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PALEOCLIMATIC ANALYSES OF MIDDLE EOCENE THROUGH OLIGOCENE PLANKTIC FORAMINIFERAL FAUNAS

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ABSTRACT

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Quantitative faunal analyses and oxygen isotope ranking of individual planktic foraminiferal species from deep sea sequences of three oceans are used to make paleoceanographic and paleoclimatic inferences. Species grouped into surface, intermediate and deep water categories based on $\delta^{18}O$ values provide evidence of major changes in water-mass stratification, and individual species abundances indicate low frequency cool—warm oscillations. These data suggest that relatively stable climatic phases with minor cool—warm oscillations of ~0.5 m.y. frequency are separated by rapid cooling events during middle Eocene to early Oligocene time.

Five major climatic phases are evident in the water-mass stratification between middle Eocene through Oligocene time. Phase changes occur at P14/P15, P15/P16, P20/P21 and P21/P22 Zone boundaries and are marked by major faunal turnovers, rapid cooling in the isotope record, hiatuses and changes in the eustatic sea level. A general cooling trend between middle Eocene to early late Oligocene is indicated by the successive replacement of warm middle Eocene surface water species by cooler late Eocene intermediate water species and still cooler Oligocene intermediate and deep water species. Increased water-mass stratification in the latest Eocene (P17), indicated by the coexistence of surface, intermediate and deep dwelling species groups, suggest that increased thermal gradients developed between the equator and poles nearly coincident with the development of the psychrosphere. This pattern may be related to significant ice accumulation between late Eocene and early late Oligocene time.

INTRODUCTION

Middle Eocene to early Oligocene time is characterized by a general cooling trend of surface waters as expressed by planktic organisms (Haq and Lohmann, 1976; Kennett, 1978; Sancetta, 1979; Keller, 1983) and of deep waters evidenced by a rapid drop in $\delta^{18}O$ near the Eocene/Oligocene boundary (Shackleton and Kennett, 1975; Douglas and Savin, 1975; Keigwin, 1980). Oxygen isotope studies have indicated that this cooling trend is not gradual, but occurs in a series of climatic thresholds. Population studies of planktic foraminifers suggest that the cooling trend occurred in a series of

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discrete phases which correlate with these climatic thresholds and on which low frequency oscillations are superimposed.

This study proposes a method to identify both the climatic thresholds and low frequency oscillations based on oxygen isotope analyses of individual planktic foraminiferal species and quantitative population studies. Oxygen isotope studies of species have revealed a definite depth ranking of planktic foraminifers within the water column. Species with the lowest $\delta^{18}O$ values are interpreted as surface water dwellers, whereas species with successively greater $\delta^{18}O$ values are considered intermediate and deep water dwellers (Williams et al., 1977; Boersma and Shackleton, 1978; Douglas and Savin, 1978; Vincent et al., 1980; Savin, pers. commun., 1982; Poore and Matthews, in press).

Depth stratification based on $\delta^{18}O$ combined with quantitative population data offers a unique opportunity to: (a) analyze the nature of water-mass stratification through middle Eocene and Oligocene time as implied by relative abundances of surface, intermediate and deep water dwellers; (b) identify water-mass changes which may have caused, or contributed to the major faunal assemblage changes that characterize the climatic thresholds; and (c) to identify the nature of the low frequency oscillations apparent in species abundances. In addition, changes in water-mass stratification through time offer new evidence for major paleoclimatic, paleoceanographic and tectonic events. These events can be dated accurately by the quantitative biostratigraphic control.

This study is based on population studies of planktic foraminifers in the low latitude Atlantic (Site 363), Pacific (Site 292) and Indian Ocean (Site 219) and high latitude South Pacific (Site 277, Fig.1). The biostratigraphy

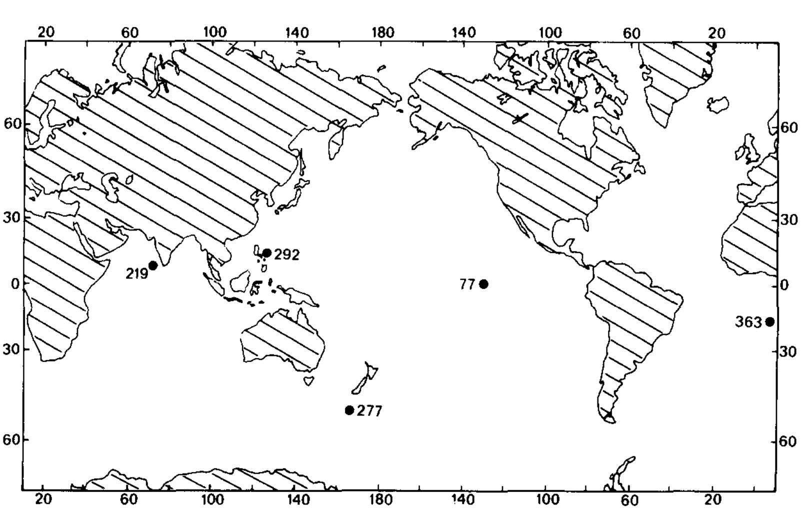

Fig.1. Location map of DSDP Sites examined.

and major faunal assemblage changes at these and other low latitude deep sea sequences are discussed in Keller (1983). We illustrate and discuss here the depth stratification of species in representative sequences in each ocean in order to show: (a) water-mass stratification changes, as inferred from depth ranking of species, occurred world wide; (b) the effect of these changes in low and high latitude regions; and (c) the nature and timing of these depth stratification changes. The data are presented in two major parts. The first part discusses the general oceanographic aspects implied by the changes in water-mass stratification, and the second part deals with the specific faunal changes within the surface and intermediate groups and identifies climatic oscillations based on species abundance changes.

ISOTOPE DATA

Isotope data of middle Eocene to Oligocene species from Sites 219, 363 and 77B are listed in Table I. For comparison, isotope data from the equatorial Pacific Site 167 (Douglas and Savin, 1978) and equatorial Atlantic Site 366 (Boersma and Shackleton, 1978) are listed in Table II. Middle to late Eocene isotope values of Sites 363 and 219 reveal major discrepancies in some species (e.g. *Globigerinatheka subconglobata*, *Globorotalia broedermanni*, *Globigerina medizzai*, Table I, asterisk). These discrepancies appear to be due to preservation at Site 219 where some species are heavily encrusted with secondary calcite deposits. Better preservation is observed in Site 363 and hence isotopic values at this site are assumed to be more reliable.

Isotope data for Oligocene species are primarily from Site 77B where planktic time series analyses were based on *Globigerina angustiumbilicata* and *Chiloguembelina cubensis.* The range of isotope values for each Zone is given in Table I for these species. Fewer samples were analyzed for other species. Preservation at Site 77B is relatively good with the exception of increased carbonate dissolution in some intervals. No secondary calcite deposits were observed.

Isotope data from the equatorial Pacific Site 167 (Douglas and Savin, 1978) and equatorial Atlantic Site 366 (Boersma and Shackleton, 1978) indicate generally lighter ^{18}O values for the same species than at Site 77B. This difference is probably due partly to the paleolatitude of these sites and partly due to preservation. Significantly heavier ^{18}O values have been reported for the mid-latitude Site 522 by Poore and Matthews (in press) (average values are listed in Table III). Despite these differences, the isotopic ranking of species generally remains the same.

^{18}O DEPTH RANKING OF PLANKTIC FORAMINIFERS

Depth ranking of planktic foraminiferal species is based on $\delta^{18}O$ analyses of individual species in numerous DSDP sites. Species with the lowest $\delta^{18}O$ values are considered surface dwellers, species with greater $\delta^{18}O$ values are

TABLE I

Sample data, biostratigraphic age, and isotopic results of samples analyzed

Samples analyzed		Zone	Taxa analyzed	^{18}O	^{13}C
Site	Core-Section				
MIDDLE EOCENE					
219	18-1 (93 cm)	P15 base	*Globigerinatheka semiinvoluta*	—0.60	1.57
	18-1 (93 cm)	P15 base	*Globorotalia cerroazulensis*	—0.60	1.39
	18-3 (61 cm)	P14 top	*Globigerina medizzai*	1.09*	2.75*
	18-3 (61 cm)	P14 top	*Globorotaloides carcosellensis*	0.12	1.15
	20-2 (68 cm)	P12	*Globigerinatheka subconglobata*	—1.22*	2.43*
	20-2 (68 cm)	P12	*Globorotalia broedermanni*	—1.14*	2.66*
	20-2 (68 cm)	P12	*Truncorotaloides rohri*	—0.93	2.20
	20-2 (68 cm)	P12	*Globorotalia lehneri, G. spinulosa*	—0.71	2.40
	20-2 (68 cm)	P12	*Globorotalia bullbrooki*	—0.87	2.66
363	10-3 (138 cm)	P14	*Truncorotaloides rohri*	—0.58	2.47
	10-3 (138 cm)	P14	*Globorotaloides carcosellensis*	—0.03	1.45
	10-3 (138 cm)	P14	*Globigerina medizzai*	—0.19	2.16
	11-2 (95 cm)	P12	*Globorotalia bullbrooki*	—0.76	2.44
	11-2 (95 cm)	P12	*Globorotalia pseudotopilensis*	—0.63	2.97
	11-2 (95 cm)	P12	*Globorotalia broedermanni*	—0.69	2.72
	11-2 (95 cm)	P12	*Globorotalia pentacamerata*	—0.77	2.81
	11-2 (95 cm)	P12	*Globigerinatheka subconglobata*	—0.22	2.22
	11-2 (95 cm)	P12	*Globigerina senni*	—1.03	2.40
OLIGOCENE					
77B	37-4/36-3	P22	*Globigerina angustiumbilicata*	—0.91 to —1.06	0.55 to 0.80
	36-6/42-5	P21	*Globigerina angustiumbilicata*	—0.36 to —0.86	0.12 to 0.75
	43-6/47-4	P20	*Globigerina angustiumbilicata*	—0.40 to —0.76	0.22 to 0.47
	49-1/50-5	P18/P19	*Globigerina angustiumbilicata*	—0.32 to —0.65	0.47 to 0.74
	45-4/48-1	P20	*Chilogeumbelina cubensis*	—0.17 to —0.45	0.98 to 1.21
	48-2/49-4	P18/P19	*Chilogeumbelina cubensis*	—0.54 to —0.53	1.60 to 1.57
	48-3	P18/P19 top	*Globigerina ampliapertura*	—0.14	0.92
	48-5	P18/P19 top	*Globigerina ampliapertura*	—0.17	0.78
	51-3	P18/P19 base	*Globigerina euapertura*	—0.35	1.22
	51-4	P18/P19 base	*Globigerina euapertura*	0.00	1.13
	48-6	P18/P19 top	*Globigerina linaperta*	0.57	0.35
	51-3	P18/P19 base	*Globigerina linaperta*	0.50	1.06
	51-4	P18/P19 base	*Globigerina linaperta*	0.65	1.01
	51-5	P18/P19 base	*Globigerina linaperta*	0.70	1.01
	51-6	P18/P19 base	*Globigerina linaperta*	0.84	1.19
	43-5	P21 base	*Globorotalia opima*	0.58	0.46
	43-6	P20/P21	*Globorotalia opima*	0.47	0.24
	43-5	P21 base	*Catapsydrax dissimilis*	1.46	0.43
	43-6	P20/P21	*Catapsydrax dissimilis*	0.81	0.30
	48-3	P18/P19 top	*Catapsydrax dissimilis*	1.19	0.61
	48-5	P18/P19 top	*Catapsydrax dissimilis*	1.38	0.51
	48-6	P18/P19 top	*Catapsydrax dissimilis*	1.15	0.44
	51-3	P18/P19 base	*Catapsydrax dissimilis*	1.20	1.04
	51-4	P18/P19 base	*Catapsydrax dissimilis*	1.26	1.03
	51-5	P18/P19 base	*Catapsydrax dissimilis*	1.33	1.09
	51-6	P18/P19 base	*Catapsydrax dissimilis*	1.38	1.03

*Problems with carbonate dissolution and diagenesis.

considered intermediate and deep water dwellers. Table III lists species ranked from light (warm) to heavy (cold) in descending order for middle to late Eocene and late Eocene to Oligocene faunas. Species are grouped into surface, intermediate and deep water dwellers based on clustering of species with similar isotope values. Average $\delta^{18}O$ values of species are indicated for

TABLE II

Oligocene isotopic results at Sites 167 (Douglas and Savin, 1978) and 366 (Boersma and Shackleton, 1978)

Samples analyzed		Zone	Taxa analyzed	^{18}O	^{13}C
Site	Core-Section				
167		P21	*Chiloguembelina*	−0.68	1.08
			Globigerina galavisi	−0.63	0.88
			Globigerina praesaepsis	−0.59	0.82
			Globigerina gortoni	−0.56	0.84
			Globigerina ouachitaensis	−0.54	0.85
			Globigerina winkleri	−0.52	0.72
			Globigerina angulioffícinalis	−0.51	0.05
			Catapsydrax dissimilis	−0.02	0.63
			Globorotalia opima	0.33	0.68
			Globorotalia opima nana	0.45	0.52
366A	28-6 (40 cm)	N4	*Catapsydrax* sp.	0.43	0.81
	28-6 (40 cm)	N4	*Globorotalia opima nana*	−0.75	0.93
	29-1 (92 cm)	N4	*Catapsydrax* sp.	0.21	−0.34
	29-1 (92 cm)	N4	*Globorotalia opima nana*	−0.65	0.19
	29-6 (77 cm)	N4	*Catapsydrax* sp.	0.82	0.31
	29-6 (77 cm)	N4	*Globorotalia opima nana*	−1.92	0.78
	31-2 (85 cm)	P22	*Catapsydrax* sp.	0.97	0.19
	31-2 (85 cm)	P22	*Globorotalia opima nana*	−0.04	0.15
	33-1 (137 cm)	P22	*Catapsydrax* sp.	0.87	0.37
	33-1 (137 cm)	P22	*Globorotalia opima nana*	0.13	0.56
	33-3 (48 cm)	P22	*Catapsydrax* sp.	1.26	0.52
	38-1 (24 cm)	P21	*Catapsydrax* sp.	−0.57	0.14
	38-4 (24 cm)	P21	*Catapsydrax* sp.	0.12	0.30
	39-1 (47 cm)	P21	*Catapsydrax* sp.	0.50	0.20
	39-1 (47 cm)	P21	*Chiloguembelina cubensis*	−0.73	0.33
366	5-2 (15 cm)	P20	*Globigerina ampliapertura*	−0.16	0.37
	5-4 (116 cm)	P20	*Catapsydrax* sp.	1.02	0.42
	5-4 (116 cm)	P20	*Globigerina ampliapertura*	0.11	0.76
	5-4 (116 cm)	P20	*Globorotalia opima nana*	−0.81	0.97
	6-6 (60 cm)	P19	*Catapsydrax* sp.	0.54	0.36
	6-6 (60 cm)	P19	*Globigerina ampliapertura*	−0.87	0.60
	6-6 (60 cm)	P19	*Globorotalia opima nana*	−0.07	0.03
	7-4 (87 cm)	P18/P19	*Catapsydrax* sp.	1.06	0.53
	7-4 (87 cm)	P18/P19	*Globigerina ampliapertura*	−0.44	0.75
	7-4 (87 cm)	P18/P19	*Chiloguembelina cubensis*	−1.33	0.81
	8-2 (48 cm)	P18/P19	*Globigerina ampliapertura*	0.03	0.84
	8-4 (23 cm)	P18/P19	*Catapsydrax* sp.	0.32	0.54
	8-4 (23 cm)	P18/P19	*Globigerina ampliapertura*	−0.42	0.59
	8-4 (23 cm)	P18/P19	*Chiloguembelina cubensis*	−1.23	0.85

low latitude sequences based on data from Tables I and II. It must be cautioned, however, that these values differ widely between low, mid and high latitude regions. In addition, long ranging species also provide variable $\delta^{18}O$ values at different geologic times as climatic conditions changed. Nevertheless, the depth ranking of species appears to have remained constant.

TABLE III

Isotopic depth ranking of species compared to faunal groups derived from quantitative faunal analyses in Figs.6 and 7 [relative temperature rating of faunal groups between −1.2 and +1.6 derived from average low latitude ^{18}O values: high negative values indicate warm, less negative and positive values indicate successively cooler faunal groups.]

A. Middle Eocene to late Eocene

Species ranking	^{18}O values		Temperature rating faunal groups
	Site 363	Site 219	
Surface			
1. *Globorotalia bullbrooki—G. boudreauxi*	−0.76	−0.87	
2. *Globorotalia broedermanni*	−0.69	−1.14*	S-5
3. *Globorotalia pentacamerata*	−0.77		−0.80 to −1.2
4. *Globorotalia planodorsalis*	no ^{18}O data		
5. *G. pseudotopilensis—G. topilensis*	−0.63		
6. *Globigerina senni*	−1.03		
7. *Truncorotaloides rohri*	−0.58	−0.93	S-4
8. *G. lehneri—G. spinulosa*		−0.71	−0.60 to −0.80
9. *Globigerinatheka semiinvoluta—G. index*		−0.60	S-3
10. *Globorotalia cerroazulensis*		−0.60	−0.50 to −0.60
Intermediate			
1. *Globigerinatheka subconglobata*	−0.22	−1.22*	I-4
2. *Globigerina medizzai*	−0.19	+1.09*	−0.20 to 0.00
3. *Globorotaloides carcoseliensis*	−0.03	+0.12	
Deep			
1. *Catapsydrax*	0.81 to 1.46 Site 77B		1.2 to 1.6
2. *Globoquadrina venezuelana*	no ^{18}O data for Eocene		

*Samples in Site 219 may be affected by dissolution or diagenesis.

B. Late Eocene to Oligocene

Species ranking	^{18}O values				Temperature rating faunal groups
	Site 71	Site 77B	Site 167	Site 366	
Surface					
11. *G. siakensis—G. mayeri* (N4)	−1.0**				
12. *G. kugleri—G. pseudokugleri—G. mendacis* (N4)	−1.0**				S-1
13. *G. ciperoensis—G. angulisut.* (P22)			−0.51		−0.60 to −1.2
14. *G. angustiumbilicata* (P18/P19)		−0.40			
15. *Chiloguembelina cubensis* (P20/P21)		−0.35	−0.68	−0.73	
16. *Globigerina ampliapertura* (P18/P19)		−0.15		−0.43	S-2
17. *Globigerina ouachitaensis* (P21)			−0.54		−0.10 to −0.50
18. *Globorotaloides gemma*		no ^{18}O data			
Intermediate					I-3
4. *Pseudohastigerina micra*	no low lat. ^{18}O data				0.00 to 0.30
5. *Globigerina angiporoides*	no low lat. ^{18}O data				I-2
6. *Globigerina linaperta*		0.67			0.50 to 0.80
7. *Globorotalia opima*		0.53	0.45		I-1
8. *Globigerina euapertura*		−0.17			0.80 to 1.2
9. *Globigerina galavisi*			−0.63		
10. *Globigerina praebulloides*	no ^{18}O data				
Deep					
1. *Catapsydrax*		0.81 to 1.46 (77B)			1.2 to 1.6
2. *Globoquadrina venezuelana*		1.00**			

**Unpublished data from Savin and Keller (1982).

Isotopic depth ranking of species is also compared to faunal groups as derived from quantitative faunal analyses of Sites 219, 363 and 292 (Table III). Faunal groups are divided into five surface (S-1 to S-5) and four intermediate (I-1 to I-4) water groups based on evolutionary succession of species. Relative temperature ratings between −1.2 and +1.6, as derived from average low latitude $\delta^{18}O$ values are assigned to these faunal groups. Negative values indicate warm surface species groups, positive values indicate cooler intermediate and deep water groups. Thus successively cooler faunal groups are represented between S-5 and I-1.

WATER-MASS STRATIFICATION

Changes in water-mass stratification can be inferred from depth ranking of species grouped into surface (warm), intermediate (cool) and deep (cold) water dwellers based on the assumption that (a) each species group retains its affinity for particular water-mass characteristics, and (b) variations in each species group reflect changes in the water-mass stratification. From distributions of living planktic foraminifers in the modern ocean we know that the bulk of the population lives in the upper 400—500 m of water, with surface dwellers living in the upper 100 m, intermediate dwellers between 100 and 400 m and deep water species in > 400 m of water (Ruddimann et al., 1970; Bé et al., 1971). We assume therefore that depth stratification of these faunal assemblages reflect water-mass conditions at approximately these depths. However, from the species stratification in Figs.2—4 it is immediately clear that the labels "surface", "intermediate" and "deep" do not necessarily refer to actual depth in the upper 400—500 m of the water column, but rather to isotopic differentiation of the species, and hence temperature. Therefore, in the following discussion "surface" refers to the warmest water temperatures, "intermediate" to cooler and "deep" to still cooler water temperatures.

In Figs.2—4 planktic foraminiferal faunas are illustrated in terms of surface, intermediate and deep dwelling species groups, using actual percent abundance data calculated from representative faunal splits of 300—500 individuals (size fraction >150 μm). To facilitate discussion, episodes of relatively stable species stratification have been labeled PSS 1 to 5 (PSS for Paleogene Species Stratification). These episodes correspond to a series of discrete faunal assemblages as will be discussed later.

Four major changes in the water-mass stratification are observed between middle Eocene and late Oligocene time (PSS 5 to 1, Figs.2, 3). Each of these changes corresponds to a global faunal turnover and major paleoclimatic event. Moreover, each change in the water-mass stratification correlates with a change in the global sea level curve (Vail and Hardenbol, 1979; Vail et al., unpublished data, 1982). Contrary to assertions of mass extinctions near the Eocene/Oligocene boundary by some workers (Alvarez et al., 1982; Ganapathy, 1982), neither of the faunal turnovers during middle Eocene through Oligocene time provide evidence to support catastrophic extinctions.

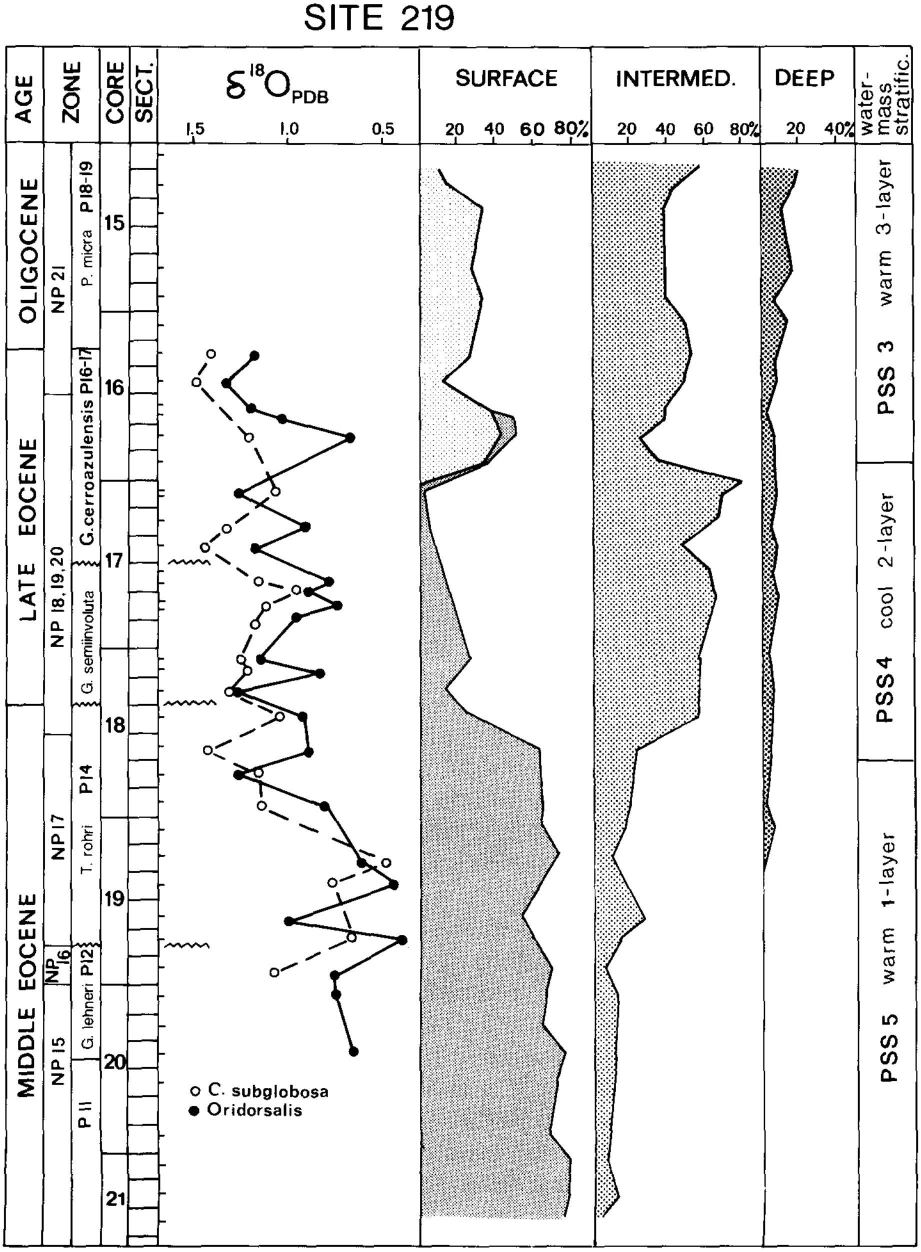

Fig. 2. Depth stratification of planktic foraminifers and benthic oxygen isotope data (Keigwin and Corliss in prep.) of Site 219. Planktic foraminiferal species are grouped into surface, intermediate and deep water species based on $\delta^{18}O$ values and listed in Table I. Zig-zag lines indicate hiatuses, tick marks along core-section indicate sample locations.

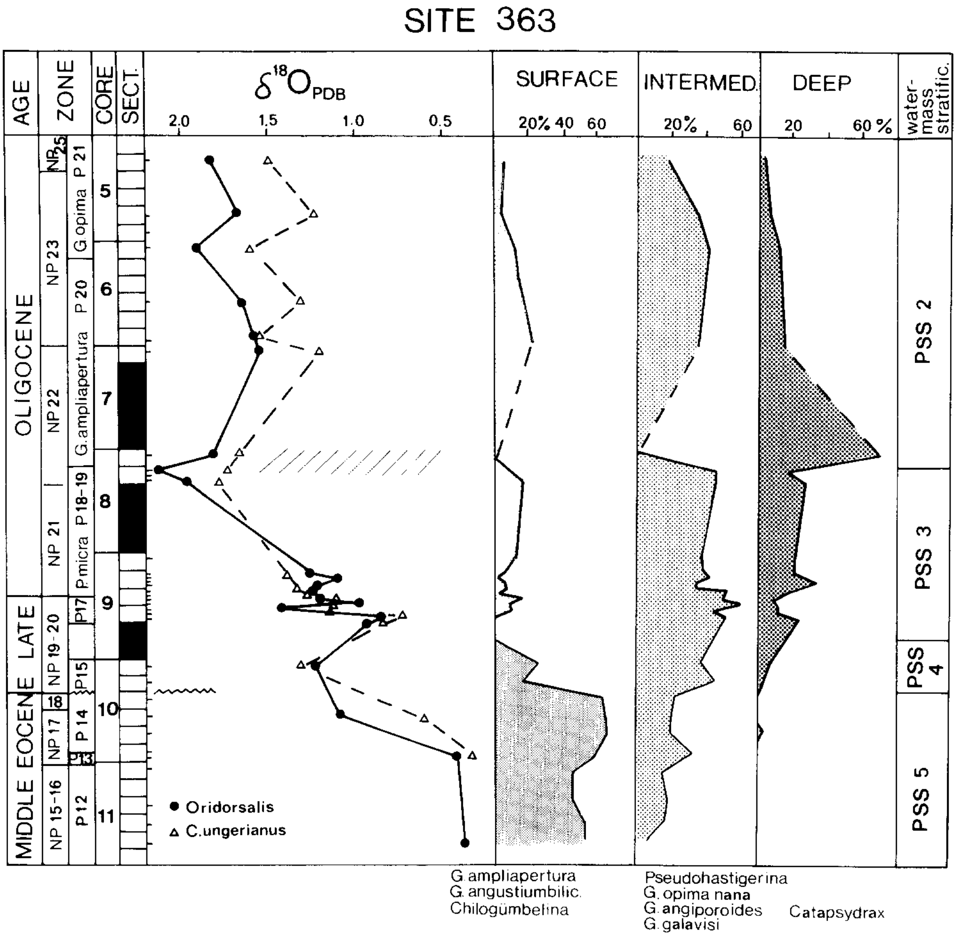

Fig.3. Depth stratification of planktic foraminifers and benthic oxygen isotope data (Keigwin and Corliss, in prep.) of Site 363. Diagonal lines mark increased carbonate dissolution. For explanation see Fig.2.

The faunal turnovers represent evolutionary adjustments to rapidly changing paleoclimatic and paleotectonic conditions.

Middle Eocene

Depth stratification of middle Eocene planktic foraminiferal faunas are illustrated in Site 219 (Indian Ocean) and Site 363 (South Atlantic, Figs.2, 3). Middle Eocene species stratification (PSS 5) is characterized by a dominance of surface dwelling species (70–80%, Site 219, and 60–70% in Site 363). The remaining fauna consists of the cooler intermediate dwelling group. This dominance of surface dwellers suggests that warm temperatures extended through much of the living habitat of planktic foraminifers, possibly as deep as 300—400 m. Assemblage changes within the surface group, however, indicate a general cooling trend began earlier in the middle Eocene, as will be discussed later.

The major turnover in the water-mass stratification occurs at the middle/late Eocene boundary, coincident with a major hiatus in Site 363 and short hiatus in Site 219. At this time all spinose surface species become extinct and the cooler intermediate group becomes dominant. Benthic $\delta^{18}O$ data indicate a major cooling phase at this time (Figs. 2 and 3) associated with a drop in the eustatic sea level (Vail et al., unpublished data, 1982). This polar cooling phase may have been responsible for the extinction of the spinose warm water species and expansion of the cooler water intermediate species group, as well as the intensification of current circulation causing erosion.

Early late Eocene

Generally cool water temperatures prevailed through the early late Eocene low latitude regions (PSS 4) as indicated by the dominance of the intermediate species group, increase in the deep water dwellers and decline and eventual extinction of the surface species group (P15—P16, Figs.2—4). This reduction is accompanied by a less significant cooling phase in the $\delta^{18}O$ record which coincides with a hiatus (P15/P16, Figs.2—4). Cooler climatic conditions, however, are indicated in the high latitude South Pacific (Fig.5) in both the isotope record and species stratification. Warm surface dwellers disappear at this time suggesting that in the high and low latitude ocean significantly cooler temperatures prevailed in the upper 400—500 m of water.

Eocene/Oligocene boundary

Return to warmer conditions is apparent in the latest Eocene (Zone P17) marked by the evolution of a new surface species group, decline in the abundance of the intermediate species group and general increase in the deep water dwellers (PSS 3). This development marks the onset of increased water-mass stratification resulting in a warm, but thin surface water layer, a cool broad intermediate water layer, and a thin cold deep water layer. Warmer, although fluctuating climatic conditions are also indicated in the planktic isotope data (Figs.2—5). Species stratification suggests that these relatively warm, but unstable climatic conditions remained throughout the PSS 3 (early Oligocene) interval with a gradual increase in deep water dwellers.

The appearance of significant deep, intermediate and surface water groups in the latest Eocene (P17) suggests that a fundamental change occurred in the water-mass stratification. Species stratification suggests that the middle to late Eocene ocean developed from a relatively uniform warm middle Eocene ocean (upper 400—500 m) to a uniform cool early late Eocene ocean and to a more stratified latest Eocene to early Oligocene ocean. The

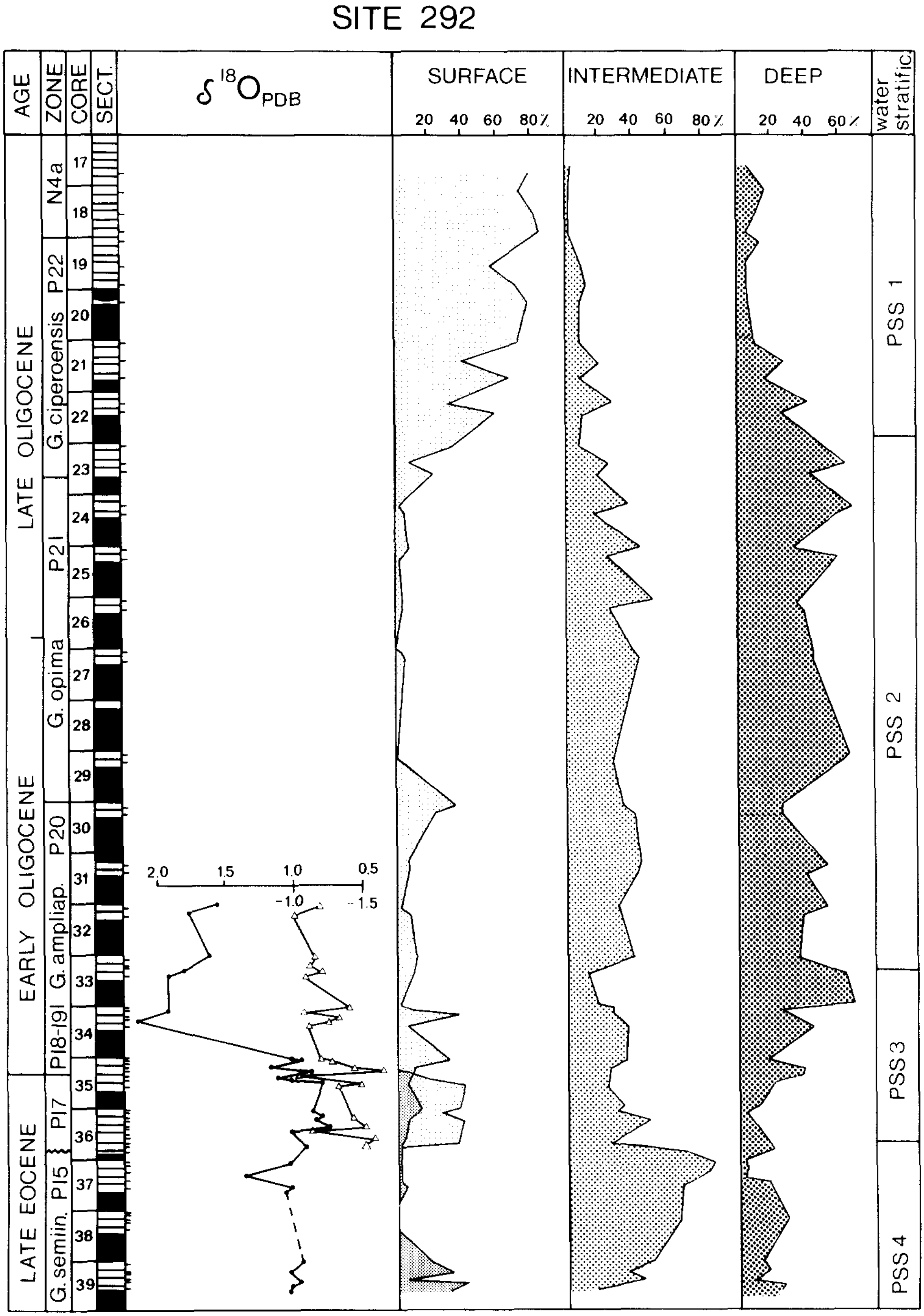

Fig. 4. Depth stratification of planktic foraminifers and oxygen isotope data (Keigwin, 1980) of Site 292. For explanation see Fig. 2.

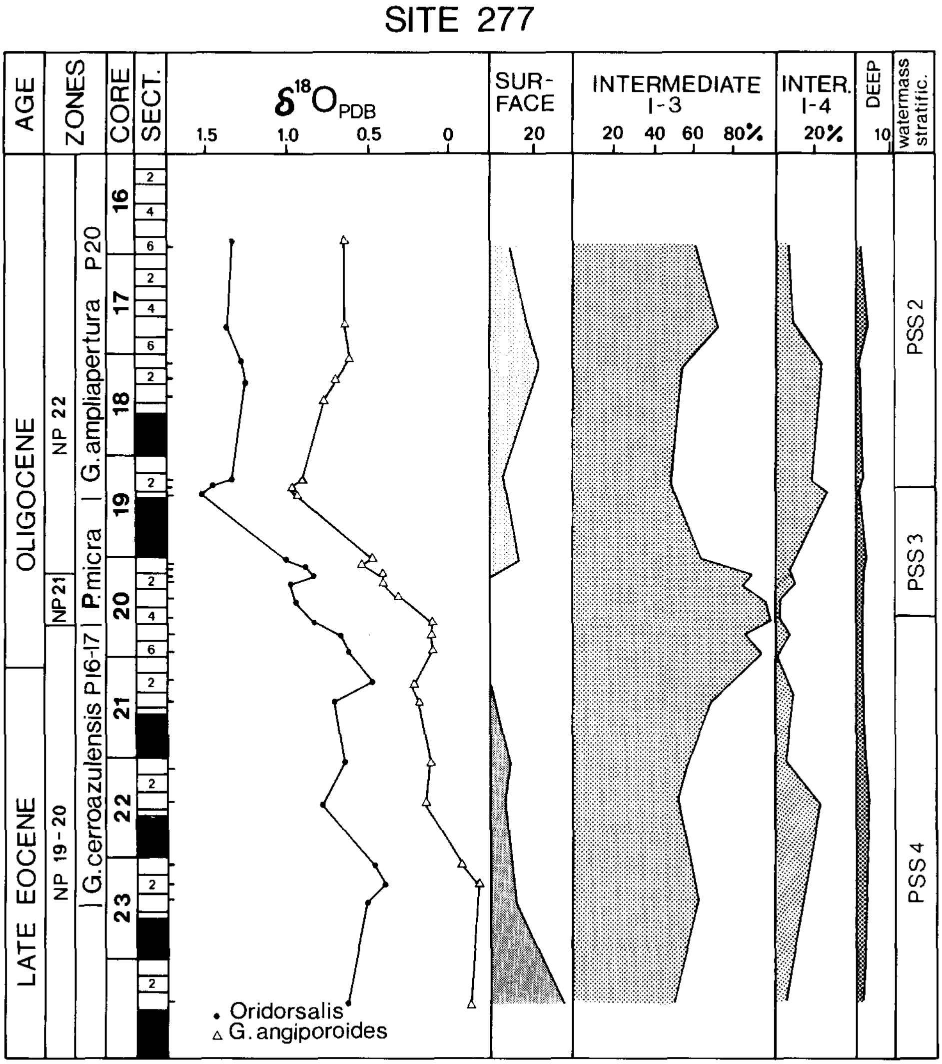

Fig. 5. Depth stratification of planktic foraminifers and oxygen isotope data (Keigwin, 1980) of Site 277. For explanation see Fig. 2.

development of a more stratified ocean, indicating increased thermal gradients, marks a fundamental change in paleoceanographic conditions which is equally pronounced in bottom water conditions.

Benthic $\delta^{18}O$ values across the Eocene/Oligocene boundary indicate that a major drop in bottom water temperatures occurred world wide (Keigwin and Corliss, in prep.) (Figs.2—5). Surface temperatures also declined at high latitudes (Fig.5), but cooling of surface waters in low latitudes was much less significant (Fig.4). This relationship has been previously interpreted as reflecting a change in the latitudinal temperature contrast (Keigwin, 1980). The benthic isotope event has been interpreted as recording the development of the psychrosphere, or two-layer ocean with cold bottom and relatively warm upper water mass resulting from major polar cooling and production of cold Antarctic bottom water (Douglas and Savin, 1975; Shackleton and Kennett, 1975; Keigwin, 1980). Prior to this event the temperature difference between surface and deep waters in the tropics is estimated at about 2—3° C as compared to 7—8° C difference after this event (Keigwin, 1980).

Early Oligocene

Relatively warm, although fluctuating climatic conditions, prevail throughout the PSS 3 interval (Zones P18—P20) with a gradual increase in the cold deep water species. A change to cooler conditions is apparent in the upper part of Zone P20, with a major increase in the intermediate and deep dwelling groups. This event gives rise to the coldest faunal assemblages (PSS 2, upper Zone P20 to base of Zone P22) of middle Eocene to Oligocene time. This cold PSS 2 interval is characterized by dominance of deep and intermediate species groups (Table III, Fig.4). Warm surface dwellers are nearly absent during this interval at Site 292, with the exception of an abundance peak at the P20/P21 boundary. The early part of this cold climatic interval (P21a) contains the major sea level drop of Vail and Hardenbol (1979) and corresponds to major faunal changes within the intermediate species group as will be discussed later. No hiatus has been observed at this sea level drop in the deep ocean, although a hiatus is commonly present in shallow waters such as the continental shelf or mid-ocean ridges (Miller et al., in press; Keller, unpubl. data). However, isotope data also indicate a major cool event at this time as generally observed at other sea level drops (Keigwin and Keller, in press). Further isotope studies will be necessary to understand the paleoceanographic changes associated with this interval.

Late Oligocene

The latest Oligocene is noted for the return to warm climatic conditions as indicated by a major change in the water-mass stratification PSS 1 (Zones P22—N4). At this time (base of Zone P22, Fig.4), a drastic increase occurs in the surface species group in both abundance of species and evolution of new species, whereas intermediate and deep water dwellers decrease. By the latest Oligocene and into the early Miocene surface dwellers dominate (80%) planktic foraminiferal assemblages similar to middle Eocene time. Hence, similar to middle Eocene time, warm water conditions conducive to the surface species group prevailed through most of the living habitat of planktic foraminifers. Water-mass stratification appears to have changed from the predominantly two layer, cold late early to early late Oligocene ocean to a uniformly warm late Oligocene surface ocean with surface waters warm to

400—500 m, as suggested by the near absence of intermediate and deep water groups.

PALEOCLIMATIC OSCILLATIONS

In the previous section major changes in the water-mass stratification have been inferred based on $\delta^{18}O$ ranking of planktic foraminifers. We will now examine abundance fluctuations of dominant species within surface and intermediate water groups in order to determine the paleoclimatic conditions associated with these major changes in water-mass stratification.

Paleoclimatic oscillations in middle Eocene through Oligocene time are identified based on species with apparent preferences for similar environmental conditions, as suggested by their sympathetic abundance fluctuations and similar $\delta^{18}O$ values. Figs.6 and 7 illustrate species of similar abundance

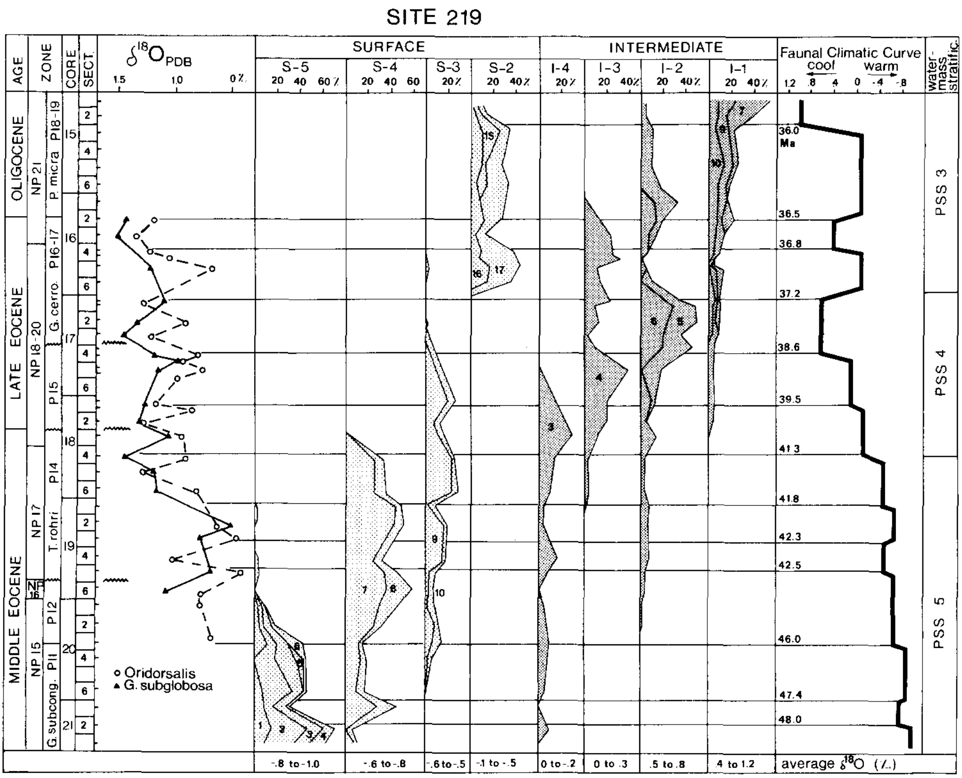

Fig.6. Species abundances in Site 219 (faunal groups of Table III) and faunal climatic curve based on dominant faunal groups. Species of faunal groups are listed in Table III. Ages for climatic fluctuations calculated from sediment accumulation curves based on datum levels tied to the revised paleomagnetic time scale of Berggren et al. (in press). Zig-zag lines indicate hiatuses, tick marks along core-section indicate sample locations.

distributions and ranges which tend to have similar $\delta^{18}O$ values (Table III). Five surface dwelling subgroups (S-5 to S-1) and four intermediate dwelling subgroups (I-4 to I-1) have been identified in middle Eocene through Oligocene sequences, and a relative temperature rating between −1.2 and +1.6 has been assigned in order to construct a faunal climatic curve (Table III). High negative values indicate warm surface species, less negative and positive values indicate successively cooler water species groups. The species subgroups S-5 to S-1 and I-4 to I-1 generally illustrate the evolutionary succession in the planktic foraminiferal fauna. The most abundant species subgroup, or subgroups, present at any given time are considered representative of paleoclimatic conditions.

Middle Eocene

The middle Eocene (PSS 5) is characterized by the surface subgroups S-5, S-4 and S-3. The warmest subgroup S-5 (species 1—6 in Table III, Fig.6) dominates in the early middle Eocene Zones P11 to P12 with a slightly cooler pulse in P11 (peak in S-4, Fig.6). The cooler surface subgroup S-4 (*Truncorotaloides rohri*, *Globorotalia lehneri*, *G. spinulosa*) dominates in Zone P14 with cool pulses marked by the surface S-3 subgroup (*Globigerinatheka semiinvoluta*, *G. index*, *G. cerroazulensis* s.l., Fig.6). This progressive cooling is indicated in the faunal climatic curve with cool events at 47.4—48.0 Ma, 46.0 Ma, 42.3—42.5 Ma and 41.8 Ma (Fig.6). The surface subgroup S-4 becomes extinct at the major cool event at the P14/P15 boundary (41.3 Ma) which is also a major cold event in the benthic $\delta^{18}O$ record (Figs.2, 3). These dates have been calculated from the sediment accumulation rate curve of Site 219 using datum events tied to the revised paleomagnetic time scale of Berggren et al. (in press).

Late Eocene

A major cooling phase occurred in the late Eocene Zones P15 to P16 accompanied by the extinction of spinose species (S-4) at the P14/P15 Zone boundary and dominance of *Globigerina linaperta* and *G. angiporoides* (I-2) in low latitudes (Fig.6, 7). These successively cooler climatic conditions occur at 41.3 Ma, 39.5 Ma and 38.6—37.2 Ma in Site 219 (Fig.6); biostratigraphic control at Site 292 is less accurate due to more extensive hiatuses.

A brief warming characterizes the latest Eocene Zone P17 in both faunal and isotopic records (Figs.3, 4) and gives rise to a new surface subgroup S-2 (*Globigerina ampliapertura*, *G. ouachitaensis*, *Chiloguembelina cubensis*, Table III). Near the Eocene/Oligocene boundary temperatures decline again coincident with the major cool event observed in the benthic $\delta^{18}O$ record (Figs.2—5). At Site 219 a minor cooling is observed near the Eocene/Oligocene boundary at 36.5—36.8 Ma, followed by a short warm event at 36.0—36.5 Ma and a major cool event begins at about 36.0 Ma (Fig.6). At Site 292

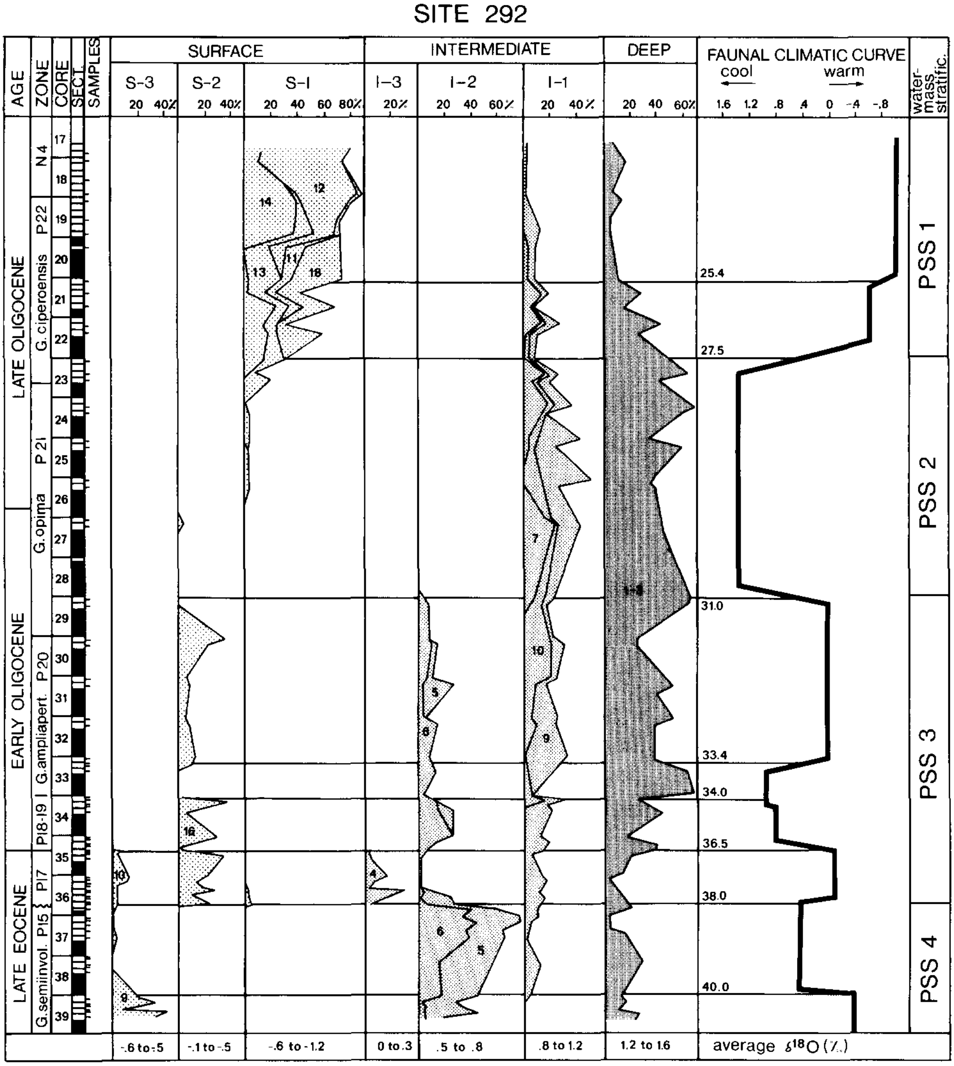

Fig.7. Species abundances in Site 292 in faunal groups of Table III and faunal climatic curve. For complete explanation see Fig.6.

this major cool event begins slightly earlier at 36.5 Ma. This discrepancy is probably due to poorer biostratigraphic resolution as a result of partial core recovery in Site 292.

Oligocene

Paleoclimatic oscillations in the Oligocene appear to have occurred at a lower frequency than during the middle and late Eocene, however, dissolution at Site 292 (Fig.7) may have biased this record. The early Oligocene

(Zone P20) is marked by a relatively warm interval, although the low abundance in the generally more fragile surface species group is biased due to carbonate dissolution. Warmer, though oscillating climatic conditions prevail between 33.4 and 31.0 Ma (Fig.7). The end of this warmer interval is marked by the extinction of surface species S-2 (*Globigerina ampliapertura*) and intermediate subgroup I-2 (*Globigerina linaperta, G. utilisindex, G. angiporoides*).

The early Oligocene warm interval is followed by a long cold interval in Zone P21 (31.0—27.5 Ma) dominated by the intermediate subgroup I-1 (primarily *Globorotalia opima opima* and *Globigerina praebulloides*) and cold deep water species (*Catapsydrax* and *Globoquadrina venezuelana*, Table III). Surface dwellers are nearly absent in Site 292 (Fig.7). Planktic foraminiferal assemblages as well as nannofossils (Haq and Lohmann, 1976) indicate that Zone P21 marks the coldest interval in middle Eocene to Oligocene time. These faunal and floral assemblage changes also correlate with a dramatic drop in the eustatic sea level (Vail and Hardenbol, 1979). The relative cooling indicated in the oxygen isotope record, however, appears to have been much less significant (Fig.3, Site 363; Keigwin and Keller, in press, Site 77B). Further analyses of Oligocene sequences will be necessary to understand the paleoceanographic and paleoclimatic events at this time.

A major increase in water temperatures occurs in Zone P22 characterized by the dominance of the surface subgroup S-1 which is dominated by the evolution of new species such as *Globorotalia siakensis, G. mendacis, G. pseudokugleri, G. kugleri, Globigerina ciperoensis* and *G. angulisuturalis.* This warm event gives rise to the Neogene planktic foraminiferal assemblages.

Middle Eocene through Oligocene paleoclimatic and paleoceanographic data are summarized in Fig.8 along with the revised paleomagnetic time scale of Berggren et al. (in press). The faunal climatic curve is a composite of Sites 219 and 292.

The main features of the oxygen isotope curves of Sites 219, 363, 292 and 277 (Figs.2—6) are quite similar to the faunal climatic curve. Both curves exhibit a series of climatic thresholds followed by rapid cooling in the middle and late Eocene and early Oligocene (Zones P14/P15, P15/P16, P18/P19, P20/P21). Both curves represent the middle Eocene as a generally warm period characterized by rapid climatic oscillations which culminated in a significant cold event at the middle/late Eocene boundary followed by a generally cooler late Eocene with maximum cool temperatures in Zones P15—P16. These two cold events are associated with widespread hiatuses and low eustatic sea level as recently identified by Baum et al. (1982, unpublished data) from Gulf and Atlantic Coastal Plain stratigraphy.

Warm climatic conditions in the latest Eocene Zone P17 and increased water-mass stratification preceding a major cool event in the earliest Oligocene are recognized in the faunal climatic and oxygen isotope curves. The earliest Oligocene (Zones P18-P19) temperature drop, however, correlates with only minor sea level changes as recently revised by Baum et al. (1982,

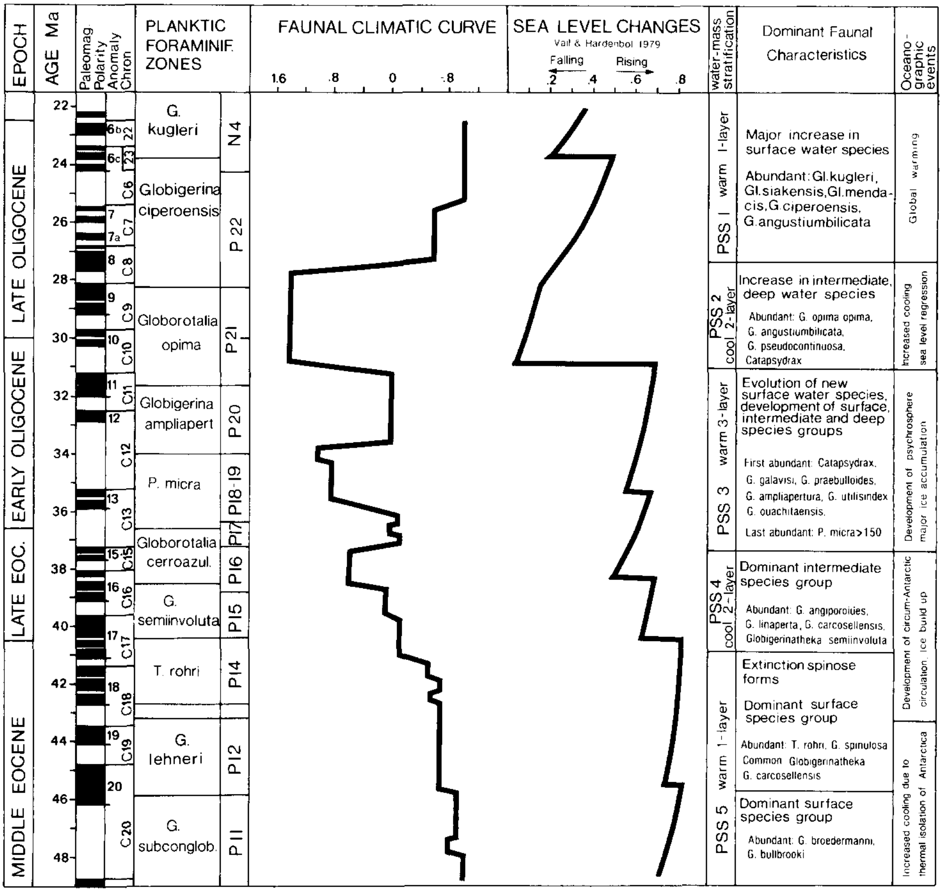

Fig.8. Faunal climatic curve (composite of Sites 219 and 292), sea level changes after Vail and Hardenbol (1979) and Baum et al. (unpublished data, 1982), dominant faunal characteristics, water-mass stratification, and major oceanographic events related to middle Miocene through Oligocene biostratigraphy and the paleomagnetic time scale of Berggren et al. (in press).

unpubl. data). Warmer temperatures during the late early Oligocene and latest Oligocene are also observed in both faunal and oxygen isotope records (Fig.3, and unpubl. data). However, what appears to have been the coldest Oligocene event according the faunal and floral assemblages (Zone P21) and correlates with a major sea level drop, is associated with a much less significant cooling in the oxygen isotope record (Keigwin and Keller, in press).

PALEOCLIMATIC IMPLICATIONS

The fact that a similar series of major cool events is implied by the oxygen isotope record, the faunal paleoclimatic curve, and the sea level curve indicates that these factors are likely responding to the same environmental input. Closer inspection of the faunal climatic curve reveals that relatively stable phases of climate separate abrupt cooling events (P14/P15, P15/P16, P20/P21). In addition, these relatively stable phases of climate contain higher frequency climatic events. These higher frequency cool—warm oscillations average between 0.5 and 1.0 m.y., between middle Eocene and early Oligocene (P18—P19) time with the exception of a warm event in P12 of 2.5 m.y. duration (Figs.6, 8). However, frequencies averaging about 2.5 to 3.0 m.y. are observed between the late early to late Oligocene time. It must be cautioned, however, that this apparent low frequency may be biased by the low diversity fauna and carbonate dissolution.

What caused these phases of relatively stable climate? Berger et al. (1981) interpreted stable climatic phases in the Cenozoic as a positive feedback system resulting from the attainment of a threshold. They observed that the most obvious feedback for these thresholds is the phase transition from water to ice. Less obvious feedback include cooling from increased albedo such as desertification, increased fertility (greening of ocean), increased exposure of land due to sea level regressions and warming due to the greenhouse effect and sea level transgressions (for discussion see Berger et al., 1981).

The relatively warm climatic phases separated by abrupt cooling events observed in the middle Eocene to Oligocene deep sea record are most easily explained by changing configurations of ocean basins and continents and associated climatic factors. Antarctic glacial development is assumed to have started as early as the early Tertiary (55—65 Ma) (Shackleton and Kennett, 1975). Separation of Australia from Antarctica in the middle to late Eocene led to thermal isolation of the Antarctic continent which favored increased ice build up. Therefore, thermal isolation, accumulation of glacial ice, and development of the circum-Antarctic current are most likely responsible for the general cooling trend marking late Eocene to Oligocene time.

The two major changes in water-mass stratification in the middle/late Eocene (P14/P15) and late Eocene (P15/P16) are associated with isotopic cooling, sea level low stands and widespread deep sea hiatuses. In high southern latitudes these hiatuses represent major erosive events suggesting major increases in the production of bottom water and intensified current circulation. Hence, vigorous bottom water circulation began developing in the late middle Eocene well before the development of the psychrosphere at the Eocene/Oligocene boundary. Moreover, the climatic cooling which started in the middle Eocene (Zone P12, Fig.6) and resulted in the major change in the water-mass stratification at the middle/late Eocene boundary, suggests that the circum-Antarctic current had developed by this time leading to thermal isolation of Antarctica and ice build up. Hence, significant ice accumulation may have started as early as the late/middle Eocene (P14/P15) as originally proposed by Matthews and Poore (1980).

The development of the psychrosphere near the Eocene/Oligocene boundary is marked by a major drop in benthic $\delta^{18}O$ values in high and low latitude sections (Figs.2—5). In high southern latitudes this cooling is evident also in surface water temperatures (Fig.5) (Shackleton and Kennett, 1975; Keigwin, 1980). In low latitude sequences, however, a more moderate cooling is indicated in surface water temperatures (Fig.4; Keigwin, 1980). Nevertheless, this cooling is associated with increased water-mass stratification in low latitudes as indicated by the appearance of distinct surface, intermediate and deep water species groups (Figs.2—4). This major high latitude cooling, but moderate low latitude cooling associated with increased water-mass stratification suggests that increased thermal gradients developed at this time similarly to middle Miocene to Recent time.

Faunal cooling in Zone P21 indicated by increased abundances of intermediate and deep water species, and a major drop in the eustatic sea level (Fig.8) suggest increasingly cool temperatures in low latitude regions during Oligocene time. By the latest Oligocene (P22) temperatures increased dramatically as indicated by the dominance of the warm water surface dwelling group. The abundance of surface dwelling species with light $\delta^{18}O$ values suggest that warm climatic conditions perhaps similar to middle Eocene time prevailed during the latest Oligocene.

CONCLUSIONS

Paleoclimatic analysis based on quantitative faunal analyses and depth stratification of planktic foraminifers as ranked by oxygen isotope differentiation of individual species lead to the following conclusions:

(1) Planktic foraminifers grouped into surface, intermediate and deep water dwellers indicate major changes occurred in the water-mass stratification during middle Eocene through Oligocene time near Zone boundaries P14/P15, P15/P16, P20/P21 and P21/P22.

(2) Middle to late Eocene water-mass stratification evolves from a relatively uniform warm middle Eocene ocean dominated by surface dwellers to a cooler early late Eocene ocean dominated by intermediate water dwellers and accompanied by a sharp decline and gradual disappearance in the surface dwelling species group.

(3) Increased water-mass stratification in the latest Eocene indicated by the first appearance of all three species groups (surface, intermediate and deep) suggests that increased thermal gradients developed between equator and poles, nearly coincident with the development of the psychrosphere.

(4) Faunal evidence indicates that the coldest climatic conditions occurred in the Oligocene Zone P21 marked by the dominance of deep and intermediate water species groups and coinciding with a major drop in the eustatic sea level. Oxygen isotope data however indicate a less significant cooling at this time.

(5) Warm climatic conditions, similar to middle Eocene time, are indicated in the latest Oligocene (Zone P22) by the dominance of the surface species group.

(6) A faunal climatic curve based on abundance fluctuations of species suggests that relatively stable climatic phases are separated by rapid cooling

events in both faunal and isotopic records. Faunal data indicate that cool—warm oscillations of lower magnitude are superimposed on these climatic phases at a frequency of about 0.5—1.0 m.y. during middle Eocene to early Oligocene time.

(7) Climatic deterioration between middle Eocene and early late Oligocene time accompanied by major changes in water-mass stratification suggests that significant ice accumulation occurred as early as late middle Eocene time with increased ice build up continuing into the early late Oligocene.

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