

### 33. LATE EOCENE-OLIGOCENE OXYGEN- AND CARBON-ISOTOPE RECORD FROM SOUTH ATLANTIC OCEAN, DEEP SEA DRILLING PROJECT SITE 522<sup>1</sup>

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#### ABSTRACT

Multiple species of upper Eocene through Oligocene planktonic and benthic foraminifers from DSDP Site 522 in the South Atlantic Ocean were analyzed for their oxygen- and carbon-isotope signatures. Comparison of the isotopic values of individual taxa from single sediment samples shows that many *Globigerina* spp., *Globorotalia opima opima*, *G. opima nana*, *Pseudohastigerina* spp., and *Chilouembelina* spp. are surface or near-surface dwellers. *Catapsydrax* spp. are confirmed as deep-dwelling planktonic foraminifers. *Cibicidoides kullenbergi* (s.l.), *Globocassidulina* spp., and *Oridorsalis umbonatus* exhibit interspecific isotopic trends that parallel the results of comparisons made on the Quaternary representatives of these taxa.

A gradual enrichment of 0.5 ‰ in the  $\delta^{18}\text{O}$  record of the benthic but not the planktonic foraminifers occurs during the late Eocene. This enrichment is believed to reflect changing bottom-water conditions at Site 522. During the earliest Oligocene a more abrupt enrichment of 0.5 ‰ in  $\delta^{18}\text{O}$  occurs in both the benthic and the planktonic records. This early Oligocene shift is interpreted as an increase in average global ice volume. High-resolution isotopic analyses of one lower Oligocene core yield suggestive but inconclusive evidence of the presence of high-frequency fluctuations in the oxygen-isotope record.

In conjunction with faunal and floral data, the isotopic data from Site 522 indicate that isotopic temperature scales must be adjusted to account for global ice volume during the Oligocene.

#### INTRODUCTION

Stable-isotope analyses of calcareous foraminifers are widely used in Cenozoic paleoceanographic and paleoclimatic studies (e.g., Savin et al., 1981, 1975; Boersma and Shackleton, 1977; Shackleton and Kennett, 1975). Recent studies, however, show that the isotopic signature of foraminifer calcites is a complex signal. Most modern benthic foraminifers deposit calcite with isotopic ratios that differ significantly both from one another and also from calculated equilibrium values (Graham et al., 1981; Woodruff et al., 1980). Planktonic foraminifers appear to deposit calcite that is in equilibrium with respect to  $\delta^{18}\text{O}$ , but different species and species groups tend to deposit their tests at different levels within the water column. Moreover, a few planktonic foraminifers appear to seek a constant-density surface within the water column, and calcite secreted by these taxa may reflect surface or near surface conditions at one location but deep conditions at another location (Curry and Matthews, 1981). Thus, determining the isotopic values for surface waters from planktonic foraminifers is greatly dependent on choosing the correct foraminifer for analysis. Studies using individual analyses of several species of Neogene foraminifers are increasing rapidly, but data on multiple species of Paleogene foraminifers from single samples are still sparse.

During Deep Sea Drilling Project Leg 73, hydraulic piston coring operations in the South Atlantic Ocean at Site 522 (26°06.8' S; 5°07.8' W; water depth, 4441 m;

Fig. 1) recovered an apparently complete and relatively undisturbed upper Eocene through Oligocene sequence that is well controlled by biostratigraphy and magnetostratigraphy. In the following sections we present the results of analyses of a number of species of planktonic and benthic foraminifers from the upper Eocene and Oligocene sediments at this site. Our objective is to evaluate the isotopic signatures of these Paleogene foraminifers and to survey some aspects of the isotopic record of this midlatitude site.

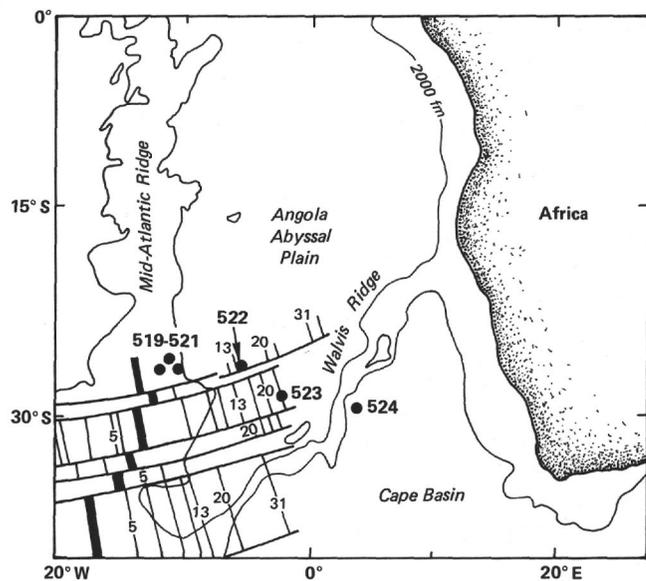


Figure 1. Location of Site 522 and other sites occupied during Leg 73. Small numbers identify magnetic anomalies.

<sup>1</sup> Hsü, K. J., LaBrecque, J. L., et al., *Init. Repts. DSDP, 73*; Washington (U.S. Govt. Printing Office).

## MATERIALS AND METHODS

A number of widely spaced sediment samples were selected from Cores 15 through 38 of Hole 522 and from Core 31 of Hole 522A to provide coverage of the late Oligocene through late Eocene. However, the foraminifer assemblages show increasing dissolution upsection, and it was difficult to find adequate material for analysis in samples taken above Core 27. In addition to the widely spaced samples, a high density series of samples was taken at intervals of 5 to 15 cm from Core 33 to look for high-frequency fluctuations in the Oligocene isotopic record.

Sediment samples were disaggregated in tap water at room temperature on an oscillating plate and then wet sieved at 63  $\mu\text{m}$ . The coarse fraction was dried on filter paper in a low-temperature oven. Multiple cycles of processing were necessary to clean most samples. Temperature never exceeded 50°C during any stage of sample processing. The foraminifers selected for isotopic analysis were cleaned ultrasonically in a dilute Calgon solution to remove adhering fines. The foraminifers were then roasted in a vacuum at 370°C for 1 hr. and reacted with polyphosphoric acid at 50°C (Shackleton and Opdyke, 1973). The  $\text{CO}_2$  and  $\text{H}_2\text{O}$  resulting from the reaction were trapped with liquid nitrogen and then separated by a series of three freezing/transfer steps, and the  $\text{CO}_2$  was analyzed in an online VG Micromass 602D mass spectrometer at the Benedum Stable Isotope Laboratory of Brown University. All isotopic data are referred to the Chicago PDB reference in standard  $\delta$  notation by comparison to aliquots of Benedum Lab standard gases BIG-II and BIG-IV; our lab gases are calibrated to PDB by multiple routine analyses of intermediate  $\text{CaCO}_3$  standards provided by other labs. Our values for NBS-20 are  $\delta^{18}\text{O} = -4.04 \pm 0.16$  and  $\delta^{13}\text{C} = -1.3 \pm 0.05$ ; for BYM,  $\delta^{18}\text{O} = -6.22 \pm 0.06$  and  $\delta^{13}\text{C} = -2.29 \pm 0.05$ . The analytical precision of carbonate standards run before each batch of samples was  $\pm 0.09$  (1 $\sigma$ ) for both  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ . The precision of all carbonate standards run during the course of the project is  $\pm 0.16$  (1 $\sigma$ ) for both  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ . Finally, precision among 23 pairs of duplicate foraminifer samples is  $\pm 0.13$  (1 $\sigma$ ) for both  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ .

Single species or species groups were analyzed separately in this study. When it was practical, several types of benthic and planktonic foraminifers were analyzed for each sample. The results of the analyses are listed in Table 1.

## ISOTOPIC RESULTS

## Comparisons of Taxa

Figure 2 shows that the  $\delta^{18}\text{O}$  values of most planktonic foraminifer taxa cluster within 0.5 ‰ at the negative end of the range within each sample. Taxa with low  $\delta^{18}\text{O}$  values are interpreted as surface- and near-surface-dwelling forms. Replicate analyses of the same taxon in a single sample exhibit a range of about 0.3 ‰. Thus, the intraspecific isotopic variability of surface and near-surface dwellers is almost as large as the interspecific isotopic variability. Site 522 is in a midlatitude location, and it is probable that surface-water temperatures underwent significant seasonal variation. Thus, some of the inter- and intraspecific variation of  $\delta^{18}\text{O}$  observed in the surface- and near-surface-dwelling forms may reflect seasonality.

Table 2 and Figure 2 compare the results of all our analyses of different species and species groups from single samples. The table and figure show that most of the planktonic foraminifers analyzed are surface- to near-surface-dwelling forms. Our most extensive data set is for *Globigerina euapertura*, so we compare other planktonic foraminifers to it. *G. galavisi*, *G. linaperta*, *G. angiporoides*, *G. perus*, and *Globorotalia opima nana* yield essentially the same values as *Globigerina eu-*

Table 1. Oxygen and carbon stable-isotope data for planktonic and benthic foraminifers from Holes 522 and 522A.

Core-Section (interval in cm)	Taxon	Size fraction ( $\mu\text{m}$ )	$\delta^{18}\text{O}$ (‰)	$\delta^{13}\text{C}$ (‰)
Hole 522				
17-2, 105-107 cm	<i>Globigerinita glutinata</i>	180-212	+0.78	+0.39
	<i>Cibicoides kullenbergi</i>	212-250	+1.54	+0.53
	<i>Oridorsalis umbonatus</i>	212-250	+1.91	-0.18
19-2, 30-32 cm		355+	+0.97	+1.18
	<i>Globigerina tripartita</i>	300-355	+1.06	+1.26
	(Mixed)		+1.08	+1.54
22-2, 50-51 cm	<i>Globigerina euapertura</i>	355+	+1.18	+1.29
	<i>Cibicoides kullenbergi</i>	212-250	+1.62	+0.52
	<i>Globigerina tripartita</i>	355+	+1.42	+1.38
25-2, 33-35 cm	<i>Cibicoides kullenbergi</i>	Mixed	+1.83	+0.46
	<i>Oridorsalis umbonatus</i>	300-355	+2.38	-0.07
	<i>Globigerina euapertura</i>	250-355	+1.16	+1.33
26-2, 49-51 cm	<i>Globorotalia opima nana</i>	212-250	+1.25	+1.18
	<i>Cibicoides kullenbergi</i>	212-250	+1.66	+0.32
	<i>Globigerina angustumilicata</i>	106-150	+0.99	+1.05
27-2, 39-41 cm		150-180	+1.29	+1.25
	<i>Globorotalia opima opima</i>	300-355	+1.25	+1.20
	<i>Globigerina sellii</i>	355+	+1.28	+1.35
28-2, 40-42 cm	<i>Globigerina tripartita</i>	355+	+1.39	+1.39
	<i>Catapsydrax dissimilis</i>	355+	+1.50	+1.69
	<i>Oridorsalis umbonatus</i>	300-355	+1.70	+1.36
29-2, 56-58 cm	<i>Globigerina euapertura</i>	425+	+2.41	-0.02
		355-425	+1.09	+1.49
	<i>Cibicoides cf. kullenbergi</i>	Mixed	+1.27	+1.66
31-2, 25-27 cm	<i>Globocassidulina subglobosa</i>	Mixed	+2.15	+0.61
	<i>Globigerina euapertura</i>	300-355	+1.19	+1.51
	<i>Cibicoides cf. kullenbergi</i>	Mixed	+1.76	+0.81
33-1, 24-26 cm	<i>Globocassidulina subglobosa</i>	180-250	+2.08	+0.42
	<i>Globigerina euapertura</i>	300-355	+1.26	+1.55
	<i>Cibicoides kullenbergi</i>	300-355	+1.35	+1.63
33-1, 34-36 cm		250-300	+1.81	+0.93
	<i>Globigerina euapertura</i>	300-355	+0.69	+1.33
	<i>Globigerina ampliapertura</i>	250-300	+1.07	+1.73
33-1, 44-46 cm	<i>Globigerina perus</i>	355+	+0.75	+1.24
		355+	+1.05	+1.54
	<i>Globigerina angustumilicata</i>	106-180	+0.87	+1.11
33-1, 54-56 cm	<i>Globigerina galavisi</i>	300-355	+1.16	+1.49
	<i>Chiloguembelina cubensis</i>	63-106	+1.16	+1.41
	<i>Globigerina euapertura</i>	300-355	+1.17	+1.73
33-1, 64-66 cm	<i>Globorotalia opima nana</i>	180-212	+1.16	+1.28
	<i>Globigerina angiporoides</i>	212-250	+1.20	+1.44
	<i>Catapsydrax dissimilis</i>	300-355	+1.72	+1.20
33-1, 74-76 cm	<i>Catapsydrax unicavus</i>	250-300	+1.74	+1.06
	<i>Globocassidulina subglobosa</i>	150-300	+2.03	+0.33
	<i>Oridorsalis umbonatus</i>	Mixed	+2.20	+0.11
33-1, 84-86 cm	<i>Globocassidulina subglobosa</i>	150-250	+2.45	+0.39
	<i>Globigerina euapertura</i>	355-425	+1.27	+1.80
	<i>Cibicoides sp.</i>	212-250	+1.78	+1.32
33-1, 95-97 cm	<i>Oridorsalis umbonatus</i>	Mixed	+2.00	-0.12
	<i>Gyroidinoides sp.</i>	212-355	+2.68	+0.73
	<i>Globigerina euapertura</i>	355-425	+1.13	+1.89
33-1, 105-107 cm	<i>Oridorsalis umbonatus</i>	Mixed	+2.11	+0.27
	<i>Globocassidulina subglobosa</i>	150-250	+1.87	-0.07
	<i>Globigerina ampliapertura</i>	250-300	+1.20	+1.56
33-1, 110-112 cm		212-250	+1.22	+1.35
	<i>Globigerina euapertura</i>	212-250	+1.46	+1.74
	<i>Oridorsalis umbonatus</i>	300-355	+1.26	+1.84
33-1, 115-117 cm	<i>Oridorsalis umbonatus</i>	Mixed	+2.06	+0.00
		300-355	+1.49	+2.04
	<i>Globigerina euapertura</i>	355-425	+1.60	+2.15
33-1, 105-107 cm	<i>Oridorsalis umbonatus</i>	150-300	+1.87	+0.03
	<i>Globocassidulina cf. subglobosa</i>	212-250	+2.52	+0.49
	<i>Globigerina euapertura</i>	300-355	+1.44	+1.96
33-1, 110-112 cm		355-425	+1.51	+1.86
	<i>Cibicoides cf. kullenbergi</i>	150-250	+1.97	+1.15
	<i>Oridorsalis umbonatus</i>	150-250	+2.20	+0.24
33-1, 105-107 cm	<i>Globigerina ampliapertura</i>	212-250	+1.43	+1.89
	<i>Globigerina euapertura</i>	300-355	+1.36	+1.98
		355-425	+1.37	+2.05
33-1, 95-97 cm	<i>Cibicoides cf. kullenbergi</i>	Mixed	+2.05	+1.26
	<i>Oridorsalis umbonatus</i>	Mixed	+2.13	+0.28
	<i>Globocassidulina subglobosa</i>	Mixed	+2.21	+0.54
33-1, 105-107 cm	<i>Globigerina ampliapertura</i>	212-250	+1.33	+1.97
	<i>Globigerina euapertura</i>	355-425	+1.33	+2.00
		300-355	+1.41	+1.92
33-1, 110-112 cm	<i>Cibicoides sp.</i>	300+	+1.95	+1.34
	<i>Oridorsalis umbonatus</i>	Mixed	+2.14	+0.17
	<i>Globocassidulina subglobosa</i>	Mixed	+2.14	+0.95
33-1, 105-107 cm	<i>Globigerina ampliapertura</i>	212-250	+1.25	+1.81
	<i>Globigerina euapertura</i>	300-355	+1.27	+1.70
	<i>Oridorsalis umbonatus</i>	Mixed	+1.99	-0.02
33-1, 110-112 cm	<i>Globocassidulina subglobosa</i>	Mixed	+2.37	+0.92
	<i>Globigerina euapertura</i>	300-355	+1.22	+1.75
	<i>Oridorsalis umbonatus</i>	Mixed	+2.23	-0.24
33-1, 115-117 cm	<i>Globigerina ampliapertura</i>	212-250	+1.10	+1.53
	<i>Globigerina euapertura</i>	300-355	+1.29	+1.71
	<i>Cibicoides kullenbergi</i>	212-300	+1.75	+0.97
	<i>Oridorsalis umbonatus</i>	Mixed	+2.28	-0.18

Table 1. (Continued)

Core-Section (interval in cm)	Taxon	Size fraction ( $\mu\text{m}$ )	$\delta^{18}\text{O}$ (‰)	$\delta^{13}\text{C}$ (‰)	
Hole 522 (Cont.)					
33-1, 125-127 cm	<i>Globigerina ampliapertura</i>	250-300	+1.18	+1.87	
		300-355	+1.35	+1.95	
		300-355	+1.00	+1.75	
		355-425	+1.37	+1.84	
33-1, 134-136 cm	<i>Globigerina ampliapertura</i>	Mixed	+2.05	+0.17	
		212-250	+1.97	+0.54	
		180-300	+1.05	+1.50	
		300-355	+1.10	+1.82	
33-1, 145-147 cm	<i>Globigerina ampliapertura</i>	180-250	+1.87	+1.21	
		Mixed	+1.96	+0.23	
		212-250	+1.14	+1.72	
		300-355	+1.04	+1.78	
33-2, 7-9 cm	<i>Globigerina ampliapertura</i>	355-425	+1.26	+1.76	
		Mixed	+1.74	+0.89	
		212-250	+1.08	+1.57	
		300-355	+1.42	+1.95	
33-2, 14-16 cm	<i>Globigerina ampliapertura</i>	Mixed	+2.18	-0.02	
		212-300	+2.30	+0.59	
		180-250	+1.30	+1.69	
		300-355	+1.32	+2.03	
33-2, 20-22 cm	<i>Globigerina ampliapertura</i>	Mixed	+2.44	+0.54	
		180-212	+1.12	+1.67	
		300-355	+1.27	+2.09	
		180-250	+1.94	+1.17	
33-2, 27-29 cm	<i>Globigerina ampliapertura</i>	Mixed	+2.23	+0.18	
		300-355	+1.54	+2.04	
		212-250	+1.92	+1.13	
		Mixed	+2.33	+0.88	
33-2, 32-34 cm	<i>Globigerina ampliapertura</i>	212-250	+1.14	+1.86	
		250-300	+1.20	+2.03	
		Mixed	+2.24	+0.30	
		63-106	+0.91	+1.45	
33-2, 38-40 cm	<i>Globigerina ampliapertura</i>	63-106	+1.20	+1.62	
		<i>Pseudohastigerina barbadoensis</i>	63-106	+1.06	+1.36
		<i>Globigerina ampliapertura</i>	212-250	+1.06	+1.83
		300-355	+1.31	+2.16	
33-2, 47-49 cm	<i>Globigerina ampliapertura</i>	212-250	+1.20	+1.52	
		212-250	+1.35	+1.73	
		355-425	+1.23	+1.74	
		355-425	+1.34	+1.85	
33-2, 52-54 cm	<i>Globigerina ampliapertura</i>	212-250	+2.23	+1.43	
		150-212	+2.11	+1.15	
		Mixed	+2.09	+0.06	
		Mixed	+2.45	+0.48	
33-2, 59-61 cm	<i>Globigerina ampliapertura</i>	Mixed	+2.37	+0.92	
		250-300	+1.40	+1.99	
		300-355	+1.46	+2.08	
		Mixed	+2.44	+0.12	
33-2, 71-73 cm	<i>Globigerina ampliapertura</i>	355-425	+1.20	+2.12	
		250-300	+1.40	+2.19	
		Mixed	+1.87	-0.07	
		212-250	+0.92	+1.76	
33-2, 86-88 cm	<i>Globigerina ampliapertura</i>	300-355	+1.18	+2.00	
		300-355	+1.27	+2.12	
		355-425	+1.26	+1.88	
		355-425	+1.94	+1.72	
33-2, 95-97 cm	<i>Globigerina ampliapertura</i>	250-300	+2.13	+1.66	
		212-300	+2.11	+1.38	
		180-250	+2.22	+0.07	
		250-300	+1.20	+2.03	
33-2, 100-102 cm	<i>Globigerina ampliapertura</i>	355-425	+1.30	+1.98	
		Mixed	+1.99	+0.26	
		Mixed	+2.14	+0.42	
		212-250	+1.55	+2.08	
33-2, 108-110 cm	<i>Globigerina ampliapertura</i>	212-300	+2.01	+1.20	
		212-250	+1.37	+2.07	
		300-355	+1.45	+2.18	
		Mixed	+2.17	+0.19	
33-2, 114-116 cm	<i>Globigerina ampliapertura</i>	212-250	+1.28	+2.01	
		300-355	+1.35	+2.09	
		Mixed	+2.08	+1.51	
		Mixed	+2.20	+0.39	
33-2, 118-120 cm	<i>Globigerina ampliapertura</i>	355-425	+1.22	+2.00	
		300-355	+1.27	+2.01	
		300-355	+1.08	+1.51	
		300-355	+1.72	+1.51	
33-2, 122-124 cm	<i>Globigerina ampliapertura</i>	212-250	+1.93	+1.37	
		Mixed	+2.29	+0.36	
		300-355	+1.23	+2.09	
		355-425	+1.25	+2.01	
33-2, 122-124 cm	<i>Globigerina ampliapertura</i>	Mixed	+2.02	+0.37	
		Mixed	+2.31	+0.23	
		300-355	+1.31	+2.13	
		Mixed	+2.33	+0.48	
33-2, 122-124 cm	<i>Globigerina ampliapertura</i>	212-250	+0.91	+1.90	
		300-355	+1.24	+2.16	
		212-355	+2.14	+0.80	
		<i>Gyroidinoides</i> sp.	212-355	+2.14	+0.80

Table 1. (Continued)

Core-Section (interval in cm)	Taxon	Size fraction ( $\mu\text{m}$ )	$\delta^{18}\text{O}$ (‰)	$\delta^{13}\text{C}$ (‰)	
Hole 522 (Cont.)					
33-2, 128-130 cm	<i>Globigerina ampliapertura</i>	212-250	+1.31	+1.84	
		300-355	+1.26	+2.06	
		Mixed	+2.30	+0.55	
		<i>Oridorsalis umbonatus</i>	212-250	+1.99	+0.91
33-2, 133-135 cm	<i>Globigerina ampliapertura</i>	<i>Globocassidulina</i> cf. <i>subglobosa</i>	212-250	+1.32	+1.96
		<i>Globigerina ampliapertura</i>	250-300	+1.42	+2.03
		<i>Globocassidulina</i> cf. <i>subglobosa</i>	212-250	+2.13	+0.57
		<i>Globigerina ampliapertura</i>	212-250	+1.90	+2.01
33-2, 137-139 cm	<i>Globigerina ampliapertura</i>	180-212	+1.38	+1.96	
		212-250	+1.38	+1.94	
		212-250	+1.42	+2.08	
		300-355	+1.34	+2.03	
33-2, 147-149 cm	<i>Globigerina ampliapertura</i>	Mixed	+2.23	+1.52	
		212-250	+0.85	+2.03	
		300-355	+0.80	+1.92	
		355+	+1.48	+1.05	
35-1, 113-115 cm	<i>Globigerina ampliapertura</i>	300-355	+0.83	+1.79	
		<i>Cibicides</i> cf. <i>kullenbergi</i>	355+	+1.54	+1.03
		<i>Globigerina ampliapertura</i>	300-355	+0.96	+1.66
		<i>Globigerina ampliapertura</i>	180-212	+1.27	+1.03
36-2, 97-99 cm	<i>Globigerina ampliapertura</i>	<i>Cibicides</i> cf. <i>kullenbergi</i>	300-355	+0.96	+1.66
		<i>Globigerina ampliapertura</i>	180-212	+1.27	+1.03
		<i>Globigerina ampliapertura</i>	300-355	+0.28	+2.32
		<i>Globigerina ampliapertura</i>	300-355	+0.86	+1.59
37-2, 50-52 cm	<i>Globigerina ampliapertura</i>	<i>Cibicides</i> cf. <i>kullenbergi</i>	180-300	+1.16	+0.85
		<i>Globigerina ampliapertura</i>	180-300	+1.16	+0.85
		<i>Globigerina ampliapertura</i>	180-300	+1.16	+0.85
		<i>Globigerina ampliapertura</i>	180-300	+1.16	+0.85
38-2, 32-34 cm	<i>Globigerina ampliapertura</i>	<i>Globigerina ampliapertura</i>	180-300	+1.16	+0.85
		<i>Globigerina ampliapertura</i>	180-300	+1.16	+0.85
		<i>Globigerina ampliapertura</i>	180-300	+1.16	+0.85
		<i>Globigerina ampliapertura</i>	180-300	+1.16	+0.85
Hole 522A					
31-1, 49-51 cm	<i>Globigerina ampliapertura</i>	<i>Globigerinatheka tropicalis</i>	300-355	+0.52	+2.87
		<i>Globigerina ampliapertura</i>	300-355	+0.71	+1.91
		<i>Cibicides</i> cf. <i>kullenbergi</i>	355+	+0.91	+0.91
		<i>Cibicides</i> cf. <i>kullenbergi</i>	250-300	+1.00	+1.16

Note: Multiple sets of isotope values for a single size fraction represent different samples. Size fractions appear in order of increasing  $\delta^{18}\text{O}$ .

*apertura*. *Pseudohastigerina barbadoensis*, *Chiloguembelina cubensis*, *G. tripartita*, *G. ampliapertura*, and a large bullate form that is referred to *Catapsydrax* cf. *unicavus* yield values that are slightly more negative than *G. euapertura*. The value for *G. angustiumbilitata* in Sample 522-31-2, 25-27 cm is 0.3 ‰ more negative than that of *G. euapertura*. The values for *G. angustiumbilitata* in Sample 522-26-2, 49-51 cm also suggest that *G. angustiumbilitata* records surface conditions. The values for *G. sellii* and *Globorotalia opima opima* in Sample 522-26-2, 49-51 cm indicate that these taxa are also surface dwellers and probably give slightly more negative  $\delta^{18}\text{O}$  values than *Globigerina euapertura*. We conclude from Table 2 and Figure 2 that long-ranging taxa such as *G. ampliapertura*, *G. galavisi*, and *G. euapertura* can be used to monitor near-surface conditions at Site 522 but that they overestimate surface  $\delta^{18}\text{O}$  values by a few tenths of a per mill. For that reason we subtract 0.3 ‰ from the  $\delta^{18}\text{O}$  values of these taxa to approximate surface values as reflected by such forms as *G. angustiumbilitata*.

In contrast to the surface- and near-surface-dwelling group, *Catapsydrax* spp. average 0.7 ‰ more positive than *G. euapertura*. *Catapsydrax* spp. are clearly deep-dwelling forms.

Among the benthic foraminifers analyzed, *Cibicides kullenbergi* (s.l.) yields the most negative  $\delta^{18}\text{O}$  values and the most positive  $\delta^{13}\text{C}$  values (Table 2). In fact, the results of our paired benthic analyses are similar to the results of the study on modern and Neogene benthic foraminifers by Graham et al. (1981). Specifically, as compared with *C. kullenbergi* (s.l.), *Globocassidulina* spp. (= *G. subglobosa* of Graham et al., 1981) give

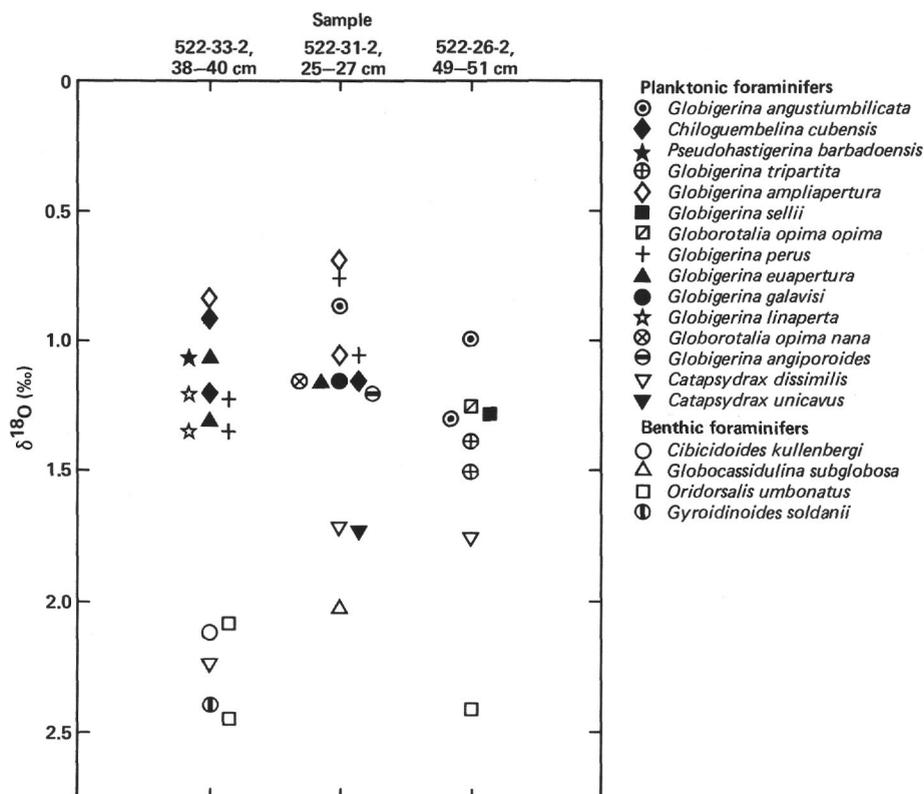


Figure 2. Oxygen-isotope results from multiple species analyses in three lower Oligocene samples from Hole 522.

more positive  $\delta^{18}\text{O}$  values, and *Oridorsalis umbonatus* (= *O. tener* of Graham et al., 1981) gives even more positive  $\delta^{18}\text{O}$  values. Similarly, *C. kullenbergi* (s.l.), *Globocassidulina* spp., and *O. umbonatus* give progressively more negative values of  $\delta^{13}\text{C}$ . The only significant difference between our Oligocene data and the Graham et al. (1981) results is that in our study the average  $\delta^{18}\text{O}$  difference between species is about half that observed between similar taxa by Graham et al. (1981). Differences in  $\delta^{13}\text{C}$  between similar taxa in the two studies are almost identical. Thus, the microhabitat preference (Belanger et al., 1981) and/or the vital fractionation of those taxa have remained similar from the Quaternary back to the early Oligocene.

For comparisons between modern and paleoceanographic bottom-water conditions, we prefer to rely on data from *C. kullenbergi* or *C. wuellerstorfi*. Graham et al. (1981) have shown that these taxa exhibit the most systematic relationship to modern oceanographic conditions. Further, Belanger et al. (1981) offer biological arguments that support this observation. Nevertheless, it is common to refer benthic isotopic data to "equilibrium". Throughout this paper, we take "equilibrium" to mean simply those values yielded by the equations published by Epstein et al. (1953), O'Neil et al. (1969), Shackleton (1974), or Woodruff et al. (1980).

There are small differences among these equations, but there is even larger disagreement between the published equations (taken collectively) and the biological arguments forwarded by Belanger et al. (1981). We therefore consider "equilibrium" to be an unsettled issue. For our calculations we use Epstein et al. (1953).

*Uvigerina* spp., considered by many workers to best approximate equilibrium, are not represented in our data set. Woodruff et al. (1980) find *Uvigerina* spp. to have the heaviest benthic  $\delta^{18}\text{O}$  values and consider these values equilibrium. Graham et al. (1981) likewise find *Uvigerina* spp. to yield the heaviest values in their core-top data set but indicate that the values are still 0.4 ‰ too light to represent equilibrium. To avoid this problem, we take a conservative approach. Because *Gyroidinoides* averages 0.5 ‰ more positive than *Cibicidoides kullenbergi* (s.l.) in our Oligocene comparisons, we add 0.5 ‰ to *C. kullenbergi* (s.l.)  $\delta^{18}\text{O}$  values whenever we wish to approximate late Eocene and Oligocene bottom-water equilibrium values. We consider the resulting estimates to be quite conservative inasmuch as paired analyses show that *Gyroidinoides* is about 0.5 ‰ depleted with respect to *Uvigerina* (Woodruff et al., 1980; Graham et al., 1981).

### Vertical Oxygen-Isotope Gradients

The multiple species analyses allow the reconstruction of the vertical oxygen-isotope gradient at Site 522 throughout the Oligocene. These gradients provide information on the possible structure and mixing rates of the oceans. The maximum observed surface-to-bottom gradient during the early Oligocene is about 1.5 ‰ (see Fig. 2). Adjusting data from other samples in accordance with the paired analyses shown in Table 2 indicates that about a 1.5 ‰ gradient was present through most of the Oligocene. For example, adding 0.5 ‰ to *Cibicidoides kullenbergi* (s.l.) and subtracting 0.3 ‰ from the *Globigerina euapertura*  $\delta^{18}\text{O}$  values from Sam-



ple 522-29-2, 56–58 cm results in a vertical gradient of 1.3 ‰. Making similar adjustments in Sample 522-19-2, 30–32 cm also indicates a vertical gradient of 1.3‰. The average of 21 pairs of benthic values to surface planktonic values from Core 33 and above is  $1.4 \pm 0.2$  ‰. Thus, we infer that the total “equilibrium” gradient at Site 522 during the Oligocene was at least 1.4 ‰, perhaps even several tenths greater. A comparable number for the modern ocean at Site 522 would be 3.5 ‰.

Information on the isotopic gradient in the upper few hundred meters of the water column during the early Oligocene at Site 522 is provided by analyses of the deep-dwelling planktonic foraminifers of the genus *Catapsydrax*. In paired analyses with *G. euapertura*, the  $\delta^{18}\text{O}$  values for *Catapsydrax* spp. average 0.7 ‰ more positive. After the  $-0.3$  ‰ correction to *G. euapertura*, these data suggest a 1.0 ‰ isotopic gradient for the upper part of the water column. The comparable number for the modern ocean at Site 522 would be 1.7 ‰ (see Tables 3 and 4). Comparisons of modern with Oligocene gradients are discussed in a following section.

### Time Series

Figure 3 shows the overall late Eocene–Oligocene oxygen- and carbon-isotope record derived from Holes

522 and Hole 522A. A gradual enrichment of 0.5 ‰ in the benthic  $\delta^{18}\text{O}$  in the late Eocene is followed by a more sudden enrichment of about 0.5 ‰ in the Oligocene. All analyses of *Cibicidoides kullenbergi* (s.l.) in the lower part of Core 33-2 exceed  $+2.00$  ‰ (see Fig. 4). Within Core 33 there is a trend in *C. kullenbergi* (s.l.)  $\delta^{18}\text{O}$  toward more negative values upsection. This trend continues above Core 33 until the late Oligocene values approach the latest Eocene and earliest Oligocene values. A brief reversal in this trend occurs in Core 27. Additional work is necessary to evaluate the significance of this reversal.

The planktonic  $\delta^{18}\text{O}$  record as measured by *Globigerina galavisi* and *G. euapertura* does not show an enrichment during the late Eocene, but it does record the early Oligocene 0.5 ‰ positive shift apparent in the benthic data. Although variable, the planktonic  $\delta^{18}\text{O}$  values do not show a clear trend toward more negative values within Core 33 (see Fig. 4). Above Core 33 there is a tendency for planktonic  $\delta^{18}\text{O}$  to become more negative, but the youngest part of the record is poorly controlled because increased dissolution has greatly reduced the planktonic assemblages in both diversity and number. In fact, planktonic values above Core 26 may be biased toward dissolution-resistant specimens.

The late Eocene positive shift in benthic  $\delta^{18}\text{O}$  that is not accompanied by a similar change in planktonic  $\delta^{18}\text{O}$  may represent a temperature effect caused by subsidence. As Site 522 subsided from ridgecrest depths, benthic calcite may have been secreted in progressively deeper and thus cooler waters. Alternatively, the late Eocene positive shift may record a temperature change in the deep waters of this area of the South Atlantic.

The early Oligocene positive shift in  $\delta^{18}\text{O}$  is recorded by both the benthic and the planktonic foraminifers and is interpreted as being caused by an increase in global ice volume. The trend toward more negative benthic  $\delta^{18}\text{O}$  values through the rest of the Oligocene—which is also seen, although less clearly, in the planktonic  $\delta^{18}\text{O}$ —suggests to us that the average volume of global ice decreased during the Oligocene. The interpretation of the

Table 3. Summary of oceanographic data used to calculate expected values for  $\delta^{18}\text{O}$  for calcite at Site 522. All data are for the modern ocean.

Water depth (m)	26°S, 5°W		33°S, 5°W	
	T (°C)	S (‰)	T (°C)	S (‰)
0	20.63	36.03	18.89	35.52
50	19.35	36.00	17.61	35.49
100	18.00	35.85	16.29	35.45
200	14.75	35.39	14.36	35.21
400	10.55	34.88	10.60	34.83
3000	2.25	34.88	2.25	34.88
3500	2.00	34.87	2.00	34.87

Note: T = water temperature, S = salinity.

Table 4. Comparison of measured and theoretical values of  $\delta^{18}\text{O}$  for the lower Oligocene. Measured values are from Core 33 and are ‰ PDB. Theoretical values are ‰ and calculated as stated below. Temperature and salinity data are listed in Table 3.

	Average lower Oligocene values for Core 33	Modern values	Late Pleistocene glacial model <sup>6</sup>	Oligocene ice model <sup>7</sup>	Oligocene ice-free model <sup>8</sup>
Lightest planktonic foraminifers (surface dwellers)	+1.0 <sup>1</sup>	-0.3 <sup>4</sup>	+1.3	+1.0	-1.3
Heaviest planktonic foraminifers (deep dwellers)	+2.0 <sup>2</sup>	+1.4 <sup>4</sup>	+1.8	+1.6	+1.4
“Equilibrium” benthic foraminifers	+2.45 <sup>3</sup>	+3.7 <sup>5</sup>	+5.3	+5.0	+2.7

<sup>1</sup> The average of 45 *Globigerina euapertura* values minus 0.3 ‰ (see text, Fig. 2, and Table 2).

<sup>2</sup> The average of 5 *Catapsydrax* sp. values and also *G. euapertura* plus 0.7 ‰ (see Table 2).

<sup>3</sup> The average of 13 *Cibicidoides* sp. values plus 0.5 ‰.

<sup>4</sup> Calculated from temperature and salinity data in the GFDL data base for 26°S, 5°W (Table 3).

<sup>5</sup> Calculated from temperature and salinity data that represent the average of GEOSECS data for Sites 103, 104, and 105 for 3000 to 3500 m water depth.

<sup>6</sup> Calculated like the modern values but assuming an effect of ice volume on the  $\delta^{18}\text{O}$  of seawater of +1.6 ‰.

<sup>7</sup> Calculated from temperature and salinity data in the GFDL data base for 33°S, 5°W (Table 3) and assuming a  $\delta^{18}\text{O}$  of seawater of +1.3 ‰ relative to modern.

<sup>8</sup> Calculated from temperature and salinity data in the GFDL data base for 33°S, 5°W (Table 3) and assuming a  $\delta^{18}\text{O}$  of seawater of -1.0 ‰ relative to modern.

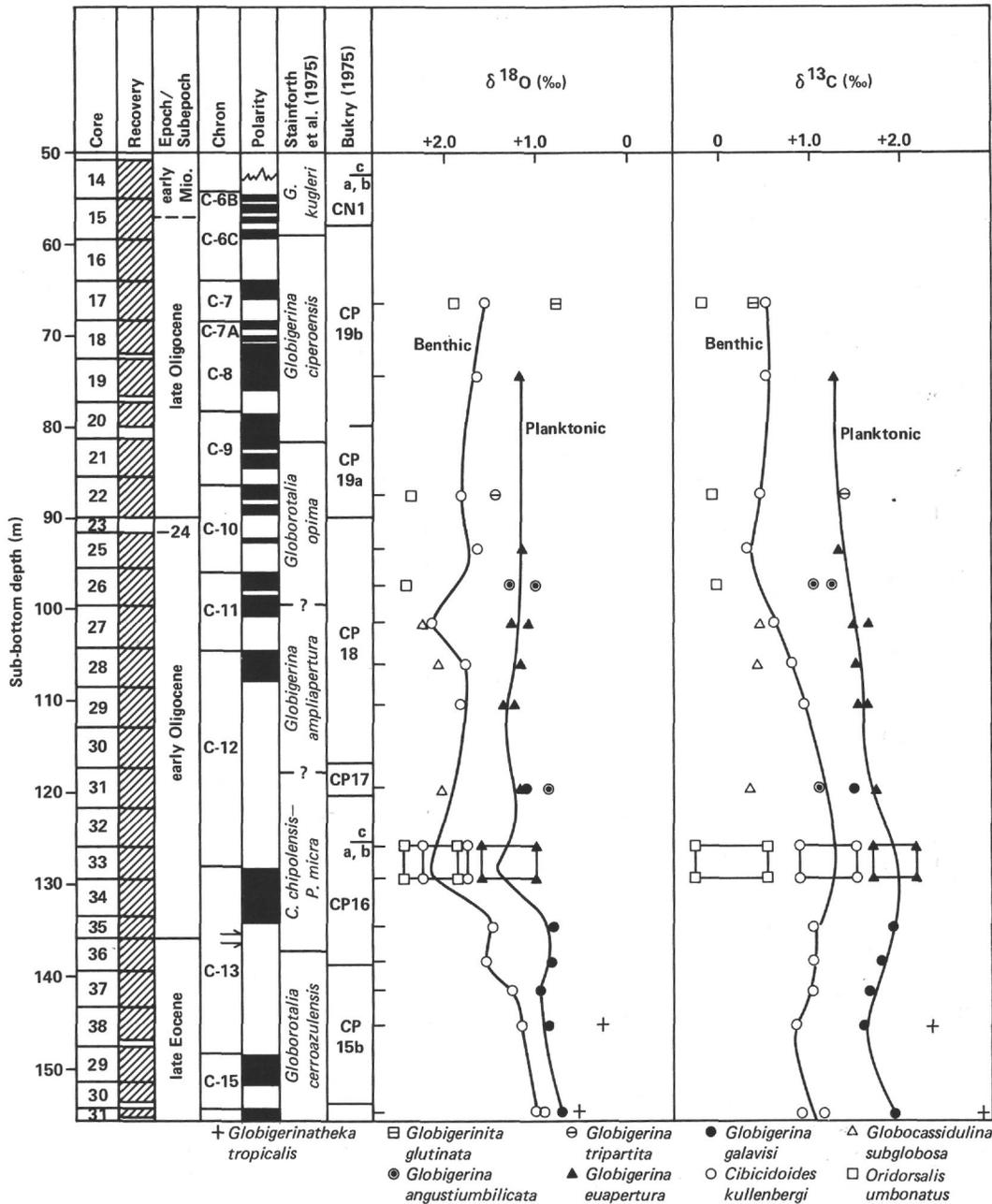


Figure 3. Late Eocene-Oligocene stable-isotope record. Data from Cores 14 to 38 are from Hole 522; data from Cores 29 to 31 at bottom of section are from Hole 522A. Boxes plotted opposite Core 33 enclose range of values found in high-resolution study; see Fig. 4.

late Oligocene planktonic record is uncertain, however, because of the paucity of data and the possibility of seasonality effects.

A striking feature of the Oligocene  $\delta^{13}\text{C}$  record shown in Figure 3 is the depletion in benthic  $\delta^{13}\text{C}$  upsection. Most of the depletion appears to occur between 110 and 100 m sub-bottom and coincides with the general change to more dissolved planktonic foraminifer assemblages and decreased carbonate content of sediments above Core 26. We interpret the benthic  $\delta^{13}\text{C}$  shift in Figure 3 as an indication of the subsidence of the seafloor at Site 522 out of one intermediate water mass into an older and more corrosive intermediate or bottom water mass.

This interpretation is supported by the sediments recovered in Hole 523, which was drilled fairly close to Site 522 but on basal middle Eocene crust (Fig. 1). In contrast to the moderately well preserved upper Eocene to lower Oligocene sequence of Hole 522, the upper Eocene to lower Oligocene section of Hole 523, which was deposited at a greater depth, shows marked effects of dissolution. For example, the upper Eocene planktonic foraminifer assemblages from Hole 523 often consist solely of fragments of the robust genus *Globigerinatheka*. Thus, at least two distinct deep-water masses existed in the vicinity of Site 522 during the late Eocene and Oligocene.

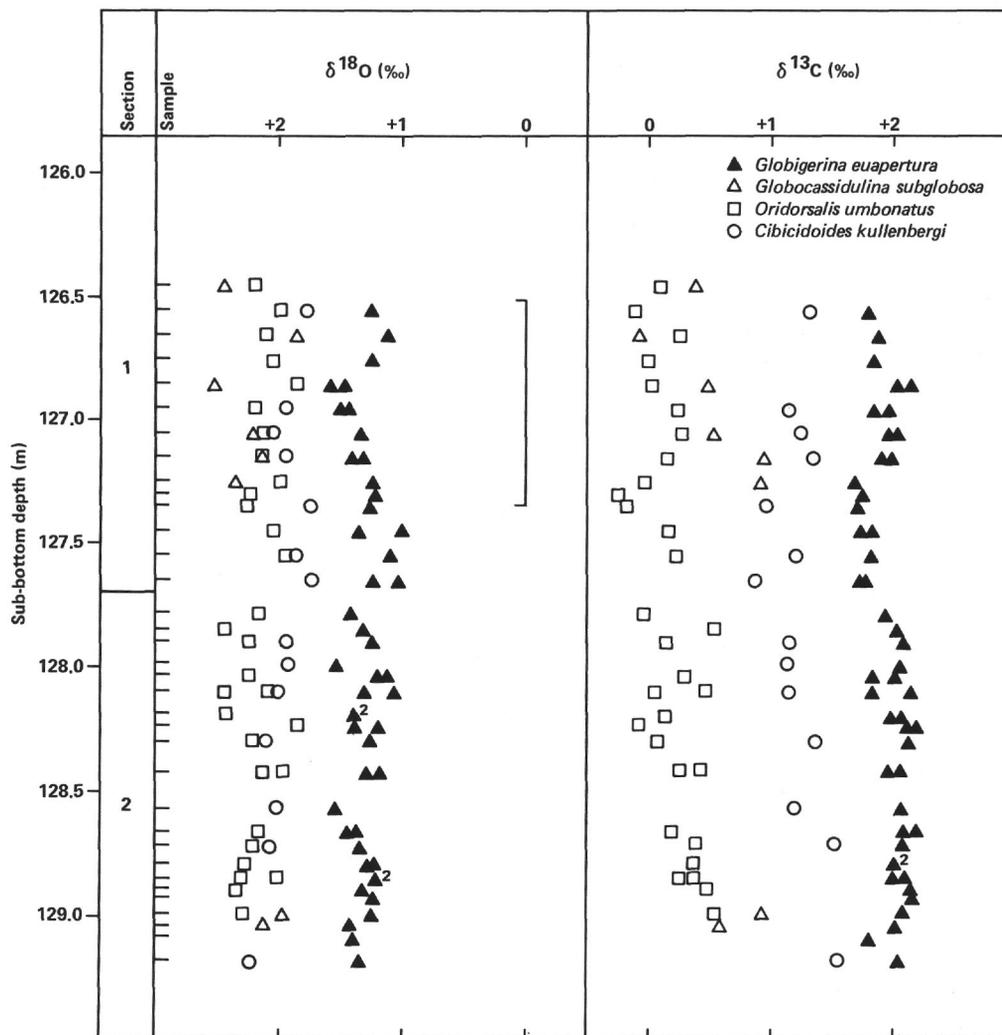


Figure 4. High-resolution study of lower Oligocene Core 33 of Hole 522. Vertical scale bar is approximately 100,000 yr. Superscripted 2 represents two analyses with the same values.

The planktonic  $\delta^{13}\text{C}$  record also becomes more negative upsection, and the change appears to occur in two successive steps—between Cores 33 and 31 and between Cores 27 and 25. We attach no particular significance to this observation at this time.

#### High-Resolution Time Series

Figures 4 and 5 show the results of a detailed analysis of Core 33. Sample spacing is on the order of every 5000 to 10,000 yr., and the study was undertaken to look for high-frequency changes in the isotopic record similar to those found in Quaternary isotopic records. The planktonic  $\delta^{18}\text{O}$  record from Section 1 of Core 33 (*Globigerina euapertura*) shows a fluctuation with an amplitude of 0.5 ‰ and a wavelength of about 100,000 yr. (Fig. 4). The *G. ampliapertura* data are in good agreement with the *G. euapertura* data (Fig. 5). In addition, a correlation coefficient of +0.75 (significant at the 95% confidence level) exists between the  $\delta^{18}\text{O}$  values of the lightest planktonic foraminifers and *Cibicoides kullenbergi* (s.l.) for this section, suggesting a common origin (such as ice-volume fluctuation) for the planktonic

and benthic signals. For Section 2 of Core 33, the relationships are less clearly defined. The  $\delta^{18}\text{O}$  data for *G. euapertura* appear to define a fluctuating signal, but the fluctuation is not confirmed by the *G. ampliapertura* or benthic data.

Taken as a whole, we consider the results of the Core 33 high-resolution experiment to be suggestive but inconclusive. If a periodicity on the order of 100,000 yr. or less is present, its amplitude lies close to the precision of this study. We plan to undertake similar studies elsewhere in Hole 522 utilizing more duplicates (larger sediment samples) and greater analytical precision (more foraminifers and a longer record).

## DISCUSSION

#### Isotopic Temperature Scale

Oxygen-isotope analyses are often used to estimate the temperatures of Tertiary oceans. Determining temperatures from measured  $\delta^{18}\text{O}$  involves making a number of assumptions, because the isotope ratio of marine biogenic calcite is a function of several factors, in-

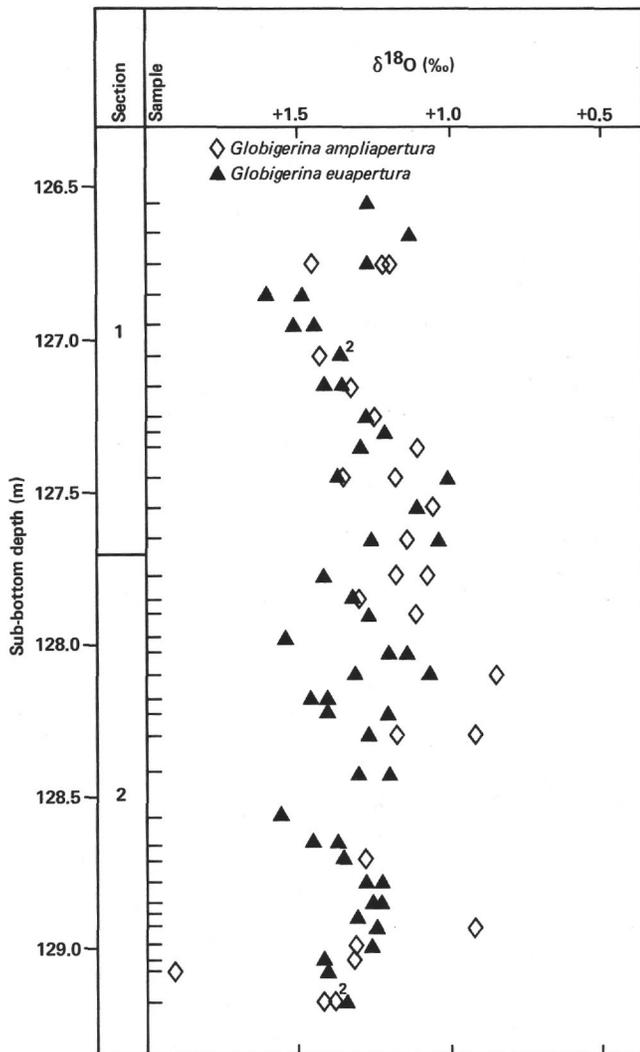


Figure 5. Comparison of  $\delta^{18}\text{O}$  of *Globigerina euapertura* and *G. ampliapertura* in lower Oligocene Core 33 of Hole 522. Superscripted 2 represents two analyses with same values.

cluding water temperature, the isotopic composition of seawater, and biologic effects. The  $\delta^{18}\text{O}$  of seawater is, in turn, influenced by the volume of global ice and local salinity. Most investigations of deep sea sediments assume that normal open ocean salinities existed back through the Tertiary unless there is strong lithologic or paleontologic evidence for abnormal conditions. The results of multiple species studies done on Quaternary and older samples are usually relied upon to mitigate the problems associated with biologic effects. There is disagreement, however, over the best way to deal with the fluctuations in the isotopic composition of seawater that are associated with changes in global ice volume.

The isotope temperature scales most commonly used for the Tertiary (Shackleton and Kennett, 1975; Savin et al., 1975) are constructed by assuming that the world was not glaciated before the middle Miocene. Thus, they incorporate an ice-free  $\delta^{18}\text{O}_{\text{seawater}}$  term to calculate paleotemperatures. However, we contend that much isotopic evidence and other data suggest the world has been glaciated during most of Tertiary and perhaps during

the late Mesozoic as well (Matthews and Poore, 1980). Isotopic and paleontological data from Hole 522 provide several lines of evidence that support the presence of a significant volume of global ice during the Oligocene. The following discussion concerns the early Oligocene because that is the interval for which we have the most data.

In Hole 522, the most negative early Oligocene  $\delta^{18}\text{O}$  values for planktonic foraminifers are between +0.7‰ and +1.0‰. We have analyzed a large number of taxa from this interval and believe that these values are representative of sea-surface conditions. According to the isotope temperature scale of Shackleton and Kennett (1975), the maximum temperature of the sea surface during the early Oligocene at Site 522 was 8 to 9°C.

The lower Oligocene foraminifer assemblages from Hole 522 are diverse; most assemblages contain 20 or more taxa (Poore, this vol.). The lower Oligocene nanofossil assemblages are also diverse, and the warm-water genera *Discoaster* and *Sphenolithus* are common to abundant in most samples (Percival, this vol.). The lower Oligocene planktonic microfossil assemblages of Site 522 are inconsistent with such low sea-surface temperatures. We conclude that the water must have been warmer than 8 to 9°C and that the isotopic temperature scale requires revision to take into account the effects of global ice volume.

We reach a similar conclusion from an evaluation of the benthic data. The observed values of  $\delta^{18}\text{O}$  for benthic calcite during the early Oligocene of Hole 522 are generally more than +2.0‰, and values around +2.5‰ are common. We established in an earlier section that the maximum observed benthic  $\delta^{18}\text{O}$  probably underestimates isotopic equilibrium by at least 0.5‰. Thus, "equilibrium" benthic calcite would be about +2.5‰ to +3.0‰. According to the isotope temperature scale of Shackleton and Kennett (1975), the temperature of the early Oligocene bottom waters at Site 522 (early Oligocene depth = 3000–3500 m) were about 0°C (+3.0‰) to 2°C (+2.5‰). This interpretation suggests that waters at a depth of 3000 to 3500 m in the western South Atlantic during the early Oligocene were up to 2°C colder than they are today (see Table 3). A more reasonable interpretation of these isotope data, in our view, is to infer that the water temperature was higher (closer to its temperature today) and that the temperature scale must be recalculated to take into account the effects on the  $\delta^{18}\text{O}$  of seawater caused by the presence of ice sheets.

#### Comparison of $\delta^{18}\text{O}$ Values to Models

In order to compare our Oligocene data to the modern and hypothetical oceans, we calculated the  $\delta^{18}\text{O}$  values expected on the basis of modern oceanographic data and explicit assumptions. The temperature (T) and salinity (S) data in Table 3 for water depths of 400 m and less are annual averages taken from the Geophysical Fluid Dynamics Laboratory (GFDL) data base (Levitus and Oort, 1977). The T and S data for water depths of 3000 and 3500 m are the average of Geochemical Ocean Sections Study (GEOSECS) data for Sites 103, 104, and 105.

The data from Craig and Gordon (1965) for 14°S to 24°S in the Atlantic were used to estimate the  $\delta^{18}\text{O}$  of seawater as follows:

$$\text{Seawater } \delta^{18}\text{O} = 0.55(\text{Salinity, } \text{‰}) - 19.278 \quad (1)$$

We can then use T from Table 3 and the  $\delta^{18}\text{O}$  of seawater from Equation (1) to solve the equation of Epstein et al. (1953) for the  $\delta^{18}\text{O}$  value of calcite.

The most enriched  $\delta^{18}\text{O}$  value in planktonic foraminifers is assumed to be the  $\delta^{18}\text{O}$  calcite value at the 26.8  $\sigma_T$  surface (Curry and Matthews, 1981). The expected  $\delta^{18}\text{O}$  calcite value for the 26.8  $\sigma_T$  surface is estimated by linear interpolation between the bracketing calculated values. For the calculation of density profiles in models, the relationship of salinity to ice volume is expressed by assuming that a 1 ‰ change in salinity is equal to a 1 ‰ change in the  $\delta^{18}\text{O}$  of seawater.

Table 4 compares some of our Site 522  $\delta^{18}\text{O}$  data with simple models. Consider first the isotopic gradient between the lightest and heaviest planktonic foraminifers. The observed average early Oligocene gradient is 1.0 ‰, considerably less than the modern gradient of 1.7 ‰. Curry and Matthews (1981) propose that deep-dwelling planktonic foraminifers occupy the 26.8  $\sigma_T$  surface and therefore move upward during glacial periods in response to the increased salinity caused by the removal of water from the world's oceans. This effect reduces the  $\delta^{18}\text{O}$  gradient between the shallow and deep dwellers. As indicated in Table 4, late Pleistocene glaciation would reduce this gradient to 0.5 ‰. Thus, an "ice volume effect" changes the surface-to-deep-dweller  $\delta^{18}\text{O}$  gradient in the proper direction to explain our Site 522 early Oligocene data.

Consider next the early Oligocene Site 522  $\delta^{18}\text{O}$  gradient of 1.45 ‰ between the planktonic and benthic foraminifers. The modern gradient is 4.0 ‰, as it is in simple "ice volume effect" models. The possibility that the gradient has been reduced by diagenesis (Baker et al., 1982, for example) is worthy of consideration, but we do not have the data to address that question here.

There may also be paleoceanographic explanations for the smaller Oligocene gradient, such as changing patterns of temperature and/or oceanic salinity. If the small planktonic-to-benthic  $\delta^{18}\text{O}$  gradient were to be explained solely as a temperature effect (i.e., reduced range of T between surface and bottom waters), the early Oligocene  $\sigma_T$  gradient would be a mere 0.9, compared with the modern gradient of 2.3. Such an ocean would have a greatly reduced rate of deep circulation as compared with the modern ocean. This would be contrary to our observation of relatively positive benthic  $\delta^{13}\text{C}$  values and to our observation of dissolution effects associated with an upper Eocene-lower Oligocene middepth water mass boundary. We therefore reject a simple temperature explanation for the small planktonic-to-benthic  $\delta^{18}\text{O}$  gradient.

The midlatitude production of warm saline bottom water (WSBW) (Peterson et al., 1981, for example) is attractive for our purposes because such production would decrease the  $\delta^{18}\text{O}$  gradients at low-latitude sites

yet permit a reasonable  $\sigma_T$  gradient. However, the conservation of water requires that the continuous production of WSBW be offset by the production of large volumes of reduced salinity water elsewhere in the world ocean. The existence of low salinity (and therefore, more negative  $\delta^{18}\text{O}$ ) polar oceans is an attractive concept, but evaluating the matter requires quantitative modeling beyond the scope of this paper.

There remains the matter of estimating the effect of ice volume on the  $\delta^{18}\text{O}$  of seawater during the Oligocene. In Table 4, the Oligocene ice model sets the  $\delta^{18}\text{O}$  of water at +1.3 ‰ with respect to modern seawater so that modern sea-surface temperatures are compatible with the lightest planktonic  $\delta^{18}\text{O}$  values observed during the early Oligocene. Since Site 522 was about 7° farther south in the early Oligocene (Barron et al., 1981), modern oceanographic conditions at 33°S, 5°W were used to calculate the Oligocene values shown in Table 4. The resulting estimate of benthic  $\delta^{18}\text{O}$  is +2.55 ‰ heavier than the observed data. On the other hand, the Oligocene ice-free model sets the  $\delta^{18}\text{O}$  of seawater at -1.0 ‰ with respect to modern seawater and thereby derives surface  $\delta^{18}\text{O}$  values 2.3 ‰ lighter than the observed data. Thus, it is clear that the Oligocene ocean was quite different from either the modern or the late Pleistocene glacial ocean. Surface water was cooler and/or bottom water was warmer. In a previous section we noted that the faunal and floral data from Hole 522 argue against very cool sea-surface temperatures. Thus, we reject the hypothesis of significantly cooler sea-surface temperatures to explain our early Oligocene isotopic data.

If the early Oligocene sea-surface temperature at Site 522 is assumed to be equivalent to modern, a  $\delta^{18}\text{O}$  of seawater ice-volume effect of +1.3 ‰ relative to modern is indicated. This would require a bottom-water temperature of 12°C to satisfy observed benthic foraminifer  $\delta^{18}\text{O}$  values. This is consistent with the Matthews and Poore (1980) estimate of Oligocene bottom-water temperature based on a similar analysis of isotopic data from tropical sites and favors the WSBW model of Peterson et al. (1981).

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