

## 46. EVOLUTION OF ANTARCTIC WATERS DURING THE MAESTRICHTIAN: FORAMINIFER OXYGEN AND CARBON ISOTOPE RATIOS, LEG 113<sup>1</sup>

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### ABSTRACT

Oxygen and carbon isotopic ratios were measured from Maestrichtian benthic and planktonic foraminifer species and bulk carbonate samples from ODP Sites 689 and 690, drilled on the Maud Rise during Leg 113. Careful scanning electron microscope observations reveal that test calcite in some intervals was diagenetically altered, although Sr/Ca and isotopic ratios of these tests do not appear to have been modified significantly. Foraminifer  $\delta^{18}\text{O}$  values at both sites document a cooling trend during early Maestrichtian time, a rapid drop in water temperatures at the time of the first appearance of *Abathomphalus mayaroensis* in the high southern latitude regions (about 69.9 Ma), and lower water temperatures during late Maestrichtian time.  $\delta^{13}\text{C}$  values record a depletion in  $^{13}\text{C}$  in the latest early Maestrichtian time beginning at about 72.2 Ma, just prior to the sharp late Maestrichtian increase in  $\delta^{18}\text{O}$  values. These trends are similar to those previously reported for well-preserved benthic foraminifer species from Seymour Island, in the Antarctic Peninsula. Paleotemperature estimates are also comparable to those at Seymour Island and suggest temperate climatic conditions in Antarctica and that bottom waters in the southern South Atlantic region were of Antarctic origin. Benthic and planktonic foraminifer  $\delta^{13}\text{C}$  values fluctuate sympathetically and are higher in upper Maestrichtian sediments than in the lower Maestrichtian sequence.

### INTRODUCTION

Most of the evidence that has been gathered for the climate of the polar regions during the Late Cretaceous and early Tertiary is qualitative and indicates considerably warmer temperatures than today (Axelrod, 1984; Creber and Chaloner, 1985; Askin, 1988). Quantitative estimates of water temperatures in polar oceans are essential to reconstruct precisely the climate of the high latitudes, global climatic conditions, and the role of polar regions in regulating global climate during the Late Cretaceous. Oxygen and carbon isotopes of well-preserved benthic and planktonic foraminifers can provide these estimates as well as evidence for resolving current controversies regarding the high and/or low latitude origin of bottom waters during most of the early Tertiary and Late Cretaceous. Yet, there are few isotopic studies of high-latitude regions (Buchardt and Weiner, 1981; Barrera et al., 1987) because carbonate fossils are not abundant in polar sediments and those with good preservation are rare.

ODP Leg 113 Holes 689B (64°31'S, 03°06'E) and 690C (65°10'S, 01°12'E) off the Coast of East Antarctica (Fig. 1) recovered a nearly continuous record of Maestrichtian carbonate sedimentation representing the southernmost occurrence of foraminifers of this age in pelagic sediments. In addition to the completeness of the record, the sections have excellent geochronological control provided by the integration of foraminifer and calcareous nannoplankton datum levels (Huber, this volume; Pospichal and Wise, this volume, chapter 30) and geomagnetic polarity events (Hamilton, this volume). We report here the first high-resolution oxygen and carbon isotope records of Maestrichtian age from pelagic sediments in Antarctic waters based on analysis of monospecific benthic and planktonic foraminifer samples from these holes. These data permit us to infer, in

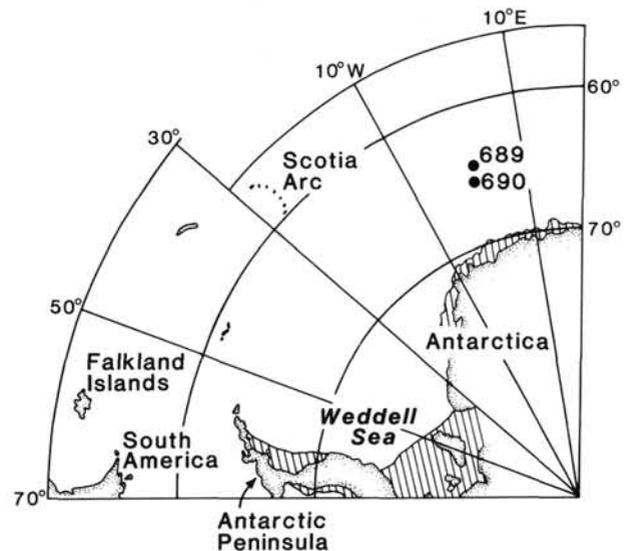


Figure 1. Map showing the location of Sites 689 and 690.

much more detail than hitherto possible, oceanographic and climatic conditions in the southern South Atlantic region during this time. Previous estimates of marine temperatures for Antarctic waters were based on oxygen isotopic ratios of Maestrichtian shallow-water benthic foraminifer taxa from Seymour Island in the Antarctic Peninsula (Barrera et al., 1987), where the isotopic composition of shelf seawater could have varied significantly through time. Age control in this section is not nearly as well resolved as at Maud Rise.

Sites 689 and 690 are located 116 km apart on the Maud Rise. Sediments at Hole 689B (present water depth of 2080 m) were deposited in upper slope depths of 1000–1500 m, whereas those of Hole 690C (present water depth of 2914 m) are from upper bathyal depths at about 1500–2000 m, based on Maestrichtian benthic foraminifers (Thomas, this volume). These sites were located at the same latitude as they are today (Lawver

<sup>1</sup> Barker, P. F., Kennett, J. P., et al., 1990. *Proc. ODP, Sci. Results*, 113: College Station, TX (Ocean Drilling Program).

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et al., 1985). The proximity and the relatively small difference in water depth of the Maud Rise sites should be reflected in the similarity of their isotopic records. This provides an independent means of assessing whether isotopic compositions have been modified by diagenetic alteration, a problem that has plagued foraminifer isotopic reconstructions of Cretaceous climates. In addition, foraminifer preservation has been evaluated by careful scanning electron microscope (SEM) observations, and foraminifer Sr/Ca ratios have been measured to estimate the extent to which the chemistry of foraminifer tests has been affected by diagenetic processes.

## MATERIALS AND METHODS

### Samples

Samples from Sites 689 and 690 analyzed in this study are listed in Tables 1 and 2. Foraminifer samples consist of the planktonic species *Abathomphalus mayaroensis*, *Archaeoglobigerina australis*, and *Globigerinelloides multispinatus*, and the benthic taxa *Nuttallides truempyi*, *Gavelinella beccariiiformis*, and *Coryphostoma incrassata*. These species were selected based on: (1) their abundance in sediment samples, (2) their stratigraphic range, and (3) the degree to which benthic taxa were cosmopolitan, facilitating comparison of isotopic data from high- and low-latitude locations.

A small portion of unprocessed sediment from each sample was dried and analyzed isotopically. In most cases, over 70% of the sediment sample was composed of particles smaller than 63  $\mu\text{m}$ , which include small foraminifers, coccoliths, and other materials. We refer to these samples as "bulk carbonate."

### ANALYTICAL METHODS

Samples were disaggregated by stirring in water heated to 40°–50°C and ultrasonically cleaned in tap water before sieving them through a 63  $\mu\text{m}$  screen. Planktonic foraminifer samples were picked from the 150–250  $\mu\text{m}$  size-fraction. A few benthic foraminifer samples were smaller than 250  $\mu\text{m}$ . Foraminifer textural preservation was judged by SEM observations of the interior and exterior chamber surfaces and the wall structure of tests. Prior to isotopic analysis and SEM observation, foraminifer tests were fractured with a sharp needle and agitated in dis-

tilled water in an ultrasonic bath to remove adhering or infilling fine-grained material. After each rinse the supernatant was pipetted out. Specimens for Sr and Ca analyses were also rinsed once with acetone before two final rinses with distilled water.

Isotopic analyses were performed at the stable isotope laboratories of Case Western Reserve University (CWRU), Cleveland, Ohio, and the University of Michigan (UM), Ann Arbor, Michigan. Analyses are reported in  $\delta$  notation as per mil deviations from the Peedee Belemnite (PDB) standard. At CWRU, samples were reacted individually with anhydrous phosphoric acid at 25°C. At UM, samples were reacted in a similar manner at 55°C in an on-line gas extraction line coupled to the inlet of a VG602E ratio mass spectrometer. At both laboratories, isotopic measurements were made relative to standard  $\text{CO}_2$  gases whose compositions are related to PDB values through numerous analyses of National Bureau of Standards standard #20 (Solnhofen limestone), which is taken to have a  $\delta^{18}\text{O}$  value of  $-4.14$  per mil and a  $\delta^{13}\text{C}$  value of  $-1.06$  per mil (Craig, 1957). Isotopic values have a precision of 0.05 per mil for  $\delta^{13}\text{C}$  and 0.1 for  $\delta^{18}\text{O}$ . Results from UM are indicated by an asterisk in Tables 1 and 2. Water temperatures were calculated using the equation of Epstein et al. (1953) and assuming that the oxygen isotopic composition of Maestrichtian oceans was  $-1$  per mil relative to Standard Mean Ocean Water (SMOW).

Sr and Ca concentrations were determined from dilutions of foraminifer samples reacted with 0.3N  $\text{HNO}_3$  acid solutions. Sr was analyzed by graphite furnace atomic absorption spectroscopy (GFAAS) and measurements have a precision of better than 5% and an accuracy better than 10% of the amount present. Ca was determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES). Ca analyses have both accuracy and precision of better than 5% of the amount present. Results are reported as molar Sr/Ca ratios.

### AGE DETERMINATIONS

Integration of planktonic foraminifer and calcareous nannoplankton biostratigraphic data (Huber, this volume; Pospichal and Wise, this volume, chapter 30) with magnetic polarity data enables assignment of the standard numbered geomagnetic anomaly sequence to the polarity reversal stratigraphy of Sites 689 and 690. This is correlated with the Haq et al. (1987) time scale.

Table 1. Maestrichtian oxygen and carbon isotope data for selected foraminifer species from Hole 689B.

	Core, section, interval (cm)	Depth (mbsf)	<i>Archaeoglobigerina australis</i>		<i>Globigerinelloides multispinatus</i>		<i>Abathomphalus mayaroensis</i>		<i>Nuttallides truempyi</i>		<i>Gavelinella beccariiiformis</i>		<i>Coryphostoma incrassata</i>		Bulk carbonate	
			$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
<i>Abath. mayar.</i>	27X-1, 85–89	246.87	0.46	1.83	0.18	2.65	0.31	1.58	1.01	1.47	0.70	1.08	0.95	0.99	0.51	1.39
	27X-2, 83–87	248.35	0.49	2.39			0.40	1.83	1.09	1.96	0.51	1.28	0.91	0.74	0.46	1.50
	27C-3, 83–87	249.87			0.47	2.23	0.43	1.73	1.10	1.21	0.74	1.25			0.36	1.44
	27X, CC	250.10	0.55	2.18			0.82	5.00	1.10	1.80	0.70	1.46			0.36	1.44
<i>Globotruncanella havanensis</i>	28X-1, 76–80	256.38			0.92	1.83	0.4	1.18	1.26	0.80	0.85	0.39			0.78	0.76
	28X-2, 80–84	257.92	0.09	1.40	0.37	1.19					0.82	0.73	1.02	0.05	0.75	1.11
	28X-3, 83–87	259.45	0.24	1.55	0.47	1.28					0.59	0.22	1.12	-0.04	0.62	0.70
	28X-4, 83–87	260.97	0.06	1.71	0.51	1.87					0.44	0.74	0.86	0.43	0.86	1.27
	28X, CC	261.80	0.08	1.90							0.68	0.75				
	29X-1, 83–87	266.05	-0.01	1.88	0.40	1.99					0.48	0.50			0.45	1.19
	29X-2, 83–87	267.55	-0.04	1.77	0.63	2.01					0.45	0.79	1.02	0.62	0.55	1.00
	29X-3, 83–87	269.05	-0.17	1.99	0.37	1.64					0.58	0.48			0.20	1.23
	29X, CC	269.50	-0.42	2.32							0.42	1.10	0.70	0.97		
	30X-1, 83–85	275.75	-0.03	1.96							0.29	1.42			0.41	1.40
	30X-2, 88–92	277.30	0.16	2.93	0.63	2.85					0.52	1.30			0.88	1.20
	30X-3, 78–83	278.70	-0.02	1.92							0.23	1.13			0.94	1.43
30X, CC	279.20	-0.13	1.95	0.31	1.86					0.24	0.85			0.94	1.43	
<i>Glob. Impen.</i>	32X-1, 41–43	291.21	-0.20	1.73							0.21	1.37			0.06	1.49
	32X, CC	291.30	-0.07		0.14	1.99					0.12	0.98				
	33X, CC	294.50			-0.05	1.85					0.30	0.81				

Note: Age determinations for the planktonic foraminifer zones shown on the left are discussed in the text.

Table 2. Maestrichtian oxygen and carbon isotope data for selected foraminifer species from Hole 690C.

	Sample (core, section, interval)	Depth (mbsf)	<i>Archaeoglobigerina australis</i>		<i>Globigerinelloides multispinatus</i>		<i>Abathomphalus mayaroensis</i>		<i>Nuttallides truempyi</i>		<i>Gavelinella beccariiiformis</i>		<i>Coryphostoma incrassata</i>		Bulk carbonate	
			$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
<i>Abathomphalus mayaroensis</i>	16X, CC	258.00			0.52	2.68	0.73	2.08	1.05	1.53			1.33	1.53		
	17X-1, 119-123	263.01	0.72	2.90	0.47	2.75	0.67 <sup>a</sup>	1.71 <sup>a</sup>	1.13 <sup>a</sup>	0.97 <sup>a</sup>	0.68 <sup>a</sup>	0.73 <sup>a</sup>	1.21	1.45	0.76	2.50
	17X-3, 119-123	265.01	0.59	2.06	0.34 <sup>a</sup>	2.77	0.40	1.74	1.03	1.39	0.69	1.17	1.23	1.49	0.57	2.30
	17X, CC	266.60	0.33	2.29	0.35	2.70 <sup>a</sup>	0.56	1.87	1.10	2.13	0.72	1.47				
	18X-1, 119-123	272.61	0.20	2.33	0.44	4.18	0.40	1.74	0.92	1.61	0.62	1.03	1.44	1.26	0.59	2.03
	18X-2, 119-123	274.11	0.18 <sup>a</sup>	2.55	0.49	2.52	0.38 <sup>a</sup>	1.88 <sup>a</sup>	0.45	1.19					0.39	2.32
	18X-3, 98-102	275.40	-0.12	2.43 <sup>a</sup>	0.45 <sup>a</sup>	2.28 <sup>a</sup>	0.39 <sup>a</sup>	1.84 <sup>a</sup>	0.71	1.33	0.72 <sup>a</sup>	1.19 <sup>a</sup>			0.58	2.08
	18X-4, 95-99	276.87	0.02 <sup>a</sup>	0.29 <sup>a</sup>	2.34 <sup>a</sup>	0.34 <sup>a</sup>	1.86 <sup>a</sup>	0.74	1.50						0.87	2.02
	18X-5, 46-49	277.87			0.52 <sup>a</sup>	2.27 <sup>a</sup>	0.42 <sup>a</sup>	1.62 <sup>a</sup>	0.78 <sup>a</sup>	1.22 <sup>a</sup>	0.74 <sup>a</sup>	1.24 <sup>a</sup>			0.57	2.28
	18X, CC	278.30	0.27 <sup>b</sup>	1.90 <sup>b</sup>	0.27	1.79 <sup>a</sup>			0.74	0.68	0.73	0.31				
<i>Globotruncanella havanensis</i>	19X-1, 119-123	282.31	-0.61	1.22	0.39	1.25			0.79	0.22	0.28	-0.02			0.42	1.27
	19X-2, 119-123	283.81			0.22	1.54			0.51	0.86	0.50	0.64	1.00	0.31	0.29	1.15
	19X-3, 119-123	285.31	-0.49 <sup>a</sup>	2.02 <sup>a</sup>							0.39 <sup>a</sup>	0.56 <sup>a</sup>			-0.07	1.54
	19X-4, 119-123	286.81	-0.10 <sup>a</sup>	1.75 <sup>a</sup>	0.19 <sup>a</sup>	1.74 <sup>a</sup>					0.42 <sup>a</sup>	0.85 <sup>a</sup>	1.11	0.49	0.24	1.64
	19X-5, 110-112	288.20	-0.42 <sup>a</sup>	2.14 <sup>a</sup>	0.23 <sup>a</sup>	1.83 <sup>a</sup>					0.32 <sup>a</sup>	0.86 <sup>a</sup>	1.31	0.63	0.33	1.70
	19X-6, 119-123	289.81	-0.24	1.98	0.18 <sup>a</sup>	1.85 <sup>a</sup>									0.28	1.64
	19X, CC	290.60	-0.13 <sup>a</sup>	1.93 <sup>a</sup>	0.34	1.93					0.46	0.94	1.07	0.56		
	20X-1, 118-121	292.00	-0.43	2.16	0.26	4.61					0.25	0.58	0.92	0.14	-0.31	0.89
	20X-2, 118-120	293.48	-0.05 <sup>a</sup>	2.11 <sup>a</sup>	0.27 <sup>a</sup>	2.09 <sup>a</sup>					0.41 <sup>a</sup>	0.81 <sup>a</sup>			0.16	1.44
	20X-3, 116-118	294.98	-0.14 <sup>a</sup>	1.90 <sup>a</sup>	0.16 <sup>a</sup>	2.00 <sup>a</sup>					0.28	0.91			0.26	1.42
	20X-4, 96-98	296.27	-0.60	2.18	0.13 <sup>a</sup>	2.01 <sup>a</sup>					0.22	0.51	0.69	0.33	-0.12	1.27
	20X-5, 108-110	297.82	-0.38 <sup>a</sup>	2.18 <sup>a</sup>	0.12 <sup>a</sup>	1.93 <sup>a</sup>					0.50 <sup>a</sup>	0.68 <sup>a</sup>			0.13	1.30
	20X-6, 119-123	299.45	-0.40 <sup>a</sup>	2.25 <sup>a</sup>	0.25 <sup>a</sup>	2.06 <sup>a</sup>					0.21 <sup>a</sup>	0.54 <sup>a</sup>	0.71	0.79		
	20X, CC	300.40	-0.82 <sup>a</sup>	2.48 <sup>a</sup>	0.02	2.18										
	21X-1, 118-122	300.94	-1.19 <sup>a</sup>	2.66 <sup>a</sup>	-0.24 <sup>a</sup>	2.15 <sup>a</sup>					0.19 <sup>a</sup>	1.04 <sup>a</sup>			-0.21	1.42
	21X-2, 118-122	302.44	-0.65 <sup>a</sup>	1.89 <sup>a</sup>	-0.33 <sup>a</sup>	1.99 <sup>a</sup>					-0.09 <sup>a</sup>	0.58 <sup>a</sup>			-0.30	1.38
	21X-3, 118-122	303.94	-0.82 <sup>b</sup>	2.42 <sup>b</sup>	0.01	5.95					0.11	1.35			0.01	1.76
	21X-4, 118-122	305.44	-0.69 <sup>a</sup>	2.47 <sup>a</sup>	-0.27 <sup>a</sup>	2.21 <sup>a</sup>					-0.04 <sup>a</sup>	1.18 <sup>a</sup>			-0.07	1.56
21X-5, 118-122	306.94	-0.59 <sup>a</sup>	2.34 <sup>a</sup>							0.15	1.17			0.07	1.43	
21X, CC	307.80	-0.16 <sup>a</sup>	2.31 <sup>a</sup>							0.20	1.29					
22X-1, 118-122	311.62	-0.31 <sup>b</sup>	2.27 <sup>b</sup>	-0.21 <sup>a</sup>	1.99 <sup>a</sup>					0.17	1.55			-0.20	1.41	
22X-1, 118-122	313.12									0.17	1.55			-0.02	1.43	
<i>Glo. Imp.</i>	22X-3, 107-111	314.52	-0.62 <sup>a</sup>	2.16 <sup>a</sup>	-0.23 <sup>a</sup>	1.94 <sup>a</sup>					0.03	0.85			0.03	1.43
	22X-4, 118-122	316.62			-0.15 <sup>a</sup>	2.00 <sup>a</sup>					-0.06	0.82			0.01	1.62

Note: Age determinations for the planktonic foraminifer zones shown on the left are discussed in the text.

<sup>a</sup>Indicates isotopic measurements performed at the University of Michigan.

<sup>b</sup>Indicates average of two samples from the same interval.

Magnetostratigraphic chron boundaries were used as datums to calculate averaged sedimentation rates (see Huber, this volume, Fig. 8), suggesting about 5.18 m/m.y. for Hole 689B and 9.53 m/m.y. for Hole 690C. Based on these rates, the lowermost sample analyzed from Hole 689B was deposited at about 75 Ma, and the lowermost sample from Hole 690C has a slightly younger age at about 74 Ma. Although samples of these ages are Campanian (Haq et al., 1987), we refer to them here as early Maestrichtian due to uncertainties in their age assignment (see Pospichal and Wise, this volume, chapter 32). The late/early Maestrichtian boundary is based on first appearance datums of the foraminifer species *Abathomphalus mayaroensis* and the calcareous nannoplankton species *Nephrolitus frequens*, both of which first occur at the same level in the middle of Chron 31R at Holes 689B and 690C.

### FORAMINIFER ISOTOPIC SYSTEMATICS

It is impossible to be certain whether oxygen or carbon isotopic compositions of Maestrichtian species analyzed in this study reflect equilibrium precipitation. Cretaceous planktonic foraminifer taxa are completely different from modern ones, and benthic foraminifer species have modern representatives only at the genus level.

Most Recent benthic foraminifer species characteristic of deep-water environments do not precipitate their tests in either oxygen or carbon isotopic equilibrium with seawater (Woodruff et al., 1980; Belanger et al., 1981). Interspecific differences in oxygen and carbon isotope fractionation of well-preserved benthic foraminifers of Tertiary age appear to remain the same through time, implying that species departure from equilibrium

also remains constant (Savin et al., 1981; Shackleton et al., 1984). The isotopic systematics of *Coryphostoma incrassata* have not been investigated. Based mostly on analysis of Tertiary specimens, Shackleton et al. (1984) estimated that species of *Nuttallides* and *Gavelinella* are depleted in  $^{18}\text{O}$  by 0.35 and 0.3 per mil, respectively, relative to equilibrium values, although carbon isotopic compositions are in equilibrium. Because the fractionations of these taxa were consistently different from those reported by Shackleton et al., no adjustments have been made to our data in tables or figures.

A "vital effect" appears to influence  $\delta^{13}\text{C}$  values of Recent planktonic foraminifer species (Vergnaud Grazzini, 1976; Williams et al., 1977). However,  $\delta^{13}\text{C}$  values of several planktonic species are very close to those of total dissolved  $\text{CO}_2$  in seawater at the depth at which calcification is inferred to have occurred (Williams et al., 1977). The deviation of  $^{18}\text{O}/^{16}\text{O}$  ratios of most planktonic foraminifer species from equilibrium values with seawater is apparently small (Williams et al., 1979). If the fractionation of Maestrichtian planktonic taxa is controlled by the same factors influencing that of Recent forms,  $\delta^{18}\text{O}$  values should reflect the temperature and isotopic composition of the water in which calcification occurred.

### FORAMINIFER PRESERVATION

Diagenetic processes affecting the isotopic composition of foraminifer calcite in deep-sea sediments commonly include dissolution and reprecipitation of calcite as secondary or replacement calcite. These two processes are usually referred to together under the term "recrystallization." Dissolution and reprecipitation can modify significantly the original isotopic com-

position of Tertiary and Cretaceous foraminifer calcite (Killingly, 1983). Consequently, we have taken three approaches to estimate the extent to which foraminifer calcite and isotopic ratios from Sites 689 and 690 have been diagenetically altered: (1) SEM observations of tests, (2) comparison of foraminifer and pore water Sr/Ca ratios, and (3) examination of the consistency in the isotopic fractionation of taxa.

### TEXTURAL PRESERVATION

Two types of textural alteration are evident in foraminifer calcite from Holes 689B and 690C: (1) encrustation of chamber walls by secondary calcite and (2) replacement of the original calcite of the walls by secondary calcite. The first is readily recognized as euhedral overgrowth crystals on chamber surfaces. The latter can be characterized by the growth of coarser calcite crystals (Neugebauer, 1974, 1975) that are often euhedral (Pl. 1, Fig. 2; Pl. 1, Fig. 3; Pl. 3, Fig. 1; Pl. 3, Fig. 2), instead of the original crystal or crystal units that are less than 0.5  $\mu\text{m}$  in size (Towe and Cifelli, 1967), and/or by the presence of blocky secondary calcite within chamber walls (Barrera, 1987). Blocky secondary calcite has a massive appearance and fractures along cleavage surfaces, as observed in *G. beccariiiformis* in Plate 2, Figure 2 and Plate 2, Figure 3.

Interior surfaces of foraminifer tests from all cores from Hole 689B, and Cores 113-690C-17X, 113-690C-18X, and 113-690C-22X and Sample 690-19X-1, 119-123 cm, are encrusted with calcite overgrowth crystals. However, encrustation is minor in samples from the lower part of Core 113-689-28X (Pl. 4, Fig. 4) and from Core 113-689B-29X. Euhedral and/or blocky secondary calcite extensively replaces chamber walls of tests from Hole 689B (Pl. 2, Fig. 2; Pl. 3, Fig. 1; Pl. 3, Fig. 2; Pl. 4, Fig. 1; Pl. 4, Fig. 3; Pl. 4, Fig. 4) and tests from Hole 690C from the levels listed above (Pl. 1, Fig. 2; Pl. 1, Fig. 3; Pl. 1, Fig. 1; Pl. 2, Fig. 4). In samples from Hole 690C, the amount of overgrowth and replacement is greater in those from Core 113-690C-17X and in general decreases with increasing sample depth through Core 113-690C-18X and 113-690C-19X. Specimens from Core 113-690C-22X show somewhat similar preservation as those from the uppermost core.

Overgrowth crystals in planktonic and benthic tests from Samples 113-690C-19X-2, 119-123 cm, to 113-690C-21X-5, 118-122 cm, are small and/or nearly absent (Pl. 1, Fig. 4; Pl. 3, Fig. 4; Pl. 4, Fig. 2). Tests from these levels show excellent preservation when observed under the binocular microscope (Huber, this volume). SEM observations reveal that most of the wall structure of foraminifer tests seems to be composed of fine-grained crystals or polycrystalline units. Well-defined pores and layers within the wall of planktonic tests are still present (Pl. 1, Fig. 4; Pl. 3, Fig. 4; Pl. 4, Fig. 2). However, there are also large patches of replacement calcite within the wall of most benthic tests from some of these samples, as illustrated in *G. beccariiiformis* from Sample 113-690C-21X-1, 118-122 cm (Pl. 2, Fig. 1). These areas are small in planktonic tests.

### CHEMICAL PRESERVATION

The approach most frequently used to estimate the extent of diagenetic alteration of deep-sea sediments from the chemistry of pore waters and solids is based on comparison of Sr/Ca ratios of pore waters and carbonate (Baker et al., 1982; Stout, 1985; Baker, 1986). Abiologically deposited calcite has lower Sr/Ca ratios than biogenic calcite precipitated under similar conditions (Katz et al., 1972; Baker et al., 1982), and thus, when biogenic calcite dissolves and reprecipitates, the  $\text{Sr}^{++}$  content of the pore water increases (Matter et al., 1974; Gieskes, 1981). Hence, the extent of calcite dissolution and reprecipitation in foraminifer tests can be inferred from its assumed initial Sr/Ca ratio, its present Sr/Ca ratio, and the Sr/Ca ratio of the inorganic calcite formed in equilibrium with the pore waters.

Sr/Ca ratios of foraminifers from Holes 689B and 690C are listed in Table 3 and plotted in Figures 2A and 2B. Ratios for *A. mayaroensis*, *G. multispinatus*, *A. australis*, and *N. truempyi* from Hole 689B range between 0.00087 and 0.00132, while those for *A. australis*, *A. mayaroensis*, and *G. beccariiiformis* from Hole 690C are between 0.00066 and 0.00210. There are no data for monospecific Cretaceous foraminifers with which to compare these values. However, Delaney et al. (1985) reported Sr/Ca ratios between 0.00188 and 0.0011 for Recent planktonic foraminifers growing at surface water temperatures between 10° and 28°C. Most of their values fall between 0.0014 and 0.0018. Lower values of approximately 0.0010 were measured for the benthic taxon *Uvigerina* from core-top sediments. Likewise, most of the Sr/Ca ratios reported by Lorens et al. (1977) for planktonic foraminifer species from core-top sediments fall between 0.0012 and 0.0016.

$\text{Sr}^{++}$  concentrations at Holes 689B and 690C increase almost linearly with depth from average seawater values of 0.09 mmol at the surface to 0.22 mmol at 259 m and 0.159 mmol at 296 m, respectively (Egeberg et al., this volume, chapter 10). Replacement calcite precipitated in equilibrium with pore waters would have values close to 0.00057 at Hole 689B (Fig. 2A) and between 0.00050 and 0.00066 at Hole 690C (Fig. 2B) based on the distribution coefficient for Sr in Katz et al. (1972) for calcite precipitated from 0.1 mmol  $\text{Sr}^{++}$  solutions and extrapolated to temperatures measured in these holes. Sr/Ca ratios of foraminifers from Holes 689B and 690C are higher than those expected for diagenetically altered calcite, but slightly lower than those measured in Recent foraminifers. Hence, Sr/Ca ratios do not indicate extensive replacement of the original foraminifer calcite by diagenetic calcite. Egeberg et al. (this volume, chapter 11) also concluded, based on Sr concentrations and  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of both pore waters and bulk carbonate, that carbonate sediments at Holes 689B and 690C have not been affected by dissolution and reprecipitation processes.

### ISOTOPIC PRESERVATION

Constancy of interspecific isotopic differences can be used as an indication of the preservation of original isotopic ratios of benthic foraminifers. Encrustation or replacement by secondary calcite can make the isotopic compositions of different species more similar to one another or increase their differences. When all taxa are altered simultaneously by similar processes, interspecific isotopic differences among species become smaller, disappearing as the amount of diagenetic calcite approaches 100%. These differences may either increase or decrease when different species are encrusted or replaced to different extent.

Interspecific isotopic differences for Holes 689B and 690C are tabulated in Table 4. The similarity in mean  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  differences between *N. truempyi* and *G. beccariiiformis* within and between sites suggests no diagenetic modification of the isotopic compositions of these taxa. However, mean  $\delta^{18}\text{O}$  differences between *G. beccariiiformis* and *C. incrassata* from the two sites are approximately 1 per mil. The mean  $\delta^{13}\text{C}$  difference between *G. beccariiiformis* and *C. incrassata* for the early Maestrichtian at Site 690 is also different from that of the same interval at Site 689, and that of the late Maestrichtian interval at Sites 689 and 690. There is a large difference between late and early Maestrichtian mean  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  differences of *C. incrassata* minus *N. truempyi* (though this is based on comparison of only one early Maestrichtian sample). This evidence suggests the diagenetic alteration of *C. incrassata* Maestrichtian  $\delta^{18}\text{O}$  values and early Maestrichtian  $\delta^{13}\text{C}$  values at Site 690. In view of that, we believe that paleoclimatic inferences based on the isotopic results of the other taxa are more reliable.

In summary, there appears to be no obvious modification of foraminifer original isotopic and elemental chemistries in concert with their microstructure alteration. The petrographic evi-

**Table 3. Sr/Ca ratios of selected foraminifer species from Holes 689B and 690C.**

Core, section, interval (cm)	Depth (mbsf)	<i>Gavelinella beccariiiformis</i>	<i>Nuttallides truempyi</i>	<i>Abathomphalus mayaroensis</i>	<i>Globigerinelloides multispinatus</i>	<i>Archaeoglobigerina australis</i>
<b>Hole 689B</b>						
27X-1, 85-89	246.87	1.1290				
27X-3, 83-87	249.87	0.8722		1.1180		
28X-1, 76-80	256.38	1.0040	0.8490	1.3250	1.2055	
28X-3, 83-87	259.45					
28X-4, 83-87	260.97	1.1462			0.9386	
29X-1, 83-87	266.05	1.2804			0.9386	
29X-2, 83-87	267.55	1.2395				
29X, CC	269.50	1.1794			1.1591	
30X-2, 88-92	277.30					
30X-3, 78-83	278.70	1.2800				
<b>Hole 690C</b>						
18X-1, 119-123	272.61	1.0180				0.9613
18X-2, 119-123	273.91		2.0980			
18X-3, 98-102	275.40	0.6567		1.4480		0.9364
18X-5, 46-49	277.87	0.9780		1.7982	1.7982	1.2432
19X-1, 119-123	282.31	1.2060				1.1212
19X-3, 119-123	285.31	1.3313				1.3169
19X-5, 110-112	288.20	0.9565				1.3476
20X-1, 118-121	292.00	1.2305				1.6314
20X-3, 116-118	294.98	1.2010				1.2347
20X-5, 108-110	297.82	1.1754				1.4409
20X, CC	300.40	0.9215				1.1907
21X-3, 118-122	303.94	0.9136				1.6107
21X-5, 118-122	306.94	1.2585				1.3643
22X-1, 118-122	311.62	1.4630				1.0182
22X-3, 107-111	314.52	1.4357				1.0851

Note: Sr/Ca ratios are given as  $1 \times 10^{-3}$  moles.

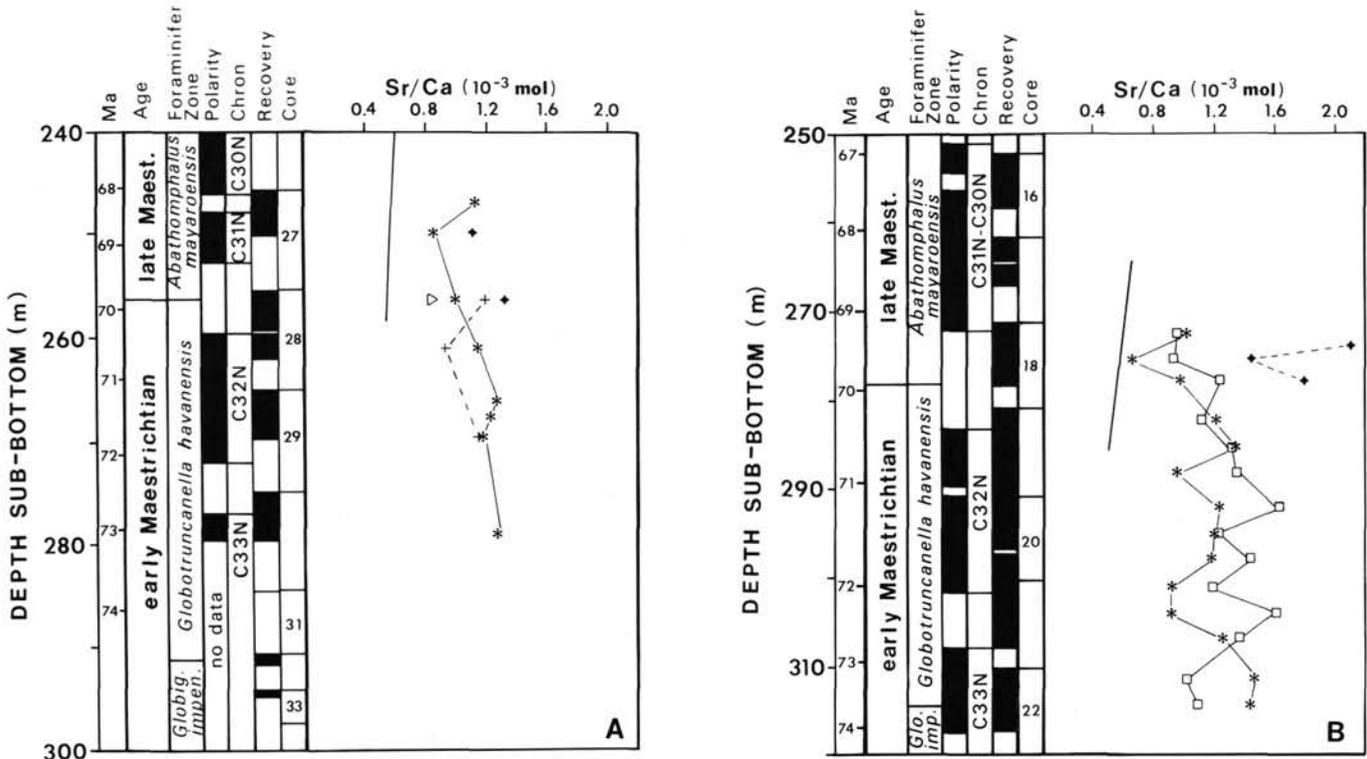


Figure 2. Sr/Ca ratios of selected foraminifer species. A. Hole 689B. B. Hole 690C. Open squares = *A. australis*; crosses = *G. multispinatus*; solid diamonds = *A. mayaroensis*; asterisks = *G. beccariiiformis*; right-pointing triangle = *N. truempyi*. The heavy solid line represents estimated Sr/Ca ratios of calcite precipitated in equilibrium with pore water interpolated between pore-water measurements in Egeberg et al. (this volume, chapter 10).

**Table 4. Mean values of interspecific oxygen and carbon isotopic differences from Holes 689B and 690C.**

Oxygen isotopic differences				
ODP Site 689		ODP Site 690		
	<i>Gavelinella beccariiiformis</i>	<i>Coryphostoma incrassata</i>	<i>Gavelinella beccariiiformis</i>	<i>Coryphostoma incrassata</i>
late Maestrichtian				
<i>Nuttallides truempyi</i>	0.41 (5) +0.09	0.44 (2) +0.13	0.21 (7) +0.18	0.53 (4) +0.3
<i>Gavelinella beccariiiformis</i>		0.32 (2) +0.07		-0.63 (3) +0.13
Carbon isotopic differences				
ODP Site 689		ODP Site 690		
	<i>Gavelinella beccariiiformis</i>	<i>Coryphostoma incrassata</i>	<i>Gavelinella beccariiiformis</i>	<i>Coryphostoma incrassata</i>
late Maestrichtian				
<i>Nuttallides truempyi</i>	0.36 (5) +0.23	0.53 (2) +0.14	0.31 (7) +0.22	0.64 (4) +0.53
<i>Gavelinella beccariiiformis</i>		-0.31 (2) +0.22		-0.42 (3) +0.21
early Maestrichtian				
<i>Nuttallides truempyi</i>			0.23 (2) +0.01	0.22 (1)
<i>Gavelinella beccariiiformis</i>		-0.31 (5) +0.2		0.32 (6) +0.08

Note. The number of samples used in the calculation is in parentheses. Numbers tabulated are mean values of the difference between  $\delta$  values of species in column minus species in row of the same sample. Early Maestrichtian values from Site 689 were calculated based on samples older than the *A. mayaroensis* Zone, whereas late Maestrichtian values are of samples from this Zone. Early Maestrichtian values from Site 690 were calculated for samples below 282 mbsf.

dence discussed above indicates that early Maestrichtian samples are texturally less altered than late Maestrichtian and earliest early Maestrichtian samples at both sites. Early Maestrichtian samples from Hole 690C are in general better preserved than those of analogous age from Hole 689B. If the extent of alteration of original isotopic signatures covaries with the extent of textural alteration,  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  interspecific differences in and between the two sites should have been modified accordingly. However, the isotopic data discussed above do not indicate this. Likewise, Sr/Ca ratios of texturally poorly preserved foraminifer species are not consistently lower than those of texturally better preserved specimens. It appears that the processes responsible for modifying the original structure of the foraminifer wall did not significantly change the chemical and isotopic compositions of foraminifer calcite. One possibility is that test replacement has occurred in a closed system with little interaction with pore waters (Barrera and Savin, 1986; Barrera, 1987), where Sr/Ca,  $^{18}\text{O}/^{16}\text{O}$ , and  $^{13}\text{C}/^{12}\text{C}$  ratios of the precipitated calcite would be controlled by those of the dissolving calcite and Sr/Ca ratios of pore waters will not be significantly changed.

### ISOTOPIC RESULTS

The  $^{18}\text{O}/^{16}\text{O}$  and  $^{13}\text{C}/^{12}\text{C}$  ratios of foraminifers from Sites 689 and 690 are plotted in Figures 3 and 4 and listed in Tables 1 and 2.

#### Benthic Foraminifer Records

The  $\delta^{18}\text{O}$  values of *G. beccariiiformis* and *C. incrassata* show a distinctive trend of decreasing values with decreasing age in lower Maestrichtian sediments. The record from Site 690, which is more densely and more continuously sampled than that of the other site, indicates that the trend of *G. beccariiiformis*  $\delta^{18}\text{O}$  val-

ues probably begins with the highest values of the Maestrichtian at about 73 Ma to 72 Ma and is terminated by  $^{18}\text{O}$  enrichment of approximately 0.3 per mil at about the time of the first appearance of *Abathomphalus mayaroensis*. Afterward, late Maestrichtian  $\delta^{18}\text{O}$  values of *G. beccariiiformis*, *C. incrassata*, and Site 689 *N. truempyi* show little change for the next 2.5 m.y.

The  $\delta^{13}\text{C}$  values of the benthic foraminifer species fluctuate sympathetically at both sites.  $\delta^{13}\text{C}$  values were relatively high during a short interval in the earliest early Maestrichtian followed by lower values until prior to the beginning of the *A. mayaroensis* Zone. Higher benthic  $\delta^{13}\text{C}$  values, similar to those in the earliest early Maestrichtian, characterize this faunal zone. A distinctive feature of these records is a sharp decrease in  $\delta^{13}\text{C}$  values, which appears to have begun at about 72.2 Ma and terminated at the onset of the late Maestrichtian. In the record from Site 690, this  $^{13}\text{C}$  excursion is immediately followed by the  $^{18}\text{O}$  enrichment of *G. beccariiiformis* discussed above.

Benthic foraminifer  $\delta^{18}\text{O}$  values from Site 689 are on the average higher than those from Site 690, although sediments from the latter were deposited in shallower waters (Table 5). For example, mean average  $\delta^{18}\text{O}$  values of early Maestrichtian *G. beccariiiformis* and late Maestrichtian *N. truempyi* from Site 689 are approximately 0.2 per mil higher than those from the same intervals at Site 690. However, average  $\delta^{18}\text{O}$  values of late Maestrichtian *G. beccariiiformis* and early Maestrichtian *C. incrassata* from Site 690 are not very different from those of their counterparts from Site 689. Only the mean  $\delta^{18}\text{O}$  value of late Maestrichtian *C. incrassata* from Site 689 is lower than that from Site 690. In contrast, mean  $\delta^{13}\text{C}$  values of benthic foraminifer taxa in each of the two Maestrichtian intervals at each site are very close, except for those of *C. incrassata* from the late Maestrichtian interval (Table 5).

Table 5. Mean values of oxygen and carbon isotopic compositions of foraminifer species from Holes 689B and 690C.

	<i>Archeoglobigerina australis</i>		<i>Globigerinelloides multispinatus</i>		<i>Abathomphalus mayaroensis</i>		<i>Nuttallides truempyi</i>		<i>Gavelinella beccariiiformis</i>		<i>Coryphostoma incrassata</i>	
	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
Site 689												
late Maestrichtian	0.50 (0.04)	2.13 (0.23)	0.52 (0.30)	2.24 (0.33)	0.50 (0.18)	2.26 (1.39)	1.11 (0.08)	1.45 (0.41)	0.70 (0.11)	1.09 (0.37)	0.93 (0.02)	0.86 (0.12)
early Maestrichtian	-0.03 (0.16)	1.92 (0.36)	0.38 (0.20)	1.85 (0.43)					0.42 (0.19)	0.88 (0.33)	0.94 (0.15)	0.41 (0.37)
Site 690												
late Maestrichtian	0.26 (0.27)	2.38 (0.29)	0.41 (0.09)	2.63 (0.60)	0.48 (0.13)	1.81 (0.12)	0.86 (0.21)	1.35 (0.40)	0.70 (0.04)	1.02 (0.36)	1.30 (0.09)	1.43 (0.10)
early Maestrichtian	-0.52 (0.30)	2.15 (0.29)	0.07 (0.22)	2.26 (1.05)			0.65 (0.14)	0.54 (0.32)	0.23 (0.17)	0.87 (0.37)	0.92 (0.21)	0.50 (0.19)

Note: Numbers tabulated are mean isotopic values and standard deviations (in parentheses). Mean isotopic values for the early Maestrichtian interval include all samples older than the first appearance of *A. mayaroensis*, whereas late Maestrichtian averages include only samples from the *A. mayaroensis* Zone.

Surface Water Records

Except for the significant high planktonic ratios in the earliest Maestrichtian (Figs. 3 and 4),  $\delta^{18}\text{O}$  values of *A. australis* increase with decreasing sediment age at both sites. This is similar to the trends observed in the benthic species'  $\delta^{18}\text{O}$  values. Bulk carbonate  $\delta^{18}\text{O}$  values at Site 690 also exhibit this general trend. At Site 690,  $\delta^{18}\text{O}$  values of *G. multispinatus* increase in the earliest early Maestrichtian and remain high throughout the remain-

der of the Maestrichtian. *G. multispinatus* and bulk carbonate  $\delta^{18}\text{O}$  values from Site 689 are variable but do not show a particular time trend.

The  $\delta^{13}\text{C}$  values of *A. australis*, *G. multispinatus*, and bulk carbonate exhibit somewhat similar trends at both sites. Sediments deposited during the latest early Maestrichtian were depleted in  $^{13}\text{C}$  relative to older or younger Maestrichtian sediments. Planktonic foraminifer and bulk carbonate records from Site 690 fluctuate quasi-sympathetically with  $\delta^{13}\text{C}$  benthic records.

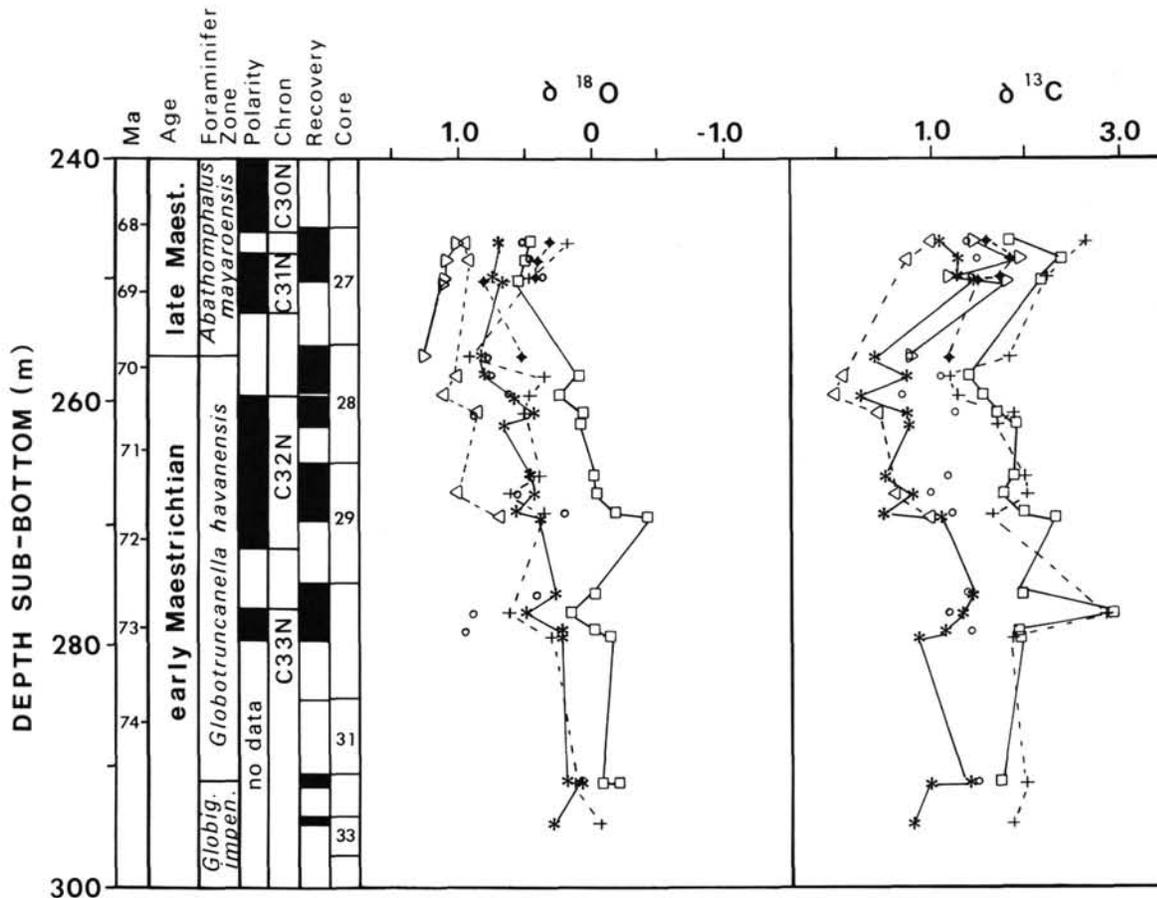


Figure 3.  $^{18}\text{O}/^{16}\text{O}$  and  $^{13}\text{C}/^{12}\text{C}$  ratios of selected foraminifer species from Hole 689B. Open squares = *A. australis*; crosses = *G. beccariiiformis*; right-pointing triangles = *N. truempyi*; left-pointing triangles = *G. incrassata*; open circles = bulk carbonate.

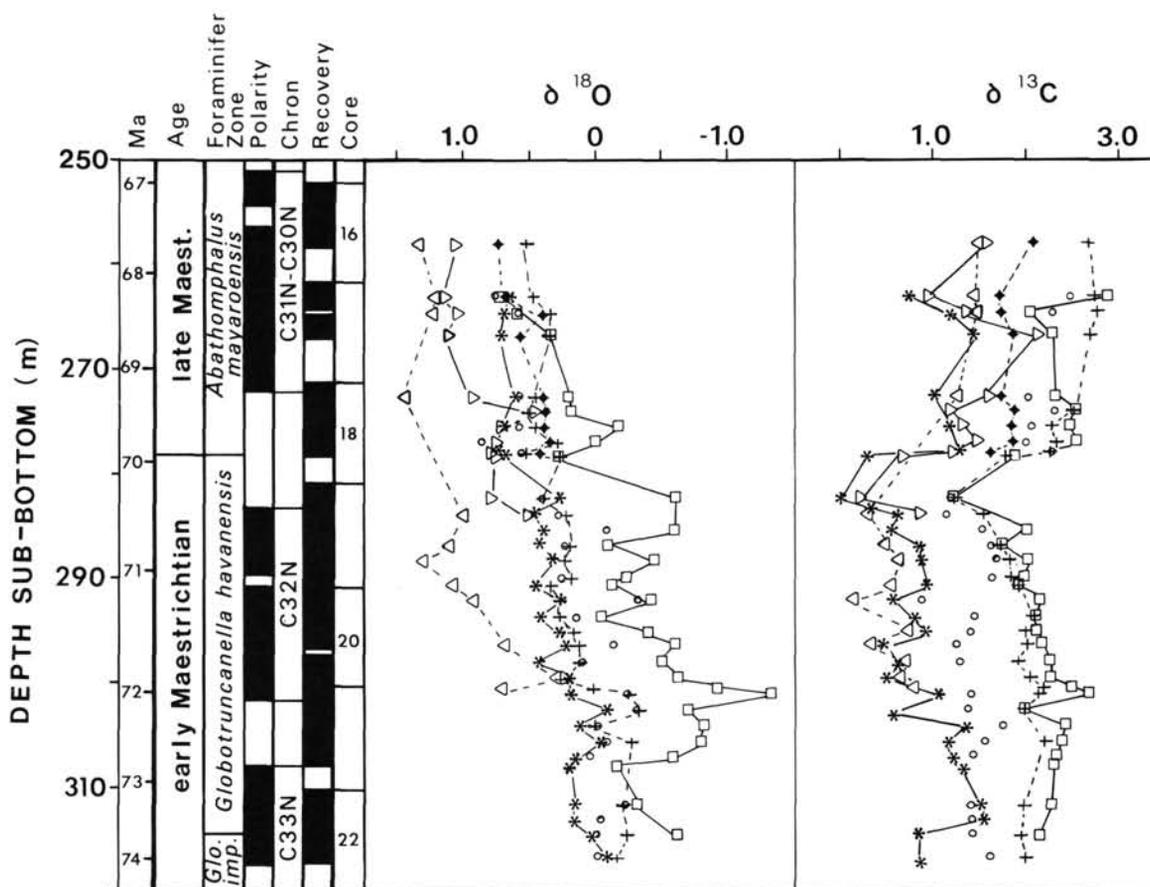


Figure 4.  $^{18}\text{O}/^{16}\text{O}$  and  $^{13}\text{C}/^{12}\text{C}$  ratios of selected foraminifer species from Hole 690C. Symbols are the same as in Figure 3.

Mean  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values of planktonic foraminifers calculated for the same Maestrichtian intervals at both sites (Table 5) indicate that Site 689 oxygen isotopic values are generally higher and carbon isotopic values are lower than at Site 690. Site 689  $\delta^{18}\text{O}$  values of *G. multispinatus* are similar to those of the benthic foraminifer *G. beccariiformis*, whereas those from Site 690 are lower. Comparison of calculated mean  $\delta^{18}\text{O}$  values of planktonic foraminifers for the two sites suggests that the change between early Maestrichtian to late Maestrichtian time was greater at Site 690 than at Site 689. An analogous comparison of mean planktonic  $\delta^{13}\text{C}$  values suggests that the change from early Maestrichtian time to late Maestrichtian time was nearly equal at both sites.

#### DEPTH STRATIFICATION OF PLANKTONIC SPECIES

There is conflicting evidence regarding the depth habitat of *Globigerinelloides* species as inferred from  $\delta^{18}\text{O}$  values. Douglas and Savin (1978) concluded, based on analyses of tropical planktonic assemblages, that *G. multispinatus* had the lowest  $\delta^{18}\text{O}$  values and, thus, lived in the uppermost level of the water column. However, Boersma and Shackleton (1981) found that the depth ranking of species of *Globigerinelloides* was variable, which they attributed to either oxygen isotopic disequilibrium effects, diagenetic alteration of isotopic ratios, or size-dependent fractionation.

The  $\delta^{18}\text{O}$  records of the planktonic foraminifer species at Sites 689 and 690 suggest that *A. australis* was a shallow-dwelling species, whereas *G. multispinatus* and *A. mayaroensis* lived

in deeper near-surface waters. The  $\delta^{13}\text{C}$  values of *A. mayaroensis*, a taxon which also inhabited intermediate to deep near-surface waters in low-latitude regions (Boersma and Shackleton, 1981), are lower than those of *G. multispinatus* and *A. australis* and are consistent with its inferred depth habitat in deeper waters. The  $\delta^{13}\text{C}$  record of *G. multispinatus*, considered to be a shallow-dwelling taxon in the low latitudes (Douglas and Savin, 1978), resembles that of *A. australis* at both sites. The predominance of *G. multispinatus* in shallow-water biofacies of Maestrichtian age on Seymour Island (Huber, 1988) also suggests a surface-water habitat in high-latitude regions. Therefore, we believe that  $\delta^{18}\text{O}$  values of *G. multispinatus* are probably affected by a vital effect and its  $\delta^{13}\text{C}$  record as that of *A. australis* reflects near-surface water conditions. The high variability in *A. australis*  $\delta^{18}\text{O}$  values is probably caused by other factors in addition to surface water temperatures.

#### DISCUSSION

Early isotopic paleoclimatic studies based on analysis of belemnite rostra from shallow-water sediments from Northern Russia (Teis et al., 1965; Naidin, 1966; and others), New Zealand (Stevens and Clayton, 1971), and Northern Europe (Lowenstam and Epstein, 1954; and others) revealed a Late Cretaceous cooling trend for high and subtropical latitude regions from a temperature maximum near the late Albian to a temperature minimum in the early Maestrichtian. Slightly higher temperatures were suggested for late Maestrichtian times. This general trend was later reproduced by the isotopic data of benthic and planktonic foraminifers and nannofossils from pelagic sedi-

ments in the tropical Pacific Ocean (Douglas and Savin, 1975; Boersma and Shackleton, 1981), implying that the Late Cretaceous climatic cooling had been global.

The foraminifer isotopic data that have been published to date do not provide a consistent picture of the temperature evolution of surface and deep waters in the low and high latitudes during the Maestrichtian. This is probably due in part to several factors including: (1) the different stratigraphic ages of the samples; (2) the sample composition, which consists of single species and of mixtures of species with unknown isotopic fractionation; (3) modification of isotopic compositions of some samples by diagenetic alteration; and (4) the configuration of ocean basins and possible multiple sources of bottom waters in the Maestrichtian. For example, Douglas and Savin (1975) reported benthic foraminifer and nannofossil  $\delta^{18}\text{O}$  values from the Shatsky Rise in the Pacific Ocean that indicated a progressive decline in surface- and deep-water temperatures during the early Maestrichtian. Surface waters cooled while deep waters warmed in the late Maestrichtian. In contrast, Boersma and Shackleton's (1981)  $\delta^{18}\text{O}$  records for Site 465, also in the tropical Pacific, show a sharp decline in deep-water temperatures in the earliest early Maestrichtian followed by higher temperatures through the remainder of the Maestrichtian. Near-surface waters at Site 465 warmed in the late Maestrichtian relative to early Maestrichtian temperatures. Benthic foraminifer  $\delta^{18}\text{O}$  records of sites in the South Atlantic are also difficult to interpret. Saito and van Donk (1974) reported  $\delta^{18}\text{O}$  values indicating cooling of deep and surface waters at Site 21 during the Maestrichtian. However, Maestrichtian  $\delta^{18}\text{O}$  values from Site 358 in the Argentine Basin decrease with sample age (Barrera and Savin, unpublished data, 1986).

The  $\delta^{18}\text{O}$  time curves of benthic and planktonic taxa from Sites 689 and 690 are consistent with time trends observed in the  $\delta^{18}\text{O}$  values of well-preserved benthic foraminifers from nearby Seymour Island in the Antarctic Peninsula (Barrera et al., 1987). The monospecific data from Seymour Island indicate warmer bottom shelf waters in the early Maestrichtian than in the late Campanian, a rapid drop in water temperatures during the transition from early to late Maestrichtian time, and lower water temperatures during the rest of the late Maestrichtian. Sites 689 and 690 oxygen isotope data likewise suggest a long-term cooling of surface and bottom waters in the southern South Atlantic during the Maestrichtian, punctuated by a sharp drop in temperatures at the onset of the late Maestrichtian (Figs. 3 and 4). This demonstrates that environmental conditions inferred from Seymour Island data were not caused solely by nearshore processes, but, indeed, represent climatic changes in the Antarctic oceans and continent at this time.

#### INFERENCES ON THE ORIGIN OF BOTTOM WATERS IN THE SOUTHERN SOUTH ATLANTIC REGION

Paleotemperature estimates based on mean  $^{18}\text{O}/^{16}\text{O}$  ratios of *G. beccariiformis* (Table 5) for the early Maestrichtian interval suggest intermediate waters (at about the depth of 1500 m) between about 11° and 10°C, whereas late Maestrichtian intermediate waters were closer to 9°C at the Maud Rise. Intermediate waters seem to have cooled by about 2°C from the early to late Maestrichtian. Seymour Island shelf bottom-water temperatures were estimated at between 5.5° and 9°C in the early Maestrichtian and between 4° and 8.5°C during late Maestrichtian, assuming seawater at this location had an average  $\delta^{18}\text{O}$  of -1.5 per mil relative to SMOW (Barrera et al., 1987). Even if the  $\delta^{18}\text{O}$  values of seawater at both locations were similar, intermediate waters at the Maud Rise sites were only slightly warmer than shelf waters on Seymour Island. These paleotemperature estimates for the Maud Rise and Seymour Island are compatible with the idea

that the Antarctic margins were probable sites of bottom water production during the Maestrichtian as occurs today. Surface waters in Antarctic shelves could have become cold and dense enough to sink and become bottom waters, although sea-ice formation did not take place then as at present. It is also possible that bottom waters were formed from the sinking of warm, saline plumes in the low latitudes (Brass et al., 1982) and that they filled some ocean basins during the Maestrichtian. Nevertheless, bottom waters in the southern South Atlantic were likely of Antarctic origin. The oxygen isotopic compositions of benthic foraminifers from upper Maestrichtian sediments deposited at depths shallower than 2000 m in the South Atlantic indicate growth in waters of temperatures in the range of those estimated for the Maud Rise intermediate waters. Boersma (1984) estimated temperatures of 9°C for intermediate waters at the Agulhas Plateau during the latest Maestrichtian based on one measurement of *G. beccariiformis*. Shackleton et al. (1984) inferred latest Maestrichtian intermediate waters temperatures between about 6.5° and 10°C based on benthic data from Sites 525 and 527 in the South Atlantic, adjusted for the isotopic fractionation of species (which renders the temperature estimates of Shackleton et al. slightly lower than those from the Maud Rise).

Higher oxygen isotopic ratios, in general, for Maestrichtian benthic foraminifer species at the shallower water depth Site 689 than those from the deeper water Site 690 (Table 5) do not necessarily indicate that the latter was bathed by warmer waters originating in a low-latitude location, as proposed for Paleogene sediments at this site (Kennett and Stott, this volume). Oxygen isotopic ratios of shallow-dwelling Maestrichtian planktonic foraminifers from Site 689 are also on the average higher than those from Site 690, although we expect no significant differences between surface-water temperatures at these sites. We cannot offer an explanation for the higher oxygen isotope ratios of Site 689 foraminifers. However, carbon isotopic ratios of benthic foraminifer species from both sites are similar, suggesting that they were in contact with the same water mass. Hence, bottom water temperatures in the southern South Atlantic were likely lower than those of intermediate waters and perhaps more similar to those estimated at Seymour Island.

#### INTERPRETATION OF CARBON ISOTOPE RATIOS

Maestrichtian planktonic foraminifer  $\delta^{13}\text{C}$  values and time trends from the Maud Rise are typical of those observed in other deep-sea sites. Boersma (1984) reported that carbon isotope records of planktonic foraminifers from South and North Atlantic and Pacific deep-sea sites were very similar, exhibiting  $\delta^{13}\text{C}$  values around 2 per mil in lower Maestrichtian sediments and between 2.3 and 2.6 per mil in the *A. mayaroensis* Zone. Our values are in the range of those observed at these locations, and the magnitude of their increase from early to late Maestrichtian is also comparable (Figs. 3 and 4). Benthic foraminifer  $\delta^{13}\text{C}$  values, which fluctuate sympathetically with planktonic values, exhibit somewhat analogous time trends to that observed for Site 465  $\delta^{13}\text{C}$  values of *Bulimina* sp. (Boersma and Shackleton, 1981). At Sites 689 and 690, surface-to-bottom carbon isotope gradients remained more or less constant from early through late Maestrichtian time, with values between about 1 and 1.5 per mil. This indicates that the late Maestrichtian increase in  $\delta^{13}\text{C}$  was not entirely due to increased productivity in surface waters as proposed by Boersma (1984) but probably resulted from a global rise in sea level (Hallam, 1968) and increased storage of organic carbon in shallow shelf areas.

The Maud Rise depletion in  $^{13}\text{C}$  of bicarbonate just prior to the earliest late Maestrichtian decline in water temperatures is observed in  $\delta^{13}\text{C}$  values of Seymour Island. Except for this feature, there is little resemblance between records at these loca-

tions, probably because Seymour Island benthic foraminifer  $\delta^{13}\text{C}$  values were largely influenced by local environmental processes. This negative excursion is potentially a good stratigraphic marker because it appears to correlate with a drop in bulk carbonate  $\delta^{13}\text{C}$  values near the first appearance of *A. mayaroensis* in the sediments at Hole 700, 13° latitude to the north of the Maud Rise (Barrera and Huber, unpubl. data, 1988).

### SURFACE WATER TEMPERATURES AND PLANKTONIC FORAMINIFER PALEOBIOGEOGRAPHY

The warmest episode of the Maestrichtian at the Maud Rise, as inferred from the oxygen isotope data from Site 690, occurred between 73 Ma and 72 Ma. Subsequently, both surface and intermediate waters cooled, but surface waters cooled sharply at about 69.9 Ma and remained cool during the late Maestrichtian. A decrease in the thermal stratification of near-surface waters after about 69.5 Ma is inferred from the decrease in interspecific  $\delta^{18}\text{O}$  differences between planktonic taxa from Sites 689 and 690 (Table 5). Several keeled and nonkeeled species that previously were thought to have been restricted to warmer low-latitude regions have diachronous first appearances at the Maud Rise at about 71 Ma, 70.5 Ma, 69.5 Ma, and 66.5 Ma (Huber, this volume). However, oxygen isotope results presented in this study suggest progressive cooling of surface waters during this time interval. Periodic expansions of warm water masses into the south polar region have been proposed in paleobiogeographic models (e.g., Krasheninnikov and Basov, 1983) for the poleward migration of typical warm-water species. However, oxygen and carbon isotopic data from Holes 689B and 690C show no conspicuous shifts that can be correlated with these first appearance datums. Instead, the immigrant species thrived when fewer niches for thermophilic foraminifers appear to have been available. We suggest that the occurrences of these immigrant species at the Maud Rise were related neither to temperature nor to major water mass changes. Unfortunately, the causes of those seemingly anomalous occurrences cannot be discerned from the available geochemical data.

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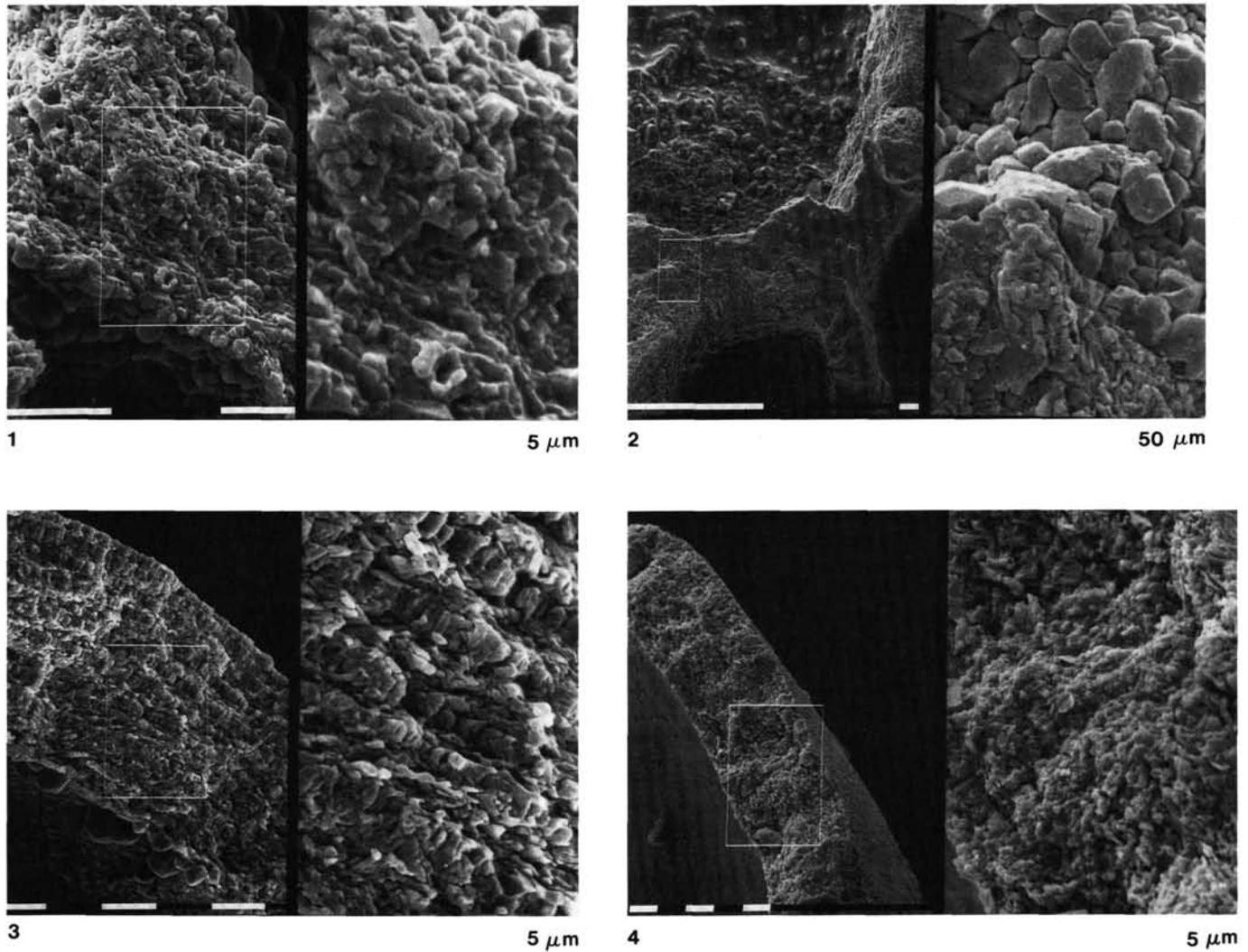
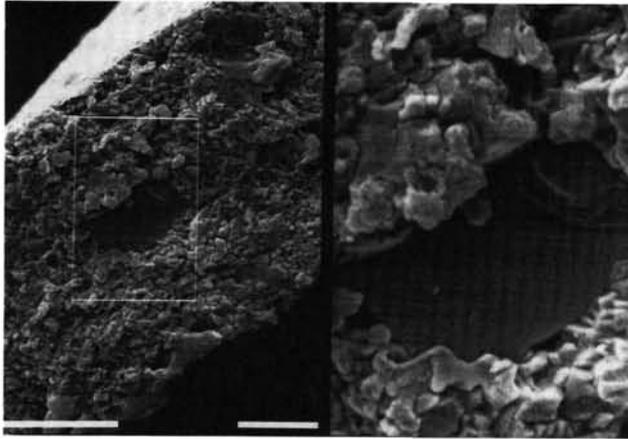
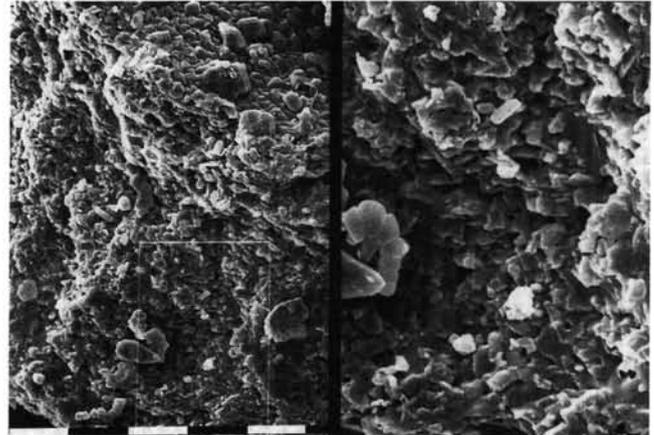


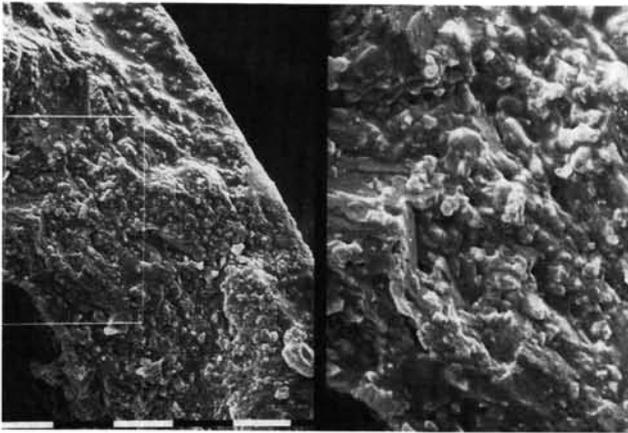
Plate 1. 1. Fractured test of *N. truempyi* showing a septal wall composed of coarse crystal of replacement calcite. The photograph in the right shows the area enclosed by the rectangle on the left. Interior surface chambers are covered by euhedral diagenetic calcite. Sample 113-690C-17X-1, 119-123 cm. 2. Septal wall of *G. beccariiformis* composed in part of large euhedral crystals (indicated by arrow) and of blocky secondary calcite. Sample 113-690C-17X-3, 119-123 cm. 3. Wall structure of *G. beccariiformis* replaced by coarse secondary calcite. Note large euhedral overgrowth calcite crystals on the interior surface of the chambers, indicated by arrow. Sample 113-690C-19X-1, 119-123 cm. 4. Wall structure of a well-preserved specimen of *G. beccariiformis* composed of fine-grained calcite. Interior surface chambers are free of overgrowth calcite. Sample 113-690C-19X-3, 119-123 cm.



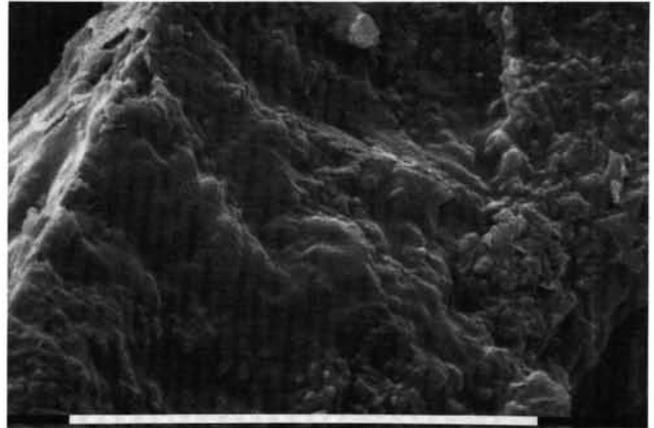
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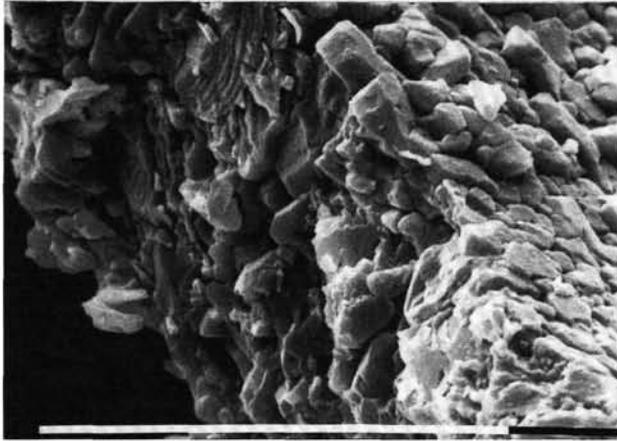


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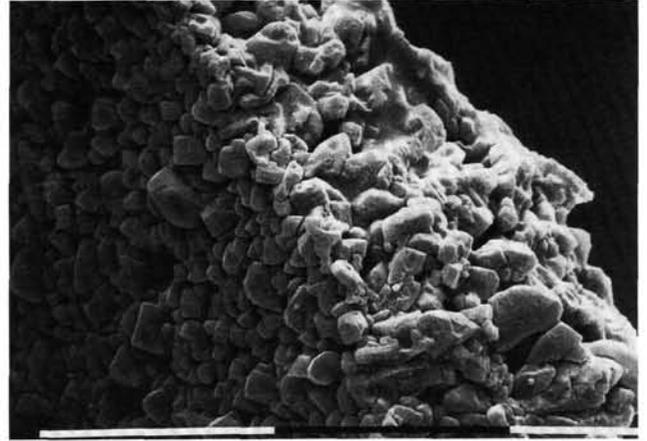
4 10 μm

Plate 2. 1. Aspect of the chamber wall of *G. beccariiformis* showing a large block of secondary calcite. Sample 113-690C-21X-1, 118-122 cm. 2. Blocky diagenetic texture (indicated by arrow) in the chamber wall of a *G. beccariiformis* specimen. Round holes distributed throughout the wall of this specimen (more apparent in lower right-side of the photograph) are microbial tubes (Claude Monty, pers. comm., 1988). Sample 113-689B-27X-1, 85-89 cm. 3. Chamber wall of *G. beccariiformis* replaced by blocky calcite (fracture surfaces are shown by arrow). Sample 113-689B-32X, CC. 4. Chamber wall of *C. incrassata* replaced by blocky calcite. Sample 113-690C-19X-1, 119-123 cm.



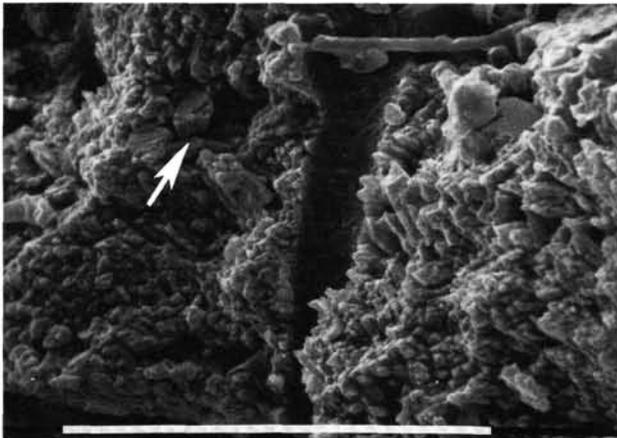
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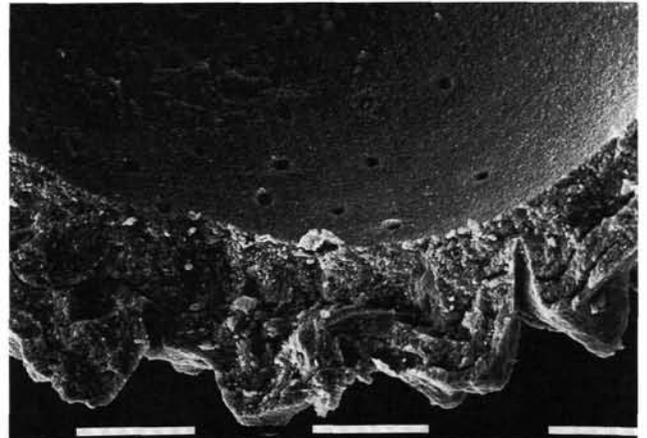
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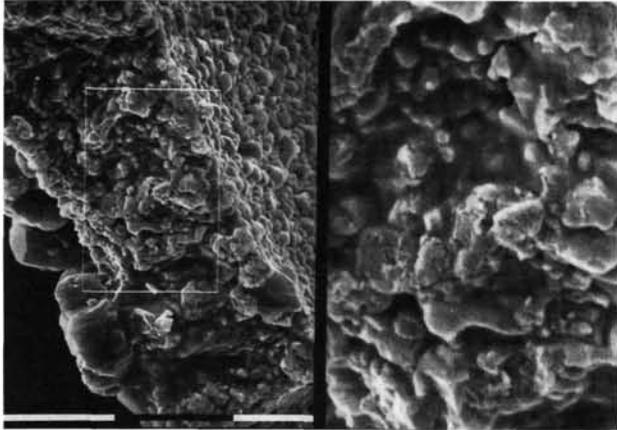
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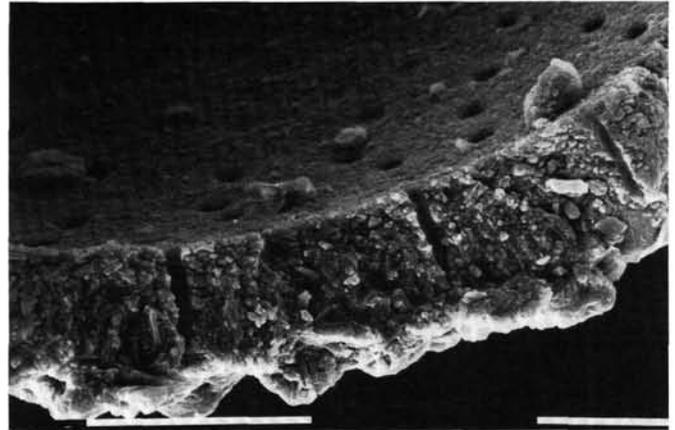
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Plate 3. 1. Wall structure of *C. incrassata* composed of large euhedral crystals of secondary calcite. Sample 113-689B-27X-2, 83-87 cm. 2. Exterior chamber wall of *A. mayaroensis* entirely composed of large euhedral secondary calcite. Interior surface chambers are overgrown with diagenetic calcite. Sample 113-689B-27X-2, 83-87 cm. 3. Chamber wall of *A. australis* with patches of fine-grained calcite and coarse-grained diagenetic calcite (shown by arrow) in what appears to be solution cavities. Pore surfaces are free of large overgrowth calcite. Sample 113-690C-19X-1, 119-123 cm. 4. Specimen of *A. australis* exhibiting apparent excellent preservation. Notice boundaries between layers of the wall structure and interior surface free of overgrowth calcite. Sample 113-690C-20X-3, 116-118 cm.



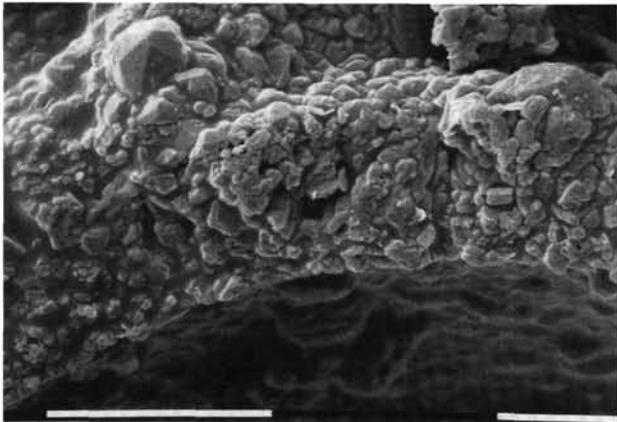
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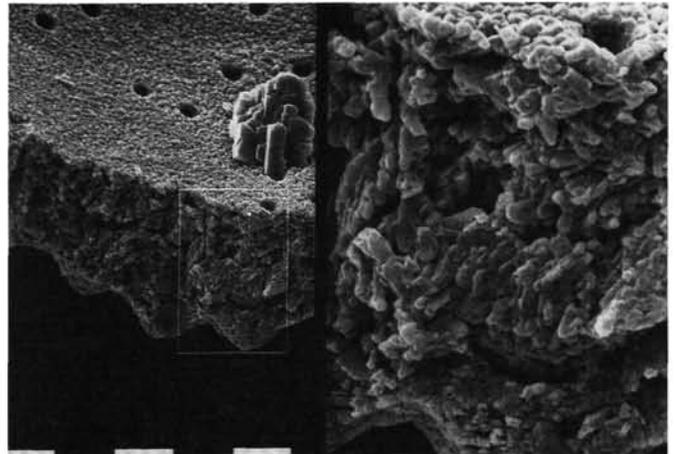
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Plate 4. 1. Exterior chamber wall of *A. australis* characterized by a diagenetic texture somewhat similar to the blocky texture seen in benthic foraminifer specimens. Sample 113-689B-32X, CC. 2. Chamber wall of *G. multispinatus* showing very good preservation and no apparent replacement by secondary calcite. Interior surface chambers are also free of large overgrowth calcite crystals. Sample 113-690C-20X-3, 116–118 cm. 3. Wall of an early chamber *G. multispinatus* replaced by coarse-grained diagenetic calcite. Sample 113-689B-28X-2, 80–84 cm. 4. Chamber wall of a *G. multispinatus* specimen affected by calcite replacement and solution. Sample 113-689B-28X, CC.