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LATITUDINAL BIOGEOGRAPHIC GRADIENTS OF LATE PALEOGENE CALCAREOUS NANNOPLANKTON IN THE SOUTH ATLANTIC OCEAN

CONTENTS

Key words: calcareous nannoplankton, paleobiogeography, paleoceanography, South Atlantic, Paleogene.

ABSTRACT

Quantitative biogeographic study of upper Eocene-Oligocene calcareous nannoplankton of the South Atlantic Ocean reveals that the distribution of warm-water taxa contracted progressively toward lower latitudes from 38 to 34 Ma, with the most rapid contraction occurring between 37 and 36 Ma. Cool-water taxa expanded progressively toward lower latitudes from 40 to 36 Ma. The changes of the distribution patterns of both warm-water taxa and cool-water taxa suggest a significant cooling in the latest Eocene to earliest Oligocene. Latitudinal biogeographic gradients of calcareous nannoplankton have been quantified by similarity analysis. Results suggest that significant latitudinal biogeographic gradients were established in the late Eocene, and that the gradients further increased in the Oligocene. Relatively low $\delta^{18}O$ values of planktonic foraminifers from high latitudes are believed to be caused by lower salinities in high latitudes than in mid or low latitudes. Failure to account for the salinity factor when estimating paleotemperatures for the high latitude using oxygen isotopic data is believed to have led to the conclusion of near flat thermal gradients between high latitudes and mid latitudes in the Paleogene oceans. Based on the latitudinal biogeographic gradient data obtained in this study, along with oxygen isotopic data from the low and mid latitudes, we estimate that temperatures were about 13°C at Site 511 and 9°C at Site 689 in the late Eocene, and about 7°C and 3°C at the two sites respectively in the early Oligocene. The biogeographic gradient data are compatible with the notion of considerable ice volume on Antarctica in the late Eocene and early Oligocene.

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RIASSUNTO

Lo studio biogeografico quantitativo sul nannoplancton calcareo dell'Eocene superiore-Oligocene dell'Atlantico meridionale mostra che la distribuzione dei taxa di acqua calda si ritira progressivamente verso le basse latitudini fra 38 e 34 Ma, con la contrazione più

rapida tra 37 e 36 Ma. I taxa di acqua fredda si espandono progressivamente verso latitudini più basse fra 40 e 36 Ma. I cambiamenti del quadro di distribuzione dei taxa, sia di acqua calda che di acqua fredda, suggeriscono che si sia verificato un sensibile raffreddamento dall'Eocene terminale all'Oligocene basale. I gradienti latitudinali biogeografici del nannoplancton calcareo sono stati quantificati mediante l'analisi della similarità. I risultati indicano che nell'Eocene superiore esistevano significativi gradienti latitudinali biogeografici e che questi sono ulteriormente aumentati nell'Oligocene. I valori relativamente bassi di $\delta^{18}O$ nei foraminiferi planctonici di alte latitudini si ritengono imputabili a valori di salinità più bassi alle alte latitudini che alle medie e basse. Si ritiene che il non aver tenuto conto del fattore salinità nella stima delle paleotemperature delle alte latitudini sulla base dei dati isotopici dell'ossigeno abbia portato alla conclusione che negli oceani del Paleogene i gradienti termali tra le alte e le medie latitudini fossere quasi piatti. In base ai gradienti latitudinali biogeografici ottenuti in questo studio, insieme ai dati isotopici delll'ossigeno di basse e medie latitudini, noi riteniamo che le temperature fossero di circa 13°C al Site 511 e 9°C al Site 689 nell'Eocene superiore, e circa 7°C e 3°C rispettivamente nell'Oligocene inferiore. I dati relativi al gradiente biogeografico sono compatibili con l'esistenza di una considerevole massa di ghiaccio sull'Antartide nell'Eocene superiore e Oligocene inferiore.

INTRODUCTION

McIntyre and Bé (1967) first showed on a global scale that there is a latitudinal differentiation of calcareous nannoplankton in the modern ocean, and that the distribution patterns are closely related to the isotherms of the surface waters. This has been substantiated by a number of subsequent studies (*e.g.*, McIntyre *et al.*, 1970; Okada and Honjo, 1973). By examining the paleobiogeographic patterns of calcareous nannoplankton and their changes through time, it should be possible to infer changes in the thermal structures of the surface waters, which in turn are related to paleoclimatic changes.

Edwards (1968) was the first to use calcareous nannofossil data to indicate Paleocene-Miocene marine climate. Paleogene calcareous nannoplankton biogeography of the Atlantic Ocean was delineated by Haq and his various co-authors in the late 1970's (Haq and Lohmann, 1976; Haq, Lohmann, and Wise, 1977; Haq, Perch-Nielsen, and Lohmann, 1977; Haq, Premoli-Silva and Lohmann, 1977; Haq, Okada and Lohmann, 1979). These studies, however, were based on very limited data from the South Atlantic; upper Paleogene material available for these studies extended only southward to 30°S latitude. No hydraulic piston cores were then available and magnetostratigraphy on the cores was virtually nonexistent. This hindered correlation of samples from different latitudes, especially for low to high latitude correlation. Subsequent drilling by the Deep Sea Drilling Project (DSDP) and the Ocean Drilling Program (ODP) in the South Atlantic has provided a wealth of high quality core mateial from different latitudes to 65°S. Many of these cores have yielded detailed biomagnetostratigraphies. This offers an excellent opportunity to carry out a new phase of paleobiogeographic studies of the South Atlantic. Wei and Wise (1990a) recently studied the biogeography of middle Eocene through Oligocene calcareous nannoplankton of the South Atlantic in time series. The present study takes a different approach and analyses the upper Paleogene (40-27 Ma) calcareous nannofossils of the South Atlantic in fourteen time slices (1 m.y. each). The major objectives of this study are to delineate expansion and contraction across latitude of the distribution patterns of temperature-sensitive nannoplankton taxa and to quantify the latitudinal biogeographic gradient in each time slice. These data are then used to infer changes in the temperatures of the surface waters and in the latitudinal thermal gradients.

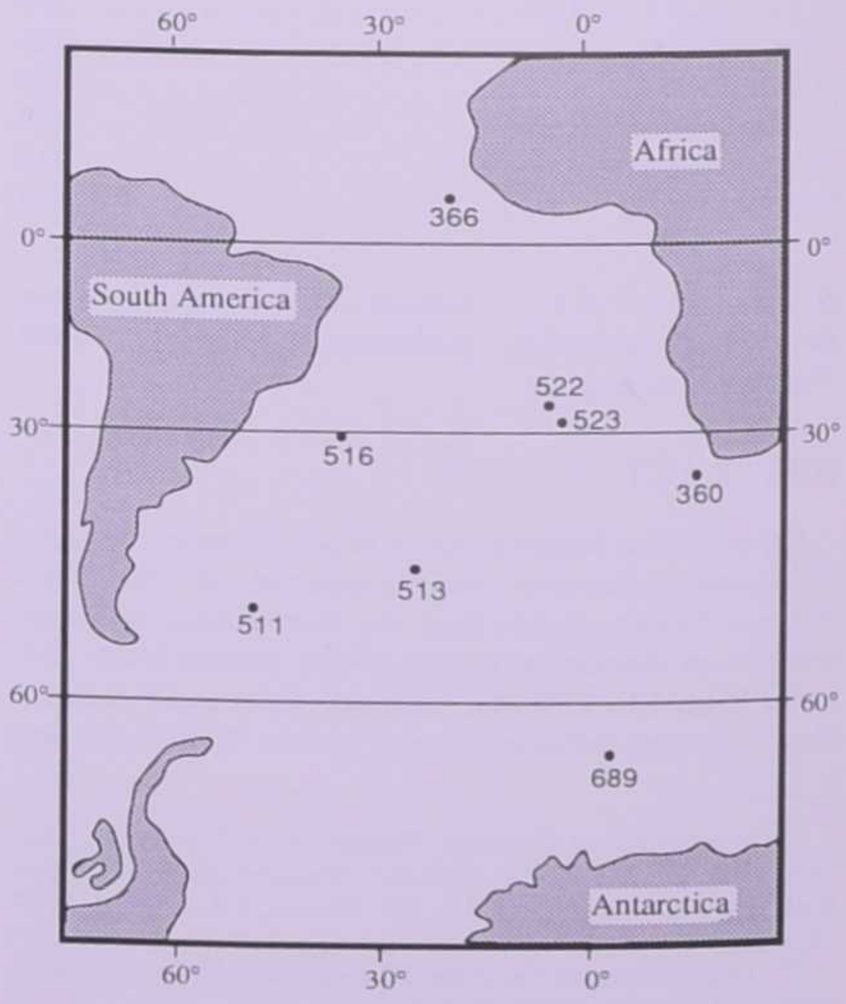


Fig. 1 - Location map of the Deep Sea Drilling Project/ Ocean Drilling Program sites from which samples have been analyzed in this study.

TABLE 1 - Locations and water depths of sites analyzed in this study (listed from low to high latitudes)

Site	Latitude	Longitude	Water depth (m)
366	5°40.7'N	19°51.1'W	2853
522	26°6.8437'S	5°7.784'W	4441
523	28°33.131'S	2°15.078'W	4562
516	30°16.59'S	35°17.10'W	1313
360	35°50.75'S	18°5.79'E	2949
513	47°34.99'S	24°38.40'W	4373
511	51°0.28'S	46°58.30'W	2589
689	64°31.009'S	3°5.996'E	2080

MATERIAL AND METHODS

Core samples used in this study come from eight DSDP and ODP drill sites, including Site 366 in the equatorial zone, Sites 522, 523, 516, 360 in the mid latitudes (in north to south order of latitude), and Sites 513, 511, and 689 in the high latitudes (Fig. 1). These sites range from 6°N to 65°S latitude and form an excellent latitudinal array for paleobiogeographic studies (Table 1). Both biostratigraphic and magnetostratigraphic information are available for Sites 516 (appendix), 522, 523, and 689, and sample ages of these sites are relatively well constrained. The geomagnetic polarity time scale of BERGGREN *et al.* (1985) is used in this study to construct age-depth curves using the magnetostratigraphic information. Sites 360, 366, 511 and 513 have only biostratigraphic information, and ages are assigned to individual samples based mainly on the calcareous nannofossil biostratigraphy, using the biomagnetostratigraphic correlations compiled by BERGGREN *et al.* (1985) and WEI and WISE (1989).

Detailed procedures for collecting census data were described in WEI and WISE (1990a) and are not repeated here. This study uses the data collected by WEI and WISE (1990a), plus some new data (Table 2) to fill in age gaps existed in the previous study. Since several data points are usually available at each site for each time slice, we averaged them for each time slice in this study. The results of this data transformation are given in Table 3. Due to some problems such as poor preservation of nannofossil assembleges or poor

TABLE 2 - Census data of calcareous nannofossils taxa expressed as percent of total number of individuals counted

Sample	Age	B.sp	Chi	C.fe	C.fo	C.pe	C.fl	disc	heli	I.re	R. bi	R.da	R.re	R.um	sphe
522-20-1,80	28.0	.0	.0	.0	.0	24.5	55.9	12.8	.0	.0	4.5	.0	.0	.0	2.4
513A-20-2,82	27.4	.0	3.9	.0	.0	47.7	.0	.0	.0	.0	3.3	45.1	.0	.0	.0
513A-27-cc	32.4	.0	17.5	.0	.0	25.5	2.3	.0	.0	.0	54.3	4.8	.0	.0	.0
511-17-2,87	37.3	.0	18.0	.0	.0	26.6	.0	.0	.0	.0	10.9	31.3	.0	12.5	.0
689B-11-4,32	30.7	.0	30.0	.0	.0	1.4	.0	.0	.0	.0	.0	68.6	.0	.0	.0
689B-11-5,32	30.8	.0	38.7	.0	.0	1.0	.0	.0	.0	.0	.0	60.3	.0	.0	.0
689B-12-1,29	32.4	.0	44.0	.0	.0	1.2	.0	.0	.0	.0	.0	54.8	.0	.0	.0
689B-12-3,29	33.0	.0	46.1	.0	.0	.3	.0	.0	.0	.0	.0	53.2	.0	.3	.0
689B-12-5,29	33.3	.0	34.9	.0	.0	1.0	.0	.0	.0	.0	.0	64.1	.0	.0	.0

Footnote: Ages are given in the time scale of Berggren et al. (1985). B.sp = *Blackites spinosus*, Chi = *Chiasmolithus* spp., C.fe = *Clausicoccus fenestratus*, C.fo = *Coccolithus formosus*, C.pe = *Coccolithus pelagicus*, C.fl = *Cyclargolithus floridanus* disc = discoasters, heli = helicosphaerids, I.re = *Isthmolithus recurvus*, R.bi = *Reticulofenestra bisecta*, R.da = *Reticulofenestra daviesii*, R.re = *Reticulofenestra reticulata*, R.um = *Reticulofenestra umbilicus*, and sphe = sphenoliths. Refer to WEI and WISE (1990a) for explanation of species concepts and taxa groupings.

TABLE 3 - Census data (percent of total) of late Eocene-Oligocene calcareous nannofossils of the South Atlantic for selected time slices analyzed in this study

Age (Ma)	B.sp	Chi	C.fe	C.fo	C.pe	C.fl	disc	heli	I.re	R. bi	R.da	R.re	R.um	sphe
(Site 366)														
27	.0	.0	.0	.0	15.3	29.6	2.2	2.6	.0	16.1	.0	.0	.0	34.3
28	.0	.0	.0	.0	20.4	23.7	3.0	3.8	.0	4.0	.0	.0	1.1	44.1
35	.0	.0	1.9	1.3	23.9	18.4	2.6	9.4	.0	24.2	.0	.0	1.0	17.4
36	.0	1.4	.0	12.2	41.7	11.5	7.3	3.8	.4	.4	.0	.0	11.1	10.5
37	.0	.9	.0	14.2	49.3	2.3	9.6	1.4	.0	7.3	.0	.0	11.4	3.7
(Site 522)														
27	.0	.0	.0	.0	22.8	19.9	4.1	.0	.0	3.7	.0	.0	.0	4.8
28	.0	.0	.0	.0	24.5	55.9	12.8	.0	.0	4.5	.0	.0	.0	2.4
29	.0	.0	.0	.0	22.6	53.6	7.1	.0	.0	12.0	.0	.0	.0	14.8
30	.0	.4	.0	.0	7.4	54.5	18.4	.0	.0	9.7	.0	.0	.0	9.5
31	.0	.0	.0	.0	13.8	74.9	1.7	.0	.0	5.3	.0	.0	.0	4.3
33	.0	.0	.0	.0	11.1	77.5	.7	.0	.0	2.7	.0	.0	.0	8.0
34	.0	.0	.0	.0	22.7	64.8	1.5	.0	.0	7.9	.0	.0	.0	3.1
35	.0	.0	2.0	6.2	19.1	60.2	1.7	.0	.0	7.3	.0	.0	.3	3.1
36	.0	.0	1.9	3.5	22.3	57.8	1.7	.0	.6	7.6	.0	.0	2.0	2.6
37	.0	.0	.0	2.7	30.0	35.5	11.5	.0	.5	7.5	.0	.0	8.6	3.9
(Site 523)														
36	.0	.3	.0	6.7	19.2	34.3	2.8	.0	1.1	21.7	4.2	.0	7.2	2.5
37	.0	.0	.0	3.7	22.0	27.3	9.9	.0	3.4	21.1	4.8	.0	3.9	3.9
39	.0	.0	.0	5.0	13.8	35.6	20.1	.0	.0	18.5	.2	.0	2.2	4.6
40	.0	.3	.0	5.6	13.6	10.5	28.0	.0	.0	23.8	.0	.0	11.5	
(Site 516)														
27	.0	.0	.0	.0	28.6	57.2	2.3	4.1	.0	3.8	2.5	.0	.0	1.7
28	.0	.3	.0	.0	32.9	48.0	10.5	.8	.0	4.3	1.4	.0	.0	2.0
29	.0	.6	.0	.0	22.4	50.0	15.9	.6	.0	4.3	1.1	.0	.0	5.1
30	.0	5.8	.0	.0	30.3	51.9	4.5	2.4	.0	.6	1.0	.0	.0	3.6
31	.0	2.2	.0	.0	25.3	50.4	10.4	.6	.0	5.4	1.5	.0	.0	4.4
32	.0	3.9	.0	.0	31.3	55.6	1.0	.7	.0	4.9	.0	.0	.0	2.6
33	.0	.6	.0	.0	22.6	67.1	.3	2.3	.0	5.2	.0	.0	.0	1.9
34	.0	2.1	.0	.0	31.1	57.0	.3	1.4	.0	7.3	.0	.0	.0	.7
35	1.0	2.1	6.3	.0	25.4	42.9	.5	4.3	.0	9.4	4.0	.0	.8	3.4
36	2.3	1.2	12.7	2.0	22.7	35.0	1.5	2.4	.0	9.7	5.7	.0	2.8	2.2
37	.9	.0	3.0	9.7	26.5	24.3	2.8	2.5	.5	10.1	12.9	.0	6.8	.3
38	.0	.0	.0	7.2	30.7	4.6	20.8	.7	.0	13.6	9.2	4.2	8.0	.8
39	.0	.0	.0	5.7	35.2	17.0	12.8	.0	.4	15.5	5.6	4.2	3.3	.5
40	.5	.8	.0	7.5	29.5	10.5	11.7	.3	.0	12.8	4.2	12.7	8.2	1.6
(Site 360)														
28	.0	2.2	.0	.0	16.0	73.7	3.3	.6	.0	2.5	.0	.0	.0	2.0
29	.0	5.3	.0	.0	18.0	70.7	3.5	.0	.0	1.8	.0	.0	.0	.7
30	.0	5.4	.0	.0	14.6	72.5	.3	.0	.0	4.4	.0	.0	.0	2.8
31	.0	5.7	.0	.0	17.8	66.6	1.1	.3	.0	6.0	.0	.0	.0	2.7

TABLE 3 - (*continued*)

Age (Ma)	B.sp	Chi	C.fe	C.fo	C.pe	C.fl	disc	heli	I.re	R. bi	R.da	R.re	R.um	sphe
32	.0	2.8	.0	.0	18.7	74.1	.0	.3	.0	1.2	.0	.0	.0	2.8
33	.0	1.2	.0	.0	14.0	76.7	.2	.0	.0	7.0	.0	.0	.0	1.0
35	.0	4.7	.0	.0	33.2	52.3	.4	.2	.1	5.6	1.0	.0	1.0	1.7
36	.0	2.3	2.2	3.7	24.6	27.0	6.0	.2	2.1	13.6	8.9	.0	9.7	.0
37	.0	1.1	.0	3.0	28.6	23.7	2.2	.3	1.4	55.2	15.2	.0	8.6	.3
38	.0	.3	.0	7.2	19.0	37.7	2.1	.0	.3	25.3	3.2	.0	3.6	.3
39	.0	1.4	.0	1.8	17.9	28.0	5.0	.0	.0	14.4	14.9	7.6	7.8	1.1
40	.0	1.1	.0	3.8	22.6	24.9	3.6	.0	.0	4.1	4.5	23.9	10.8	.9
(Site 513)														
27	.0	3.9	.0	.0	47.7	.0	.0	.0	.0	3.3	45.1	.0	.0	.0
30	.0	2.3	.0	.0	13.6	25.5	.0	.0	.0	.0	54.2	.0	.0	.0
32	.0	17.5	.0	.0	25.5	2.3	.0	.0	.0	54.3	4.8	.0	.0	.0
33	.0	13.3	.0	.0	24.0	1.1	.0	.0	.0	.2	41.9	.0	18.1	.0
34	.3	29.1	6.7	.0	16.0	.0	.0	.0	.0	3.6	39.6	.0	4.3	.0
35	2.8	11.2	27.1	.1	10.2	.0	.0	.0	1.3	3.1	40.2	.0	5.8	.0
36	2.2	13.1	19.4	.0	19.1	.0	.0	.0	1.4	.8	44.0	.0	.0	.0
(Site 511)														
34	.0	15.0	1.0	.0	8.3	.0	.1	.0	.0	5.8	60.0	.0	9.8	.0
35	.6	19.0	2.9	.0	2.2	.0	.0	.0	1.2	7.2	59.4	.0	7.4	.0
36	.3	10.0	1.9	.0	4.2	.0	.0	.0	1.1	2.0	66.3	.0	14.3	.0
37	.0	18.0	.0	.0	26.6	.0	.0	.0	.0	10.9	31.3	.0	12.5	.0
38	.0	15.4	.0	.0	18.5	.0	.0	.0	1.5	10.6	36.9	.0	17.4	.0
39	.0	22.4	.0	.0	13.6	.0	.0	.0	1.4	11.3	26.6	.0	24.6	.0
(Site 689)														
27	.0	16.8	.0	.0	1.2	.0	.3	.0	.0	.0	81.7	.0	.0	.0
28	.0	24.7	.0	.0	.1	.0	1.3	.0	.0	.0	74.0	.0	.0	.0
29	.0	21.2	.0	.0	2.0	.0	.0	.0	.0	.0	76.9	.0	.0	.0
30	.0	19.2	.0	.0	5.4	.0	.1	.0	.0	.0	75.3	.0	.0	.0
31	.0	34.4	.0	.0	1.2	.0	.0	.0	.0	.0	64.5	.0	.0	.0
32	.0	44.0	.0	.0	1.0	.0	.0	.0	.0	.0	55.0	.0	.0	.0
33	.0	40.5	.0	.0	.7	.0	.0	.0	.0	.0	58.7	.0	.2	.0
34	.0	20.5	.0	.0	.6	.0	.0	.0	.0	.1	78.1	.0	.7	.0
35	.0	18.3	.0	.0	.0	.0	.0	.0	2.2	.1	75.8	.0	3.6	.0
36	.0	6.3	.0	.0	19.8	.0	.0	.0	1.1	.2	69.1	.0	3.5	.0
37	.0	9.8	.0	.0	27.9	.0	.0	.0	1.7	4.9	46.5	.0	9.3	.0
38	.0	8.4	.0	.0	24.0	.0	.0	.0	.6	3.0	44.0	.0	19.4	.0
39	.0	26.3	.0	.0	24.5	.0	.0	.0	2.1	9.0	34.1	2.3	2.1	.0
40	1.2	3.8	.0	.0	22.1	.0	.0	.0	.0	2.1	36.5	32.3	2.1	.0

Footnote: Data are derived from Table 2 and WEI and WISE (1990a). Refer to footnote of Table 2 for abbreviations.

core recovery, we were not able to obtain census data for all age intervals at all sites. No suitable Eocene-Oligocene materials were available from sites in the vicinity of the equator in the South Atlantic. Site 366 at 6°N latitude was selected for this study. This site was located about 10° south of its present position during the late Paleogene (SCLATER *et al.*, 1977). The data from Site 366 will be treated as 6°S latitude when discussing the latitudinal biogeographic gradient of the South Atlantic later in the paper.

Based on latitudinal distribution patterns of individual species or taxa and R-mode cluster analysis, WEI and WISE (1990a) identified *Coccolithus formosus*, discoaster, helicosphaerids and sphenoliths as warm-water taxa, and chiasmoliths, *Isthmolithus recurvus,* and *Reticulofenestra daviesii* as cool-water taxa in each time slice. We assumed that expansion or contraction of warm-water and cool-water taxa across latitudes in the South Atlantic reflect climatic changes.

Similarity analysis was run for each time slice. CosΘ values were calculated for different sites in relation to the equatorial site (366). A CosΘ value of 1 means that the two samples compared are identical, whereas a CosΘ value of 0 means that the two samples are totally different. CosΘ values were plotted against latitude and a linear regression was run for the data points in each time slice. For time slices that do not contain data points from Site 366, CosΘ values were calculated in relation to Sites 522 or 523, the next lowest latitude sites, and these values were translated into the same scale as those in relation to Site 366, using an average CosΘ value of 0.64 for Sites 522 or 523 as derived from time-slices 36, 35, 28, and 27 Ma.

RESULTS

The abundances of warm-water taxa and cool-water taxa are plotted according to the latitudes of the sites for time-slices 40 to 27 Ma (Fig. 2). Second order fit regressions were run for warm-water and cool-water taxa respectively. These curves seem to fit the data points better than those of linear regression analysis. The intercepted latitudes for 10% warm-water and cool-water taxa are determined using abundance curves of warm-water and cool-water taxa respectively. This information is summarized in Figure 3.

Figure 3 shows that the distribution of warm-water taxa contracted progressively toward lower latitudes from 38 to 34 Ma. The most rapid contraction occurred between 37 and 36 Ma, coincident with the Eocene/Oligocene boundary. Warm water taxa expanded toward higher latitudes in 31 Ma and reached a maximum (33°S) in 30 Ma. On the other hand, cool-water taxa expanded progressively toward lower latitudes from 40 Ma to 36 Ma. After that cool-water taxa began to contract toward higher latitudes and reached 38°S by 31 Ma.

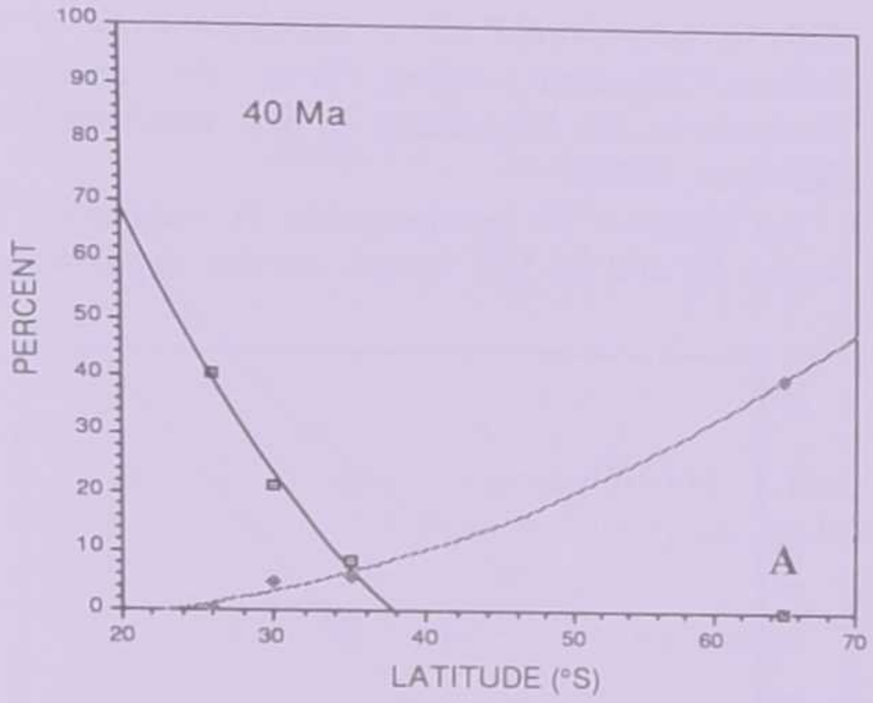
CosΘ similarity values of sites in relation to the equatorial site (366) for time-slices 36, 35, 28, and 27 Ma are plotted in Figures 4D, 4E, 4K, and 4L. Data points in each time slice are generally distributed around a straight line, therefore a linear regression analysis was run for each time slice to determine the slope of the line, or the latitudinal biogeographic gradient. Similarly, CosΘ similarity values of sites in relation to Sites 522 and 523 for time-slices 40, 39, 37, 34, 33, 31, 30, and 29 are plotted in Figures 4A-4C, 4F-4J, and a linear regression analysis was also run for each time slice. Changes in the slopes of the lines are summarized in Figure 5.

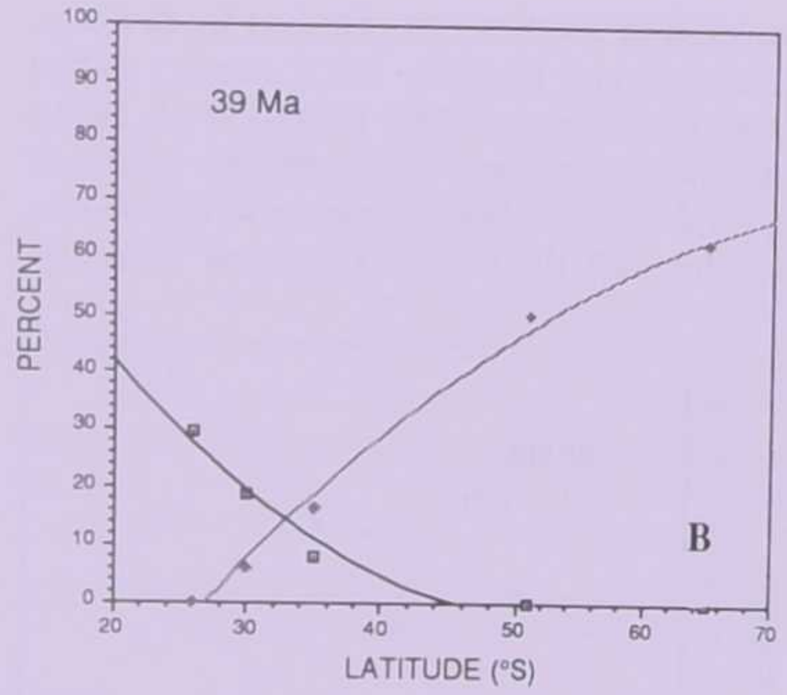
Figure 5 shows decrease in latitudinal biogeographic gradient from 40 to 37 Ma, a large increase from 37 to 36 Ma, another decrease from 33 to 31 Ma, and a relatively stable gradient from 31 to 27 Ma.

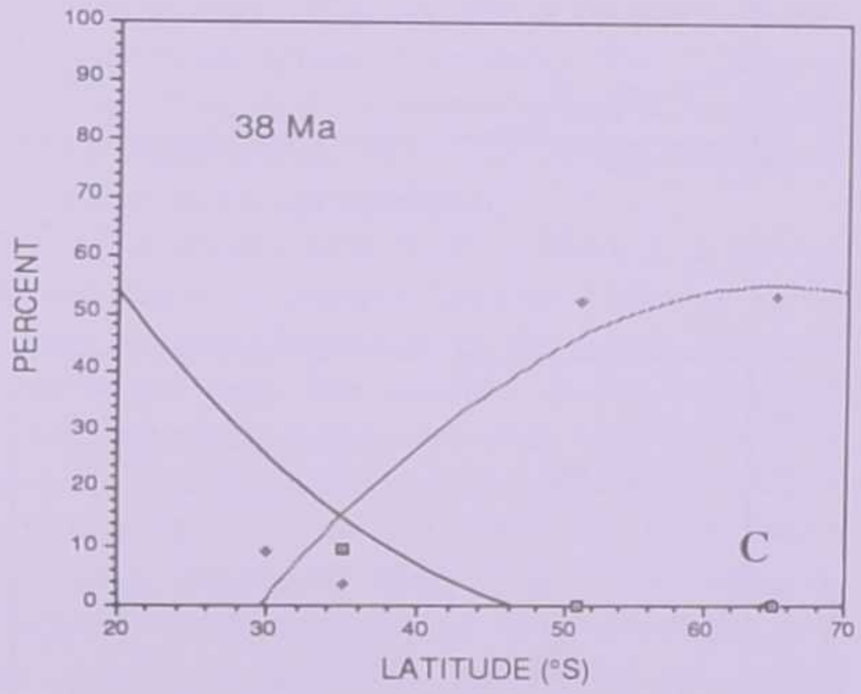
INTERPRETATION

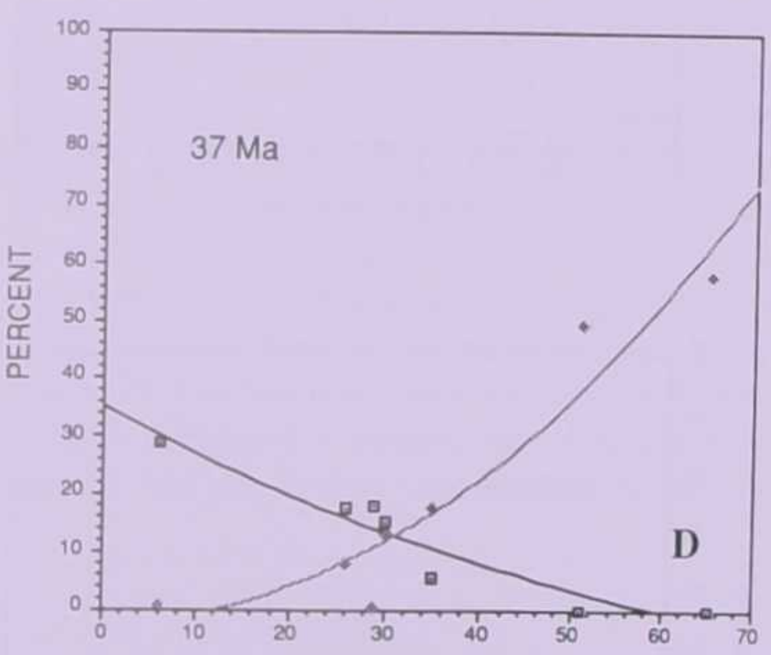
HAQ and LOHMANN (1976) discussed in detail problems involved in using quantitative nannofossil data to reconstruct paleoenvironments but concluded that it is still possible and useful to study nannoplankton paleobiogeography to address some paleoclimatic and paleoceanographic questions. It is generally valid to assume that expansion and contraction of warm-water or cool-water taxa across latitudes are a reflection of climatic changes, that is, during a warmer climate period, warm-water taxa will expand toward higher latitudes and cool-water taxa will contract toward higher latitudes; during a cooler climate period, the reverse would be true. It is also generally true that low latitudes show relatively small temperature change whereas high latitudes respond to climatic change in much larger amplitude. Consequently, latitudinal thermal gradients increase when climate becomes colder and decrease when climate becomes warmer, and changes in latitudinal thermal gradients can be reflected in the changes of latitudinal biogeographic gradients.

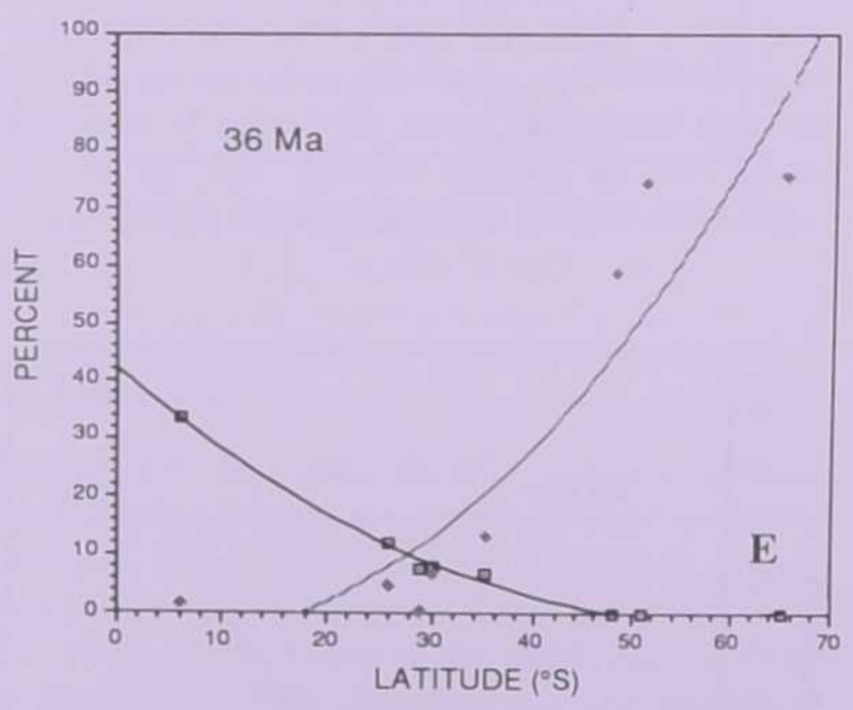
Figure 3 suggests that climate became progressively cooler in the latest Eocene to the earliest Oligocene, as indicated by the contraction of warm-water taxa and the expansion of cool-water taxa toward lower latitudes. This cooling has been











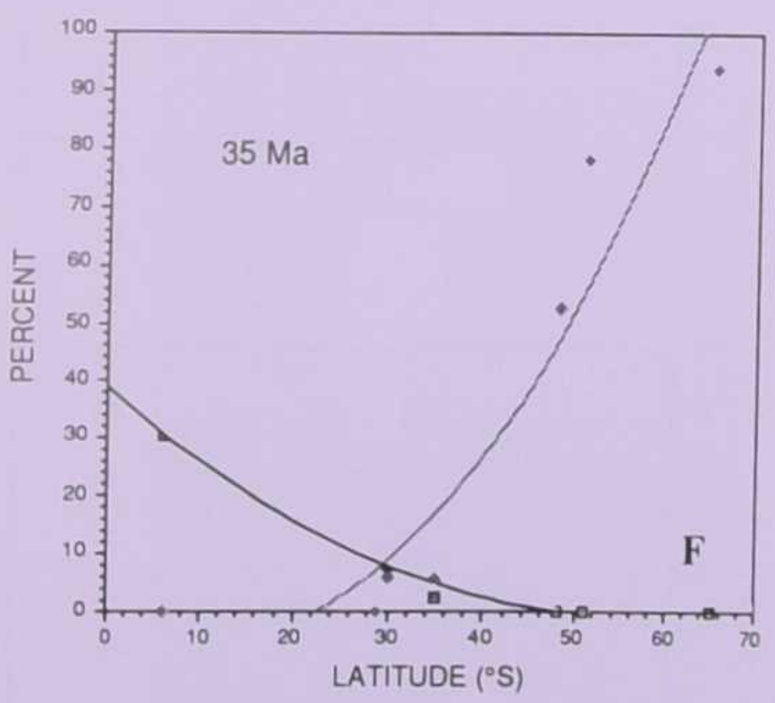


FIG. 2 - Relative abundances of warm-water and cool-water taxa in percent of total assemblage plotted against latitude for time-slices 40 to 27 Ma (A to N) (refer to Table 1 for latitudes of the sites). Second order fit regressions are run for warm-water taxa (solid line) and cool-water taxa (dotted line) respectively for each time slice.

recognized by a number of previous studies (*e.g.*, SHACKLETON and KENNET, 1975; BUKRY, 1978a; WOLFE, 1978; KELLER, 1983; CORLISS *et al.*, 1984). In addition, latitudinal biogeographic gradients (Fig. 5) sharply increased between 37 and 36 Ma, coincident with the Eocene/Oligocene boundary. This is interpreted as a manifestation of the Eocene/Oligocene cooling (WEI, 1991), an event that marks the beginning of the psychrosphere (KENNET, 1978).

An increase in temperature is suggested between 32 and 30 Ma, based on the expansion of

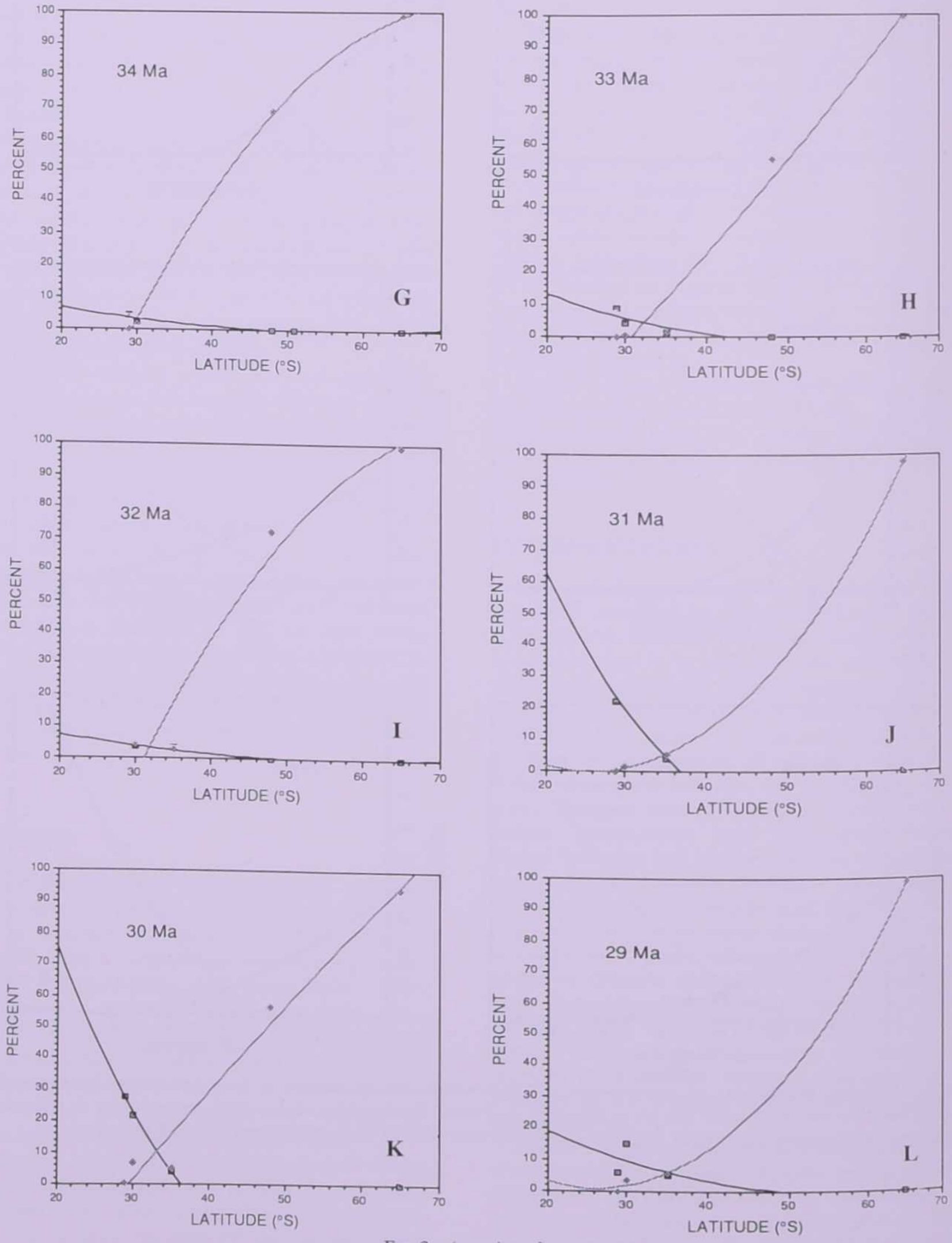


FIG. 2 - (*continued*)

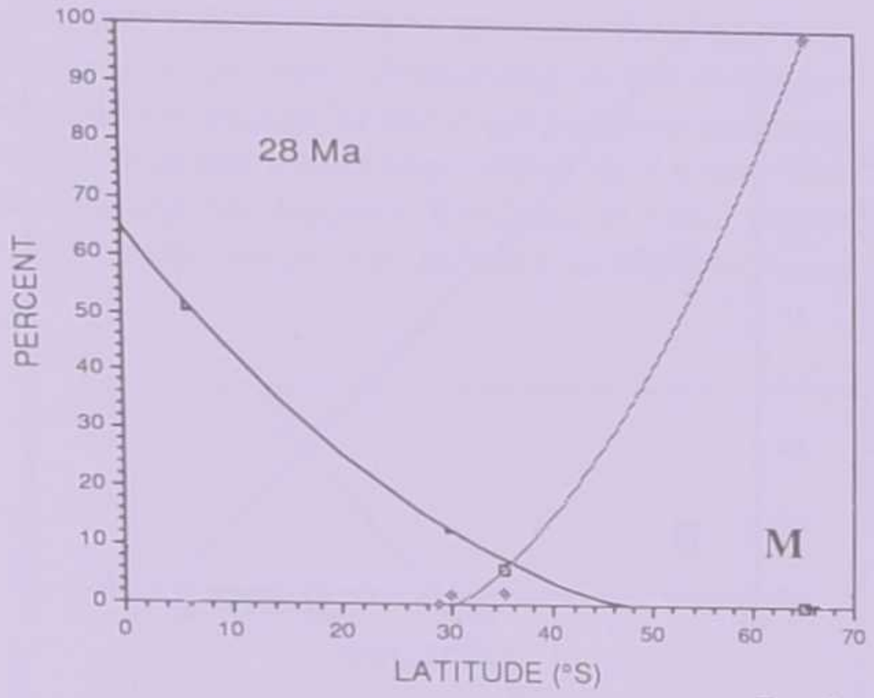


FIG. 2 - (*continued*)

warm-water taxa (Fig. 3) and a decrease in the latitudinal biogeographic gradient (Fig. 5) during this time. This rise in temperature is, however, less well documented in the literature, and needs to be tested in future studies.

Figure 2 shows clearly that there is a strong differentiation of nannoplankton latitudinally in the late Eocene-Oligocene in the South Atlantic. Warm-water taxa are limited to the equatorial and mid-latitude regions whereas cool-water taxa constitute nearly 100% of the total assemblages at the highest latitude site (689) and their abundance drop drastically toward lower latitudes. A latitudinal differentiation of nannoplankton has been noted in previous qualitative or semi-quantitative studies. Figures 4 and 5, however, quantify this latitudinal differentiation in similarity values for the first time. The rather steep latitudinal biogeographic gradients are believed to be a reflection of relatively steep latitudinal thermal gradients of the surface waters in the South Atlantic Ocean during the late Eocene and Oligocene.

DISCUSSION

During the last two decades, oxygen isotopic data of marine calcareous microplankton and benthos have been widely used to estimate paleotemperatures of the oceans (DOUGLAS and SAVIN, 1971; 1973; 1976; SAVIN *et al.*, 1975; SHACKLETON and KENNETT, 1975; SHACKLETON and BOERSMA, 1981; and others). KEIGWIN and CORLISS (1986) summarized oxygen isotopic data of the Eocene and Oligocene and discussed latitudinal thermal gradients. They averaged the late Eocene and early Oligocene oxygen isotopic values of planktonic foraminifers respectively and plotted them against latitude in order to reveal latitudinal isotopic gradients from which latitudinal thermal gradients can be inferred. For easy discussion, their figure 11 is recast here in Figure 6. It is readily noted in Figure 6 that the two high latitude sites (277 and 511) have very similar or even lower oxygen isotopic values than the mid-latitude sites. This appears to suggest that the high latitudes were as warm as or even warmer than the mid-latitudes. SHACKLETON and BOERSMA (1981) presented a similar set of data and suggested that the Eocene oceans were cooler in the

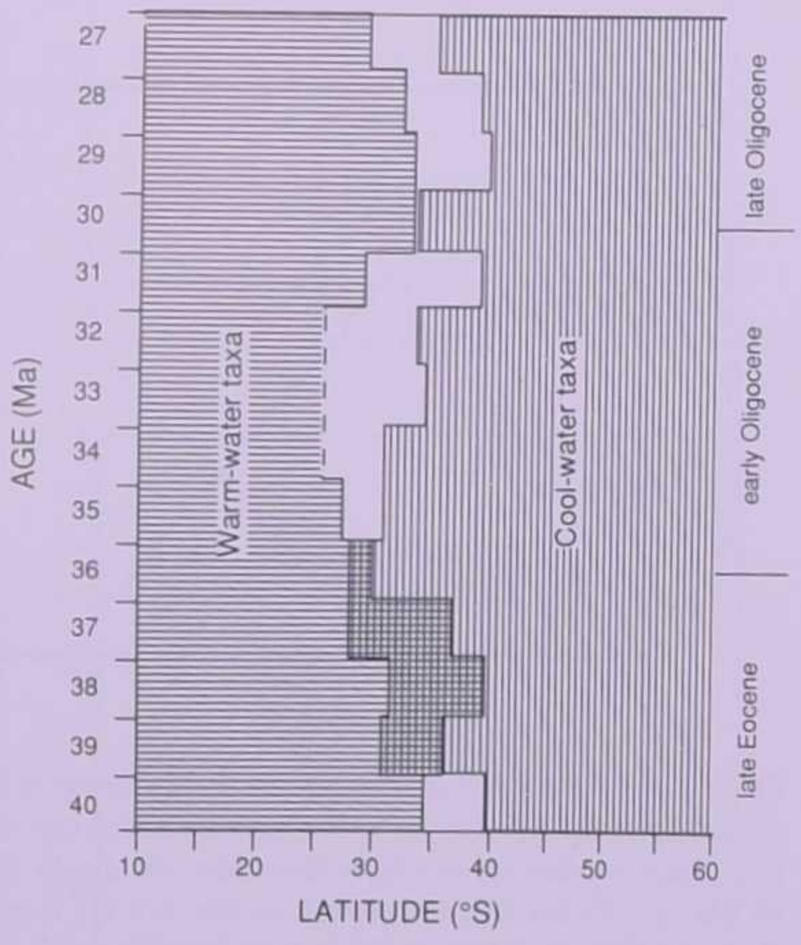
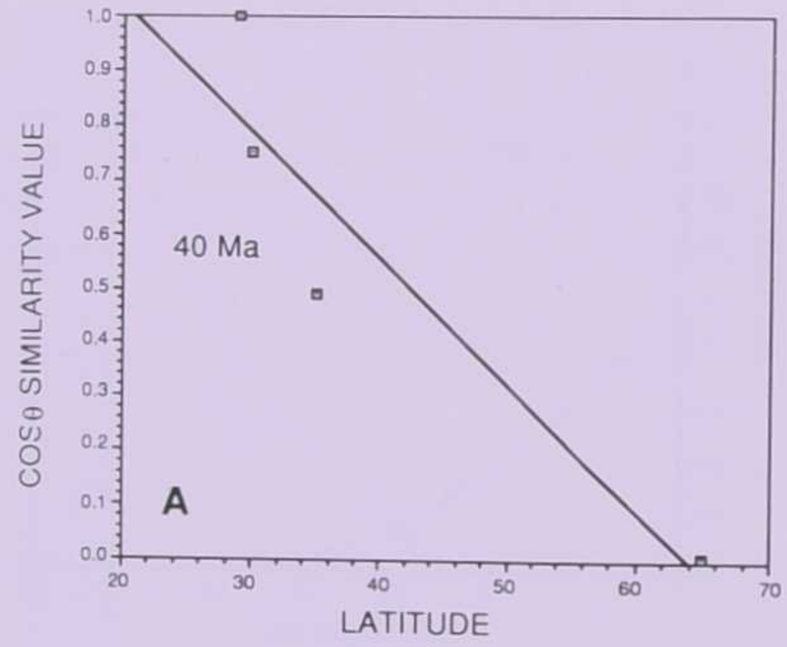
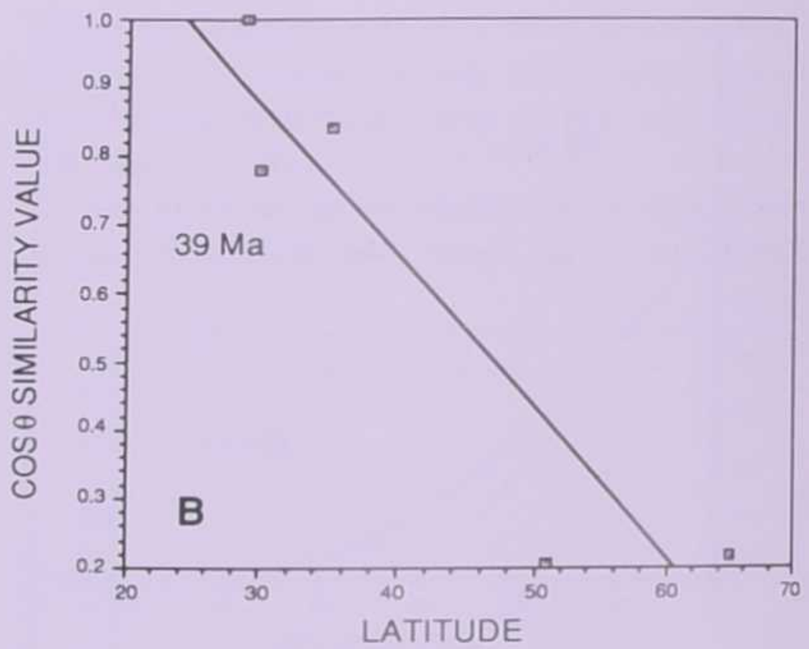
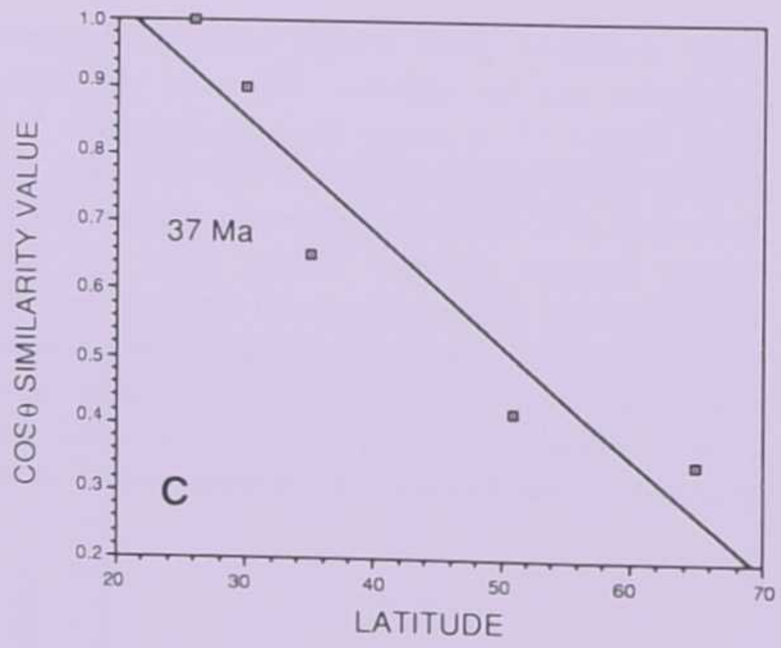
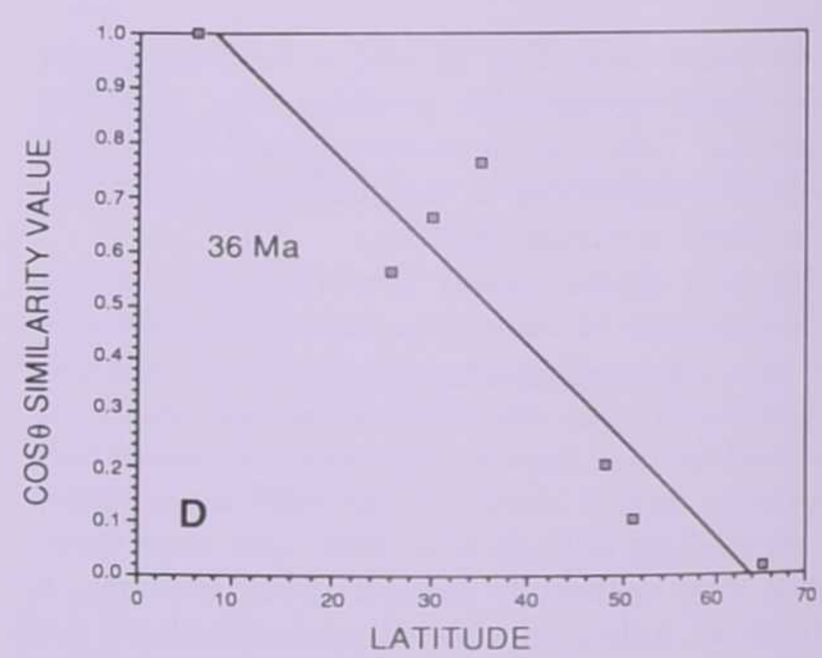


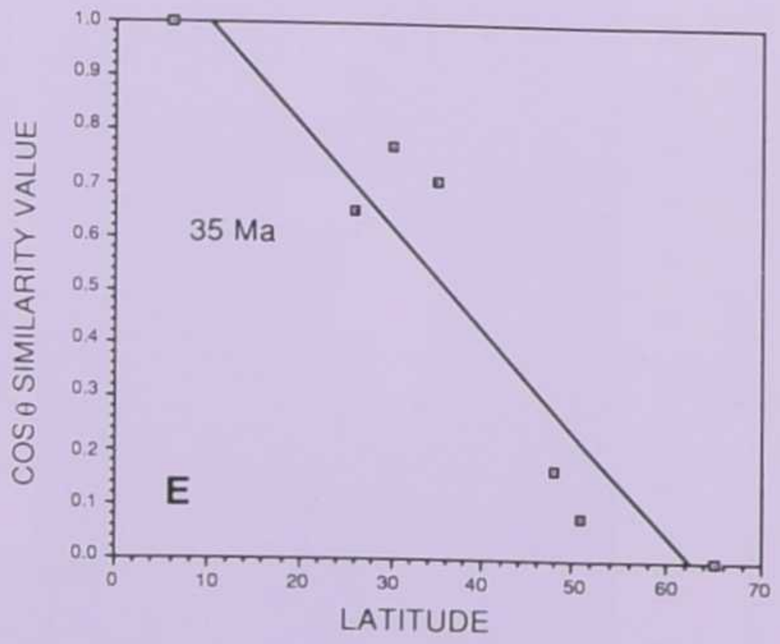
FIG. 3 - Composite diagram showing distributions of warm-water taxa and cool-water taxa based on information given in Figure 2. Shaded areas indicate >10% warm-water taxa or cool-water taxa.











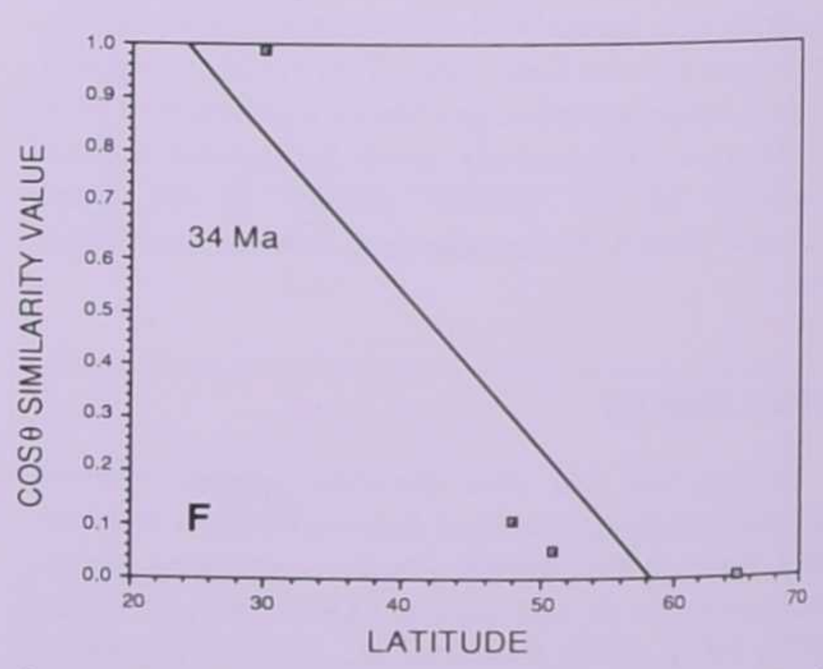


FIG. 4 - Late Eocene-Oligocene latitudinal biogeographic gradients of the South Atlantic Ocean expressed as CosΘ similarity values in relation to the equatorial site (366) for time-slices 36 Ma (D), 35 Ma (E), 28 Ma (K), and 27 Ma (L); where no data are available from Site 366, CosΘ similarity values are given in relation to Site 523 for time-slices 40 Ma (A), 39 Ma (B), in relation to Site 522 for time-slices 37 Ma (C), 34 Ma (F), 33 Ma (G), 31 Ma (H), 30 Ma (I), and 29 Ma (J). Refer to Table 1 for latitudes of the sites.

tropics but substantially warmer in the high latitudes than at present. According to the latter authors, temperatures in the high latitudes were only a few degrees lower than those in the mid latitudes during the Eocene. Findings of fossil plants of seemingly temperate affinity in high latitudes (Dorf, 1964, Hickey, 1977; Kemp, 1978) or the existence of plants beyond 65°S in Antarctica (Kemp and Barrett, 1975) have been taken as another line of strong evidence for very warm conditions in high latitudes or polar regions during the Eocene.

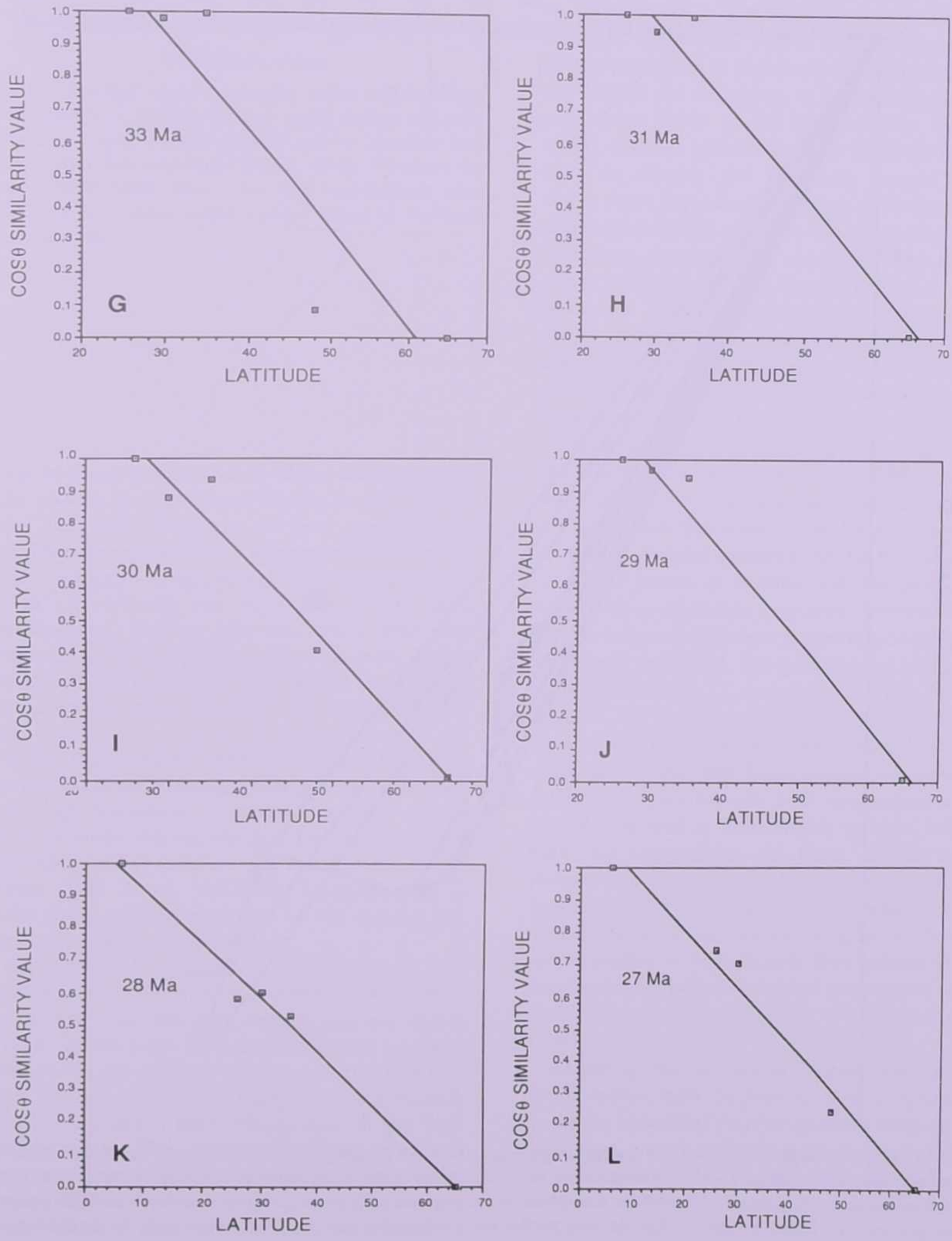


Fig. 4 - (*continued*)

Climate models, however, suggest that significantly greater poleward heat transport as implied by the isotopic and paleobotanical data is enigmatic (*e.g.*, MANABE *et al.*, 1975; STONE, 1978). The problem is so puzzling that a polar wander hypothesis has been proposed recently by DONN (1989) to reconcile the conflicting data. DONN (1989) hypothesized that the South Pole was lo-

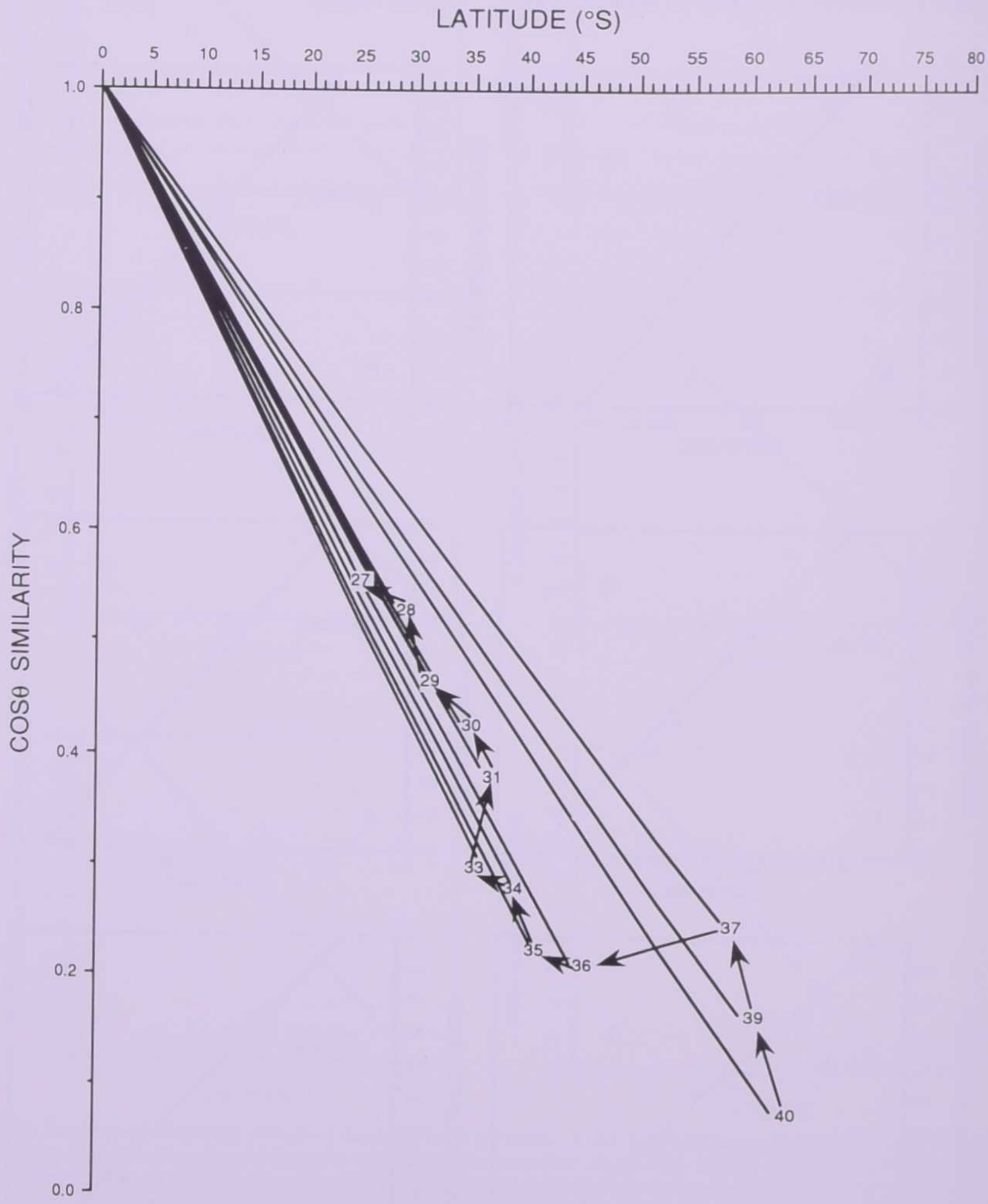


FIG. 5 - Composite diagram showing late Eocene-Oligocene latitudinal biogeographic gradients of the South Atlantic. Data are taken from Figure 4 and converted to the same similarity scale. Each number indicates a time slice. Lines are drawn progressively shorter for younger time slices for easier visual inspection. Note that latitudinal biogeographic gradients are flatter in the late Eocene than in the early Oligocene and there is a relatively large increase in latitudinal biogeographic gradient between 37 and 36 Ma.

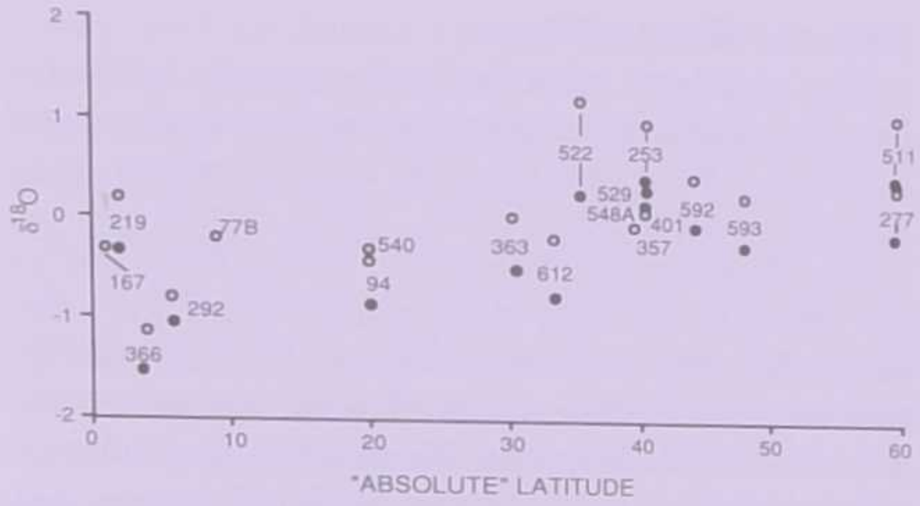


FIG. 6 - Average oxygen isotopic values of planktonic foraminifers of the late Eocene (solid circles) and early Oligocene (open circles) plotted against "absolute latitude" (after KEIGWIN and CORLISS, 1986). Numbers denote DSDP sites. Note that the high-latitude sites (277 and 511) have quite similar values as the mid-latitude sites.

cated in the southern Indian Ocean and the North Pole was in the northeast Pacific during the Eocene. This would explain the very weak latitudinal thermal gradients. However, this model would suggest longitudinal thermal gradients, which are virtually not supported by any data. Furthermore, Eocene marine fossils from the proposed polar regions (the southern Indian Ocean and northeast Pacific) do not show cooler characteristics than those in the Weddell Sea or Ross Sea.

Since the present study has found relatively steep latitudinal biogeographic gradients that signal large latitudinal thermal gradients in the South Atlantic during the late Eocene and Oligocene, and similar results were found in the Indian Ocean (WEI *et al.*, 1992), it is appropriate to make some reinterpretations of the oxygen isotopic and paleobotanical data.

As previously suggested by THIERSTEIN and BERGER (1978) and POORE and MATTHEWS (1984), we believe that the low oxygen isotopic values (Fig. 6) in the high latitudes are caused by lower salinities in the surface waters than at lower latitudes. It is well known that there is presently more precipitation than evaporation in the high latitude oceans. This lowers the salinity as well as the isotopic value of the sea waters. A linear relationship exists between salinity and the isotopic composition of the water (CRAIG and GORDON, 1965). A 1‰ salinity change causes 0.5‰ change in $\delta^{18}O$ of the water (RYE and SOMMER, 1980; BROECKER, 1989). Salinity of the present oceans varies a few ‰ at different latitudes, with the maximum in the mid-latitudes and the minimum in the high latitudes (LEVITUS and OORT, 1977). Measurements of the $\delta^{18}O$ for modern surface waters in the Atlantic and Pacific show values up to 1.8‰ lower in high latitudes relative to mid latitudes (BROECKER, 1989). More precipitation than evaporation in high latitudes is expected for the Eocene and Oligocene, as is also suggested by rain forest floras in the high latitudes (KEMP, 1978). Another possible example of salinity influence on Eocene and Oligocene isotopic data comes from New Zealand, where $\delta^{18}O$ values of DEVEREAUX (1967) are over 1‰ lower compared with those reported from nearby but more open-ocean drillsites on the Campbell Plateau and Macquarie Ridge by SHACKLETON and KENNETT (1975). Differences in laboratory techniques may contribute to the discrepancy, but it may also due to lower salinity in the nearshore environment of New Zealand than at the open-ocean drillsites.

Unfortunately, most previous studies ignored the salinity factor when estimating paleotemperatures using oxygen isotopic data. This has caused misleading interpretations in the literature on the latitudinal thermal gradients of the Eocene and Oligocene oceans. It is difficult to interpret isotopic paleotemperature gradients, however, unless an independent means is used to establish the latitudinal profile of the gradients, as we have done in this study.

As to the paleobotanical data, FRAKES (1979) pointed out correctly that determination of climatic parameters from fossil plants is notoriously difficult, in part because both temperature and humidity as well as non-climatic variables influence the composition of floras. Within the temperature factor, annual temperature range, temperature of the coldest month, and mean annual temperature are all controlling factors. Some recent studies of high latitude flora indicate that they could survive mean annual temperature less than 5°C and perhaps as low as -6°C (RICH *et al.*, 1988).

Assuming the latitudinal biogeographic gradients derived from the present study can approximate the latitudinal thermal gradients of the surface ocean, we can estimate temperatures in high latitude surface waters. If we use δw ($\delta^{18}O$ of sea water) = -1.2‰, as SHACKLETON and KENNETT (1975) and many other authors did, to calculate the average late Eocene surface temperatures for

Sites 366 and 522 based on the oxygen isotopic data given in Figure 6, we obtain 18°C and 11°C respectively. This would suggest about 5°C for Site 511 (51°S) and 0°C for Site 689 (65°C) based on the latitudinal biogeographic gradient data (Fig. 5). Similarly, we calculate the average early Oligocene surface temperature to be 16°C for Site 366 and 7°C for Site 522. This would suggest about -1°C for Site 511 and -6°C for Site 689.

The calculated isotope temperatures (18°C and 16°C) for the equatorial site (366) with tropical coccolith assemblages (BUKRY, 1978b) are apparently too low, because there is no reason to expect the equatorial to be substantially cooler than the present temperature of about 28°C considering that the difference between the tropical sea surface temperature of the last glacial age and that of today has been determined to be less than 1°C (CLIMAP, 1976). In addition, all the calculated temperatures for Sites 511 and 689 are unreasonably low or virtually impossible. This is because no calcareous nannoplankton can thrive at temperature near freezing or below and late Eocene and early Oligocene calcareous nannofossils are abundant at Sites 511 (WISE, 1983) and 689 (WEI and WISE, 1990b).

The problems must lie in the use of -1.2‰ for δw. This value was suggested by SHACKLETON and KENNET (1975) and used by many authors (*e.g.*, KENNET and SHACKLETON, 1976; MUZA *et al.*, 1983; MURPHY and KENNETT, 1985; WILLIAMS *et al.*, 1985) to calculate paleotemperature for samples older than middle Miocene, because no significant ice was believed to exist on Antarctica before the middle Miocene. However, significant ice volume during parts of the early Oligocene has been suggested by reinterpretations of the oxygen isotopic data (MATTHEWS and POORE, 1980; MILLER and FAIRBANKS, 1983; KEIGWIN and KELLER, 1984; WISE *et al.*, 1985; SHACKLETON, 1986) and by direct glacial evidence obtained from recent drilling around Antarctica (BARRETT, 1989; BARKER, KENNETT *et al.*, 1990; BARRON, LARSEN *et al.*, 1991; WISE, SCHLICH *et al.*, 1992; WISE *et al.*, 1991). Significant ice at times during the Eocene is also suggested by MARGOLIS and KENNETT (1971), and WEI (1992) based on glacial sediment, by MATTHEWS and POORE (1980), POORE and MATTHEWS (1984) and PRENTICE and MATTHEWS (1988) based on oxygen isotopic evi-

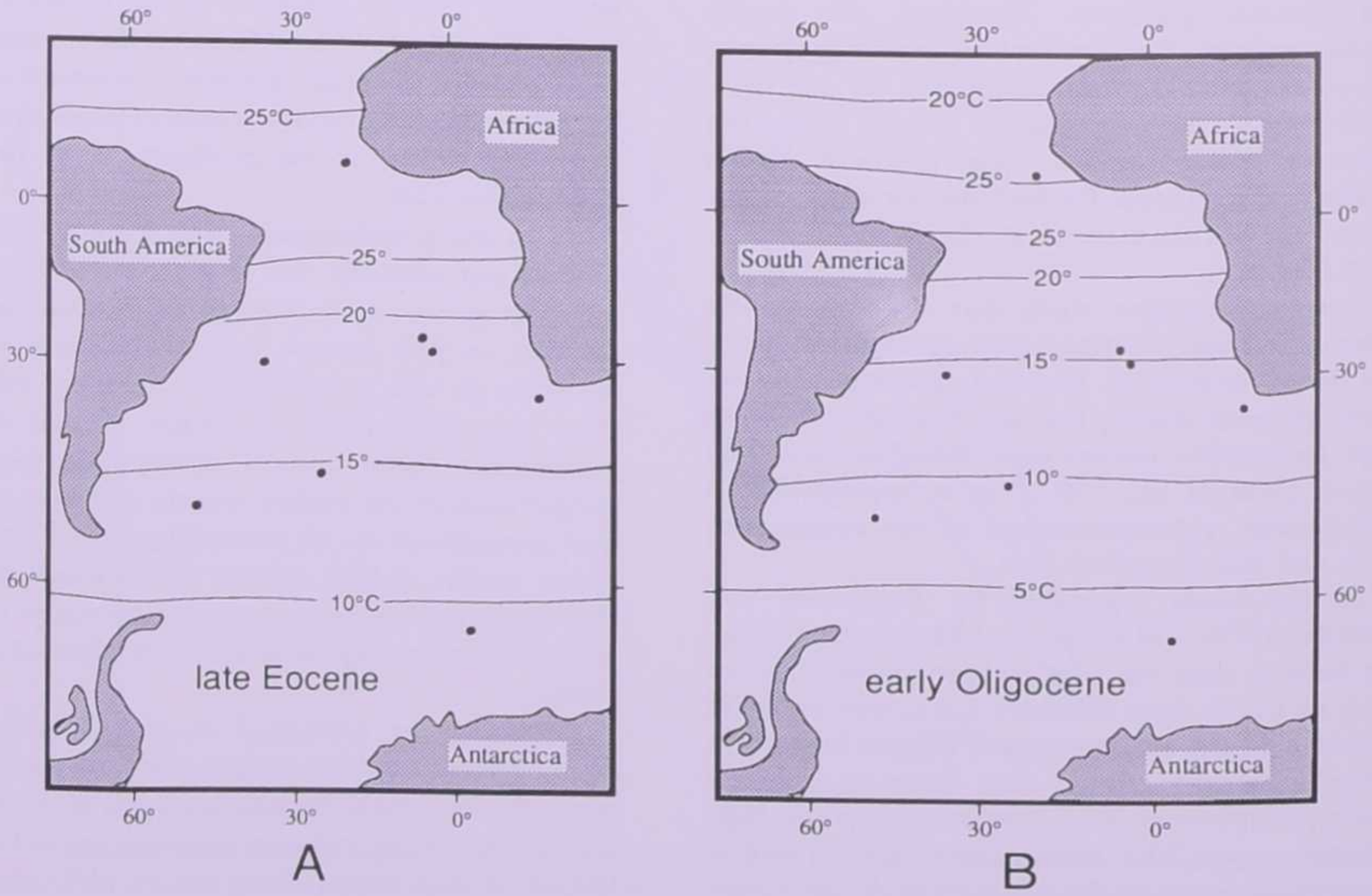


FIG. 7 - Estimated surface temperatures of the South Atlantic Ocean during the late Eocene (A) and early Oligocene (B) based on oxygen isotopic data (Fig. 6) and latitudinal biogeographic gradient data (Fig. 5). For simplicity, possible current inflections of isotherms are not represented. See text for detailed explanation.

dence, and by ROBIN (1988) based on ice sheet model prediction. FRAKES and FRANCIS (1988) even found Lower Cretaceous ice-rafted boulders in central Australia indicating glacial activity during what was generally one of the warmest periods in the Phanerozoic. Compiling data on ice-rafted deposits in different parts of the world leads FRAKES and FRANCIS (1988) to conclude that "the possibility of an ice-free Earth having ever existed appears small".

Assuming that there was significant ice on Antarctica in the late Eocene and Oligocene (but not necessarily ice sheet calving at sea level all the time), we can apply MATTHEWS and POORE'S (1980) model as a working model and use a value of +0.8‰ for δw. This would give 26°C for Site 366 and 19°C for Site 522 in the Eocene calculated from the isotopic data (Fig. 6). Site 511 is estimated to be about 13°C and Site 689 to be around 9°C in the late Eocene based on the latitudinal biogeographic gradient data (Fig. 5). For the early Oligocene, the calculated temperatures are 24°C at Site 366 and 15°C at Site 522. Consequently, Sites 511 and 689 have estimated temperatures of 8°C and 3°C respectively. Based on the isotopic and latitudinal biogeographic gradient data, surface-water temperatures are estimated for the South Atlantic ocean for the late Eocene (Fig. 7A) and early Oligocene (Fig. 7B). Note that in Figure 7A surface water temperatures are inferred to be about 6° near the Antarctic continent in the late Eocene. Are these temperatures compatible with the notion of significant ice on Antarctica during that time? We think so. Modeling experiments suggest that the interior of the Antarctic continent remains quite cold regardless of the Southern Ocean surface temperature (BARRON *et al.*, 1981; OERLEMANS, 1982). Relatively warm coastal conditions facilitate the transport of more moisture inland and thus more ice buildup. Figure 7B suggests temperatures near 0°C for the surface waters close to the Antarctic continent in the early Oligocene. Substantial ice must have accumulated on the continent, which was much colder by this time.

SUMMARY

Quantitative biogeographic study of late Eocene-Oligocene calcareous nannoplankton of the South Atlantic Ocean reveals that the distribution of warm-water taxa contraced progressively toward lower latitudes from 38 to 34 Ma, with the most rapid contraction occurring between 37 and 36 Ma. Cool-water taxa expanded progressively toward lower latitudes from 40 to 36 Ma. The changes in distribution patterns of both warm-water taxa and cool-water taxa show a significant cooling in the latest Eocene to earliest Oligocene. This is also supported by a rapid steepening of the latitudinal biogeographic gradient from the latest Eocene to the earliest Oligocene.

Quantitative study of latitudinal biogeographic gradients shows that latitudinal differentiation of the nannoflora was well established in the late Eocene-Oligocene. Warm-water taxa were limited to the equatorial and mid-latitude regions. Cool-water taxa dominated the assemblages in high latitudes and their abundances sharply decrease toward lower latitudes, becoming virtually absent in equatorial waters. Latitudinal biogeographic gradients have been quantified by similarity analysis of coccolith floras. The results conflict with oxygen isotopic data from the high latitudes. The present study does not support the notion that latitudinal thermal gradients were nearly flat in the Eocene as suggested by interpretation of oxygen isotopic data (*e.g.*, SHACKLETON and BOERSMA, 1981). Relatively low $\delta^{18}O$ values of planktonic foraminifers from high latitudes are believed to be caused by lower salinities in high latitudes than in mid or low latitudes. Failure to account for the salinity factor when estimating paleotemperatures from oxygen isotopic data has resulted in misleading interpretations in the literature. Latitudinal variations in salinity apparently did not have significant effect on the distribution of calcareous nannoplankton, which offer an independent means for estimating latitudinal thermal gradients. Based on the latitudinal biogeographic gradient data obtained in this study, along with oxygen isotopic data from the low and mid latitudes, we have estimated that temperatures were about 13°C at Site 511 and 9°C at Site 689 in the late Eocene, and about 7°C and 3°C at the two sites respectively in the early Oligocene. The biogeographic gradient data are compatible with the model of considerable ice volume on Antarctica in the late Eocene and early Oligocene.

APPENDIX

Detailed Paleogene nannofossil magnetobiostratigraphy is give here (Fig. 8) for Site 516 analyzed in this study. Over 700 m of a Paleogene carbonate section was recovered in Hole 516F. The sequence contains very abundant, diverse, and moderately preserved calcareous nannofossils, and has yielded a fairly good magnetostratigraphy (BERGGREN *et al.*, 1984). The upper Eocene and

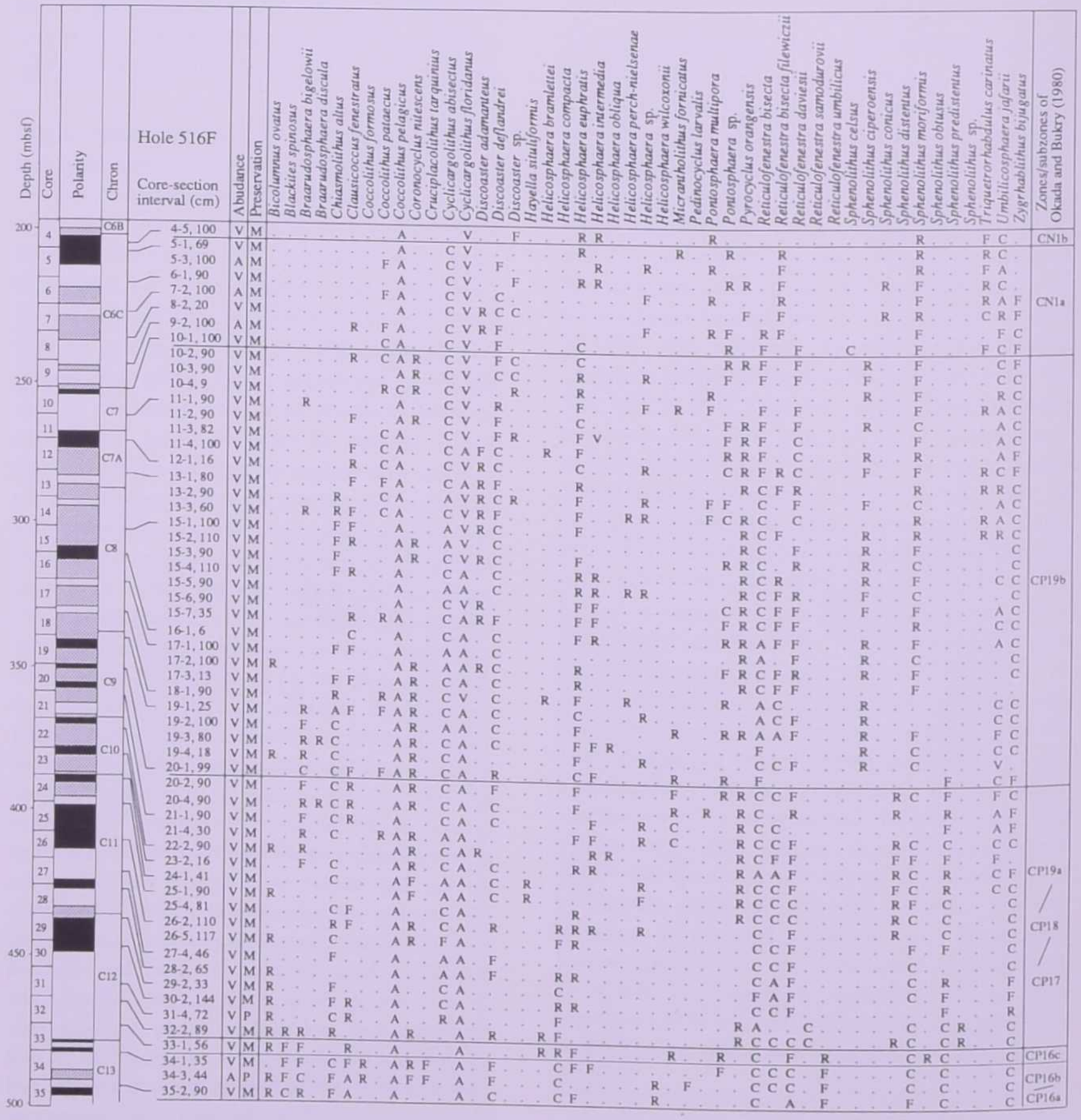


FIG. 8 - Stratigraphic distribution of Paleogene calcareous nannofossil species and its correlation with the magnetostratigraphy of BERGGREN *et al.* (1984) in DSDP Hole 516F. Black interval indicates normal polarity; white interval indicates reversed polarity; and shaded interval denotes no paleomagnetic data. For nannofossil abundance, V=very abundant; A=abundant; C=common; F=few; and R=rare. For preservation of nannofossil assemblages, M=moderate; and P=poor.

Oligocene section is unique because it shows a rather uniform sedimentation rate for over 350 m (WEI and WISE, 1989). All these factors make Hole 516F one of the best section for magnetobiochronologic studies. Hole 516F has provided a Sr-isotope stratigraphic standard section (HESS *et al.*, 1986) and critical information for paleobiogeographic and paleoceanographic studies of the Atlantic Ocean (BOERSMA *et al.* 1987; WEI and WISE, 1990a; this study).

WEI and WISE (1989) documented selected Paleogene calcareous nannofossil species in Hole 516F and discussed the key datums. Figure 8 presents a complete range chart for all the nannofossil species (total =~200) recognized in Hole 516F. This information is important because the stratigraphic ranges of all the species and their abundance patterns have been correlated with magnetostratigraphy, many for the first time. Many of these species are potentially useful for

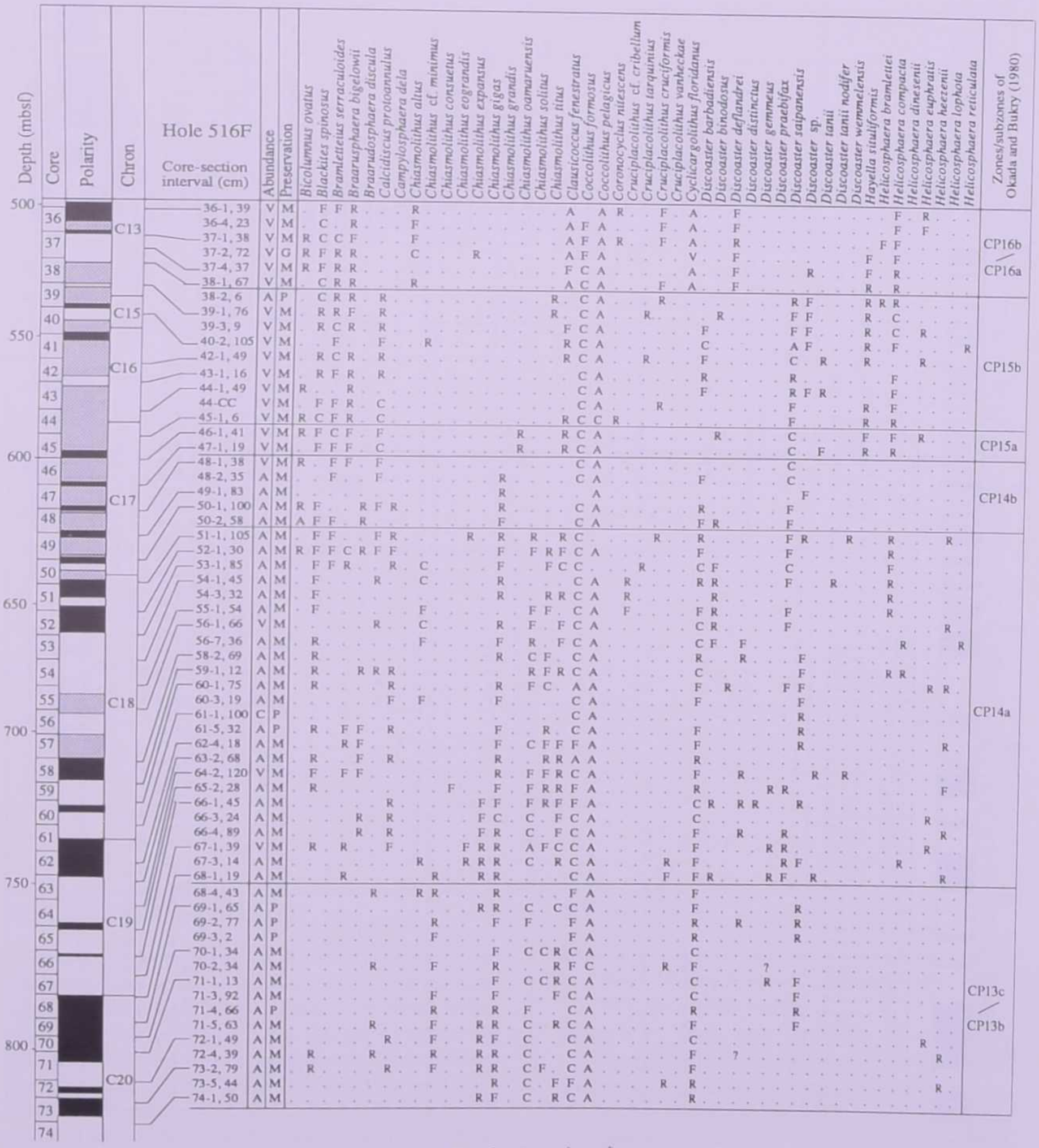


FIG. 8 - (*continued*)

biostratigraphic or paleoecologic studies when their stratigraphic ranges and abundance patterns are calibrated with magnetostratigraphy at a large number of sites in different areas. That is, those first or last occurrences that are synchronous from region to region or are time-transgressive with regular patterns across latitudes can be used effectively for global biostratigraphic correlation. Those that show seemingly irregular first or last occurrence patterns at different localities, on the other hand, provide important information for paleoecologic and paleoceanographic studies. It is apparent that full documentation of distribution patterns of nannofossil species, such as in Figure 8, are badly needed in order to significantly improve nannofossil biochronologic resolution and to facilitate nannofossil paleoecologic and paleoceanographic studies.

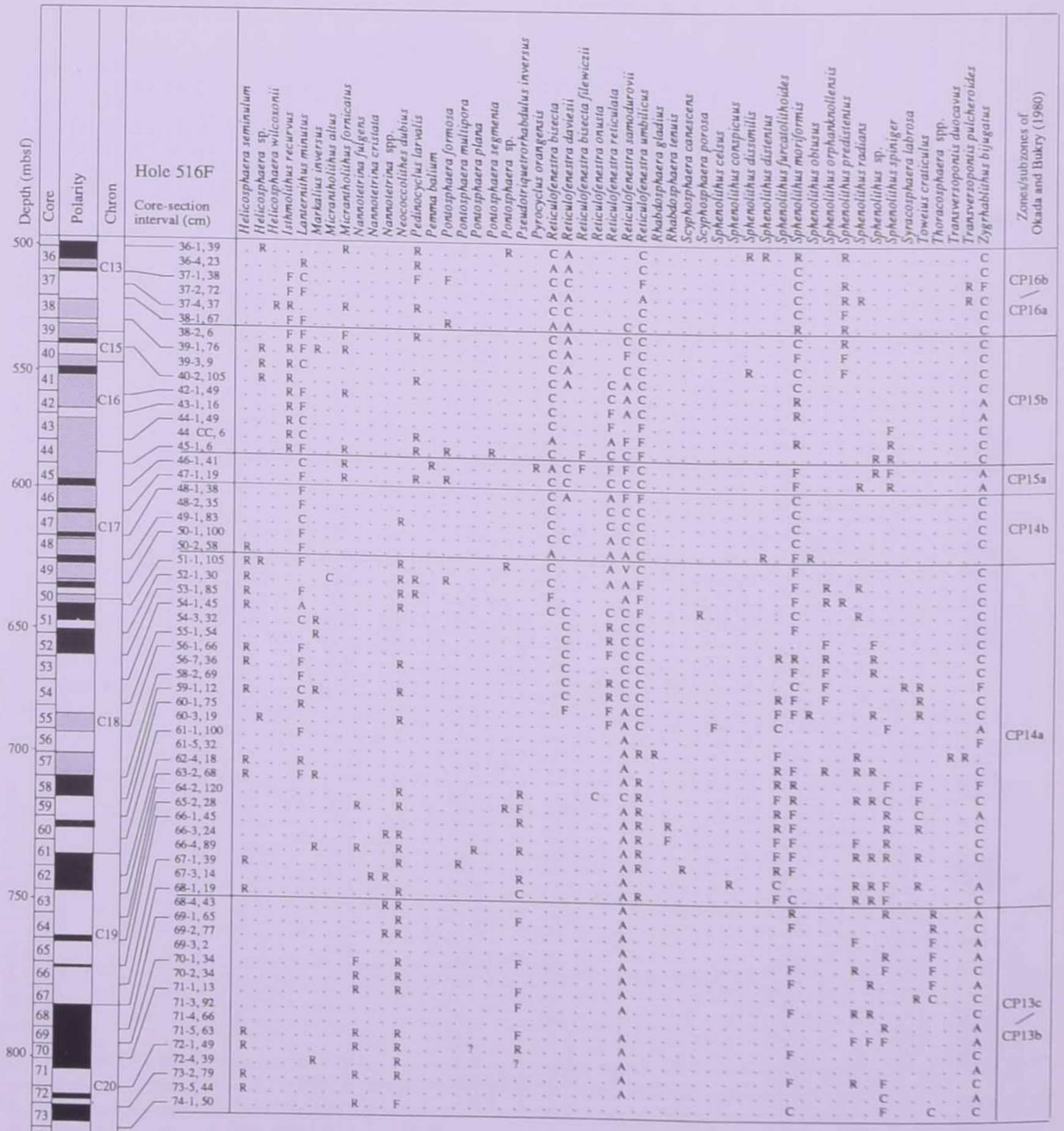


FIG. 8 - (*continued*)

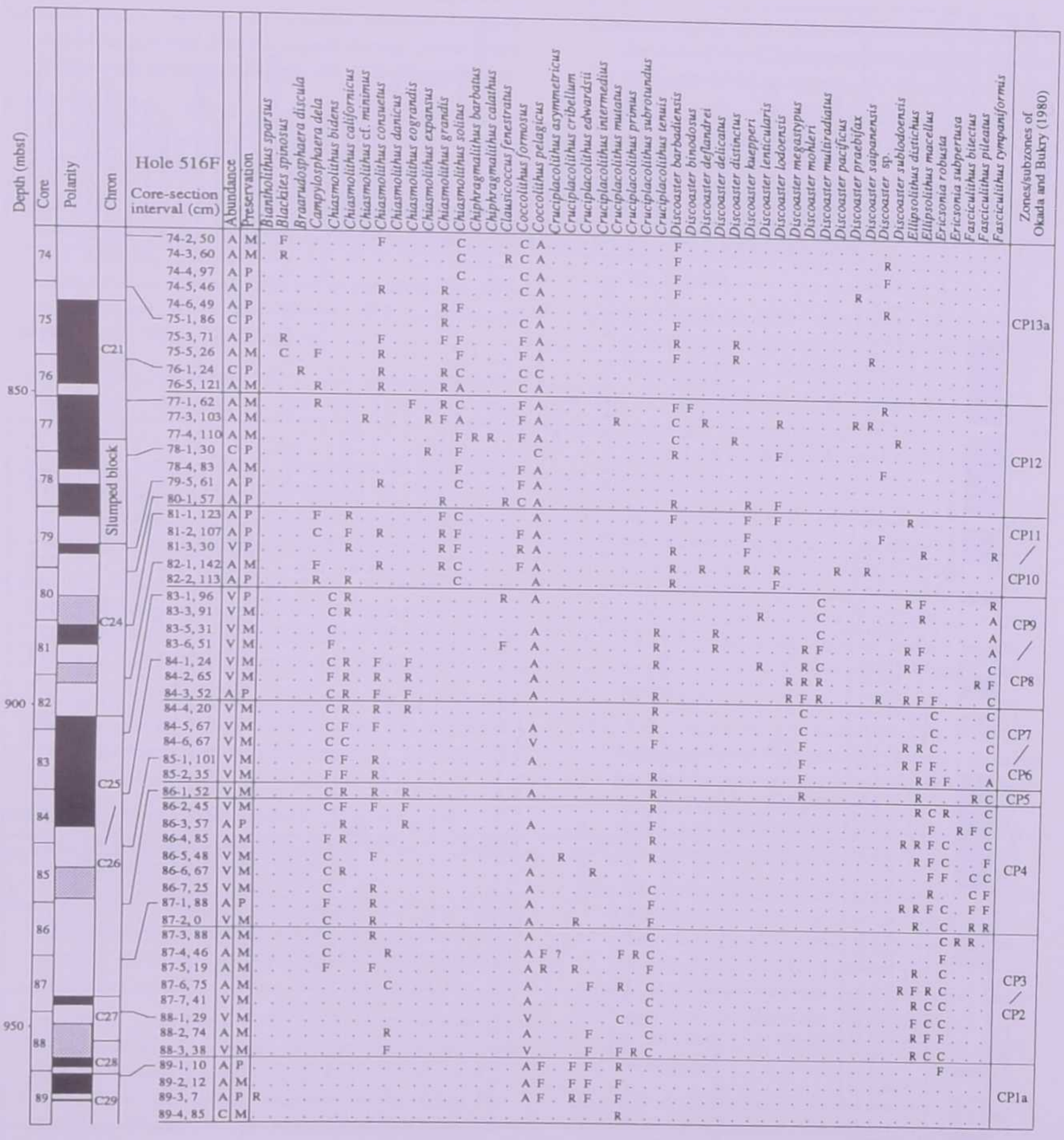


FIG. 8 - (*continued*)

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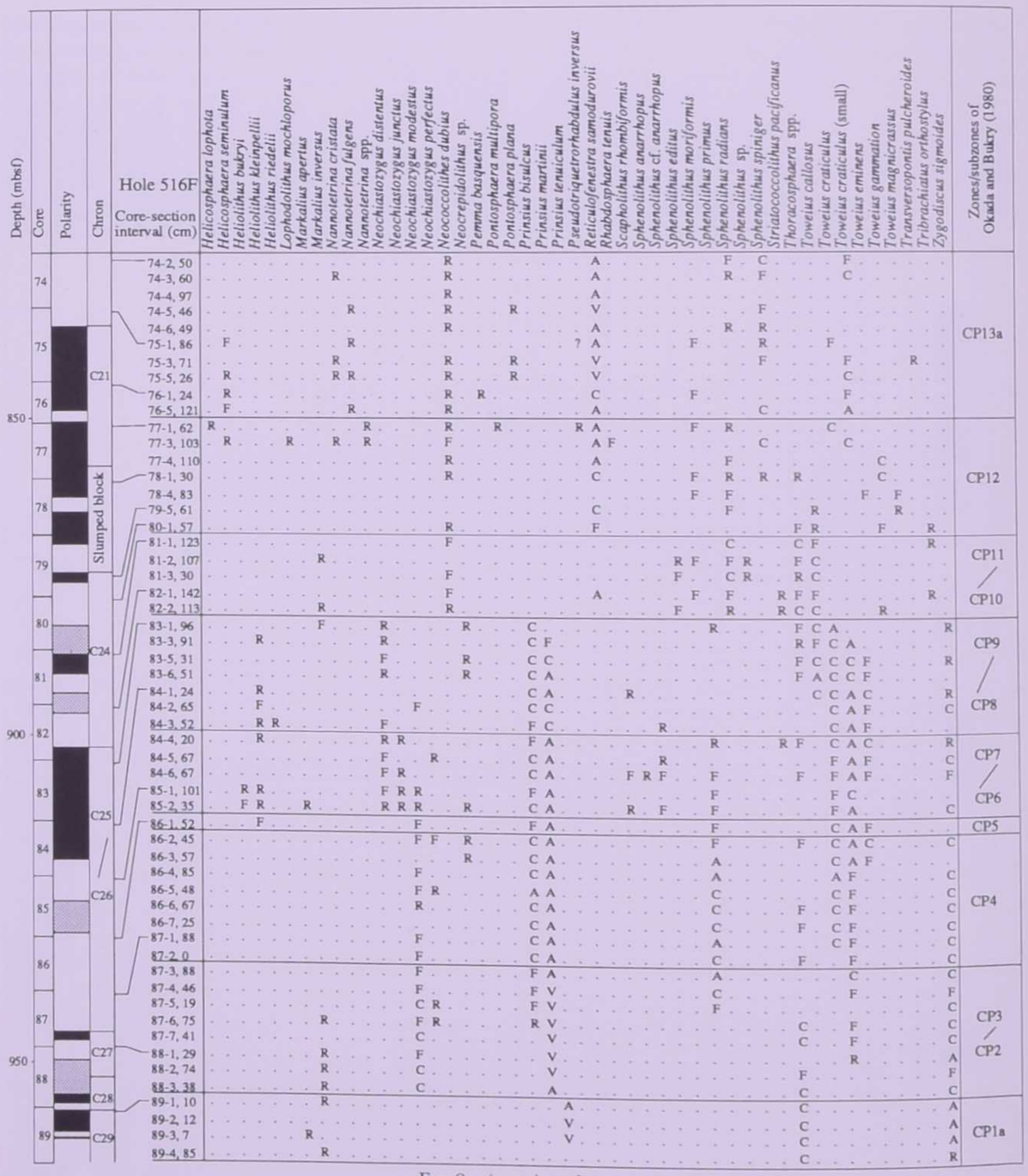

FIG. 8 - (*continued*)

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