

8. COMPARISON OF UPPER PLIOCENE *DISCOASTER* ABUNDANCE VARIATIONS FROM NORTH ATLANTIC SITES 552, 607, 658, 659, AND 662: FURTHER EVIDENCE FOR MARINE PLANKTON RESPONDING TO ORBITAL FORCING¹

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ABSTRACT

Abundance variations of six Pliocene species of discoasters have been analyzed over the time interval from 1.89 to 2.95 Ma at five contrasting sites in the North Atlantic: Deep Sea Drilling Project Sites 552 (56°N) and 607 (41°N) and Ocean Drilling Program 658 (20°N), 659 (18°N), and 662 (1°S). A sampling interval equivalent to approximately 3 k.y. was used. Total *Discoaster* abundance showed a reduction with increasing latitude and from the effects of upwelling.

This phenomenon is most obvious in *Discoaster brouweri*, the only species that survived over the entire time interval studied. Prior to 2.38 Ma, *Discoaster pentaradiatus* and *Discoaster surculus* are important components of the *Discoaster* assemblage: *Discoaster pentaradiatus* increases slightly with latitude up to 41°N, and its abundance relative to *D. brouweri* increases up to 56°N; *D. surculus* increases in abundance with latitude and with upwelling conditions relative to both *D. brouweri* and *D. pentaradiatus* and is dominant to the latter species at upwelling Site 658 and at the highest latitude sites. *Discoaster asymmetricus* and *Discoaster tamalis* appear to increase in abundance with latitude relative to *D. brouweri*.

Many of the abundance changes observed appear to be connected with the initiation of glaciation in the North Atlantic at 2.4 Ma. The long-term trend of decreasing *Discoaster* abundance probably reflects the fall of sea-surface temperatures. This trend of cooling is overprinted by short-term variations that are probably associated with orbital forcing. Evidence for the astronomical elements of eccentricity and obliquity periodicities were found at all sites; however, only at Sites 607, 659, and 662 were precessional periodicities detected. Furthermore, only at Site 659 was precession found to be dominant to obliquity.

Abundance peaks of individual species were found to cross-correlate between sites. The distinct abundance fluctuations observed especially in the tropics suggest that temperature is not the only factor responsible for this variation. This study reveals for the first time the importance of productivity pressure on the suppression of *Discoaster* abundance.

INTRODUCTION

Discoasters are known in the oceanic record from the upper Paleocene to the upper Pliocene, when the last two representatives of the genus disappeared synchronously just below the base of the Olduvai Subchron, 1.89 Ma ago (Takayama, 1970; Rio, 1982; Backman and Shackleton, 1983). Numerous studies have shown that discoasters are particularly common in low-latitude sediments and therefore probably favored warm-water masses (e.g., Haq and Lohmann, 1976; Bukry, 1978). The organism from which discoasters evolved is not known, but it was presumably related to the coccolithophorids. Discoasters are favorable for quantitative study since they resist dissolution better than planktonic foraminifers or most placoliths (Lohmann and Carlson, 1981).

A number of factors probably affected their distribution, but this genus appears especially sensitive to temperature change (Haq and Lohmann, 1976). Backman et al. (1986) and Backman and Pestiaux (1987) have shown that orbital forcing is strongly imprinted on *Discoaster* abundance variation at Deep Sea Drilling Project (DSDP) Hole 552A (56°N) and DSDP Site 606 (37°N) during the Pliocene in the North Atlantic. The former is dominated by the 41-k.y. obliquity periodicity and the latter by the 400-k.y. eccentricity periodicity.

In the present study, individual species and total abundances of discoasters are compared among five sites across a wide latitudinal range of the North Atlantic. We hope to extend this research approach to other oceans and develop a global data base. As more sites are analyzed and compared, *Discoaster* abundance variations may give us a global record of ocean temperature changes and/or nutrient levels.

In addition, after we obtain continuous quantitative estimates of *Discoaster* abundances, we will also be able to use spectral analysis to determine whether orbital forcing is imprinted on the *Discoaster* record at these sites. The time interval investigated is approximately the million years preceding the extinction of the discoasters (i.e., between 1.9 and 2.9 Ma) using closely spaced samples (around 3 k.y.). The taxonomy of the six species of discoasters counted (Plate 1) and the methods used in this study follow those of Backman and Shackleton (1983).

SITES SELECTED

The five sites chosen (Fig. 1 and Table 1) were picked to contrast with each other either in terms of latitude, upwelling vs. nonupwelling systems, and the effects of cool currents. However, all sites are from the eastern North Atlantic, which may limit our interpretations. The sites possess good sequences of upper Pliocene sediment and, except for Hole 552A, fairly high sedimentation rates. Sampling was at 10-cm intervals except for Sites 607 and 658, which were at 15-cm and 30-cm intervals, respectively.

Site 659

This site was selected as the nonupwelling, open-ocean reference site. It is located on the top of the Cape Verde

¹ Ruddiman, W., Sarnthein, M., et al., 1989. *Proc. ODP, Sci. Results*, 108: College Station, TX (Ocean Drilling Program).

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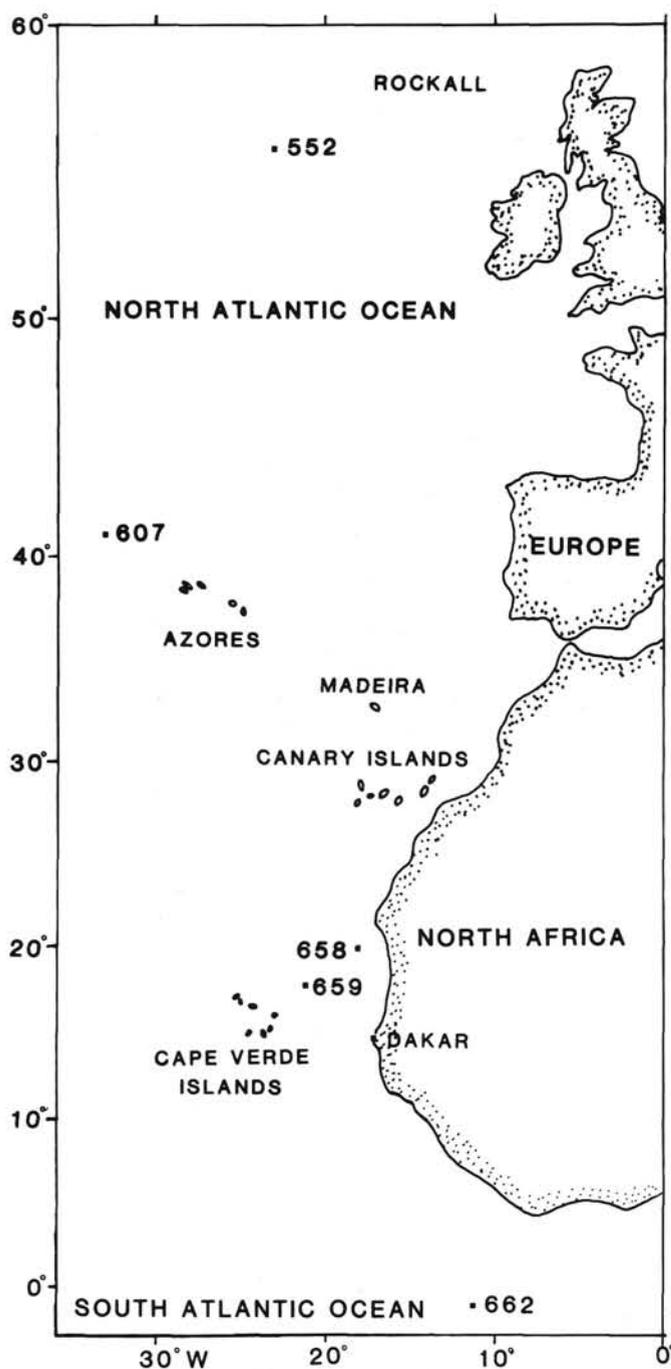


Figure 1. Location of sites studied in the North Atlantic.

Plateau. The oceanographic setting is not complicated by the cool Canaries Current or by large inputs of terrigenous matter from northwest Africa. The lithology is mostly nannofossil-foraminifer ooze with good preservation and no noticeable dissolution in the interval studied.

Site 658

In contrast, Site 658 was the upwelling, high-productivity site chosen in close proximity to Site 659. It is located on the continental slope 160 km west of Cap Blanc and lies beneath a major productive cell of oceanic upwelling. The sediments are hemipelagic due to the combined influence of oceanic

Table 1. North Atlantic sites selected, their geographic positions, and water depth.

Hole	Location	Depth (m)	Reference
662A	1°S, 11°W	3,824	Ruddiman, Sarnthein, et al., 1988
659A	18°N, 21°W	3,067	Ruddiman, Sarnthein, et al., 1988
658A	20°N, 18°W	2,263	Ruddiman, Sarnthein, et al., 1988
607	41°N, 33°W	3,427	Ruddiman, Kidd, Thomas, et al., 1987
552A	56°N, 23°W	2,304	Roberts, Schnitker, et al., 1984

production and eolian input. Discoasters may have fluctuated in response to the intensity of upwelling.

Site 662

This site is located close to the equator on the upper eastern flank of the mid-Atlantic Ridge. The relevant interval is a nannofossil and foraminifer-nannofossil ooze. One would expect discoasters to be extremely abundant in such low latitudes, although this site is influenced by the South Equatorial Current, which is the successor to the Benguela Current. It is within the equatorial divergence and may be affected by upwelling.

Site 607

This site is presently located along the northernmost part of the subtropical gyre; however, in the late Pliocene, it was exposed to major circulation changes and lower temperatures (Ruddiman, Sarnthein, et al., 1988). The lithology is interbedded foraminifer-nannofossil oozes and marls representing the North Atlantic glacial marine cycles.

Site 552

This site is at the northernmost latitude of our transect. The data for this site was published by Backman and Pestiaux (1987) and has been replotted to provide a comparison with the other sites. It was drilled on the southwest margin of the Rockall Plateau and the lithology is similar to Site 607 in that it consists of cycles of alternating beds of foraminifer-nannofossil ooze and calcareous marls and mud that began abruptly about 2.4 Ma. Prior to this age, the lithology is relatively uniform foraminifer-nannofossil ooze and nannofossil ooze.

AGE MODELS AND SEDIMENTATION RATES

In the absence of magnetostratigraphic data from Sites 659 and 662 and imprecise data from Site 658, all age models are based on biostratigraphic datums. However, at Sites 552 and 607 very reliable magnetic stratigraphies were obtained. Only three stratigraphic datums have been selected as control points for the age models at each site. Where it was possible, biostratigraphic datums were selected preferentially, especially those related to *Discoaster* events (Table 2). This ensures that the age models from the five sites are self-consistent.

At Site 659 magnetic data was available for most of Hole 659B, but magnetic reversals were unambiguous only in the upper section of Hole 659A. Using distinct *D. brouweri* abundance peaks for correlation, it was possible to switch from Hole 659A to Hole 659B to obtain the extinction event, which was not recovered in Hole 659A. Most of the species events fit a single line on the age-depth plot (Fig. 2). To develop the age model, we used the datums of the extinction of *D. brouweri* and *D. triradiatus* at 1.89 Ma, the base of the *D. triradiatus* acme at 2.07 Ma (Backman and Shackleton, 1983), and the extinction of *D. tamalis* at 2.65 Ma (Table 3).

Table 2. Summary of *Discoaster* events between 1.89 and 3.00 Ma from previous work (e.g., Backman and Shackleton, 1983; Backman et al., 1986).

Species	Age (Ma)	Event
<i>D. brouweri</i>	1.89	Extinction
<i>D. triradiatus</i>	1.89	Extinction
<i>D. triradiatus</i>	2.07	Peak abundance began
<i>D. pentaradiatus</i>	2.33–2.43	Extinction
<i>D. surculus</i>	2.42–2.46	Extinction
<i>D. surculus</i>	2.39	^a Extinction
<i>D. asymmetricus</i>	2.65	Abundance decline
<i>D. tamalis</i>	2.65	Extinction
<i>D. variabilis</i>	2.87–2.93	Extinction

^a Estimate for extinction from this study.

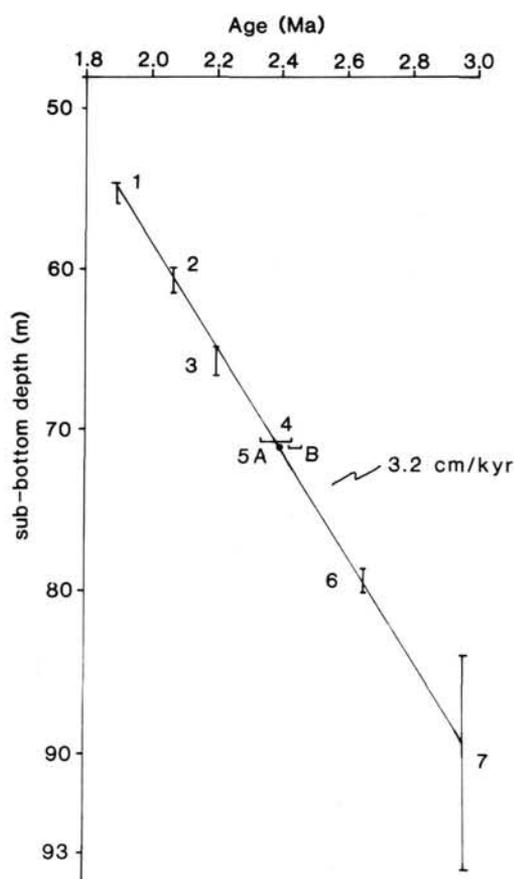


Figure 2. Age/depth relationships of biochronologic control points in Hole 659A. Refer to Table 4 for control points used.

Site 659 may provide new information about the extinction of *D. surculus*. Backman and Shackleton (1983) originally determined the extinction of *D. surculus* from several piston cores having magnetostratigraphy. Core V32-127 (North Pacific) provided an unambiguous final sharp decline in the abundance of *D. surculus*, and the age of this event was estimated to range from 2.38 to 2.44 Ma in this core. Subsequently, Backman and Pestiaux (1987) derived an age range from 2.42 to 2.46 Ma for the *D. surculus* extinction event, based on a less clear final abundance pattern obtained from DSDP Hole 606 (North Atlantic). Thus, the question if this species experienced a synchronous extinction in different ocean basins (or latitudes) will remain open until additional

Table 3. Summary of control points used in age models.

Datum	Age (Ma)	Depth (mbsf)	Event	Sedimentation rate
Hole 659A:				
<i>D. brouweri</i>	1.89	54.8	Extinction	3.2 cm/k.y.
<i>D. triradiatus</i>	2.07	60.6	Peak abundance began	
<i>D. tamalis</i>	2.65	79.4	Extinction	
Hole 658A:				
<i>D. brouweri</i>	1.89	26.4	Extinction	7.9 cm/k.y.
<i>D. surculus</i>	2.39	166.0	Extinction	
<i>D. altispira</i>	2.95	^a 220.0	Extinction	
Hole 662A:				
<i>D. brouweri</i>	1.89	123.2	Extinction	5.6 cm/k.y.
<i>D. surculus</i>	2.39	151.4	Extinction	
<i>G. altispira</i>	2.95	^a 168.5	Extinction	
Hole 607A:				
<i>D. brouweri</i>	1.89	82.86	Extinction	4.8 cm/k.y.
<i>D. surculus</i>	2.39	106.78	Extinction	
Kaena	2.99	130.73	Bottom	
Hole 552A:				
<i>D. brouweri</i>	1.89	35.2	Extinction	1.4 cm/k.y.
<i>D. surculus</i>	2.39	42.5	Extinction	
Kaena	2.99	48.6	Bottom	

^a Refers to P. Weaver (this vol.).

Table 4. Datum levels used to construct Figure 2.

Number	Datum level	Depth (mbsf)	Age (Ma)
Hole 659A:			
1	LAD <i>D. brouweri</i>	54.7–55.9	1.89
2	Base of <i>D. triradiatus</i> acme	59.8–61.3	2.07
3	LAD <i>G. miocenica</i>	64.8–65.6	2.20
4	LAD <i>D. pentaradiatus</i>	70.7	2.33–2.43
5A	New LAD <i>D. surculus</i>	71.0	^a 2.39
5B	LAD <i>D. surculus</i>	71.0	^b 2.42–2.45
6	LAD <i>D. tamalis</i>	78.5–80.0	2.65
7	LAD <i>G. altispira</i>	83.8–93.8	2.95

^a Estimated from Figure 2.

^b Backman and Shackleton, 1983.

independent evidence (e.g., highly resolved stable isotope stratigraphy) can be used for precise calibration. Currently, the uncertainty is about 80 k.y. between 2.38 and 2.46 Ma.

The three Leg 108 sites analyzed in this study reveal rather similar patterns of abundance variation of *D. surculus*, particularly toward the end of its range, finishing with a final sharp peak that is assumed to be synchronous. The Pliocene/Pleistocene sedimentation rate at Site 659 appears remarkably constant (Ruddiman, Sarnthein, et al., 1988), fitting all available biostratigraphic datum events, from the last appearance datum (LAD) of *D. brouweri* at 1.89 Ma to the LAD of *Globorotalia altispira* at 2.95 Ma (Fig. 2 and Table 4). Only the LAD of *D. surculus* falls slightly off the line if the age estimates from DSDP Site 606 are used. As a working hypothesis, the age estimate of *D. surculus* is adjusted in order to fit the apparently linear sedimentation rate at Site 659. This gives a value of 2.39 Ma for the final peak, which is within the range of the estimates derived from Core V32-127. This value of 2.39 Ma was applied thereafter to all other investigated sites in order to produce consistent age models.

At Site 658, magnetostratigraphic data was available for the interval representing the base of the Olduvai, but the Matuyama/Gauss boundary data was too scattered to be reliable. To be internally consistent, only biostratigraphic datums have

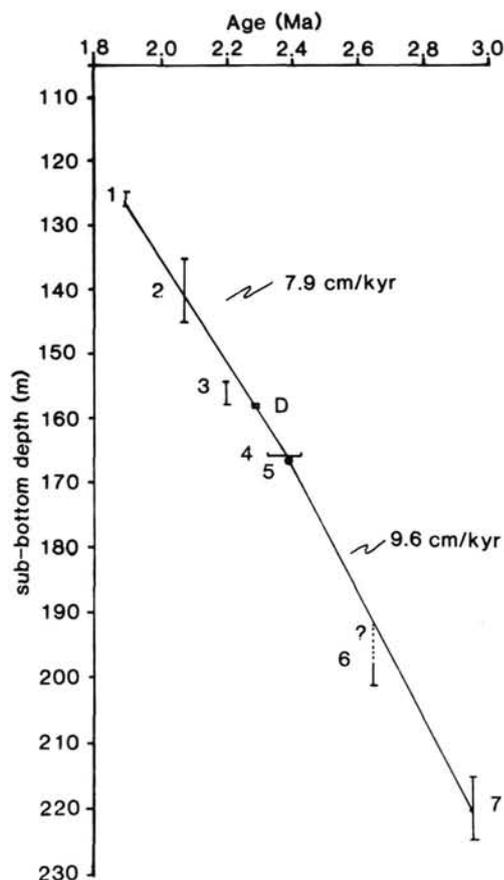


Figure 3. Age/depth relationships of biochronologic and magnetostratigraphic control points in Hole 658A. Refer to Table 5 for control points used.

Table 5. Datum levels used to construct Figure 3.

Number	Datum level	Depth (mbsf)	Age (Ma)
Hole 658A:			
1	LAD <i>D. brouweri</i>	124.7–126.9	1.89
2	Base of <i>D. triradiatus</i> acme	135.0–145.0	2.07
3	LAD <i>G. miocenica</i>	154.3–157.7	2.20
4	LAD <i>D. pentaradiatus</i>	165.5	2.33–2.43
^a 5	LAD <i>D. surculus</i>	166.0	2.39
6	LAD <i>D. tamalis</i>	197.7–201.3	2.65
7	LAD <i>G. altispira</i>	214.9–224.4	2.95
D	Diagenetic event	157.8–158.4	^b 2.30

^a LAD for *D. surculus* taken as 2.39 Ma from Site 659 (Table 4).

^b Inferred from Figure 3.

been used in the construction of the age-depth plot at Site 658 (Fig. 3 and Table 5). *Discoaster brouweri* provided a clear extinction, but the base of the *D. triradiatus* acme has a fairly wide estimate that is probably due to the low numbers of these two species. A line was drawn through the extinction of *D. brouweri* to the extinction of *D. surculus*, passing through the range of estimates for the base of the *D. triradiatus* acme and the extinction of *D. pentaradiatus*.

For the rest of the age-depth plot for Site 658, a line was drawn from the extinction of *D. surculus* through the extinction of *Globorotalia altispira* at 2.95 Ma (Ruddiman, Sarnthein, et al., 1988). *Discoaster tamalis* was not useful in the age-depth plot

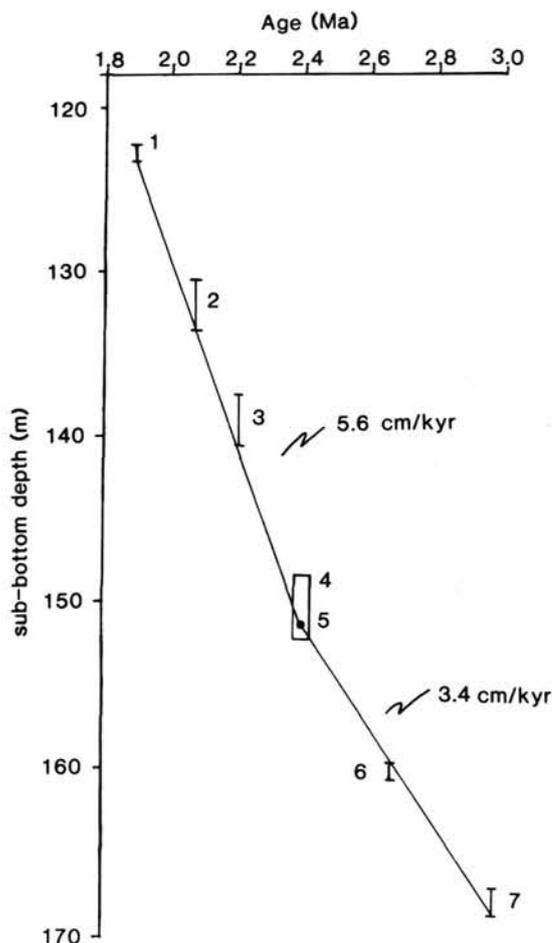


Figure 4. Age/depth relationships of biochronologic control points in Hole 662A. Refer to Table 6 for control points used.

Table 6. Datum levels used to construct Figure 4.

Number	Datum level	Depth (mbsf)	Age (Ma)
Hole 662A:			
1	LAD <i>D. brouweri</i>	122.2–123.2	1.89
2	Base of <i>D. triradiatus</i> acme	130.4–133.5	2.07
3	LAD <i>G. miocenica</i>	137.5–140.5	2.20
4	LAD <i>D. pentaradiatus</i>	148.3–152.1	2.33–2.43
^a 5	LAD <i>D. surculus</i>	151.4	2.39
6	LAD <i>D. tamalis</i>	159.5–160.5	2.65
7	LAD <i>G. altispira</i>	166.9–168.5	2.95

^a LAD for *D. surculus* taken as 2.39 Ma from Site 659 (Table 4).

since it occurred in numbers too low to provide a reliable datum. Thus, we used the extinction datums of *D. brouweri*, *D. surculus*, and *G. altispira* in our age model (Table 3).

An interesting diagenetic event, the formation of a possible "hardground" occurring between 157.8 and 158.4 mbsf, is associated with some reworking of *D. pentaradiatus* and *D. surculus*. This event necessitated a change of drilling from hydraulic piston corer (HPC) to extended core barrel (XCB). From the age model this occurred at approximately 2.3 Ma.

At Site 662 (Fig. 4 and Table 6), there was no magnetic stratigraphy available, and reworking was noticeably greater than at Sites 658 and 659. This site was affected by slumping, but this was above the interval studied. Due to the reworking, some

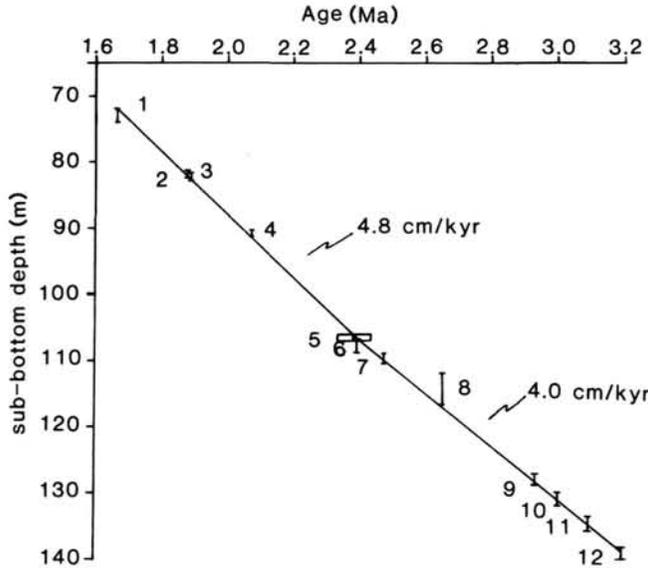


Figure 5. Age/depth relationships of biochronologic and magnetostratigraphic control points in Hole 607A. Refer to Table 7 for control points used.

Table 7. Datum levels used to construct Figure 5.

Number	Datum level	Depth (mbsf)	Age (Ma)
1	Olduvai (Top)	72.08–74.18	1.66
2	Olduvai (Bottom)	81.68–82.46	1.88
3	LAD <i>D. brouweri</i>	81.80–83.10	1.89
4	Base of <i>D. triradiatus</i> acme	90.60–91.48	2.07
5	LAD <i>D. pentaradiatus</i>	106.35–107.38	2.33–2.43
^a 6	LAD <i>D. surculus</i>	106.78–108.52	2.39
7	Matuyama/Gauss boundary	108.98–110.57	2.47
8	LAD <i>D. tamalis</i>	111.90–116.68	2.65
9	Kaena (Top)	126.68–128.18	2.92
10	Kaena (Bottom)	129.68–131.78	2.99
11	Mammoth (Top)	133.28–135.05	3.08
12	Mammoth (Bottom)	137.78–139.28	3.18

^a LAD for *D. surculus* taken as 2.39 Ma from Site 659 (Table 4).

events such as the base of the *D. triradiatus* acme were difficult to identify precisely. *Discoaster pentaradiatus* was heavily reworked through the interval, and it is important to have some concept of the background reworking level when defining extinction events. *Discoaster surculus* again produced a distinct peak at its extinction. Likewise, *D. tamalis* produced a clear extinction at 2.65 Ma. From the age-depth plot, the extinction of *D. brouweri*, *D. surculus*, and *G. altispira* were selected as datums to be used in the age model (Table 3).

At Site 607, a very reliable magnetic stratigraphy was obtained (Fig. 5 and Table 7) (Clement and Robinson, 1987). A straight line connects the top of the Olduvai with the extinction of *D. surculus* at 2.39 Ma, passing through the base of the Olduvai, the extinction of *D. brouweri*, the base of the acme of *D. triradiatus*, and the extinction of *D. pentaradiatus*. Prior to 2.39 Ma, there is a slightly lower sedimentation rate, but a straight line can be drawn between the extinction of *D. surculus* and the bottom of the Mammoth (3.18 Ma), passing through the Matuyama/Gauss boundary, the top and bottom of the Kaena, and the top of the Mammoth. *Discoaster tamalis* was not useful since the extinction was disguised by reworking, clearly indicated by the presence of *Reticu-*

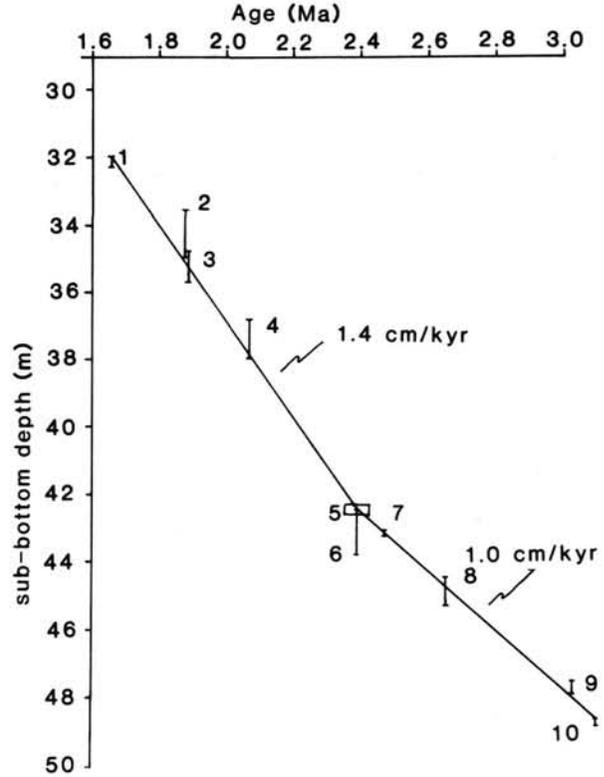


Figure 6. Age/depth relationships of biochronologic and magnetostratigraphic control points in Hole 552A. Refer to Table 8 for control points used.

Table 8. Datum levels used to construct Figure 6.

Number	Datum level	Depth (mbsf)	Age (Ma)
Hole 552A:			
1	Olduvai (Top)	31.96–32.24	1.66
2	Olduvai (Bottom)	33.53–34.96	1.88
3	LAD <i>D. brouweri</i>	34.80–35.69	1.89
4	Base of <i>D. triradiatus</i> acme	36.79–38.00	2.07
5	LAD <i>D. pentaradiatus</i>	42.20–42.60	2.33–2.43
^a 6	LAD <i>D. surculus</i>	42.40–43.80	2.39
7	Matuyama/Gauss boundary	43.04–43.24	2.47
8	LAD <i>D. tamalis</i>	44.50–45.30	2.65
9	Kaena (Top)	47.53–47.86	2.92
10	Kaena (Bottom)	47.58–48.75	2.99

^a LAD for *D. surculus* taken as 2.39 Ma from Site 659 (Table 4).

lofenestra pseudumbilica (LAD = 3.56 Ma). From the age-depth plot, we selected the LAD of *D. brouweri* and *D. surculus* and the midpoint of the base of the Kaena at 2.99 Ma as control points for the age model (Table 3).

At Site 552, reliable magnetic stratigraphy was available and helped verify that, in spite of the extremely low abundances of discoasters at high latitudes, the events recognized were genuine and not an artifact of reworking (Fig. 6 and Table 8). A straight line connects the top of the Olduvai and the extinction of *D. surculus* (2.39 Ma), passing through the extinction of *D. brouweri* (and close to the base of the Olduvai), the base of the *D. triradiatus* acme, and the extinction of *D. pentaradiatus*. Prior to 2.39 Ma, there is a slight reduction in the sedimentation rate, but a straight line can be drawn through the Matuyama/Gauss boundary, the extinction

of *D. tamalis*, and the bottom of the Kaena, passing close to the top of the Kaena. From the age-depth plot, we selected the LAD of *D. brouweri* and *D. surculus* and the bottom of the Kaena as control points for the age model (Table 3). Sedimentation rates at this site were much lower than at any of the other sites.

COMPARISON OF SPECIES AND TOTAL ABUNDANCE AMONG SITES

Smear slides were prepared and counted as described by Backman and Shackleton (1983). The number of view fields selected is related to the overall abundance of discoasters at each site. Normally, a constant number of view fields are used for a single site, except possibly during intervals of extremely low abundances. Abundances among sites were directly comparable when they were multiplied by a conversion factor, which yielded the abundances per mm² of slide.

At Site 659, it was necessary to count only 20 view fields in view of the high *Discoaster* abundances. This is at a view-field diameter of 0.3 mm, which contains roughly 250 nannofossils or other particles in each view field. However, at Site 658, where the abundances observed were found to be much lower, 40 view fields were counted. Similarly, at Site 662, 40 view fields were used. However, at Site 552, where low abundances were observed due to the high latitude, 100 view fields were used. Lastly, at Site 607, the second highest latitude site, 30 view fields were counted at a view field diameter of 0.28 mm, as a different microscope used for this site. We found that this method is an accurate tool for gathering reproducible data rapidly.

Discoaster brouweri and *Discoaster triradiatus*

These two species have extinctions at 1.89 Ma. An interesting phenomenon occurs globally at 2.07 Ma (Backman and Shackleton, 1983) when *D. triradiatus* increases in proportion (>20%) relative to *D. brouweri*, whereas prior to 2.07 Ma it is insignificant. At Sites 607 and 659 (Figs. 7 and 8), this event was clearly defined; but at Sites 658 and 552 (Figs. 9 and 10) and to a lesser extent at Site 662 (Fig. 11), it was less easy to identify precisely. Extremely low abundances of the two species occur at Site 658, and the base of the acme probably lies between 138.7 and 141.5 mbsf (approximately 2.05–2.08 Ma).

At Site 552, where discoasters are less abundant than at Site 658, this event was difficult to define. It is estimated to occur between 36.9 and 38.0 mbsf (approximately 2.00–2.08 Ma). However, this stratigraphic placement is based on the absolute abundance plots, which may be more useful than the percentage relationship in this case. Backman and Shackleton (1983), Backman et al. (1986), and Backman and Pestiaux (1987) only illustrated the abundance of *D. triradiatus* relative to *D. brouweri* and not the absolute abundances of *D. triradiatus*.

Because of the greater abundances of *D. brouweri* and *D. triradiatus* at Site 662 than at Sites 552 and 658, it was easier to define the base of the *D. triradiatus* acme, but the >20% boundary is not so useful. The first occurrence of >20% is at 138.7 mbsf (2.03 Ma), whereas at 133.5 mbsf (2.07 Ma) the relative proportion between these two species is 12%, which is thought to be approximately the base of the acme as a worldwide event. However, at Sites 658 and 662, this event could probably be refined by counting greater numbers of view fields throughout this interval. *Discoaster triradiatus* shows a distinct order of reduction in abundance from Sites 659, 662, and 607 to Site 658. Site 552, however, has much lower abundances than any of the other sites.

Considering that Site 659 was selected as the reference site, it was not expected that the *Discoaster* abundance variations

would be so marked (Fig. 12). The final extinction was quite a sudden event after some high abundances between 1.93 and 1.95 Ma. At Site 658, a high abundance event observed at Site 659 is reflected at 1.96 Ma. This is the only major event of *Discoaster* abundance from 2.35 to 1.89 Ma at Site 658. At Site 607, the greatest abundance of *D. brouweri* occurs between 1.89 and 2.07 Ma (approximately 1.93 Ma), which may be related to the high abundance events at Sites 658 and 659. A similar pattern is also reflected in *D. triradiatus*, which is to be expected in view of the evidence implying a strong taxonomic affinity (Backman and Shackleton, 1983).

At Site 662 (Fig. 12), although *D. brouweri* abundance is lower than at Site 659, the abundances are still very high in comparison with Sites 607, 552, and 658. At Site 662, there is a major decline in abundance of *D. brouweri* from 2.05 Ma to the extinction at 1.89 Ma, and no noticeable abundance peaks occur at 1.95–1.96 Ma, although there is a small core gap close to this interval. Thus, this event may possibly be missing, or it may be a relatively local phenomenon affecting Sites 658, 659, and, to a lesser degree, 607.

Site 607 shows a much greater abundance of *D. brouweri* than Site 658 after 2.4 Ma and a slightly higher overall abundance prior to this age with a distinct trend toward abundance reduction, although there are a number of distinct peaks in the record of Site 658 at which abundance is higher than at Site 607. Many of the major abundance peaks at Site 662 appear to coincide with those at Site 659 (e.g., at approximately 2.33, 2.22, and 2.18 Ma). An abundance peak at roughly 2.74 Ma appears to occur at all four sites. No cross-correlation is attempted with Site 552 for any of the species since the abundances are so low (Fig. 13).

Discoaster pentaradiatus and *Discoaster surculus*

The abundance of these two species has been compared in different cores and ocean basins by Backman and Shackleton (1983), Backman et al. (1986), and Backman and Pestiaux (1987) and the extinctions are estimated to occur at 2.35–2.45 Ma. It is widely agreed that *D. surculus* disappeared slightly earlier than *D. pentaradiatus*, which is true of the five sites analyzed (Figs. 14 and 15).

At Sites 659, 658, 607, and 552, a distinct synchronous extinction for *D. pentaradiatus* was recorded at approximately 2.38 Ma (Fig. 14). However, at Site 662, it was less easy to define this extinction due to the heavy reworking despite knowledge of the background level. The age range for the extinction is suggested to occur between the major peak at 2.34 Ma and another peak at 2.41 Ma; everything younger than 2.34 Ma is considered to represent reworking. A synchronous extinction for *D. pentaradiatus* at Sites 659 and 658 would be expected in view of their close proximity, but it is interesting that Sites 552 and 607 display the same extinction age in view of the wide range of estimates for the age of this event.

As in the abundance for *D. brouweri*, Site 659 has higher abundances of *D. pentaradiatus* than Site 658 and, to a lesser extent, Site 662. However, Site 607 showed comparable abundances to Sites 659 and 662. The two highest latitude sites, 607 and 552, have abundances of *D. pentaradiatus* numerically more significant than *D. brouweri* during this time interval (i.e., prior to 2.38 Ma).

Sites 659 and 662 clearly show an overall decrease in *D. pentaradiatus* abundance in the period prior to 2.38 Ma that may correspond to a temperature decrease in the North Atlantic. However, Sites 607 and, to a lesser extent, 552, show no clear trend of abundance reduction; indeed, prior to the extinction of *D. pentaradiatus* there is even a slight trend of increasing abundance. It is tempting once again to connect the extinction of *D. pentaradiatus* with the onset of glaciation

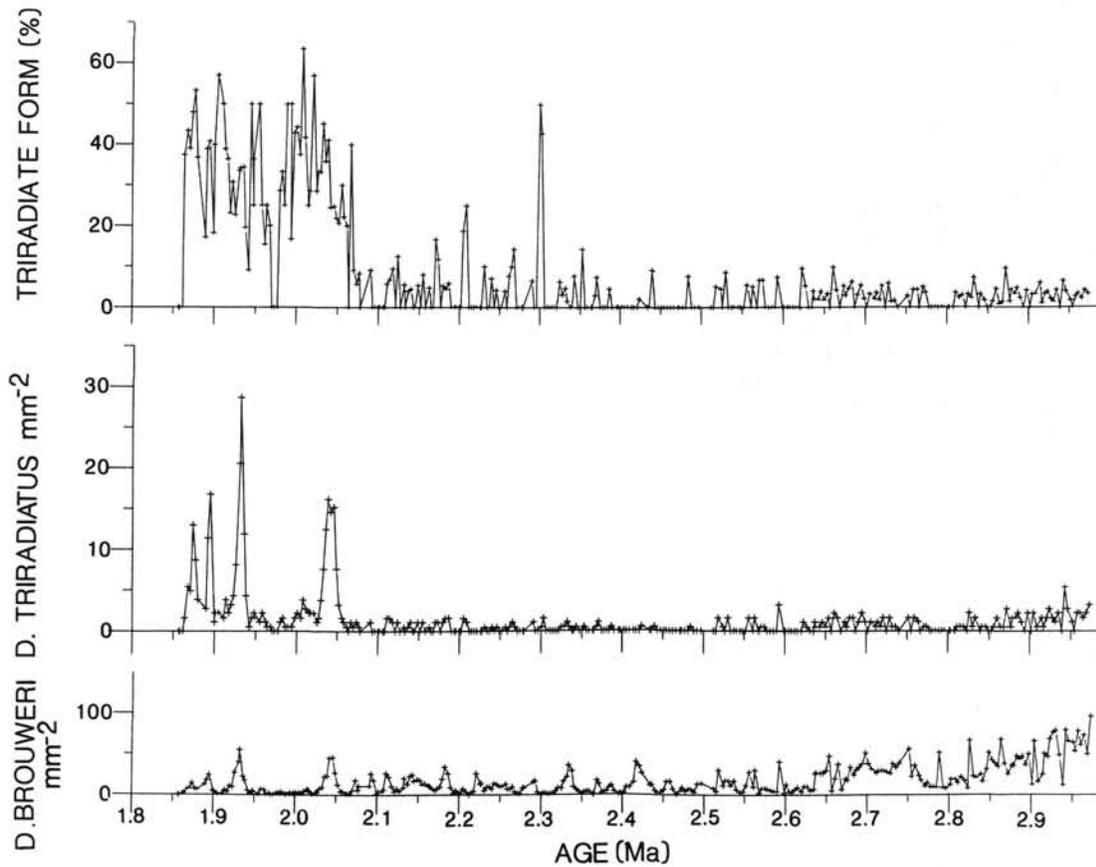


Figure 7. Abundance plots of *D. brouweri* and *D. triradiatus* at Site 607. The percentage of the triradiate form is the relative abundance of *D. triradiatus* to the sum of this species with *D. brouweri*.

in the North Atlantic at 2.4 Ma. Many of the abundance peaks seem to correspond among the four sites (e.g., at approximately 2.38, 2.71, and 2.80 Ma).

Discoaster surculus (Fig. 15) disappeared with a final distinctive peak at 2.39 Ma, except at Sites 552 and 607 where the same age is ascertained, although no distinctive peak is identified. The first noticeable feature is that *D. surculus* is more abundant at Site 658 than at Site 662, although Site 659 displays a still higher abundance. However, at Site 607, *D. surculus* shows a greater overall abundance than at all the other sites, which probably relates to its higher latitudinal position. At Site 552, the highest latitudinal site, the abundances are extremely low, but *D. surculus* is the most abundant species (Fig. 13).

Bukry (1978) observed that *D. surculus* favored the cooler end of the warm-water spectrum among the species of the warm-water genus *Discoaster*. It can be seen that *D. surculus* is more abundant than *D. pentaradiatus* at Site 658. Frequently, *D. surculus* is co-dominant with *D. brouweri*. Since Site 658 is an upwelling site with the associated cooler surface water, it would seem reasonable that *D. surculus* should form a major component of the *Discoaster* assemblage. At Site 607, *D. surculus* is still slightly lower in overall abundance to *D. pentaradiatus*, but its abundance is comparable to *D. brouweri*. *Discoaster brouweri* only becomes important when compared with *D. surculus* and *D. pentaradiatus* at Site 607 prior to 2.9 Ma.

At Site 607, *D. surculus* appears to increase in abundance between roughly 2.55 and 2.50 Ma, whereas *D. pentaradiatus* continues to increase up until 2.40 Ma. At Site 552 (Fig. 13),

there is an apparent trend of increasing abundance in *D. surculus* up until 2.50 Ma, which is followed by an abrupt decline to the extinction event, though extremely low abundances are involved. *Discoaster surculus* is presumably less significant at Site 662, because although this site is supposedly affected by the South Equatorial Current and upwelling to some extent, the reduction in sea-surface temperature is not so marked as in upwelling Site 658. No noticeable trend of overall decrease in abundance is apparent prior to 2.38 Ma, except after 2.54 Ma.

There are a number of abundance peaks that appear to correspond among the four sites at approximately 2.54, 2.60, and 2.70 Ma. At all five sites, *D. pentaradiatus* and *D. surculus* frequently exhibit an inverse abundance relationship (Backman and Shackleton, 1983). This may provide a potential tool for determining subtle temperature or productivity changes, if we assume that these two species had different ranges of ecological tolerance.

Discoaster asymmetricus and *Discoaster tamalis*

The abundance of these two species co-varies, as shown in the almost identical abundance plots at each site (Figs. 16 and 17). This phenomenon has been demonstrated by Backman and Shackleton (1983), Backman et al. (1986), and Backman and Pestiaux (1987) and seems to suggest strong taxonomic affinity. Site 659 shows greater abundances than Site 658 and Site 662.

Unexpectedly, the abundances of *D. asymmetricus* and *D. tamalis* at Site 607 were higher than at Site 662. At Site 552, the northernmost site, there is a further increase in abundance

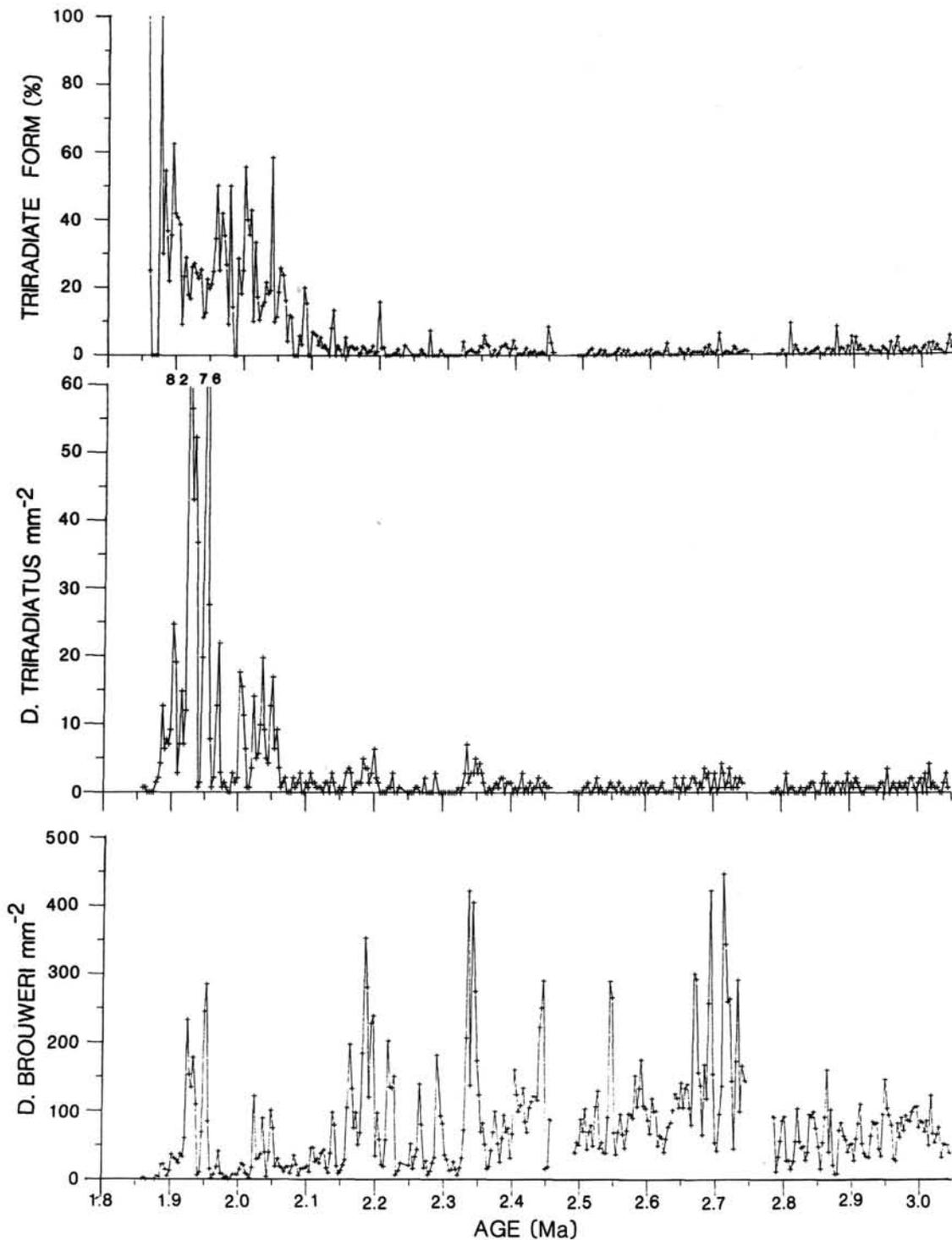


Figure 8. Abundance plots of *D. brouweri* and *D. triradiatus* at Site 659.

relative to *D. brouweri*, even though the abundances are extremely low. There may exist a relationship between latitude and the production of *D. tamalis* and *D. asymmetricus*. Upwelling at Sites 658 and 662 may even suppress the production of these two species.

At Site 659, the synchronous extinction of *D. tamalis* at 2.65 Ma was selected at 79.4 mbsf. Arguably, it may even occur a little higher up in the section, but up until this point *D. tamalis* (and *D. asymmetricus*) had been present continu-

ously, even if in low abundances. *Discoaster tamalis* above this level is considered reworked. At Site 662, the extinction age interpolates to approximately 2.65 Ma. Due to the very low abundances of these two species at Site 658, it was impossible to assess a true extinction level.

At Site 607, the extinction event is partially concealed by reworking, as shown by the association of *D. tamalis* with *Reticulofenestra pseudoumbilica*. However, the abundance peaks are discontinuous and the true extinction is observed at

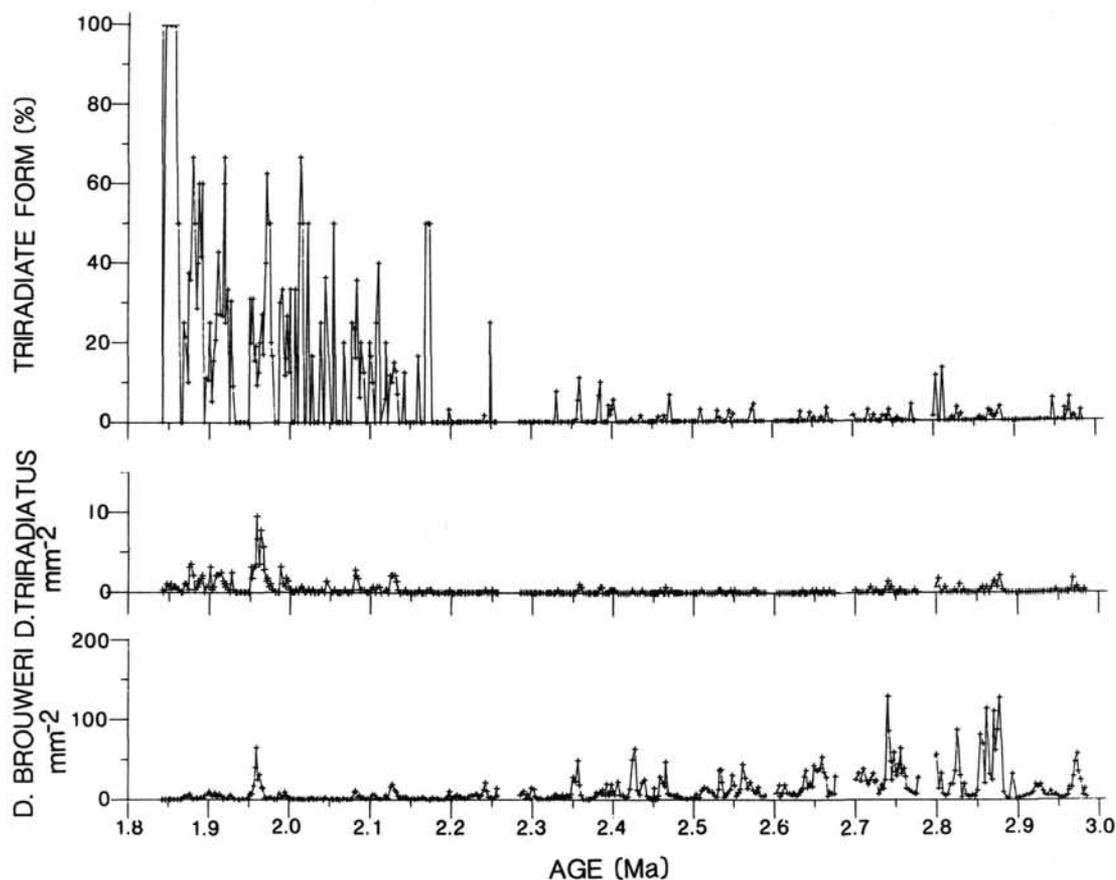


Figure 9. Abundance plots of *D. brouweri* and *D. triradiatus* at Site 658.

approximately 2.65 Ma, since a continuous presence is recorded prior to this age. This event is not easy to define at Site 552 because it is difficult to distinguish between very low abundances and possible reworking combined with low sedimentation rates. Sites 659, 662, and 607 indicate a clear reduction in abundance through the time interval for both these species up until the extinction of *D. tamalis* at 2.65 Ma.

Discoaster asymmetricus shows an abundance reduction at approximately 2.65 Ma, but it continues to occur in low abundances. In such low abundances, it is virtually impossible to attach a reliable age to its extinction. This low abundance phenomenon after 2.65 Ma is observed at all five sites and, thus, is not simply reworking (Backman and Shackleton, 1983). However, at Site 607, it is difficult to distinguish between the presence of *D. asymmetricus* in low abundances and reworking after 2.65 Ma, because it is associated with reworked *D. tamalis*. The extinction may even be as young as 2.2 Ma, so this is not a useful datum. Another interesting feature is that *D. tamalis* and *D. asymmetricus* mimic the abundance of *D. brouweri* at the five sites. This may indicate taxonomic affinity among these three species. Since *D. tamalis* and *D. asymmetricus* are numerically insignificant in this interval, except at high latitudes, it would seem more sensible to cross-correlate sites using abundance peaks of *D. brouweri*.

Total Abundance

Interesting differences are to be noted below 2.35 Ma when one begins to move into the range of other species beside *D. brouweri*, which is the only species covering the whole time interval. Excluding *D. variabilis*, which begins to appear in small numbers at the base of our time interval, it is only at 2.65

Ma that all the *Discoaster* species are present. Of the other species, *D. pentaradiatus* and *D. surculus* are numerically most significant.

An immediately noticeable difference among the five sites (Fig. 18) is the higher overall abundance of discoasters at Sites 659 and 662 than at Sites 552, 607, and 658. At Sites 607 and 552, the effect of cooler surface-water temperatures in association with higher latitudes is probably one important factor; likewise, at Site 658, its association with upwelling. Shackleton et al. (1984) have shown that the onset of Northern Hemisphere glaciation was a well-defined event at about 2.4 Ma, and it may correlate with the sudden abundance reduction of discoasters at 2.4 Ma at Site 607 and the following 50 k.y. at Site 658. At the latter site, this may perhaps indicate an intensification of upwelling, which may have been less intense before. Even at Site 552, where the abundances are extremely low, an abrupt drop in abundance after 2.4 Ma can be seen (Fig. 13).

At Site 662, discoasters are still reasonably abundant, but the effects of the South Equatorial Current appear to reduce their overall numbers. It is very clear that short-term variations are imprinted on the *Discoaster* record, but the long-term trend of abundance reduction is apparent, which is possibly linked to the initiation of glaciation in the North Atlantic at 2.4 Ma.

To account for the dilution effect by high sedimentation rates, the observed abundances should be multiplied by the sedimentation rates to give a figure more closely proportional to accumulation rates for each species. Sites 607, 659, and 662 would still be roughly comparable as shown, and Site 658 would be increased by a factor of only 2 or 3 relative to these

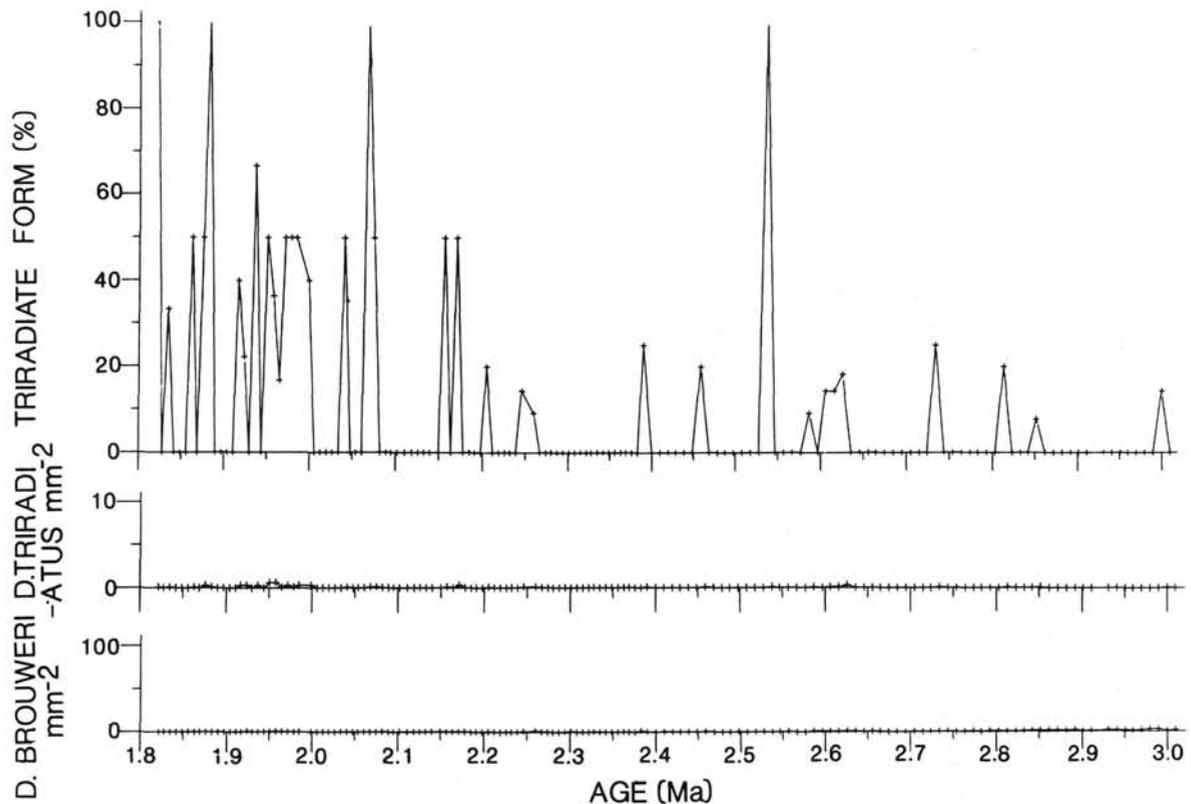


Figure 10. Abundance plots of *D. brouweri* and *D. triradiatus* at Site 552.

sites, still showing much lower abundances. Values for Site 552, however, would be reduced further by roughly a factor of 3 to show even lower abundances.

SPECTRAL ANALYSIS

Numerous studies have shown that the late Cenozoic paleoclimate varied in response to orbital forcing (e.g., Hays et al., 1976; Pisias and Leinen, 1984; Pestiaux and Berger, 1984). Similarly, since many groups of nannoplankton are restricted to specific temperature ranges (e.g., McIntyre, 1967; Okada and Honjo, 1973; Okada and McIntyre, 1979), it would be expected that their abundances would respond, for example, to changes in sea-surface temperature resulting from orbital forcing. Backman et al. (1986) and Backman and Pestiaux (1987) have already demonstrated this at DSDP Site 606 and Hole 552A.

At Site 606, variance at the frequency of all three orbital elements were obtained, dominated by the 400-k.y. periodicity. At DSDP Hole 552A, only the eccentricity and obliquity periodicities were present, of which obliquity was dominant; at this site precessional periodicities may have been undetectable due to the low sedimentation rate, resulting in a temporally coarse sampling interval.

In this study, spectral analysis is based on linear interpolation between the biostratigraphic and magnetostratigraphic control points selected for the age models (Table 3). The data sets have been divided into two time intervals: from 1.88 to 2.39 Ma and from 2.39 to 3.00 Ma (Fig. 19). At approximately 2.39 Ma, several important events occur, including sudden cooling in the North Atlantic, changes in the sedimentation rate, total *Discoaster* abundance reduction, the extinction of *D. surculus*, and the near extinction of *D. pentaradiatus*.

For the purposes of this analysis, the sum of all the *Discoaster* species was investigated in order to reduce the

effect of the idiosyncracies of particular species. There is frequently an order-of-magnitude change in *Discoaster* abundances that is associated with regularly spaced abundance peaks, which indicates that there is a large signal available for spectral analysis.

During the time interval from 1.88 to 2.39 Ma, *D. brouweri* is effectively the only species present, except between 1.89 and 2.07 when *D. triradiatus* had its acme. At Sites 662, 552 (precession very weak), and 607, concentrations of variance around the frequencies of the orbital elements of eccentricity (100 k.y.), obliquity (41 k.y.), and precession (21 k.y.) are distinguished. At Site 658, only a possible eccentricity signal is noticeable in this time interval, but this may be due to the very low abundances. The obliquity periodicity occurs at Site 659, but it is much less defined than the eccentricity and precessional periodicities.

Between 2.39 and 3.00 Ma, when a greater *Discoaster* assemblage is present, the obliquity periodicity is distinct at all the sites except Site 659, which is dominated by the precessional periodicities. There is some indication of the influence of eccentricity at all sites, but precession is only clearly indicated at Sites 662, 659, and 607.

Clearly these results will be significantly modified as we apply more complex age models. Our strategy here was to investigate whether in the presence of marked aperiodic fluctuations in the abundance of individual species and a long-term decline toward extinction in the *Discoaster* group, it would still be possible to detect the periodicities characteristic of orbital forcing. Our data suggests that it is indeed possible.

After oxygen isotope data becomes available for more of the sites, it will be possible to generate refined time scales for each site and to gain a better estimate of the characteristics of the forced and unforced components of *Discoaster* variability.

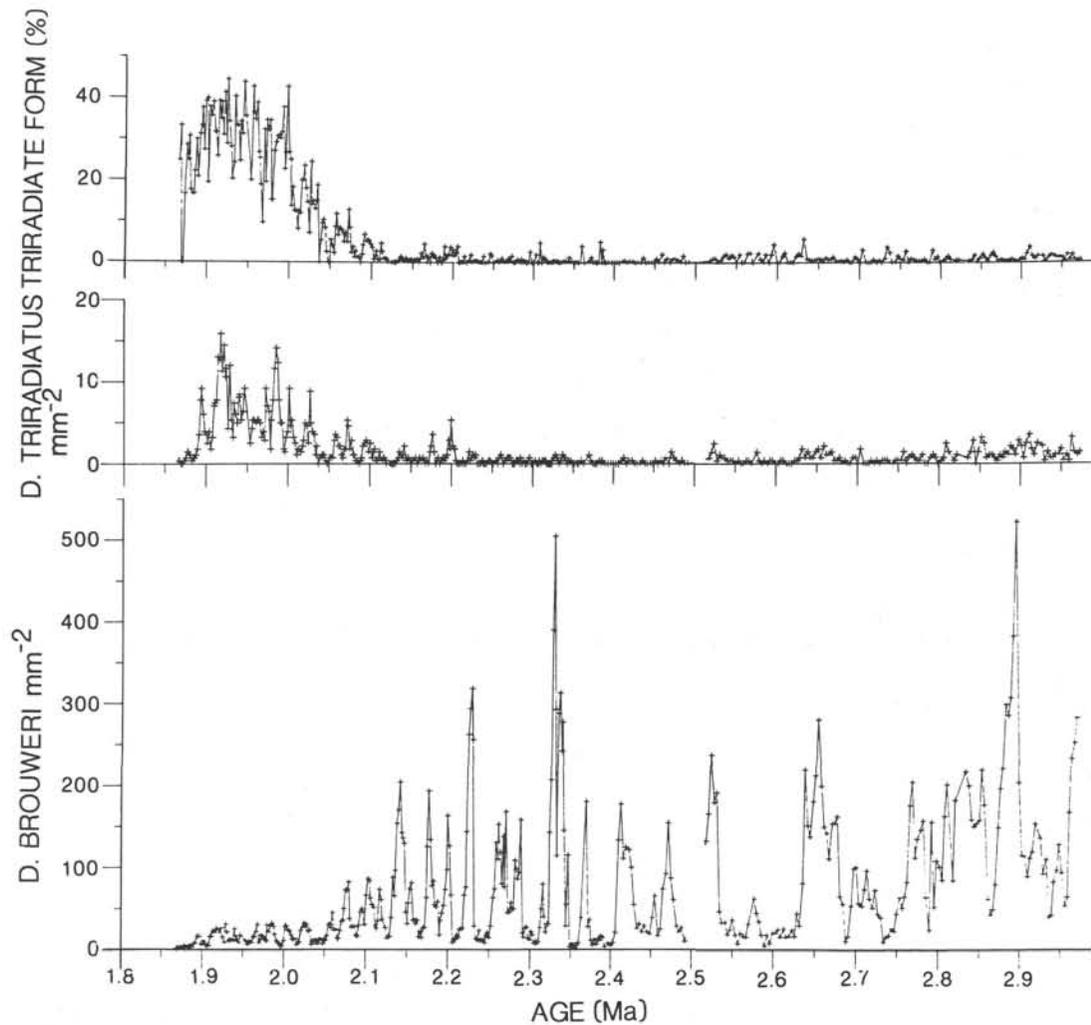


Figure 11. Abundance plots of *D. brouweri* and *D. triradiatus* at Site 662.

This will enable us to assess the prospects for using apparent orbital frequencies in *Discoaster* data to develop an astronomically calibrated time scale in the interval prior to 2.4 Ma, when isotopic fluctuations are much reduced.

DISCUSSION

Orbital forcing has been shown to be imprinted strongly on the *Discoaster* abundances at these sites, presumably acting through sea-surface temperature variability. Total *Discoaster* abundances are reduced with increasing latitude and upward toward their extinction. Is this caused only by a reduction in temperature with latitude and through time?

Previous studies have suggested that *Discoaster* abundances are responding only to temperature changes. However, results from this work, especially from the tropical sites, that show large abundance variations clearly suggest that other factors must be important. One possible factor is productivity pressure. In view of the suppressed abundances at the upwelling site (Site 658), it seems tenable to conclude that regions of high productivity are associated with reduced *Discoaster* abundance (supported by our unpublished observations at Site 677 in the Panama Basin). The *Discoaster* assemblage appears to tolerate a wide temperature range up to 41°N; but between this latitude and 56°N, a threshold is reached beyond which the abundances are suddenly reduced.

Discoaster brouweri was certainly reduced in abundance with latitude. Prior to 2.38 Ma, *D. surculus* and *D. pentaradiatus* are important components of the *Discoaster* assemblage. Rapid cooling in the North Atlantic at 2.4 Ma (Shackleton et al., 1984) seems to correlate (coincidentally?) with the extinction of these two species at 2.39 and 2.38 Ma, respectively. *Discoaster surculus* increased significantly relative to *D. brouweri* as a function of increasing latitude and upwelling conditions. Its distribution through time, however, shows no clear trend of abundance reduction, and it seems to signal a reduction in sea-surface temperatures less than any of the other species. It seems probable that its distribution through time and space was in response to a productivity signal. Nevertheless, latitude does limit its distribution and its abundance is reduced above 41°N.

As far north as 18°N, *D. pentaradiatus* shows a clear trend of reduction through time, but north of this latitude no such trend is apparent. It maintained a fairly constant abundance up to 41°N, excluding upwelling Site 658; it was less abundant at higher latitudes.

These two species clearly possess an inverse abundance relationship, so what could have been their differences in ecological requirements? *Discoaster surculus* may have favored cooler, more nutrient-rich waters, and *D. pentaradiatus* may have preferred slightly warmer, less nutrient-rich waters. Assuming ecological tolerances did not shift greatly through

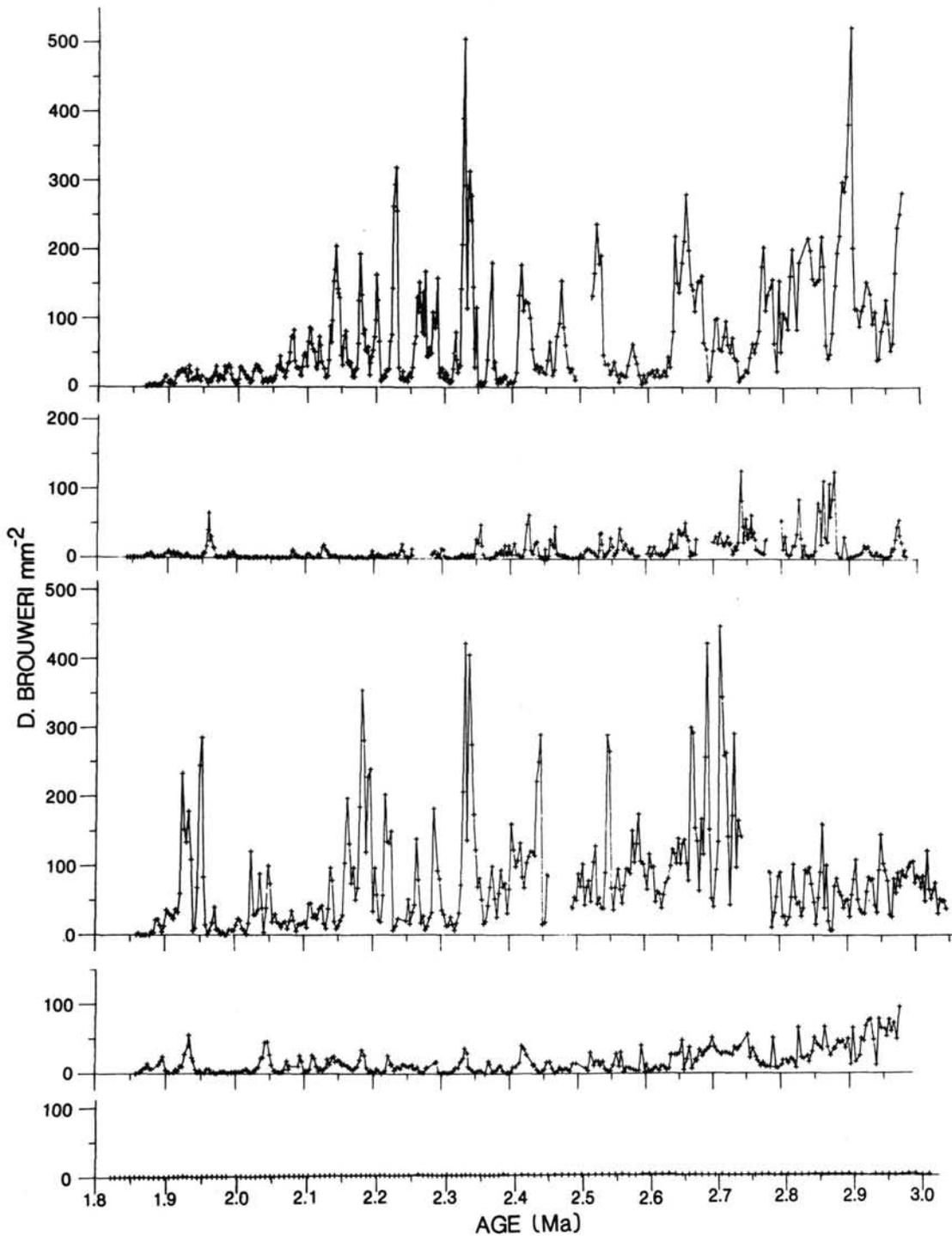


Figure 12. Abundance plots of *D. brouweri* at Sites 552, 607, 659, 658, and 662. Gaps in plots are core breaks.

time, *D. brouweri* may have favored even warmer, less nutrient-rich waters.

The covariation of *D. brouweri* with *D. triradiatus*, and *D. brouweri* with *D. asymmetricus* and *D. tamalis* seems to suggest taxonomic affinity, but this creates some interesting questions. A single species of phytoplankton may have produced different types of discs at different times, with a trend toward reducing calcite (e.g., *D. tamalis* to *D. triradiatus*). However, this species must have consistently produced the

six-rayed *D. brouweri* through the time interval investigated (1.89–3.00 Ma).

Discoaster tamalis and *D. asymmetricus* were also produced in virtually identical abundances, but only one of these disappeared globally at 2.65 Ma; *D. asymmetricus* continued to occur in low abundances as late as 2.2 Ma, though the true extinction is indistinct. It may even be that the continuing presence of *D. asymmetricus* is not of any ecological significance, but merely some error in the mechanism for producing

COMPARISON OF UPPER PLIOCENE DISCOASTER ABUNDANCE VARIATIONS

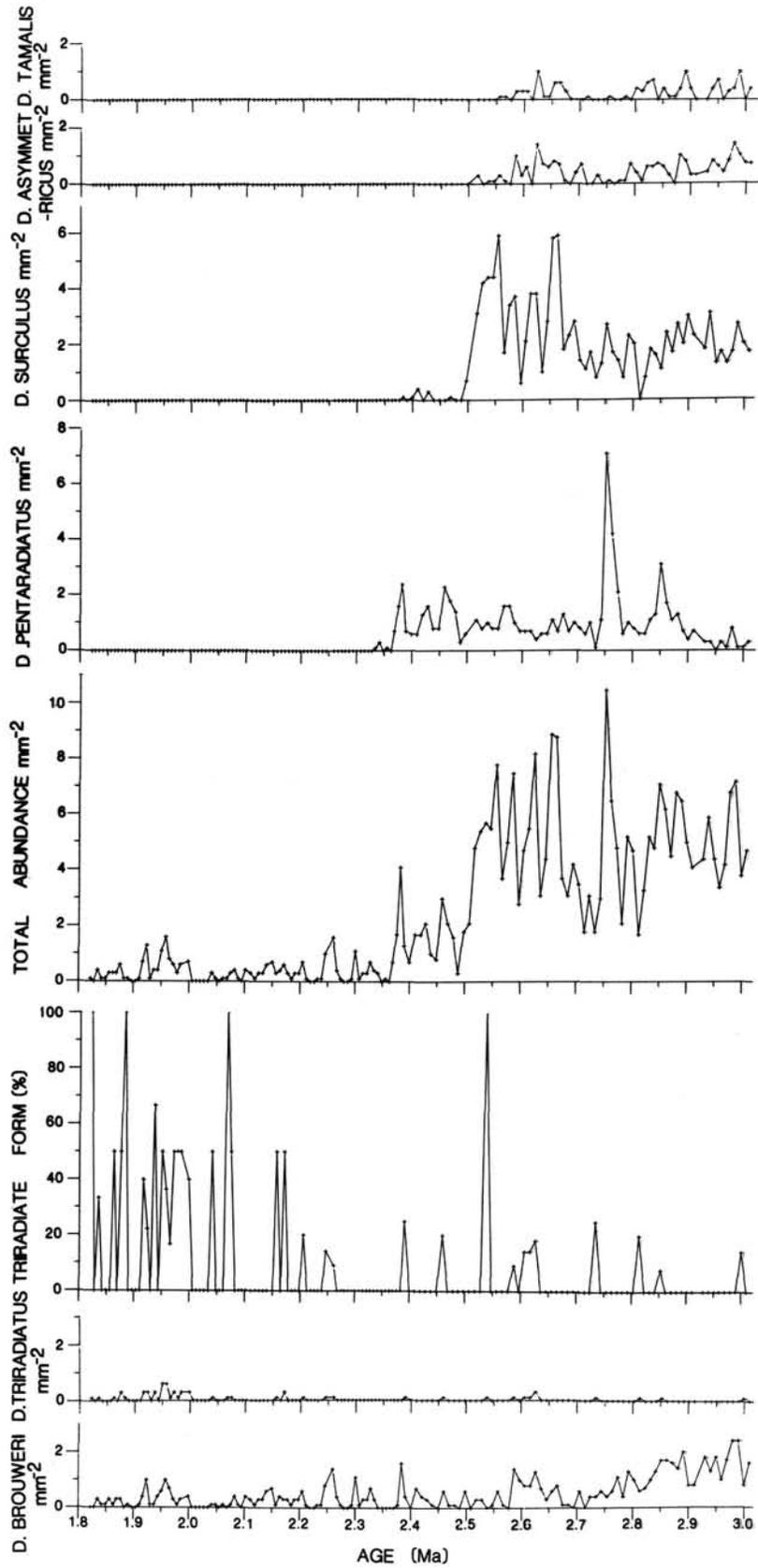


Figure 13. Abundance plots of *D. brouweri*, *D. triradiatus*, total abundance, *D. pentaradiatus*, *D. surculus*, *D. asymmetricus*, and *D. tamalis* at Site 552. Notice the change in abundance scale.

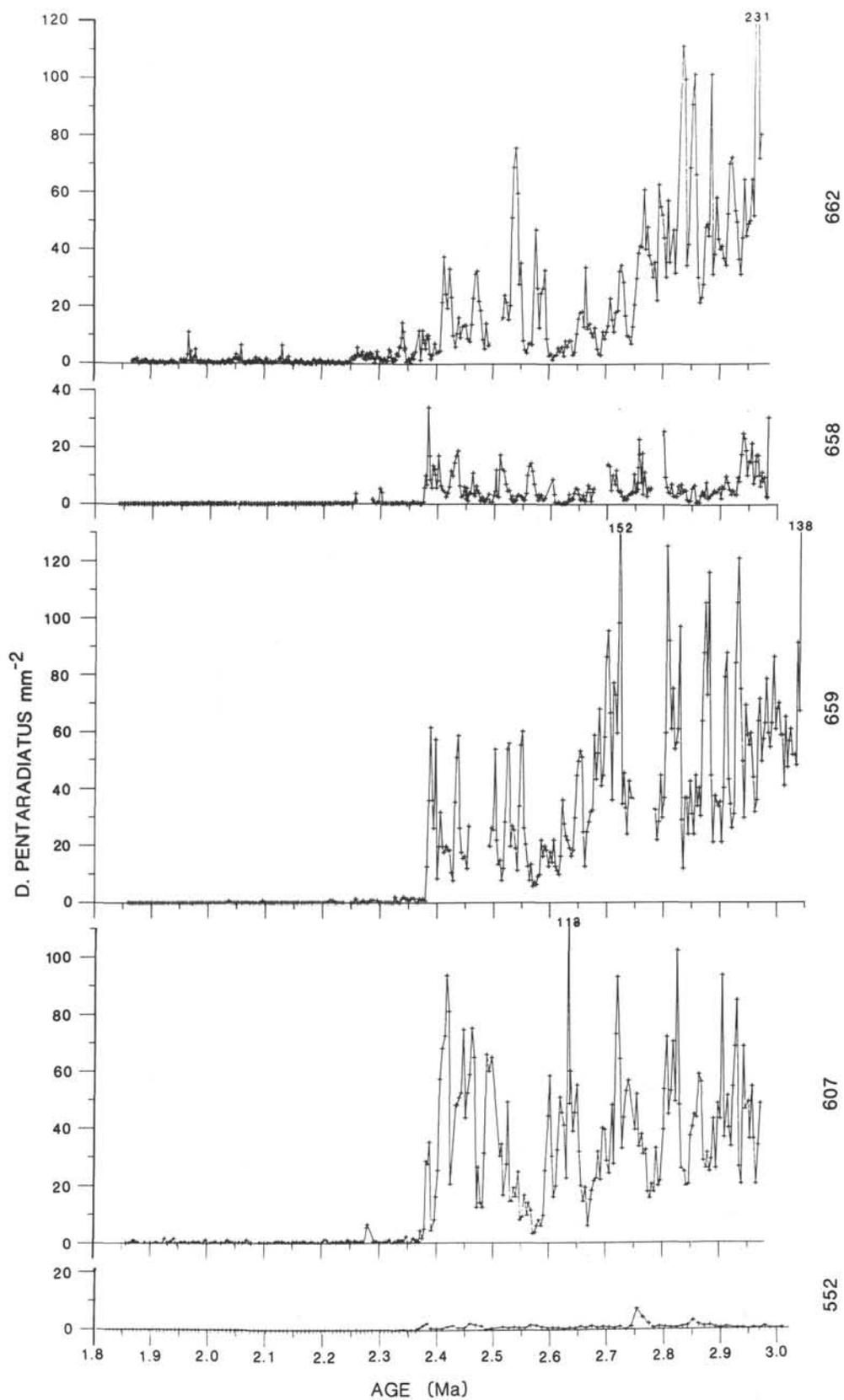


Figure 14. Abundance plots of *D. pentaradiatus* at Sites 552, 607, 659, 658, and 662. The abundance scale has been reduced five times in comparison with the abundance plots of *D. brouweri*.

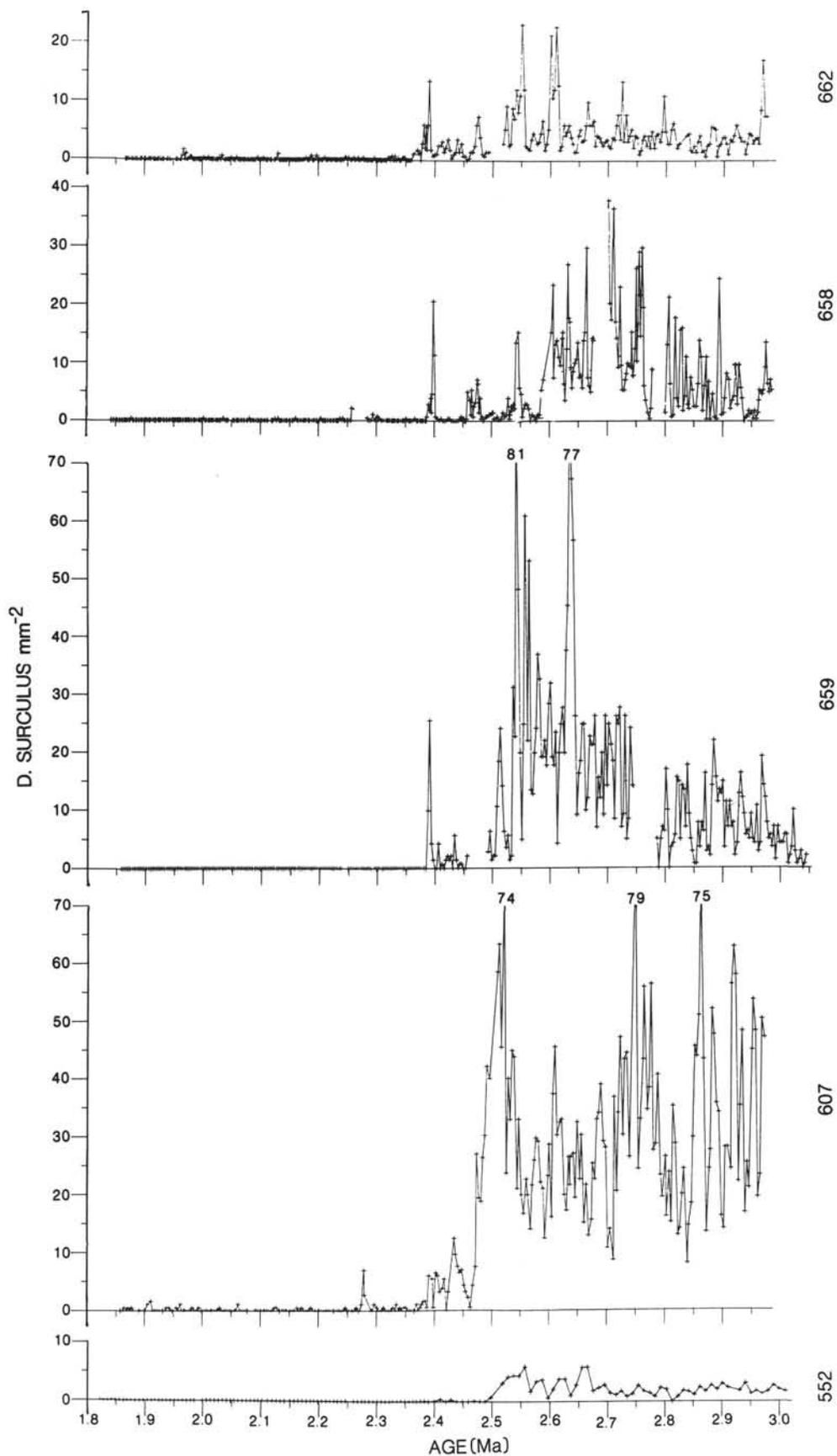


Figure 15. Abundance plots of *D. surculus* at Sites 552, 607, 659, 658, and 662. The abundance scale has been reduced twice in comparison with the abundance plots of *D. pentaradiatus*.

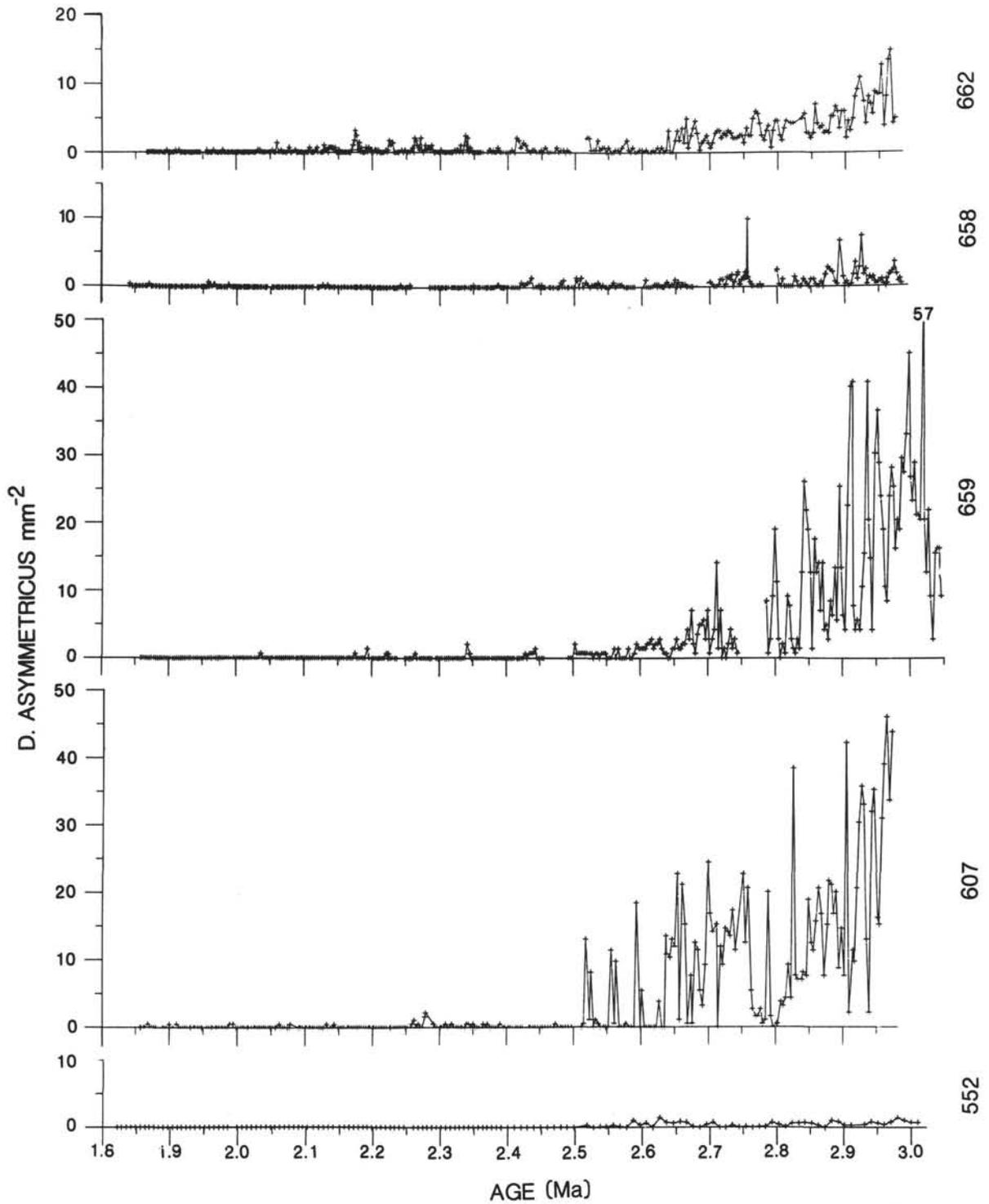


Figure 16. Abundance plots of *D. asymmetricus* at Sites 552, 607, 659, 658, and 662. The abundance scale is the same as *D. surculus* and *D. tamalis*.

the six-armed *D. brouweri*. *Discoaster asymmetricus* and *D. tamalis* show a distinct trend of reduction in abundance through time up until 2.65 Ma, but they actually increase in abundance relative to *D. brouweri* with increasing latitude. A possible solution is that the unknown phytoplankton species produced *D. asymmetricus* and *D. tamalis* in equal amounts in

its structure, but more commonly with lower temperatures and higher latitude.

Since it is not known what the *Discoaster* organism looked like, it is difficult to speculate about the function of these different types of discs. However, some species of coccolithophorids today are known to produce different types of cocco-

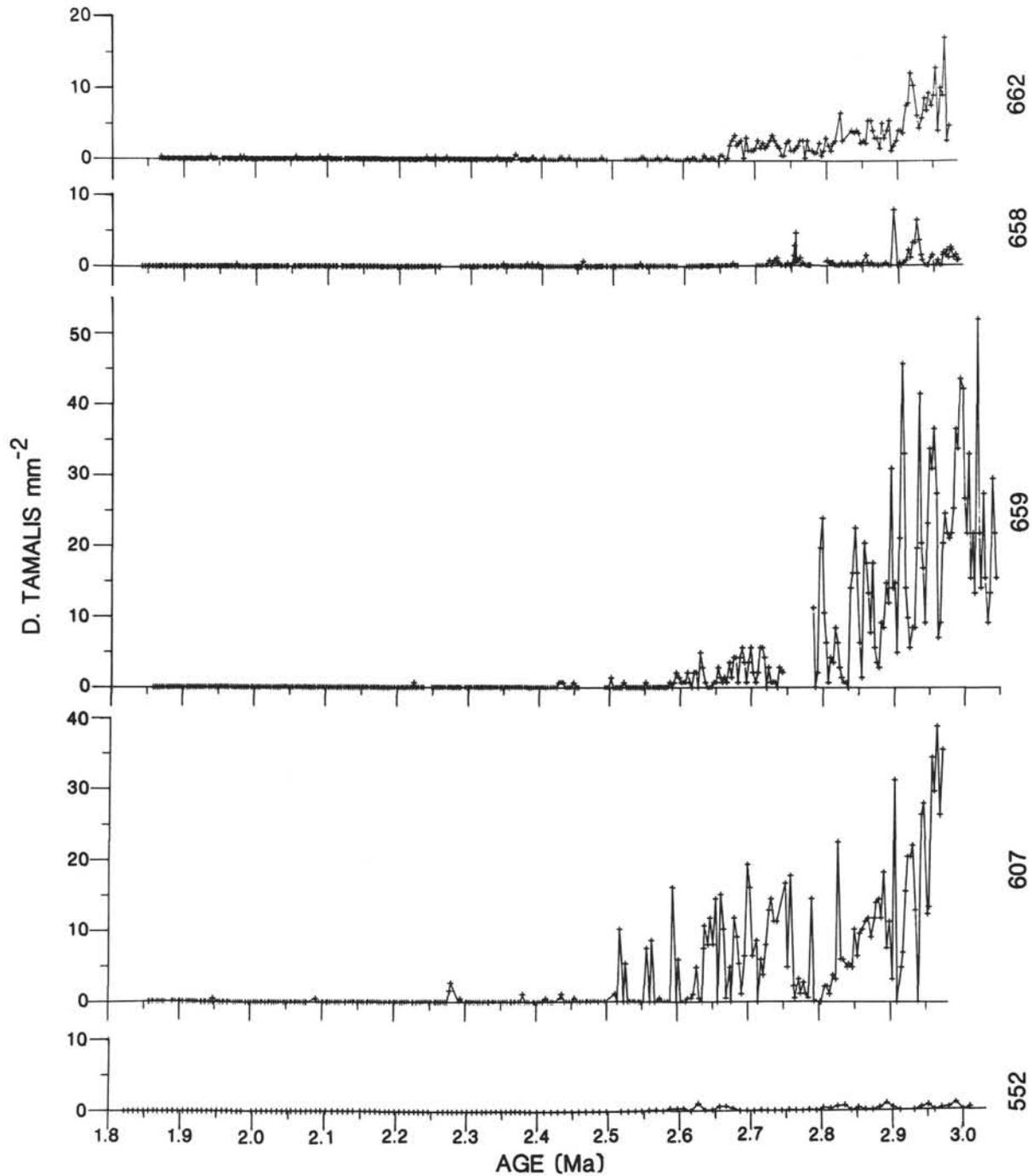


Figure 17. Abundance plots of *D. tamalis* at Sites 552, 607, 659, 658, and 662. The abundance scale is the same as *D. surculus* and *D. asymmetricus*.

liths in the same organism at the same time or under different ecological conditions.

SUMMARY

Total *Discoaster* abundance is reduced by increasing latitude. Prior to 2.38 Ma, the abundance of *D. brouweri* declines more rapidly with increasing latitude than the abundance of such other species as *D. pentaradiatus* and *D. surculus*.

Discoaster surculus forms a greater component of the *Discoaster* assemblage with increasing latitude and in upwelling conditions.

Discoaster asymmetricus and *D. tamalis* increase with latitude relative to *D. brouweri*, with which they appear to be taxonomically related.

Marked fluctuations in the abundance of discoasters are in the frequency range of earth orbital variations. However, the high variability observed in the tropics cannot be solely related to temperature changes resulting from orbital forcing,

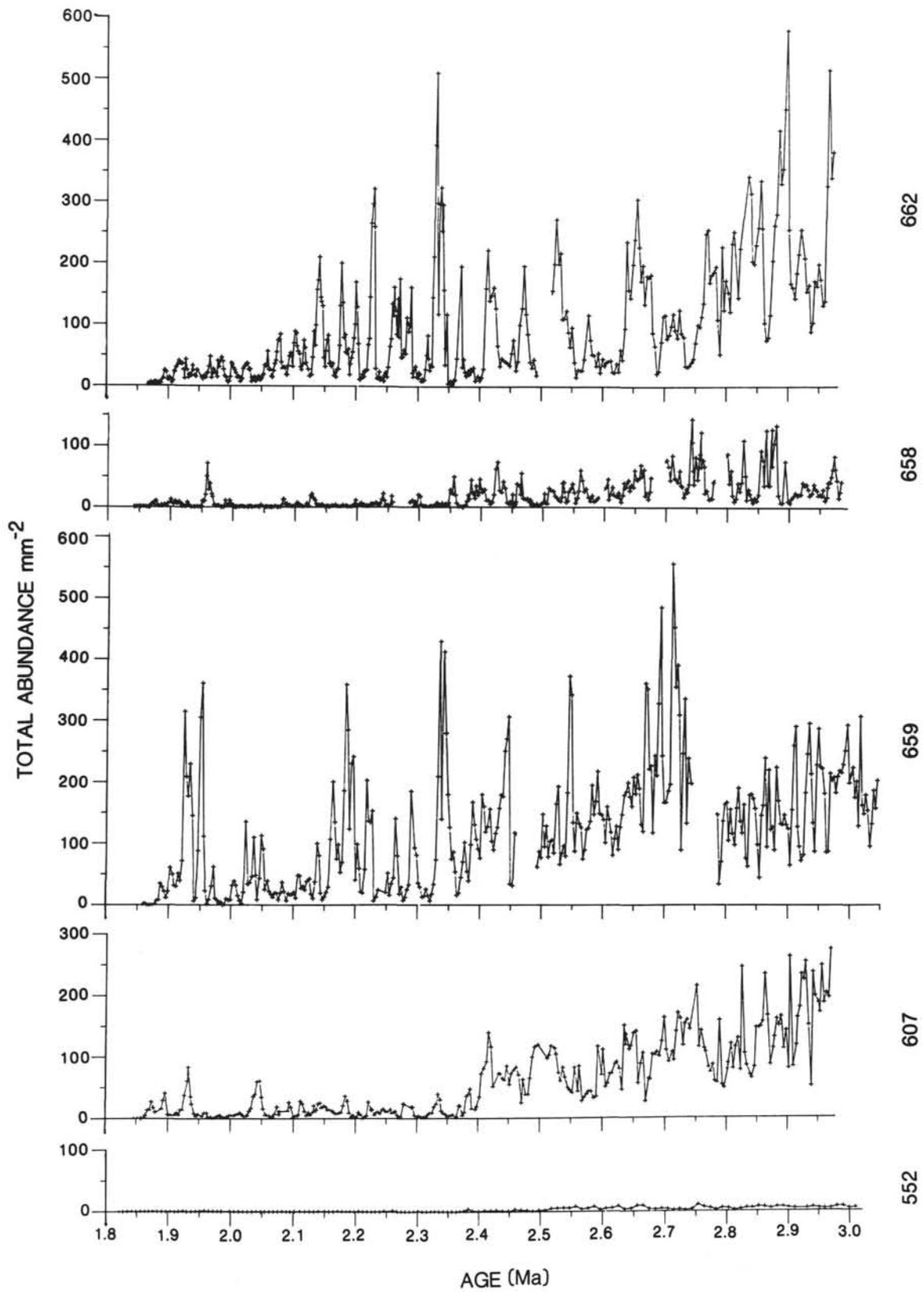


Figure 18. Plots of total *Discoaster* abundance at Sites 552, 607, 659, 658, and 662. Gaps in plots are core breaks.

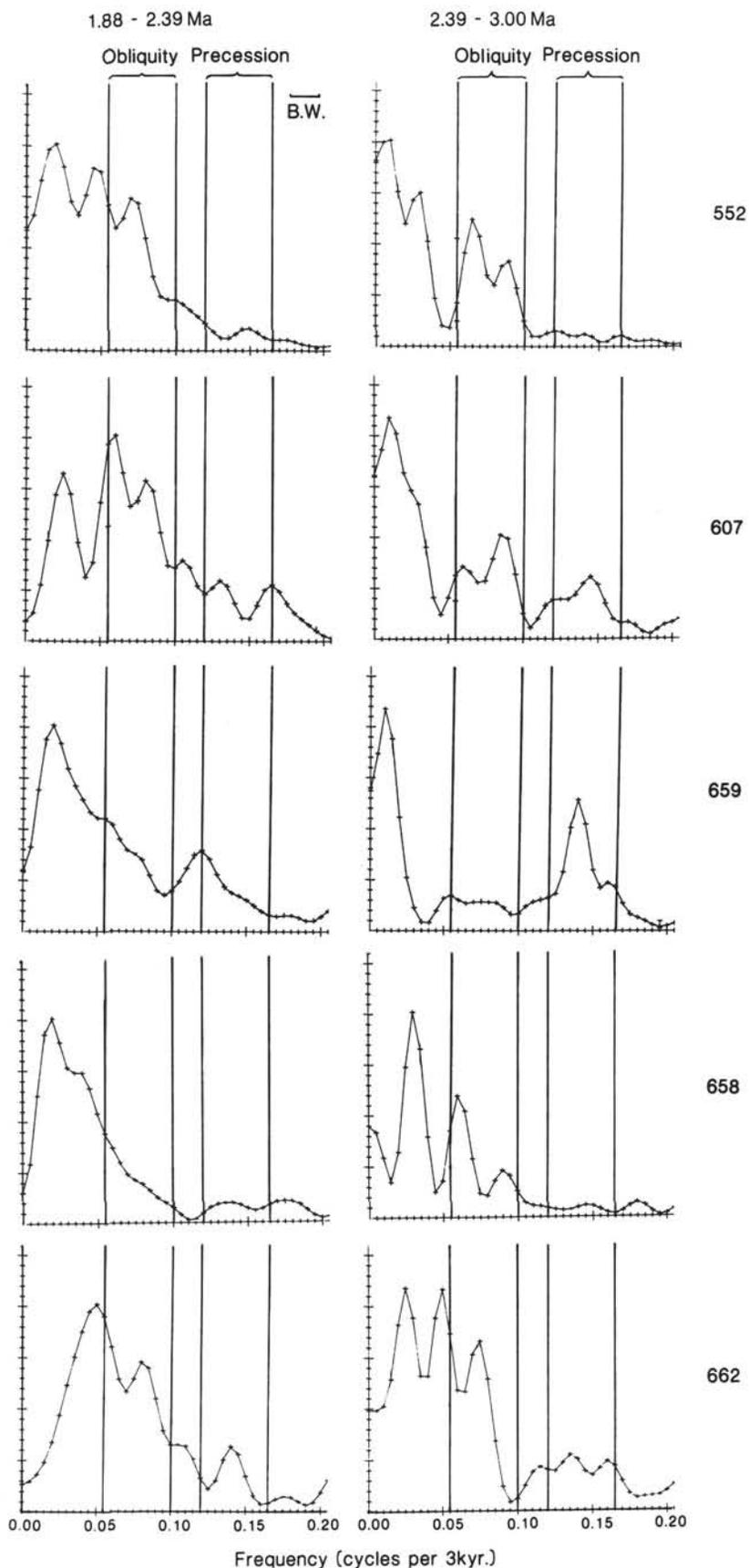


Figure 19. Spectral power density estimated on two time intervals of the total *Discoaster* data set at Sites 552, 607, 659, 658, and 662. B.W. indicates band width.

but may imply that varying productivity pressure was the primary control.

The extinctions of *D. surculus* and *D. pentaradiatus* as well as the drastic reduction in total *Discoaster* abundance north of 18°N and at upwelling Site 658 seem to correlate with an abrupt drop in sea-surface temperature in the North Atlantic at 2.4 Ma. At sites south of 20°N, the extinction of *D. surculus* is characteristically preceded by a distinctive brief peak in abundance.

Many of the distinct *Discoaster* abundance peaks that are observed can be correlated between sites, an observation that may prove useful in the future in refining stratigraphic correlations.

ACKNOWLEDGMENTS

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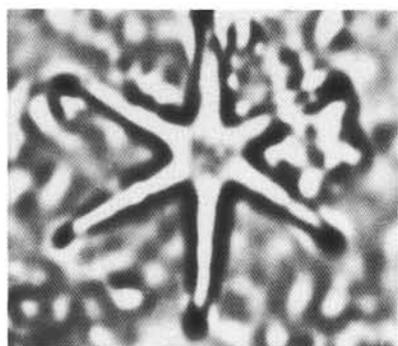
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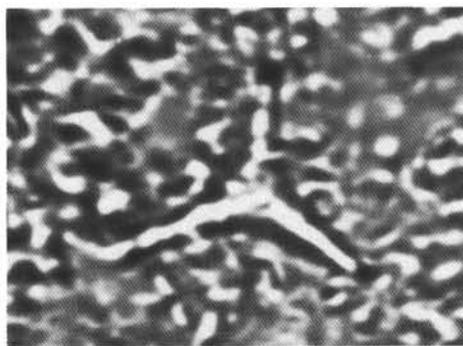
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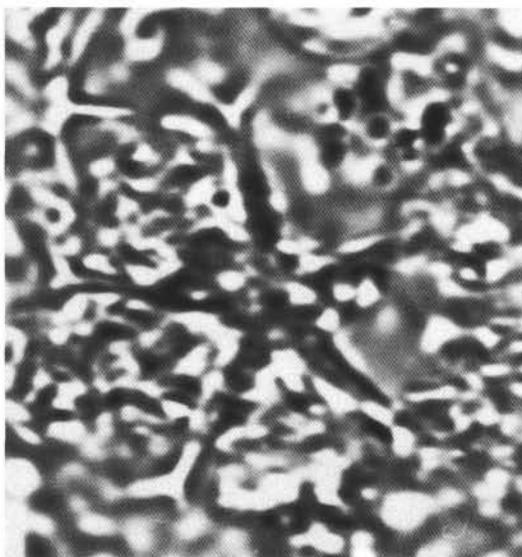
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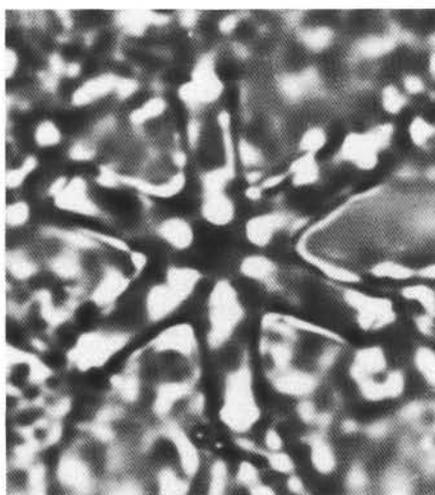
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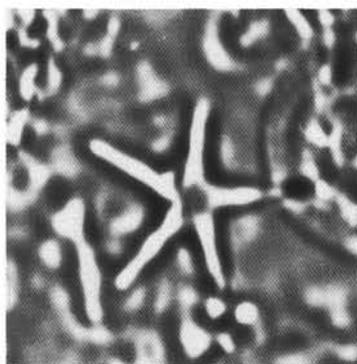
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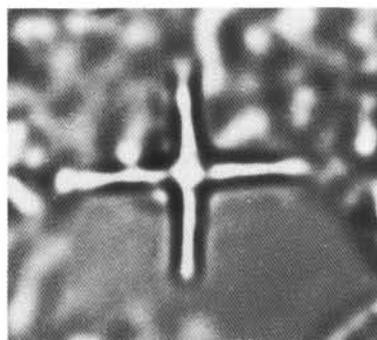
3



4



5



6

10 μ

Plate 1. Species of *Discoaster*. 1. *Discoaster brouweri* Tan Sin Hok. 2. *Discoaster triradiatus* Tan Sin Hok. 3. *Discoaster pentaradiatus* Tan Sin Hok. 4. *Discoaster surculus* Martini and Bramlette. 5. *Discoaster asymmetricus* Gartner. 6. *Discoaster tamalis* Kamptner.