rutten). However, its occurrence with an Assemblage 2 fauna almost certainly means that the genus can no longer be relied on to mark the base of Upper *e*.

Family NUMMULITIDAE Blainville, 1825
Subfamily CYCLOCYPEINAE Butschli, 1880
Genus CYCLOCYPEUS Carpenter, 1856

Type species. C. mammilatus Carter, 1861.

Cycloclypeus cf. *eidae* Tan Sin Hok

1932 *Cycloclypeus eidae* Tan Sin Hok, p. 50, pl. 5, fig. 6; pl. 12, figs. 2-3; pl. 13, fig. 2.

1965 *Cycloclypeus* cf. *eidae* Tan Sin Hok; Ludbrook, p. 291.

Remarks. This species is rather rare. It occurs in a number of samples from 'D' Traverse (Assemblage 1); Ludbrook reported it from sample P. 52, Flying Fish Cove.

Genus HETEROSTEGINA d'Orbigny, 1826

Type species. H. depressa d'Orbigny.

Heterostegina barriei sp. nov.

Plate 71, figs. 1-4

1900 *Heterostegina depressa* d'Orbigny; Jones and Chapman, pp. 244 and 252. Not p. 229, pl. 20, fig. 1.

This species is named after Mr. J. M. Barrie, in whose samples it was first recognized.

Description of holotype. Test small, with evolute primary chambers arranged in 3 rapidly expanding whorls. Proloculus and deutoconch minute, followed by 5 operculine chambers. Secondary septa long, and well developed from their first appearance. No ornament visible.

Dimensions. Diameter 1.0 mm (test incomplete). Internal diameter of proloculus 0.05 mm; external diameter of proloculus and second chamber 0.091 mm.

Variation. Other specimens show that the diameter of the test ranges at least up to 2.1 mm, although the flange is almost always broken. The number of operculine chambers ranges from 5 to 8, and the number of whorls from 3 to 3½. Secondary septa are always long. Although no ornament has been observed, its presence cannot be entirely ruled out since small pustules do not always show up in random sections.

Locality and horizon. Holotype from sample 1168, 'D' Traverse, at base of the limestone outcrop at this locality. This species is characteristic of Assemblage 2. Age: Lower *e*.

H. barriei appears to differ from all other described species of the genus in being unusually small (under 2 mm average diameter) and in having a very small embryonic apparatus followed by from 5 to 8 operculine chambers in the megalospheric form. It most closely resembles *H. granulata* subsp. *praeformis* Papp and Kupper from the middle Miocene of southern Europe, but is smaller and has long secondary septa only. *H. suborbicularis* d'Orbigny is the commonly reported Tertiary *e* species in the Indo-Pacific region, but this is involute and has very many more operculine chambers (cf. Cole 1969, pl. 3, figs. 1-5, 18).

Heterostegina cf. *borneensis* van der Vlerk, 1929

Plate 71, figs. 5-7

Remarks. Specimens probably referable to this species have been seen in a few samples (G. 837, G. 838, and G. 862) from Flying Fish Cove. They are two or three times the size of the largest specimens of *H. barriei*, and the two species have not been seen in association. A positive identification is, unfortunately, impossible in the absence of sections showing the embryonic apparatus and first whorl.

Genus OPERCULINA d'Orbigny, 1825

Remarks. Specimens occur at intervals throughout the succession. They are rarely numerous and appear to be specifically indeterminable in random sections. It is possible that more than one species is represented.

Genus SPIROCLYPEUS Douvillé, 1905

Type species. *S. orbitoides* Douvillé.

At least eleven nominal species of this genus have been described from Tertiary *e* strata in the Indo-West Pacific region, and although attempts have been made to distinguish between them (e.g. Krijnen 1931), authors have found the greatest difficulty in naming specimens satisfactorily. It is undoubtedly significant that no

one has yet described a succession in which even a few of these species have been shown to succeed one another in time, and as Cole (1969) has pointed out, several authors have found two or three so-called species in the same beds. Cole (1969) therefore assigned seven of the 'species' occurring in the Tertiary *e* rocks of the region to *S. margaritatus* (Schlumberger). Although first inspection of the present material suggested that several species were represented, closer examination indicated that transitional forms occur. This, together with the absence of any obvious pattern of stratigraphical distribution, strongly suggests that only one species is present despite the wide range of morphological variation.

Spiroclypeus occurs abundantly only in 'D' Traverse. It is common at some levels in 'G' Traverse, but well-oriented individuals have not been seen. It occurs in four samples near the base of the Ross Hill Traverse, but except in 1302, specimens are rare and specifically indeterminable. It is also present in four samples from the succession in Sydney's Dale.

Spiroclypeus margaritatus (Schlumberger)

Plate 72, figs. 1-11

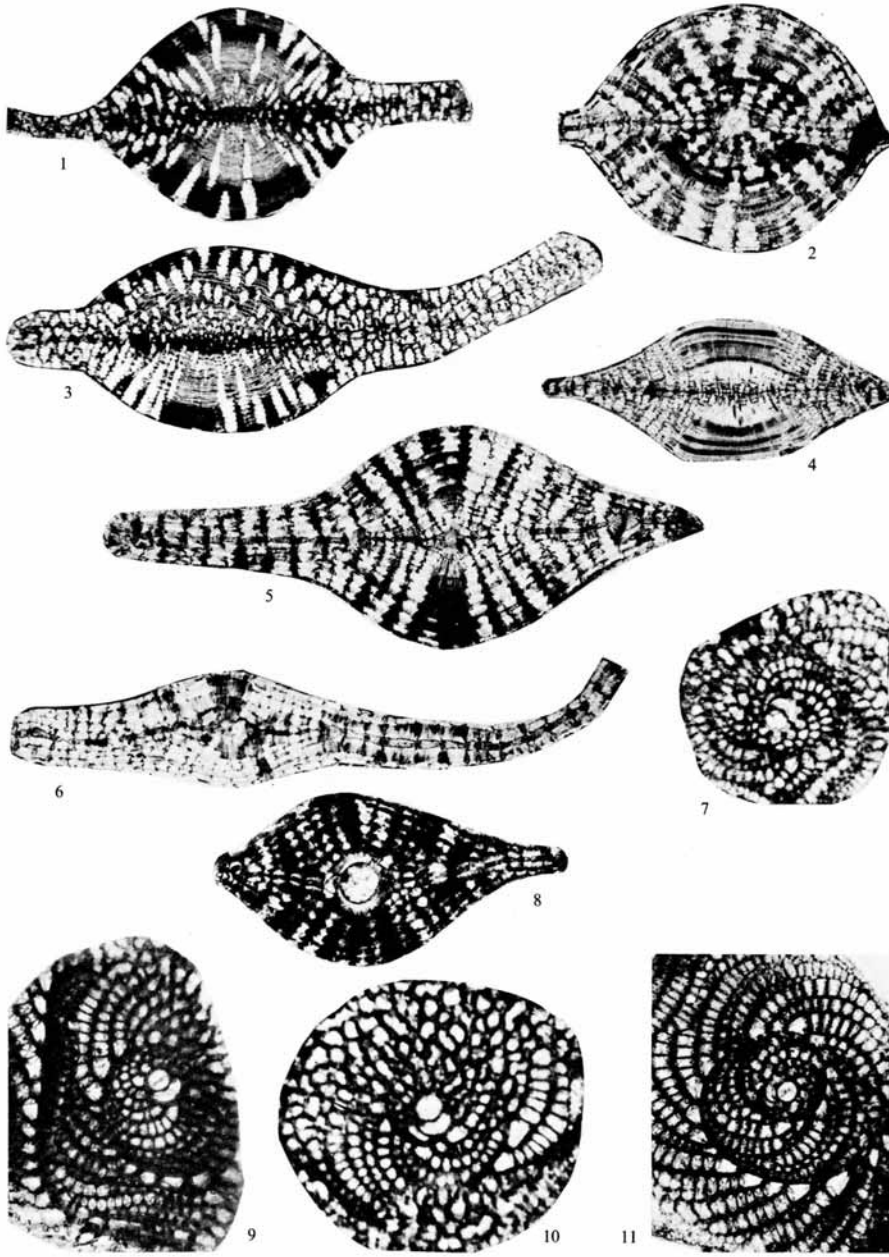
- 1900 *Orbitoides (Lepidocyclina) sumatrensis* Brady; Jones and Chapman, p. 244, pl. 20, fig. 6.
 1902 *Heterostegina margaritatus* Schlumberger, p. 252, pl. 7, fig. 4.
 1926 *Spiroclypeus globulus* Nuttall, pp. 36, 37, pl. 5, figs. 5-7, text-fig. 1.
 1965 *Spiroclypeus globulus* Nuttall; Ludbrook, p. 291, pl. 22, fig. 3.
 1969 *Spiroclypeus margaritatus* (Schlumberger); Cole, p. C8, pl. 2, figs. 1-20; pl. 3, figs. 9-14, 19 (synonymy).

Remarks. The highly inflated form (*S. globulus* of Nuttall) of this species is common to abundant throughout the upper part of 'D' Traverse (Assemblage 2). However, it is usually abraded and shows signs of having been rolled and redeposited. The flange is rarely preserved except in the thicker and stronger 'B' forms. It occurs also in Assemblage 2 at the base of the Ross Hill Traverse and in Assemblages 2 and 3 at Waterfall.

The chief variation in the present material is in the strength of the ornament, the number of lateral layers, and the width of the walls between the lateral chambers. Some highly inflated forms, particularly those of the microspheric generation, seem to possess a single umbonal pillar (Pl. 72, fig. 4); however, this effect can also be produced by sections through thickened lateral walls (see Pl. 74, fig. 13).

EXPLANATION OF PLATE 72

Figs. 1-11. *Spiroclypeus margaritatus* (Schlumberger). All except fig. 7 from 'D' Traverse. 1, CPC. 13747, sample 1172, off-centre transverse section through microspheric form, $\times 10$. Note thick pseudo-pillars and compare with figs. 3 and 4. 2, CPC. 13748, sample 1177, typical transverse section through inflated form ('*S. globulus*' of Nuttall), $\times 20$. Most individuals from Christmas Island are of this type. 3, CPC. 13749, sample 1171, oblique transverse section showing pseudo-pillars, $\times 10$. Probably a microspheric form. 4, CPC. 13750, sample 1332, off-centre transverse section, probably through a microspheric form, $\times 10$. Note the massive umbonal pseudo-pillar and compare with *Lepidocyclina* sp., Plate 74, fig. 13. 5, CPC. 13751, sample 1026, slightly off-centre transverse section through megalospheric form, $\times 20$. 6, CPC. 13752, sample 1169, slightly off-centre transverse section through megalospheric form, $\times 20$. A more typical shape for the species, but not common on Christmas Island. 7, CPC. 13753, sample 1302, Ross Hill Traverse, median section through megalospheric form, $\times 20$. 8, CPC. 13754, sample 1172, transverse section, $\times 20$. 9, CPC. 13755, sample 1332, median section, $\times 20$. 10, CPC. 13756, sample 1036, median section, $\times 20$. 11, CPC. 13757, sample 1079, median section, $\times 20$.



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The only differences between *S. leupoldi* and *S. margaritatus* seem to be the inflation of the test and the number of lateral layers. No differences can be seen in equatorial sections obtained from samples near the base and top of 'D' Traverse (1332-1177).

Family MIOGYPSINIDAE Vaughan, 1928

Genus MIOGYPSINA Sacco, 1893

Type species. Nummulites globulina Michelotti, 1841.

Subgenus MIOGYPSINOIDES Yabe and Hanzawa, 1928

Type species. Miogypsina dehaartii van der Vlerk, 1924.

Subgenus MIOGYPSINOIDES Yabe and Hanzawa, 1928

Plate 73, figs. 1-5

1900 *Miogypsina complanata* Schlumberger, p. 330, pl. 2, figs. 13-16.

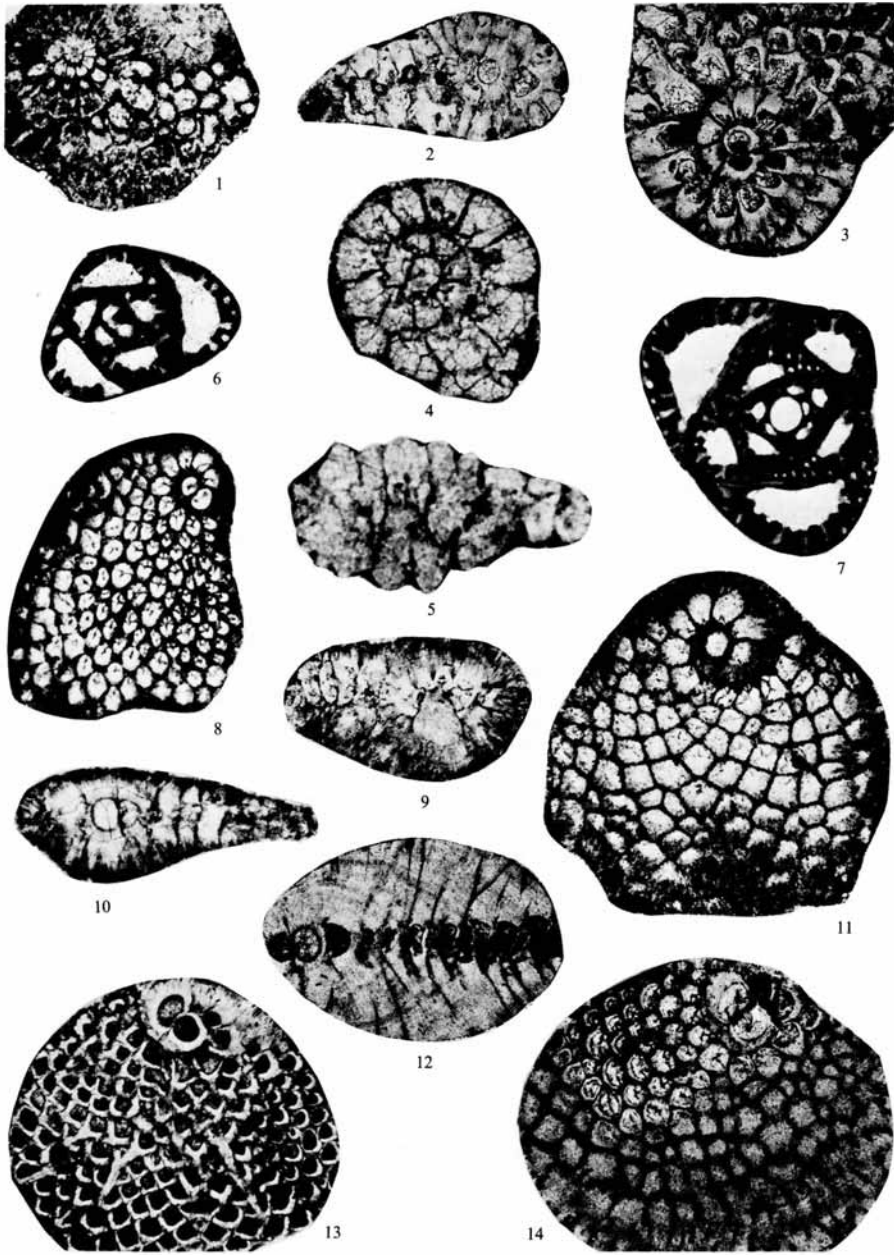
1936 *Miogypsinoides ubaghsi* Tan Sin Hok, p. 48, pl. 1, figs. 1-7.

Remarks. This primitive species is found at only four localities. It occurs in 1302 and 1303, Ross Hill Traverse (Assemblage 2); in Barrie's samples D. 3 from the 'D' Traverse and 135B above Dolly Beach (East Coast), each with an Assemblage 2 fauna; and it forms a true foraminiferal coquinite in Barrie's sample 64 near Jemma Cave in the centre of the island. Sample D. 3 is accurately located in the sequence; 64 and 135B are isolated samples which cannot at present be located relative to the local stratigraphical succession. Samples 1302 and 1303 are from a boulder-strewn slope and must be older than other samples collected from boulders occurring at lower levels along the same traverse. There are two possible explanations for this peculiar distribution. Either all rocks containing *M. (M.) complanata* are up-faulted relative to all those containing *M. (M.) bantamensis* or the ability to produce a long peribryonic spire had not been entirely lost by the time *M. (M.) bantamensis* evolved. The former explanation is considered to be the most likely since all the specimens seen in each sample appear to have the same grade of structure.

Cole (1969) argued that because *M. (M.) dehaartii*, *M. (M.) lateralis*, *M. (M.)*

EXPLANATION OF PLATE 73

- Figs. 1-5. *Miogypsina (Miogypsinoides) complanata* Schlumberger. 1, CPC. 13758, Ross Hill Traverse, sample 1302, oblique median section through microspheric form, $\times 30$. 2, CPC. 13759, Ross Hill Traverse, sample 1303, transverse section through megalospheric form, $\times 30$. 3, CPC. 13760, Ross Hill Traverse, sample 1303, median section through megalospheric form, $\times 30$. 4, CPC. 13761, 'D' Traverse (Barrie's sample D3), median section through megalospheric form, $\times 40$. 5, CPC. 13762, same locality as 4, off-centre transverse section, $\times 40$.
- Fig. 6. *Austrotrillina striata* Todd and Post, CPC. 13763, Ross Hill Traverse, sample 1303, off-centre transverse section.
- Fig. 7. *Austrotrillina howchini* (Schlumberger), CPC. 13764, Ross Hill Traverse, sample 1239, transverse section, $\times 50$.
- Figs. 8-11. *Miogypsina (Miogypsinoides) bantamensis* Tan Sin Hok, all $\times 30$. All from 'D' Traverse. 8, CPC. 13765, sample 1079, megalospheric form in median section. 9, CPC. 13766, sample 1334, off-centre transverse section. 10, CPC. 13767, sample 1079, transverse section of megalospheric form. 11, CPC. 13768, sample 1079, median section of megalospheric form.
- Figs. 12-14. *Miogypsina (Miogypsinoides) dehaartii* van der Vlerk. All from 'G' Traverse. 12, CPC. 13769, sample 1061, transverse section through megalospheric form, $\times 50$. 13, CPC. 13770, sample 1059, median section through megalospheric form, $\times 30$. 14, CPC. 13771, sample 1061, slightly oblique median section through megalospheric form, $\times 30$.



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mauretanicus, *M. (M.) formosensis*, and *M. (M.) bantamensis* could be shown to occur in association in one part of the region or another, only one species should be recognized. However, he failed to notice that the gradation is in time rather than in space. Hence, *M. (M.) complanata* is never found with *M. (M.) dehaarti*, whereas either (but not both) may occur with *M. (M.) bantamensis*.

Variation. Nepionic spire long (16–23 chambers in the A form), test relatively small (up to 1.3 mm in maximum diameter), lateral walls nearly always thin.

Miogypsina (Miogypsinoides) bantamensis Tan Sin Hok

Plate 73, figs. 8–11

1936 *Miogypsinoides complanata* (Schlumberger) forma *bantamensis* Tan Sin Hok, p. 48, pl. 1, fig. 13.

1940 *Miogypsinoides lateralis* Hanzawa, p. 783, pl. 39, figs. 10–14.

Remarks. Cole (1969) has argued that *M. (M.) bantamensis* is a junior synonym of *M. (M.) dehaarti* and that the two cannot be distinguished in the drill holes on Midway Atoll. However, if the principle of nepionic acceleration is valid, *M. (M.) bantamensis* must be slightly older than *M. (M.) dehaarti*. This is supported by the stratigraphical distribution of these two species on Christmas Island. *M. (M.) bantamensis* is common in Assemblage 1 ('D' Traverse) and also occurs in Assemblage 3 (Ross Hill and Sydney's Dale), although the paucity of well-oriented individuals renders identification difficult in many samples.

Present evidence suggests that the earliest representative of *M. (Miogypsinoides)* in the Indo-Pacific region (*M. (M.) complanata*) gradually underwent a shortening of the perieubryonic spire leading to the condition seen in *M. (M.) bantamensis*. This process continued until individuals recognizable as *M. (M.) dehaarti* were produced. This shortening of the spire was accompanied at first by an increase in the number of equatorial chambers, thus producing a larger test, and later by an increase in the thickness of the lateral walls. The shortening of the spire may have been linked with an increase in the internal diameter (volume) of the proloculus. The evolutionary sequence is tabulated below:

- | | |
|-------------------------------|-----------------------|
| 3. <i>M. (M.) dehaarti</i> | Upper <i>e</i> |
| 2. <i>M. (M.) bantamensis</i> | } Late Lower <i>e</i> |
| 1. <i>M. (M.) complanata</i> | |

As these changes in shell form were gradual and progressive, transitional forms occur between 1 and 2, and 2 and 3. However, *M. (M.) complanata* and *M. (M.) dehaarti* have never been found in natural association.

Cole's evidence from Midway is not opposed to this hypothesis. His figured specimens show an overall increase in the length of the spire with age.

Data from Cole (1969, pl. 1)

Depth	No. of chambers in spire (—)
595–600 ft	figs. 3 and 4 (7); figs. 1, 11, and 12 (9)
901–906 ft	figs. 9 (10); fig. 20 (9+); fig. 8 is a microspheric form
926–927 ft	figs. 5 and 6 (10); figs. 13, 14, 16, and 17 (13); figs. 18 and 19 (12+)

Hanzawa (1957) and others have attributed importance to the attitude of the embryonic chambers relative to the apex of the shell. However, this is determined by the length of the spire. Once median chambers have begun to form, the spire cannot be continued for more than half a turn (usually 7–9 chambers) without the typical fan shape being lost.

Variation. Periembrionic spire of medium length and formed of 9 to 13 chambers. Internal diameter of the proloculus 0.133 to 0.150 mm (six measured specimens). Test up to 2.2 mm long and 0.76 mm thick; always longer than wide.

Since this species evolved from *M. (M.) complanata* and into *M. (M.) dehaarti*, it follows that transitional forms occur and that an arbitrary specific diagnosis will not be satisfactory for the early and late representatives of the 'bantamensis' part of the lineage.

Miogypsina (Miogypsinoides) dehaarti van der Vlerk

Plate 73, figs. 12–14

- 1900 *Heterostegina depressa* d'Orbigny; Jones and Chapman, p. 257.
 1924 *Miogypsina dehaartii* van der Vlerk, p. 429, text-figs. 1–3.
 1965 *Miogypsinoides dehaarti* (van der Vlerk); Ludbrook, p. 293, pl. 21, figs. 9–11 and fig. 12 (part).

Remarks. Little can be added to previous descriptions. In the present material the nepionic spire consists of from 7 to 10 chambers of which the last few are usually very small. The test is usually wider than long, and the lateral walls are well developed. The test ranges up to 1.2 mm in thickness; some specimens have a strongly pustulate appearance, others are smooth.

This species forms a foraminiferal coquina in some samples (e.g. 1058, 1059, 1061, 'G' Traverse, and Andrews's no. 131, Flying Fish Cove); it is common in the Ross Hill and Waterfall sequences.

M. (M.) dehaarti occurs in Assemblages 3 and 4. It overlaps and grades into *M. (M.) bantamensis* in the lower part of Assemblage 3, and overlaps with *M. (Miogypsina)* cf. *neodispansa* in Assemblage 4. Ludbrook (1965) figured an association of *M. (M.) dehaarti* and *M. (Miogypsina) neodispansa*.

Miogypsina (Miogypsina) neodispansa (Jones and Chapman)

Plate 71, figs. 16–18, text-fig. 11

- 1900 *Orbitoides (Lepidocyclina) neodispansa* Jones and Chapman, pp. 235, 240, pl. 20, figs. 3 and 4.
 1926 *Miogypsina neodispansa* (Jones and Chapman); Nuttall, pp. 37, 38, pl. 5, fig. 4.
 1965 *Miogypsina neodispansa* (Jones and Chapman); Ludbrook, p. 290, pl. 2, fig. 12 (part).

Remarks. The original description of *M. (M.) neodispansa* is poor, and Nuttall's emendation little better since he gave no information about the nepionic spire, the one part of the test considered to be of diagnostic importance by modern workers.

Examination of numerous random sections has revealed the following variation in test morphology:

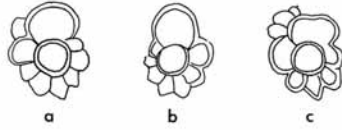
Size. The maximum diameter of the test ranges from 2 to 4 mm, and averages about 2.5 mm. The maximum thickness (1.6 mm in the type slides) is dependent on the number (6–12) of lateral chamber layers developed.

Surface ornament. This varies from finely to coarsely pustulate. The maximum diameter of the pustules is about 250 μm , but many individuals are ornamented with pustules not exceeding 50 μm in diameter.

Chamber shape and arrangement. The embryonic and median chambers do not always lie in the same plane, a feature which makes the preparation of oriented thin sections rather difficult.

The median layer is composed of a few rhombic and many hexagonal chambers. This layer is not always flat, and wavy tests of the *M. (M.) bifida* and *M. (M.) polymorpha* types are quite common.

Embryonic apparatus. The internal diameter of the protoconch in most specimens falls within the range 0.12–0.20 mm. However, one individual in a sample from South Point has an initial chamber with a diameter of 0.25 mm. The deuteroconch is usually considerably larger than the protoconch. Two



TEXT-FIG. 11. Periembryonic spirals of three typical specimens of *Miogypsina neodispansa*. All from Andrews's sample 220, south side of Flying Fish Cove; (a) P. 49093, (b) P. 49092, (c) P. 49090.

protoconchal spirals are clearly visible, and some individuals seem also to possess a third spire (text-fig. 11) but this is much less clear. The two primary auxiliary chambers are usually unequal in size; the larger chamber usually gives rise to a spire of three chambers while the smaller produces a shorter spire of two chambers.

M. (M.) neodispansa was one of the first miogypsinids to be described from the Indo-West Pacific region, and as such is an important species. Its association with *M. (Miogypsinoides) dehaarti* and a fairly primitive form of *Austrotrillina howchini* fixes its position as Upper *e*, while the fact that it occurs fairly high in the succession (not very far below *Flosculinella bontangensis*) probably means that it is a late Upper *e* form.

It is still impossible to state clearly how *M. (M.) neodispansa* differs from other described Indo-West Pacific species of the genus. Further data on the periembryonic and median chambers of this and other species are required, and these await the collection of better material. However, present evidence suggests that *M. (M.) neodispansa* is more highly evolved than *M. (M.) thecideaformis* and *M. (M.) globulina* (= *M. (M.) kotoi*) since both protoconchal spires are well developed and the median chambers appear to be markedly hexagonal. On the other hand, it is less advanced than *M. (M.) indonesiensis* which has subequal primary auxiliary chambers and median chambers that are hexagonal throughout.

On the basis of individual specimens it would be possible to recognize four or five 'species' in the Christmas Island samples.

M. (M.) neodispansa occurs in great abundance in three samples from different parts of the island (Flying Fish Cove, nos. 220 and 924; South Point area, K. 129). Specimens probably referable to this species occur in three samples from the upper part of the Ross Hill Traverse.

Family LEPIDOCYCLINIDAE Scheffen, 1932
Genus LEPIDOCYCLINA Gmbel, 1870

Type species. Nummulites mantelli Morton 1833.

Christmas Island is the type locality for six species of *Lepidocyclina*, five of which were erected by Jones and Chapman (1900) on the basis of a small number of random sections through fourteen samples of limestone. Nuttall (1926), after having additional sections cut from the same material, recognized the following species: *Lepidocyclina andrewsiana* (Jones and Chapman), *L. ehippioides* (J. and C.), *L. (E.) ?formosa* Schlumberger (= *L. murrayana* J. and C.), *L. chapmani* Nuttall, *L. inaequalis* J. and C., and *L. insulaenatalis* J. and C. Ludbrook (1965) reported, but did not figure or describe, all six species from two samples (P. 132 and P. 52). None of these authors had access to material collected in stratigraphical order, and all used test shape and size as the basis for distinguishing between species; internal characters, although sometimes mentioned, were not used in a systematic manner.

The present material shows that *Lepidocyclina* occurs mainly in the north-west of the island. The megalospheric form of *Eulepidina* occurs most commonly in the lowermost 250 feet of 'D' Traverse (Assemblage 1). There is one doubtful occurrence (1095) in the Waterfall Traverse (Assemblage 2), and numerous inflated 'A' forms (*E. andrewsiana* type) occur in sample 1122 (Assemblage 3, Sydney's Dale Traverse). Individuals present in the higher part of 'D' Traverse (Assemblage 2) are mainly microspheric forms of the *chapmani/insulaenatalis* type and show obvious signs (breakage and abrasion) of redeposition. Many are coated with calcareous algae. No recognizable megalospheric forms are seen above sample 1030, other than a single specimen in sample 1045 (from a rolled boulder).

It is clear that *Eulepidina* is represented here by several types of test (flattened or disc-like; lenticular; saddle-shaped; and highly inflated with a flange), but so far as can be ascertained from random sections, gradation occurs between the different types. The fact that most of these can be found in two of the lowest samples (1328 and 1078) from 'D' Traverse, and that no type is restricted to a definite stratigraphical interval, probably mean that this diversity of form reflects variation within a single species. However, Andrews's sample 827 from 3 km south of Flying Fish Cove and four of Belford's samples from Smith Point contain a few inflated megalospheric forms which must be referred to *L. (E.) andrewsiana*, pending further investigation. Unfortunately, the associated foraminifera in these five samples are undiagnostic and could represent either Assemblage 1 or Assemblage 2.

The subgenus *Eulepidina* is in need of revision. The specific characters on which the numerous nominal species have been based need to be evaluated statistically on the basis of matrix-free material. Until this has been done it will not be possible to name specimens occurring in hard limestones satisfactorily.

LEPIDOCYCLINA (EULEPIDINA) H. Douvill, 1911

Type species. Orbitoides dilatata Michelotti, 1861.

Lepidocyclina (Eulepidina) andrewsiana (Jones and Chapman)

Plate 74, figs. 7-8

1900 *Orbitoides (Lepidocyclina) andrewsiana* Jones and Chapman, p. 255, pl. 21, fig. 14.

Remarks. The specimens referred to this species occur in four samples from Smith Point (1257, 1258, 1262, 1263) and one (827, the type sample) from the base of a limestone cliff resting on basalt at 150 m, 3 km south of Flying Fish Cove. They appear to differ from *E. ephippioides* in being more inflated and in tending to develop very thick walls between the lateral chambers. It is, however, quite possible that transitional forms to *E. ephippioides* would be found if matrix-free material were available.

Lepidocyclina (Eulepidina) ephippioides (Jones and Chapman)

Plate 74, figs. 4-6, 9, 12, 14, text-fig. 12

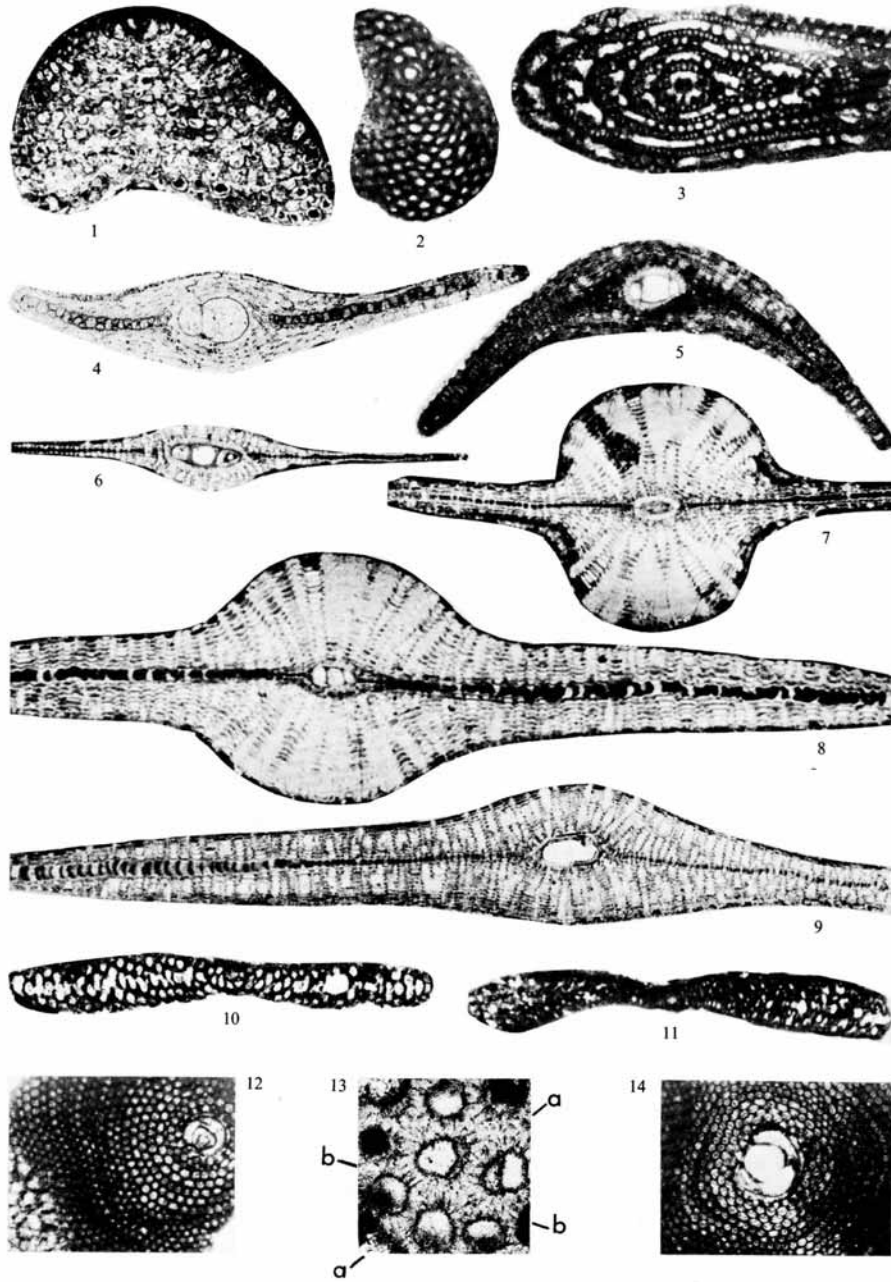
- 1900 *Orbitoides (Lepidocyclina) ephippioides* Jones and Chapman, pp. 251-252, pl. 20, fig. 9.
 1900 *Orbitoides (Lepidocyclina) murrayana* Jones and Chapman, pp. 252-253, pl. 21, fig. 10.
 1902 *Lepidocyclina (Eulepidina) formosa* Schlumberger, p. 251, pl. 7, figs. 1-3.
 1926 *Lepidocyclina ephippioides* Jones and Chapman; Nuttall, pp. 34-36, pl. 5, figs. 1, 2, 3, 8, and 10.
 1926 *Lepidocyclina (Eulepidina) ?formosa* Schlumberger; Nuttall, pp. 22-30.
 1965 *Lepidocyclina (Eulepidina) ephippioides* (Jones and Chapman); Ludbrook, pp. 290, 291.
 1965 *Lepidocyclina (Eulepidina) murrayana* Jones and Chapman; Ludbrook, p. 290.

Remarks. Nuttall (1926) distinguished *L. ephippioides* from *L. andrewsiana* on size (the former was, he thought, slightly larger) and on the appearance of the embryonic apparatus, which he considered to be truly eulepidine only in *L. andrewsiana*. However, he was comparing a well-centred section of *L. andrewsiana* with off-centre sections of *L. ephippioides*, and as shown by text-fig. 12 the appearance of the embryonic apparatus in *Eulepidina* depends entirely on the plane of section. Nuttall (op. cit., p. 35) himself observed that *L. ephippioides* 'except for the nucleocoenoch strongly resembles *E. formosa*', a taxon now generally regarded as synonymous with *E. ephippioides*.

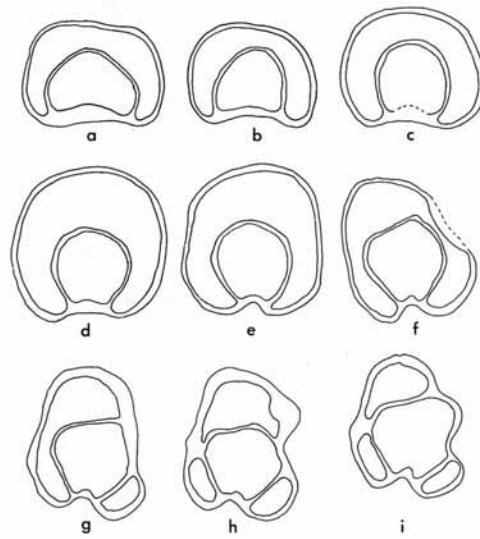
The lectotype designated by Nuttall is from Andrews's sample 549 taken 'at the

EXPLANATION OF PLATE 74

- Fig. 1. *Tayamaia marianensis* (Hanzawa), CPC. 13722, sample 1065, between 'G' Traverse and Waterfall, slightly off-centre transverse section, $\times 20$.
 Figs. 2, 10. *Sorites cf. orbiculus* (Forskål). 2, CPC. 13773, sample 1358, 'D' Traverse, oblique median section, $\times 40$. 10, CPC. 13744, sample 1355, 'G' Traverse, highly oblique median section, $\times 30$.
 Fig. 3. *Flosculinella bontangensis* (Rutten), CPC. 13775, sample 1237 (Ludbrook's P33 locality), near Ross Hill, off-centre axial section, $\times 30$.
 Figs. 4-6, 9, 12, 14. *Lepidocyclina (E.) ephippioides* (Jones and Chapman), all from 'D' Traverse. 4-6, 9, transverse sections showing variation in shape, size, and number of lateral chambers. 4, CPC. 13776, sample 1045, $\times 20$. 5, CPC. 13777, sample 1044, $\times 10$. 6, CPC. 13778, sample 1331, $\times 10$. 9, CPC. 13779, sample 1331, $\times 10$. 12, 14, median sections through megalospheric forms, both $\times 20$. 12, CPC. 13783, sample 1078. 14, CPC. 13784, sample 1328.
 Figs. 7-8. *Lepidocyclina (E.) andrewsiana* (Jones and Chapman), CPC. 13780 and 13781. Transverse sections showing inflated umbonal region, $\times 10$. Both from sample 1261, Smith Point at 60 ft.
 Fig. 11. *Marginopora vertebralis* Blainville, CPC. 13782, sample 1238, off-centre transverse section, $\times 40$.
 Fig. 13. *Lepidocyclina* sp., P. 49091. Tangential section through umbonal region of inflated form (probably *L. (E.) andrewsiana*) showing greatly thickened walls of lateral chambers, $\times 16$. Thin sections cut along lines *a-a* or *b-b* would appear to show thickened umbonal pillars; Andrews's sample 827, 2 miles south of Flying Fish Cove.



ADAMS and BELFORD, Oligocene-Miocene foraminifera



TEXT-FIG. 12. Parallel median sections through the embryonic apparatus of a single specimen of *Lepidocyclina (Eulepidina) ehippioides* (sample NB 9051, Kinabatangan River, Sabah, Borneo). It is clear from these drawings that the degree to which the deuterocoel appears to encircle the protoconch depends entirely on the plane of section. Nuttall (1926) would have regarded *a-d* as typical of *L. (E.) ehippioides*, and *e-f* as typical of *L. (E.) andreusiana* (see p. 500).

base of an inland cliff at 500 feet, running south from Flying Fish Cove'. Whether from a fallen block or *in situ* rock was not stated. The occurrence of *Eulepidina* in Assemblage 1 makes it certain that *L. (E.) ehippioides* came from low in the post-Eocene succession. It is usually associated with *Spiroclypeus margaritatus*, *Miogypsina (Miogypsinoides) bantamensis*, and *Austrotrillina striata*, and is therefore of Lower *e* age. It is worth noting that the type slides of *L. murrayana* contain a typical Assemblage 2 fauna.

Lepidocyclina sp.

Plate 74, fig. 13

Large inflated 'B' forms are common throughout 'D' Traverse and are virtually the only specimens present in the upper part of the section, i.e. above sample 1045. They show considerable variation in shape and size. A particularly prominent feature is the tendency of inflated forms to develop thick walls between the lateral chambers in the umbonal region (Pl. 74, fig. 13). Cuts through these walls can produce the appearance of coarse pustules or pillars in sagittal sections.

LEPIDOCYCLINA (NEPHROLEPIDINA) H. Douvillé, 1911

Type species. *Nummulites marginata* Michelotti, 1841.

L. (*Nephrolepidina*) spp.

This subgenus is surprisingly rare in the samples so far obtained from Christmas Island. It occurs sparsely in 'D' Traverse, Sydney's Dale Traverse, and in a few other localities (e.g. Flying Fish Cove, Andrews's sample 646). In the absence of oriented thin sections it is impossible to assign specific names to these individuals, some of which have hexagonal equatorial chambers. They occur in Assemblages 1-3, and it is certain that more than one species is represented.

Family HOMOTREMATIDAE Cushman, 1927

Genus CARPENTERIA Gray, 1858

Type species. *Carpenteria balaniformis* Gray, 1858.

Carpenteria spp.

Numerous fragments and some larger specimens of this genus occur throughout Assemblages 2-5. No attempt has been made to distinguish between different species.

Family ACERVULINIDAE Schultze, 1854

Genus GYPSINA Carter, 1877

Type species. *Polytrema planum* Carter, 1876.

Gypsina globula (Reuss)

1848 *Ceripora globulus* Reuss, p. 33.

1900 *Gypsina globulus* (Reuss); Jones and Chapman, p. 229 et seq.

Remarks. *G. globula* occurs throughout most of the succession and it is particularly common in Assemblages 2 and 3. There is nothing to add to previous descriptions.

Family PLANORBULINIDAE Schwager, 1877

Genus TAYAMAIA Hanzawa, 1967

Type species. *Gypsina marianensis* Hanzawa.

Tayamaia marianensis (Hanzawa)

Plate 71, fig. 8; Plate 74, fig. 1

1957 *Gypsina marianensis* Hanzawa, p. 66, pl. 21, fig. 9; pl. 27, figs. 1-8.

1965 *Gypsina marianensis* Hanzawa; Ludbrook, p. 292, pl. 22, fig. 2.

1967 *Tayamaia marianensis* (Hanzawa); Hanzawa, p. 22, fig. 3.

Remarks. A long-ranging species that occurs particularly frequently in Assemblages 2-4.

OTHER ATTACHED AND ENCRUSTING GENERA

Numerous attached and encrusting forms referable to *Acervulina*, *Borodinia*, *Kanakaia*, and *Sporadotrema* are present throughout the succession, being particularly common in Assemblages 2-5. The comparative rarity of these forms in Assemblage 1 is consistent with deposition in a fore-reef environment.

SUMMARY

The larger Tertiary foraminifera occurring in the post-Eocene limestones of Christmas Island appear to be characteristic of the Tertiary Lower *e*, Upper *e*, and Lower *f* Letter Stages. Five locally significant faunal assemblages can be recognized; two of these are probably in part laterally equivalent, and brought into their present topographical positions by fault movements.

The close stratigraphical juxtaposition of *Miogypsina* (*Miogypsinoides*) *complanata*, *M. (M.) bantamensis*, and *M. (M.) dehaarti* seems to indicate that the evolution of this lineage proceeded very rapidly during the late Oligocene. The early members of the *M. (Miogypsina) kotoi*-*M. (M.) indonesiensis* lineage have not been observed on Christmas Island. *M. (M.) neodispansa* is a fairly advanced form which may well prove to be of regional value in the recognition of late Upper *e* sediments. *Flosculinella* is poorly represented on the island. Apart from a single, specifically indeterminate specimen in Assemblage 2 (sample 69F, Batu Merah, Flying Fish Cove), the genus is not seen until well-developed specimens of *F. bontangensis* appear high in the Ross Hill Traverse. However, the occurrence of what appears to be a primitive form with a good Assemblage 2 fauna almost certainly means that this genus can no longer be relied on to define unequivocally the base of Upper *e*.

Although it has not been possible to determine how many species of *Lepidocyclina* are represented in the Christmas Island succession, it can be stated that all those described by Jones and Chapman were from limestones of late Lower *e* age.

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Permission to publish has been received by one of us (D. J. B.) from the Director, Bureau of Mineral Resources, Geology, and Geophysics, Canberra.

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