MASTER

Final Technical Report

COO-1796-2

1. TIME-DEPENDENT VARIATIONS IN SURFACE
OCEANIC CURRENTS

Dr. Robert G. Douglas
Principal Investigator
Department of Geology
Case Western Reserve University
Cleveland, Ohio 44106

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2. SCIENTIFIC SCOPE

Objective

The objective of our investigation was to 1) determine the surface circulation pattern responsive to the conditions associated with the climatic extremes of the last 120,000 years, and 2) to search the record since the end of the Wisconsin for circulation models responsive to smaller scale climate changes.

Previous Work

The first contract year was spent in developing and testing various methods for reconstructing surface current patterns based on isotherm surfaces. The methods developed were based upon interpreting the temperature significance of the tests of planktonic foraminifera recovered from bottom sediments. The temperature record contained in the microfossils was deciphered from an analysis of 1) species diversity, and 2) faunal gradients calculated from species assemblages. The methods were applied to data derived from plankton and sediment samples and yielded foraminiferal surfaces for the South Pacific which resemble present-day isotherm surfaces. From the foraminiferal surfaces we concluded that: 1) the position of the major oceanic fronts and the eastern boundary currents could be identified; 2) the surfaces could be quantitatively evaluated within about $\pm 2^{\circ}$ C; and 3) the structure of the present-day surface circulation pattern is closely reflected in bottom sediments. Our analyses also

noted that the effects of selective dissolution of planktonic foraminiferal tests in bottom sediments acts in opposition to the recovery of the desired information stored in the foraminifera.

Current Work

In the second contract year two objectives were pursued:

- 1) oxygen isotope geochemical analysis of the tests of planktonic foraminifera as a means for calculating paleotemperatures, and
- 2) reconstruction of the surface circulation pattern responsive to the climatic extremes of the Wisconsin (the last glacial period).

Isotopic paleotemperature analysis was required as an independent check of the isotherm surfaces determined from faunal data and to increase our temperature resolution in critical latitudinal belts. Our previous work with species diversity surfaces and standardized faunal gradient surfaces, calibrated in terms of temperature, indicated that overall the biological methods yield isotherms within $\pm 2-3^{\circ}\text{C}$ of average sea-surface values in low and high latitudes, but in mid-latitudes and in regions of seasonally shifting oceanic fronts the methods fall off sharply. Also, as noted previously, selected dissolution of foraminiferal tests in bottom sediments acts in opposition to information recovery and can introduce subtle distortions in the foraminiferal results. Selective dissolution and the resulting faunal bias is more profound than was originally anticipated and emphasized the need for a third independent method of determining temperature.

Isotherm surfaces from which circulation patterns could be interpreted were previously produced (Douglas, 1969; Figs. 3a, 15, 16) for the present-day ocean and a time interval represented by the upper few centimeters of bottom sediment, about 1,000-2,000 years ago. The surfaces were quite similar except that the older surface seems to suggest a shift in the position of the convergence zone. Analysis of a glacial interval was desired to determine the surface circulation pattern response to a climate colder than at present time or the last several thousand years.

A total of nearly 18 man-months, spread out over two years, were expended in pursuing the research objectives. By far most of this time was invested in the geochemical analyses which proved to be considerably more time-consuming than anticipated, both in terms of sample preparation and machine run-time. Nearly 5 months in downtime in the operation of the mass spectrometer also contributed to delays in the investigation. The high cost/yield ratio renders the isotopic method marginal for regional investigations involving large numbers of determinations. Primarily for this reason, but influenced by other factors discussed below, the contract research was not renewed in March, 1970.

3. METHODS

Isotopic Paleotemperature Analysis

The technique of oxygen extraction and analysis for paleotemperature studies is now fairly standardized (Epstein, et al.,

1964). Samples for isotopic analysis were selected based on state of fossil preservation, abundance of foraminifera, degree of dissolution, type of core sample, and geographic location of the site. We strived for maximum precision by undertaking duplicate runs (and in many cases triplicate or quadruplicate runs) for oxygen extraction in all samples except where insufficient material was available. Carbon isotopes were also determined. Paleotemperatures were calculated using the equation (Craig and Gordon, 1965):

$$t = 16.9 - 4.2(\delta c^+ - \delta w^+) + 0.13(\delta c^+ - \delta w^+)^2$$

where δc^+ is the oxygen isotope values for carbonate relative to the PDB standard, and δw^+ is 0.20 per mil less than δO^{18H_2O} for Standard Mean Ocean Water (SMOW). δO^{18H_2O} SMOW values for the South Pacific were determined from graphs already corrected for salinity contained in Craig and Gordon (1965). Calculated temperatures are believed to be accurate to $\pm 1.5^\circ C$; the lack of detailed information regarding salinity changes with depth hampered more accurate determinations. A total of 165 analyses were made on samples from 61 sites (Table 1).

The major problems in application of the paleotemperature technique to our research were: 1) the influence of the method of sample preparation on the measured isotopic composition; 2) the effect on the oxygen isotopic composition of foraminifera which are depth-stratified in the water column; and 3) how close the isotopic paleotemperatures determined for planktonic foraminifera correlate to actual near-surface isotherm values.

TABLE 1

CORE	Depth in Core (cm)	STATION		WATER DEPTH (m)	GENUS ANALYZED	ISOTOPIC RESULTS			N.O.C. DATA		
		Lat	Long			δC^{13}	δO^{18} ^{PBD}	Isotopic Temp. °C	Surface Temp. °C	Δt	Equival. Depth (m)
AMPH 22G	3-5	8°34'S	107°12'W	3240	GD	+1.64	-1.04	23.0	24.0	1.0	74
					GR	+3.17	-1.06 -0.01 +0.16	18.0	24.0	6.0	87
AMPH 30PG	0-4	18°31'S	111°09'W	(3100)	GD	+1.77	-0.49 -0.46	20.6	25	4.4	151
					GR	+2.27	+0.32 +0.38	17.0	25	8	202
AMPH 37	3-5	18°16'S	121°05'W	3720	GD	+2.09	-0.47 -0.30	19.3	26.5	6.2	70
					GR	+3.79	+0.31 +0.06	17.0	26.5	8.5	85
AMPH 79	0-4	12°08'S	163°20'W	3188	GD	+2.39	-1.38 +0.18	21.0	29.0	8.0	124
					GR	+2.14	+0.02	18.5	29.0	10.5	212
AMPH 99PG	0-5	1°56'S	156°42'W	4983	GR	+1.95	+0.55 +0.53	15.3	25.5	102	194
AMPH 134	0-4	3°32'S	141°26'W	4255	GR	+1.79	+0.41 +0.43	16.2	27.0	10.8	145
AMPH 138	0-4	3°33'N	133°10'W	4300	GR	+1.82	+0.15 -0.04	17.3	24	6.7	70
					GR	+1.84	+0.14 +0.01	17.5	26	8.5	200
DWBG 11	0-5	5°26'N	131°19'W	4155	GR	+1.81	-0.10 +0.13	17.9	28	10.1	41
DWBG 14	0-4	1°24'S	131°30'W	4511	GR	+1.89	+0.55 +0.53	15.5	24.5	9.0	71
DWBG 23A	0-4	16°42'S	145°48'W	(2000)	GD	+3.62	-1.31 -1.44 -1.56	24.5	27.5	3.0	0
					GD	+1.59	+0.16	17.8	27.5	9.7	220
DWBG 32	4-7	24°5'S	146°11'W	4020	GR	+1.64	+1.60	10.5	27.5	17.5	420

Globigerinoides = GD

Globorotalia = GR

CORE	Depth in Core (cm)	STATION		WATER DEPTH (m)	GENUS ANALYZED	ISOTOPIC RESULTS				N.O.C. DATA	
		Lat	Long			δ^{13}	$\delta^{18\text{PBD}}$	Isotopic Temp. °C	Surface Temp. °C	Δt	Equival. Depth (m)
DWBG 60	6-9	45°27'S	124°01'W	4040	GR	+1.04	+3.33	4.5	9.0	4.5	849
DWBG 73	0-5	43°48'S	108°09'W	3080	ASSEMBLAGE	+0.83	+3.21	6.5	11.0	4.5	170
DWBG 73	0-5	43°48'S	108°09'W	3080			+2.75				
							+2.68				
					GR	+1.28	+2.89	7.5	11.0	3.5	127
							+2.14				
							+2.42				
DWBG 76	0-5	43°45'S	104°28'W	3840	GR	+1.73	+3.03	5.0	10.0	5.0	646
							+3.29				
							+3.14				
DWBG 79	4-8	44°06'S	100°04'W	3940	GR	+1.60	+3.40	4.0	13.5	9.5	-
							+3.47				
DWBG 83	2-7	44°03'S	95°42'W	4660	GR	+1.41	+3.72	3.3	9.0	5.7	935
							+3.60				
DWBG 98C	20-22	20°49'S	81°08'W	2300	GD	+1.43	+0.10	18.0	17.5	-0.5	0
							+0.03				
					GR	+0.97	+1.32	13.3	17.5	4.2	77
							+1.29				
DWBG 100	0-5	19°17'S	79°32'W	3640	GR	+2.43	+0.26	17.5	17.0	-6.5	0
							+0.15				
DWBG 118C	0-2	28°02'S	96°20'W	3400	GD	+1.98	+0.81	15.8	20.0	4.2	175
							+0.81				
					GR	+1.65	+1.76	11.0	20.0	9.0	277
							+1.40				
							+1.54				
DWBG 119BP	3-5	27°54'S	106°53'W	3200	GR	+1.60	+1.51	12.5	22.5	10.0	300
							+1.40				
DWBG 120	23-25	27°56'S	106°55'W	3060	GD	+1.66	+0.26	17.2	22.5	4.3	184
							+0.27				
					GR	+1.83	+1.29	14.0	22.5	8.5	269
							+1.07				
DWBG 137	2-5	9°53'S	110°41'W	2770	GD	+2.56	-1.01	23.0	23.0	0	0
							-0.99				
					GR	+1.96	-0.01	18.6	23.0	4.4	101
							-0.09				
DWBG 140	2-5.5	5°55'S	112°31'W	4120	GR	+1.83	+0.34	17.0	25	8.0	48
							+0.28				
DWBG 143	0-5	3°37'S	114°18'W	4310	GR	+1.81	+0.64	15.4	25	9.6	52
							+0.67				
RIS 91G	0-6	15°40'S	147°27'W	2518	GD	+2.31	-1.61	25.0	27.5	2.5	0
							-1.47				

CORE	STATION		WATER DEPTH	GENUS ANALYZED	ISOTOPIC RESULTS			N.O.C. DATA			
	Depth in Core (cm)	Lat			Long	(m)	δC^{13}	$\delta O^{18}PBD$	Isotopic Temp. °C	Surface Temp. °C	Δt
DWHG 37	0-3	46°03'S	116°11'W	3400	GR	+1.29	+3.34 +3.02 +3.15	5	9.0	4.0	647
DWHG 74	0-5	28°29'S	106°30'W	3030	GD	+2.01	+0.49 +0.60	15.6	23.0	9.4	227
					GR	+1.70	+1.48 +1.39	12.0	23.0	11.0	309
DWHG 84	0-3	15°44'S	112°13'W	3200	GD	+1.89	-0.59 -0.65	20.6	25.0	4.4	103
					GR	+2.30	+0.61	15.6	25.0	9.4	182
DWHG 85	0-4	13°09'S	110°38'W	3100	ASSEMBLAGE	+1.90	+0.12 +0.08				
					GD		-1.07	22.5	25.0	2.5	48
					GD*	+2.30	-0.77 -0.80				-
					GR	+2.17	+0.01 +0.11 +0.05	17.6	25.0	7.4	151
					GR*	+2.39	+0.37 +0.33				
LSDH 77	0-5	5°39'S	165°28'E	2556	GD	+1.94	-1.76 -1.77	25.0	29.0	4.0	139
					GR		-0.25 -0.43	19.0	29.0	10.0	190
LSDH 78G	0-3	4°31'S	168°02'E	3208	ASSEMBLAGE	+1.25	-0.48 -0.61	24.0	28.5	4.5	-
					GD	+1.54	-1.24 -1.32	23.5	28.5	5.0	151
					GR		-1.11	24.5	28.5	4.5	143
					GD*	+1.71	-0.96 -1.06				-
					GR*	+1.63	-0.06 -0.06				-
MSN 104PG	0-4	46°21'S	175°14'E	1865	GR	+1.30	+2.24 +2.10	10.0	14.0	4.0	376
MSN 126	0-4	24°41'S	154°45'W	4542	GD	+1.67	-0.11 -0.01	18.5	27.0	8.5	199
					GR	+1.42	+1.79 +1.25 +1.31	12.5	27.0	14.5	406

*sample technique experiment

*sample technique experiment

CORE	STATION		WATER DEPTH	GENUS ANALYZED	ISOTOPIC RESULTS				N.O.C. DATA		
	Depth in Core(cm)	Lat			Long	(m)	δC^{13}	δO^{18PBD}	Isotopic Temp.°C	Surface Temp.°C	Δt
PROA 47G	0-4	21°57'S	167°57'E	2010	GD	0.99	-1.64	25.5	23.0	-2.5	0
PROA 66	0-3	10°45'S	175°25'E	4265	GD		-1.64				
						-0.77	21.0	28.5	7.5	275	
					GR	+1.29	+0.61	15.5	28.5	13.0	347
PROA 69D	Dredge	11°36'S	175°09'E	1000	GD	+2.09	+0.58				
						-2.00	26.5	28.5	2.0	76	
						-2.00					
PROA 71D	Dredge	11°34'S	175°11'E	1550	GD	+2.17	-2.73				
						-2.47	29.4	28.5	-0.9	0	
						-2.61					
RIS 29G	7-10	2°18'N	89°27'W	2230	GD	+3.31	-1.69	26.0	19.5	-6.5	-
						-1.68					
					GR	+1.59	+0.02	18.5	19.5	1.0	-
RIS 51G	0-5	13°32'S	97°48'W	3742	GR	+2.49	-0.06				
						+0.57	16.5	23.0	6.5	162	
						+0.44					
RIS 74G	0-7	14°00'S	119°36'W	3685	GD	+2.06	-0.86	21.5	26.0	4.5	127
						-0.78					
					GR	+2.54	+0.40	15.2	26.0	10.8	225
RIS 76G	0-4	13°54'S	125°21'W	3800	GD	+2.27	+0.36				
						-1.07	24.0	27.0	3.0	70	
						-1.20					
RIS 78V	0-10	14°02'S	130°18'W	4080	GR	+2.07	-1.11	18.7	27.0	8.3	205
						-0.15					
						-0.23					
RIS 78V	0-10	14°02'S	130°18'W	4080	GD	+2.27	-0.80				
						-0.94	21.3	27.5	6.2	141	
						-0.98					
RIS 84G	0-4	15°15'S	142°27'W	3675	GR	+2.54	0.00	17.5	27.5	10.0	211
						+0.14					
						-1.11					
RIS 87G	0-3.5	16°30'S	145°07'W	1443	GD	+2.92	-1.09	22.7	23.5	0.8	120
						-1.00					
						-1.61	25.5	27.5	2.0	0	
TET 38	0-7	5°21'N	160°30'W	3614	GD	+2.78	-1.73				
						-2.08	26.5	27.5	1.0	0	
						-1.89					
TET 38	0-7	5°21'N	160°30'W	3614	GR	+2.01	-0.56	21.0	27.0	6.0	114
						-0.80					
						+1.63					
WAH 8FF	0-3	0°02'N	147°59'W	4308	GR	+2.02	-0.05	17.5	25.0	7.5	169
						+0.17					
GD ave Δt = 4.1 GR ave Δt = 7.9											

Emiliani (1964), Van Donk (1970) and studies undertaken in our laboratory show that the method of sample preparation influences the measured isotopic composition of the samples (Table 2). In the case of foraminifera, the amount of organic matrix in the shell, which serves to control the calcification process, influences the measured oxygen isotope ratios. Untreated sediment samples were found to contain various amounts of organic matrix within the shells, depending on the species involved, the residence time in the sediments and water depth. It was therefore, necessary to remove all organic material from the foraminifera prior to mass spectrometry. After a series of experiments the following procedure was adopted: 1) clean sample in a sonic bath for 2 minutes; 2) grind to less than 200 μ size; 3) soak in 10% solution of sodium hypochlorite for 24 hours. Any error due to the method of pretreatment is small ($<0.5^{\circ}\text{C}$) and constant for all the analyses.

Detailed studies of living planktonic foraminifera reveal that different species tend to live at different depths in the water columns, i.e., they are depth-stratified. While most species inhabit the upper 200-300 meters, some spend all or parts of their existence at depths up to 1500-2000 meters. (In equatorial regions, for example, a depth range of 1000 meters can correspond to a temperature range of 20-25 $^{\circ}\text{C}$.) Studies by Lidz, et al. (1968), Oba (1969), Hecht (1970) and ourselves have shown that Recent and Pleistocene species from single samples tend to have the same ranking of isotopic temperatures, and shallow-dwelling species invariably record the warmest values,

TABLE 2

Effect of pretreatment on isotopic results obtained from planktonic foraminifera

<u>Sample</u>	<u>Genus</u>	<u>Isotopic Results ($\delta^{18}\text{PDB}$ per mil.)</u>		
		Untreated ¹	Treated ²	ave. Δ
DWHG 85 0-4 cm	<u>Globorotalia</u>	+0.37	+0.01	0.29
		+0.33	+0.11	
	<u>Globigerinoides</u>	-0.77	-1.07	0.29
		-0.80		
LSDH 78G 0-3 cm	<u>Globorotalia</u>	-0.06	-1.11	1.05
		-0.06		
	<u>Globigerinoides</u>	-0.96	-1.24	0.27
		-1.06	-1.32	

¹Untreated = samples cleaned in distilled water and analyzed

²Treated = samples cleaned in sonic bath, crushed to 200 μ size and soaked in 5% sodium hypochlorite for 24 hours to remove organic matrix

and deep-dwelling species record the coldest temperatures. Genera representing two depth categories were chosen for analyses: Globigerinoides, representing the shallow layer, and Globorotalia, representing the intermediate layer in the ocean. Generic determinations rather than species determination were used because of the limited areal distribution of individual species and because dissolution preferentially removes species of Globigerinoides at most equatorial and deep water sample sites. The influence of depth-stratification on the geochemical results was evaluated by calculating water depths equivalent to the isotopic temperature at each sample site from temperature-depth profile supplied by the National Oceanographic Data Center (NODC). These data are given in Table 1 and summarized in Figure 1.

Since the planktonic foraminiferal tests used in isotopic analyses were secreted at depths below the surface but generally within the upper 300 meters, isotopic temperatures are only estimates of actual surface temperature. The estimates were evaluated by comparing isotopic temperatures for each site to surface temperatures supplied by the NODC. Only NODC records for summer months (January to March) and collected at stations within 5° of the sample sites were used (Figure 2). The departure values (NODC temperature-isotopic temperature) averaged 4.1° for Globigerinoides and 7.9° C for Globorotalia (see Table 1).

Figure 2 - Sea surface isotherms for South Pacific (summer months) based on National Oceanographic Data Center information.

4. RESULTS OF THE INVESTIGATION

Geochemical Analyses

Paleotemperature surfaces calculated from the isotopic analyses of Globigerinoides and Globorotalia are shown in Figures 3 and 4. A comparison of these surfaces to the surface isotherm pattern for the South Pacific (Figure 2) reveals only a gross resemblance (even though the isotopic surfaces are based on the widest geographic distribution of sample sites presently available from cores). The lack of detail is largely the result of two factors: 1) the depth-stratification of foraminiferal species, and 2) selective dissolution of foraminiferal species in the sediment.

Isotopic temperatures determined for Globigerinoides have the smallest departure values (i.e., surface temperature minus isotopic temperature) and provide the best estimate of sea surface temperatures (Figures 5a, 6). Plankton tows indicate that Globigerinoides is the shallowest-dwelling genus of living planktonic foraminifera (Berger, 1969; Jones, 1968); even so, individual species tend to occupy the upper 300 meters of water. Globigerinoides ruber is most common in the upper 50 meters and isotopically yields the warmest values (Figure 1). The other common species of the genus, G. sacculifer and G. conglobatus, inhabit deeper depths, between about 70 to 180 meters and 150 to 300 meters, respectively. Isotopic determinations for the genus usually involved a mixture of species rather than monospecific samples, and the variation between closely

Figure 4 - Isotopic isotherms surface based on Globorotalia.

Figure 5 - a) Latitudinal distribution of isotopic temperatures based on Globigerinoides.
 b) Latitudinal distribution of isotopic temperatures based on Globorotalia.

x = *Globigerinoides*
 • = *Globorotalia*

Figure 6 - a) Departure values (NODC sea surface temperatures minus isotopic temperatures) arranged by latitude.
 b) Longitudinal distribution of all isotopic temperatures.

spaced sites can be explained by the varying depth range, hence temperature, represented by the composite of species present. On the average, temperatures determined from Globigerinoides are within 4.1° C of N.O.D.C. sea surface values. The position of the 15° and 20° isotope isotherms in the eastern South Pacific (Figure 3) are, however, closer to the average position of the isotherms at 200 meters (Figure 7) than their average surface position.

Species of Globorotalia occupy a wide range of depths but most are associated with the intermediate layer of the ocean. The genus has a broader geographic range than Globigerinoides and four common species, with overlapping ranges, were analyzed: G. cultrata, G. tumida, G. truncatulinoides, and G. crassaformis. Plankton tows indicate a broad depth range for these taxa, which is corroborated by our isotopic analyses (Figure 1). G. cultrata and G. tumida yield depths ranging from the surface to about 200 meters, but G. crassaformis and G. truncatulinoides are most common at levels between 300 to 1000 meters. Temperature values averaged about 8° C less than surface temperatures, and the pattern of isotopic isotherms (Figure 4) resembles the average thermal structure at 400 meters (Figure 8). In longitudinal profile, analyses of Globorotalia reveal a fairly smooth change in isotopic temperature with latitude plus indicating the position of the cool equatorial current just south of the equator (Figure 5b).

The basic technique employed in our investigation of current-circulation models has been the analysis of isotherm surfaces recon-

Figure 7 - Temperature of the Pacific Ocean at a depth of 200 meters (from Sverdrup et.al., 1942).

Figure 8 - Temperature of the Pacific Ocean at a depth of 400 meters (from Sverdrup, et.al., 1942)

structed from foraminiferal data. As we recognized earlier (Douglas, 1969), selective dissolution of the tests of planktonic foraminifera tends to act in opposition to information recovery. It is becoming apparent that the effects of selective dissolution are highly pervasive in the South Pacific (probably in all oceans), and all but a very few sediment samples are affected and therefore biased. The final result of intense dissolution, usually fairly obvious, is the total (or nearly) removal of the more soluble species from sediment assemblages. This effect is apparent in the case of Globigerinoides for all sites south of about 40° S, adjacent to South America and in a narrow band beneath the equator (Figure 3). Conversely, at the same sites, species of Globorotalia which are more resistant to dissolution, show an increased relative abundance. Of equal concern are the less dramatic effects of dissolution which can subtly distort information recovery. Our geochemical analyses illustrate one such effect.

A plot of δO^{18PDB} values, corrected for salinity and the oxygen isotope content of Pacific water, against water depth at the core site indicates an apparent correlation for determinations based on Globigerinoides (Figure 9b). The correlation is linear (statistically valid at the .99 level, $r = 0.534$) and suggests that isotopic temperatures increase at about 2° C per 1000 meters. Three models can be suggested which explain this relationship: 1) an oxygen isotope exchange with bottom water; 2) a fortuitous distribution of sites where the shallowest sites occur only in tropical regions

Figure 9 - a) Isotopic temperatures based on Globorotalia and water depth at the core site.
 b) Isotopic temperatures based on Globigerinoides and water depth at the core site.

and the deeper sites occur in cooler regions; or 3) preferential dissolution of species such that the tropical shallow water forms are removed before cooler, deep water forms.

The first explanation seems unlikely as isotopic exchange time, based on theoretical calculations for carbonate crystals of 1 micron or larger, are on the order to 10^5 years (Urey, et al., 1951) and none of the studied samples are more than a few thousand years old. However, it must be noted that the microstructure of the calcite crystals in planktonic foraminifera is not well known, and the possibility exists that individual calcite crystallites are less than one micron in size.

The second possibility can be tested by examining the temperature and salinity properties of the core sites. Salinity at a depth of 10 meters at each site shows no relationship with the site water depth (Figure 10a); it does not appear to be a contributing factor. However, an examination of temperature distribution versus site bathymetry reveals that most of the cores from the eastern Pacific were raised from depths between 3000-4000 meters. Average surface temperature is about 2.5° lower for the east Pacific sites than at sites in the west Pacific, which are located in an area of positive thermal anomaly (Figure 10b). Thus, the geographic distribution of core sites accounts for a portion of the apparent increase in oxygen isotope values with increasing water depth, but the relationship persists after correction for core location.

The major cause of the relationship is discovered when the

data points in Figure 9b are identified according to species and these species ranked according to their resistance to dissolution and the depth in the water column that they inhabit (Table 3).

This analysis reveals a strong correlation between dissolution, depth-stratification, and also temperature sensitivity, i.e., the range of temperatures within which the species lives. Clearly, in generic isotopic analyses, based on a mixture of Globigerinoides species, increasing selective dissolution in the sediments will result in cooler temperatures as the relative frequency of the shallowest-dwelling, hence warmest, species is reduced. Determinations for Globorotalia are less susceptible to the depth stratification-dissolution effect because the warmest species are highly resistant to dissolution. An exception exists for mid-latitude stations which contains a mixture of subtropical and temperate species; the latter usually having somewhat better chances for preservation than subtropical forms. The potential result can be seen in Figure 9a. All of the isotopic values >1.50 per mil represent G. truncatulinoides for stations located between 40° - 46° S. The warmer species, G. cultrata, which also occurs at these latitudes is less abundant because it is near the limits of its zoogeographic range and because it is less resistant to dissolution. Thus, isotopic analyses of species of Globorotalia subjected to increasing selective dissolution in low latitudes tend to yield warmer isotopic values while assemblages from mid-latitudes tend

TABLE 3

Ranking of resistance to dissolution, depth-stratification and temperature sensitivity of planktonic foraminiferal species used in geochemical analysis.

	<u>DISSOLUTION</u>	<u>DEPTH-STRATIFICATION</u>		<u>TEMPERATURE</u>
↓ resistance	1. Globigerionides ruber	1. G. ruber	↓ range of temperature	1. G. conglobatus
	2. G. sacculifer	2. G. sacculifer		2. G. cultrata
	3. G. conglobatus	3. G. conglobatus		3. G. tumida
	4. Globorotalia cultrata	4. G. tumida		4. G. ruber
	5. G. crassaformis	5. G. cultrata		5. G. sacculifer
	6. G. truncatulinoides	6. G. crassaformis		6. G. crassaformis
	7. G. tumida	7. G. truncatulinoides		7. G. truncatulinoides

to yield cooler isotopic values, depending upon the dominant species in the assemblage.

Determinations for δC^{13} were made concurrently with the oxygen extractions, primarily for use in calculating paleotemperatures. However, it is known that carbon-13 fixation is related to biological productivity in the ocean and that the high δC^{13} values are associated with the areas of high biological overturn. High biological productivity in the ocean occurs at oceanic fronts and where deep water is advected to the surface by upwelling or ridging; the productive zones are in turn related to surface circulation patterns, though in a rather complex way. For this reason, the potential use of δC^{13} values as an oceanographic index was briefly examined. Highest δC^{13} values were found in samples from beneath the mid-ocean subtropical gyral in the belt between 10° to 25° S latitude while the lowest δC^{13} values were found in samples from beneath the eastern equatorial belt, adjacent to South America and beneath the subtropical convergence (Figure 11). The high carbon-13 area is within a belt where annual evaporation exceeds precipitation, resulting in salinities of 36.00 to 36.5‰ (high for the Pacific Ocean) and is a region of low productivity (Fleming, 1957). Conversely, the remaining samples come from regions of normal, or lower salinity which include the zones of highest productivity in the ocean (Fleming, 1957). The most important variable appears to be salinity (Figure 12), but more detailed data on the productivity of foraminifera are required before the relationship can be critically assessed.

Figure 11 - Regional distribution of isotopic Carbon 13 shown as areas of high values, $\delta C^{13} \geq 2.0$ per mil, and low values, $\delta C^{13} < 2.0$ per mil.

Figure 12 - Relationship of isotopic carbon values and latitude.

Analysis of Wisconsin (Ice Age) Samples

Geochemical and faunal examinations of core samples believed to represent the latter part of the last glacial period (Wisconsin) were in progress when the investigation was terminated. The results, though incomplete, reveal several important problems in identifying pre-Recent time intervals on an ocean-wide basis.

Two approaches are normally employed in identifying glacial and non-glacial time intervals in deep-sea cores: geochronological methods which determine the absolute age of a sample and paleontological methods which determine relative age by comparison of the fossils in the sample. The applicable geochronological methods, radiocarbon-14 and ionium-thorium, provide excellent results but are impractical as routine dating techniques (because of the cost per date). Therefore paleontological means usually supply the basis for age determinations, the usual practice is to interpret the change in temperature sensitive planktonic foraminifera down the core (through time) with respect to present-day species. Intervals in the core which contain a relative decrease in certain tropical species (or an increase in temperate or polar forms) with respect to the species presently living at that location are interpreted as glacial; intervals which contain a relative increase in tropical species, etc., are interpreted as non-glacial. Beside the possibility of being circular (e.g., the last glacial event is defined as Wisconsin, therefore all Wisconsin fossils represent a glacial climate), the method is susceptible to error in application because of the subtle changes in species frequency and species assemblage.

resulting from selective dissolution. Samples from five different cores for which a climatic interpretation had been independently determined (Blackman, 1966; J. Kennett and G. Geitzenhauer, pers. comm.) were subjected to a form of cluster analysis using the relative frequency of all the species present. The results agreed only in part with the previous climatic interpretations of the same samples. The differences in interpretation can be traced to core intervals which contained varying abundances of temperature sensitive species, such as Globigerinoides ruber, which have a low resistance to solution destruction. Our results suggest that the faunal variation between nearby sites from water depths at or below the lysocline (Parker and Berger, 1971) is equal to the faunal variation between adjacent samples from within a core. Faunal variation resulting from varying degrees of preferential preservation may resemble the results due to climatic fluctuations and criteria are needed which will allow the recognition of foraminiferal ^c changes responsive to these two factors.

5. CONCLUSIONS

Based upon the results obtained in our investigation, we can conclude:

1. Surface oceanic current pattern can be determined in varying detail by faunistic and geochemical data derived from planktonic foraminifera. Faunistic methods, based on taxonomic diversity and

standardized faunal gradients, accurately portray thermal anomalies and circulation patterns resulting from wind-driven currents and can be quantitatively evaluated to within about $\pm 3^{\circ}$ C. in low and high latitudes, but accuracy falls off rapidly in mid-latitudes. The oxygen isotope paleotemperature method permits a direct determination of isotherm surfaces for any given time interval which are accurate to within $\pm 1.5^{\circ}$ C. However, the accuracy of the method is more than offset by the high cost per analysis and the method is considered of marginal value for regional oceanic studies.

2. Isotopic carbon (δC^{13}) in the tests of planktonic foraminifera correlates with biological productivity in surface waters and surface salinity, the correlation being strongest with salinity. The approach has potential for reconstructing paleosalinity structure in oceans.

3. Selective dissolution of planktonic foraminifera in the sediments occurs at all depths below about 1000 meters, and increases rapidly below about 3000 meters until the compensation depths of calcium carbonate is reached. Species of planktonic foraminifera are preferentially removed by dissolution such that species ranking for temperature sensitivity, depth at which they live in the water column, and resistance to dissolution (especially the latter two) are strongly correlative. Shallow-dwelling, tropical-subtropical species are the least resistant to dissolution, and deep-dwelling, tropical and subtropical species are the most resistant. Dissolution acts in opposition to information recovery by first altering species frequencies in sediment assemblages, then preferentially removing the

the more soluble taxa, and, ultimately by removing all or nearly all planktonic foraminifera. Depending on the latitude, water depth and original species assemblage, selective dissolution can result in a climatic interpretation of a sediment assemblage which is "warmer" or "warmer" and then "cooler" than the original assemblage. The climatic distortion due to preservation affects the faunistic methods, oxygen isotope paleotemperatures for genera and determination of the relative age of assemblages.

4. The structure of present-day surface circulation is closely reflected in sediments from the top few centimeters. The apparent shift in the subtropical convergence noted in our earlier report (Douglas, 1969, p. 20) is now believed to be an artifact introduced by preservation on the basis of more complete faunal and oxygen isotope analyses. The circulation pattern in the South Pacific, at the resolution of our methods, has been stationary for about the last 2000-3000 years. Expected displacements due to the Little Ice Age were not detected.

Oxygen isotope temperatures for selected Wisconsin (glacial) samples from low latitudes yielded values 3.5 to 5° cooler than isotopic temperatures for modern samples.

These values are in good agreement with a glacial/interglacial temperature range of 3° to 4° C for the equatorial Pacific derived by others (Emiliani, 1970; Blackman, 1966).

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