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Oxygen-18 Studies of Recent Planktonic Foraminifera: Comparisons of Phenotypes and of Test Parts

Abstract. *Oxygen isotopic comparisons of phenotypes of Recent Planktonic Foraminifera with both normal and diminutive final chambers are compatible with a model in which the latter develop as a response to environmental stress. Isotopic evidence shows that* Spheroidinella dehiscens *is probably not a late-stage, aberrant form of* Globogerinoides sacculifer.

We report herein comparisons of oxygen isotopes in phenotypes of the same species of Recent Planktonic Foraminifera and in test parts of individual species. We have studied the following paleontologic problems by means of paleotemperature techniques: (i) the significance of the presence or absence of diminutive final chambers (*1*); (ii) the significance of the presence or absence of bullae (platelike structures covering the primary and secondary apertures); (iii) the significance of the shape of the final chamber in *Globogerinoides sacculifer-trilobus*; and (iv) the validity of Bé's hypothesis that *Spheroidinella dehiscens* is an aberrant deep-water form of *G. sacculifer-trilobus* (*2*).

All samples for isotopic analysis, taken from core tops except where otherwise indicated, were washed in distilled water and sized. Hand-picked samples from the fraction larger than 250 μm were reacted uncrushed and isotopically analyzed by means of standard techniques (*3*). Values of δ (*4*) are reported relative to the PDB-I (Pee Dee Formation belemnite) standard. Isotopic temperatures were calculated by means of the equation given by Craig (*5*). Isotopic compositions of seawater were taken from the literature for surface stations as close as possible to the core locations (*6*, *7*). Estimates of the depths at which the Foraminifera populations occurred were made from isotopic temperatures and bathythermographic data supplied by the National Oceanographic Data Center. All results are shown in Table 1.

Berger (*1*) has suggested that the presence of diminutive final chambers in Planktonic Foraminifera from ocean sediments is indicative of growth in a stressed environment in the overlying water column. This stress may be physical (temperature, salinity) or biological (insufficient food). Our data show that phenotypes of *Globogerinoides ruber* with a diminutive final chamber from three localities have isotopic temperatures 1° to 4.5°C colder than do phenotypes with a normal final chamber from the same samples. The temperature difference is greatest in the sample from the Blake Plateau, in which the small final chamber of the test was also flattened. No significant difference in temperatures was obtained for pink and white "normal" types from one locality. If a species has a range of optimum depth at or near the surface, as does *G. ruber*, then a stressed environment in the same water column must lie in deeper, colder water. Thus, the isotopic data for this species are compatible with Berger's hypothesis.

In the case of species with distributions of optimum depth at intermediate depths, a stressed environment might lie either in cooler, deeper water; in warmer, shallower water; or conceivably in both simultaneously. *Globorotalia cultrata* lives at intermediate depths. Two samples of this species showed that the phenotype with a normal final chamber recorded essentially the same temperature as the phenotype with a diminutive final chamber. In a third sample, from an area of coastal upwelling, the "normal" phenotype recorded a temperature about 1.5°C colder. In the case of *Globoquadrina dutertrei* (*8*), another species living at intermediate depths, both phenotypes of one sample recorded virtually identical isotopic temperatures. In another sample, the form with a diminutive final chamber recorded a temperature 1.2°C colder than did the "normal" phenotype, but the difference is virtually at the level of uncertainty for these analyses. Thus our results suggest that the presence of a diminutive final chamber may be related to some environmental factors in that phenotypes may have different distributions in the water column, but that temperature is not the only factor in determining the occurrence of this phenotype.

In the case of *Globogerinoides conglobatus*, we have investigated the possible existence of temperature differences between populations with and without bullae. A bullate population in the Gulf of Mexico recorded a temperature 1.8°C warmer than the nonbullate one did. Three other samples showed no significant differences in temperatures between phenotypes.

Globogerinoides sacculifer and *G. trilobus* have been distinguished from each other on the basis of a saclike as opposed to a more spherical final chamber. According to Bermudez (*9*), the final chamber has the function of increasing the buoyancy of the test; thus the sacculifer form would live in shallower water than would the trilobus type. However, Jones (*10*) has observed *G. sacculifer* at greater depths than *G. trilobus* in plankton tows in the Carribbean area.

Our results show that *G. sacculifer* and *G. trilobus* are isotopically similar. In samples from the Gulf of Mexico and the Indian Ocean *G. sacculifer* recorded a slightly warmer temperature than *G. trilobus*, whereas for a few Atlantic samples, *G. trilobus* recorded a slightly warmer temperature. Isotopic comparison of the last chamber of *G. sacculifer* with the entire test for a sample from the Gulf of Mexico shows the two to be almost identical.

The data indicate that both *G. sacculifer* and *G. trilobus* form their tests at similar temperatures, and presumably at similar depths. Thus, depth stratification at any one place as reported by Jones may be related to factors other than temperature. Our results do not exclude the possibility that the final chamber in *G. sacculifer* increases the buoyancy of the test, but it does suggest that this chamber is formed at the same temperature as the bulk of the early formed parts of the test.

Finally, Bé (*2*) has suggested that *Spheroidinella dehiscens* is an aberrant terminal form of *G. sacculifer-trilobus*

which, after early growth at shallow depths, sinks to bathypelagic depths (300 to 2000 m), where maximum encrustation with additional calcite occurs. However, other workers argue that *S. dehiscens* is a separate species which may live in waters as shallow as 150 m (*11*).

Our isotopic comparisons of the outer crust of *S. dehiscens* (*12*), the entire test of the same species, and *G. sacculifer-trilobus* from the same sample population show that in an equatorial Atlantic sample the crust records a warmer temperature than the entire animal does. Temperatures for the entire animal and the crust are both colder than that recorded by either *G. sacculifer* or *G. trilobus* from the same location, so it is inconceivable that *S. dehiscens* from this location is a variant of *G. sacculifer-trilobus* formed by encrustation at depth. The Indian Ocean comparison is not as clear-cut in that

Table 1. Results of oxygen isotope analyses.

Core name	Location	Species	Phenotype	δO^{18} (‰)	Runs (No.)	Average deviation (‰)	δ-water (‰)	Isotopic temperature (°C)	Average depth (m)*	Depth range (m)*
				Atlantic						
Blake Plateau	32°53′N	*G. ruber*	Normal chamber	−1.55	2	.01	+0.87†	27.8	10	0–20
Blake Plateau	77°18′W	*G. ruber*	Diminutive chamber	−0.77	2	.07		23.3	95	10–120
				Gulf of Mexico						
G-1290	25°35′N	*G. ruber*	Normal chamber pink	−1.76	2	.10	+0.68†	27.9	15	0–35
G-1290	84°49′W	*G. ruber*	Normal chamber white	−1.67	3	.15		27.5	15	0–50
G-1290	84°49′W	*G. ruber*	Diminutive chamber	−1.45	2	.18		26.4	30	0–60
				Pacific						
DWHG 84	15°S	*G. ruber*	Normal chamber	−0.59	2	.03	+0.22‡	20.6	65	55–85
DWHG 84	112°W	*G. ruber*	Diminutive chamber	−0.07	2	.03		18.3	75	65–95
				Atlantic						
C-1	2°48′N	*G. trilobus*		−0.78	2	.10	+0.43‡	22.1	60	50–70
C-1	16°28′W	*G. sacculifer*		−0.48	2	.09		20.8	65	65–75
V22-28	5°49′N	*G. trilobus*		−1.16	2	.14	+0.43‡	23.9	50	40–60
V22-28	39°16′W	*G. sacculifer*		−0.91	2	.14		22.8	60	55–70
A181-7	10°33′N	*G. trilobus*		−1.09	2	.02	+0.43	23.6	50	40–60
A181-7	57°20′W	*G. sacculifer*		−1.08	2	.09		23.5	50	40–60
Blake Plateau	32°53′N	*G. trilobus*		− .43	2	.18	+0.87†	22.6	100	85–150
Blake Plateau	77°18′W	*G. sacculifer*		− .44	2	.11		22.6	100	85–150
				Gulf of Mexico						
G-1290	25°35′N	*G. trilobus*		− .86	2	.08	+0.68†	23.7	60	0–80
G-1290	84°49′W	*G. sacculifer*	Whole	−1.03	2	.09		24.4	50	0–80
G-1290	84°49′W	*G. sacculifer*	Last chamber	−1.09	2	.02		24.7	50	0–80
				Pacific						
DWHG 84	15°S	*G. trilobus*		− .25	2	.05	+0.22‡	19.1	70	60–90
DWHG 84	112°W	*G. sacculifer*		− .38	2	.13		19.7	70	60–90
				Indian Ocean						
DODO 124D	11°54′S	*G. trilobus*		−1.57	2	.03	+0.19‡	24.7	40	N.A.§
DODO 124D	66°27′E	*G. sacculifer*		−1.84	2	.15		26.0	30	N.A.§
				Atlantic						
C-1	2°48′N	*S. dehiscens*	Whole test	+ .14	3	.06	+0.43‡	18.1	75	65–85
C-1	16°28′W	*S. dehiscens*	Outer crust	+0.04	2	.04		18.6	75	65–85
				Indian Ocean						
DODO 124D	11°54′S	*S. dehiscens*	Whole	−1.07	2	.24	+0.19‡	22.4	55	N.A.
DODO 124D	66°27′E	*S. dehiscens*	Outer crust	−0.99	1			22.0	60	N.A.
				Atlantic						
E-1	33°00′N	*G. conglobatus*	Bulla	− .06	2	.07	+0.87†	20.9	N.A.	
E-1	72°00′W	*G. conglobatus*	Non-bulla	− .07	2	.05		21.0		
				Gulf of Mexico						
G-1290	25°35′N	*G. conglobatus*	Bulla	− .42	2	.17	+0.68†	21.7	75	55–105
G-1290	84°49′W	*G. conglobatus*	Non-bulla	− .03	2	.12		19.9	100	70–135
				Pacific Ocean						
DWHG 84	15°S	*G. conglobatus*	Bulla	− .09	2	.02	+0.22‡	18.5	70	60–95
DWHG 84	112°W	*G. conglobatus*	Non-bulla	− .03	2	.01		17.9	75	60–100
				Indian Ocean						
DODO 124D	11°54′S	*G. conglobatus*	Bulla	−1.39	2	.05	+0.19‡	23.9	45	N.A.
DODO 124D	66°27′E	*G. conglobatus*	Non-bulla	−1.47	2	.11		24.5	40	N.A.
				Atlantic						
C-1	2°48′N	*G. cultrata*	Normal chamber	+ .72	2	.04	+0.43‡	15.7	100	95–110
C-1	16°28′W	*G. cultrata*	Diminutive chamber	+ .37	2	.06		17.2	85	70–95
A-181-7	10°33′N	*G. cultrata*	Normal chamber	+ .12	2	.00	+0.43‡	18.2	75	65–95
A-181-7	57°20′W	*G. cultrata*	Diminutive chamber	+ .07	2	.05		18.4	75	65–95
				Gulf of Mexico						
G-1290	25°35′N	*G. cultrata*	Normal chamber	− .02	2	.12	+0.68†	19.9	95	70–130
G-1290	84°49′W	*G. cultrata*	Diminutive chamber	− .08	2	.07		20.1	95	70–130
G-1290	25°35′N	*G. dutertrei*	Normal chamber	− .24	2	.11	+0.68†	20.9	80	60–120
G-1290	84°49′W	*G. dutertrei*	Diminutive chamber	+ .02	2	.11		19.7	105	70–130
				Atlantic						
C-1	2°48′N	*G. dutertrei*	Normal chamber	+ .10	2	.07	+0.43‡	18.4	75	60–85
C-1	16°28′W	*G. dutertrei*	Diminutive chamber	insufficient material						
				Pacific ||						
DWBG 140	5°S	*G. dutertrei*	Normal chamber	+ .37	2	.01	+0.22‡	16.4	85	70–105
DWBG 140	112°W	*G. dutertrei*	Diminutive chamber	+ .32	2	.22		16.6	85	70–105

* Average depth is calculated from average depth-temperature profile. Depth range is calculated from warmest and coldest depth-temperature profiles available. † Epstein and Mayaeda (*6*). ‡ Craig and Gordon (*7*). § Not available. || Sample from core at level of 2 to 5 cm.

the test of *S. dehiscens* has an isotopic composition intermediate between that of its crust and that of *G. sacculifer-trilobus* from the same sample. Visual estimates indicate that the crust comprises roughly 70 ± 20 percent of the mass of *S. dehiscens*. Thus, within the uncertainty limits of the visual estimation of the relative masses of the two parts, the measured isotopic composition of the bulk is not far from the calculated isotopic composition of a mixture of 70 percent crust and 30 percent *G. sacculifer-trilobus*. Although the isotope data do not rule out the possibility that *S. dehiscens* from this location is simply encrusted *G. sacculifer-trilobus*, encrustation could not possibly have taken place at the depths suggested by Bé. The sum of the isotope data argues very strongly for the consideration of *S. dehiscens* as a separate species.

In summary, phenotypes of a single species and test parts of individual phenotypes sometimes record different isotopic temperatures. Where test parts record different temperatures, as in the case of *S. dehiscens*, conclusions may be drawn concerning the temperatures at which the animal lived during different stages of growth. The occurrence of diminutive final chambers is correlated with temperature for the shallow-water species, *G. ruber*. This is particularly important for paleotemperature studies, since if our model is correct, temperatures determined on entire populations of shallow-water species may be colder than those determined when only the "normal" phenotype is used.

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DDT Residues in Marine Phytoplankton: Increase from 1955 to 1969

Abstract. *Phytoplankton samples collected in Monterey Bay, California, from 1955 to 1969 contained compounds identified as* p,p'-*DDT,* p,p'-*DDD, and* p,p'-*DDE. Total concentrations of these compounds were approximately three times greater in the later samples. Lower concentrations throughout the period were associated with higher densities of standing crop.*

Annual use of DDT in the United States has declined in the past decade (*1*), yet there is recent evidence of abnormally high DDT residues in marine fish from U.S. coastal waters, and such contamination in these areas may exceed that in freshwater habitats (*2*). This could indicate either (i) that environmental DDT residues are increasing or (ii) that these recent analyses simply reflect current DDT input and that DDT concentrations have in fact been even higher in the past. Although DDT residues in estuarine shellfish (*3*) have shown no consistent upward or downward trends, the time has been too short and the estuarine system too responsive to weather conditions and local sources of pesticides to provide any measure of the trends in the coastal environment. Declining reproductive success in species of marine pelagic birds, attributable to DDT residues (*4*), does suggest that residues of DDT are increasing in the coastal pelagic food chains of which these birds are high-order consumers.

A decision between the alternatives could be made if historical collections of marine organisms were available. At the Hopkins Marine Station, samples (composed primarily of phytoplankton) collected with a fine-mesh net from Monterey Bay, California, have been collected from 1955 to 1969 (*5*). Phytoplankton samples are particularly suited for analysis because they represent the first link in pelagic food chains. Trends in their concentrations of DDT residues are relevant to all higher-order consumers on the food chain. Also, DDT uptake by phytoplankton is rapid and essentially irreversible (*6*); thus, it can be assumed that the content of DDT residues of phytoplankton reflect prevailing amounts of environmental DDT. To examine the change in content of DDT residues over the collection period, 23 samples from the collection were analyzed. All the samples had been preserved in a 3 percent solution of formalin in seawater. The estimated concentrations of DDT residues (*7*) for the samples were based on their carbon content as determined by wet combustion (*8*) of replicate portions. Formalin induces error in carbon determinations of marine planktonic material (*9*), but the errors in this instance were small (< 10 percent). Treatment of freshly collected material from the same station with formalin had no apparent effect on estimates of the DDT content when compared to that of frozen controls.

Samples were filtered onto combusted GFC glass-fiber filters (Whatman) after filtration through 0.33-mm netting to remove larger zooplankton. The sample and filter pad were ground together in three successive rinses of high-purity *n*-hexane. The pooled rinses were concentrated and chromatographed on silica-gel microcolumns (*10*). Eluates from the columns were concentrated at 37°C under a stream of nitrogen and analyzed by gas-liquid chromatography (GLC). All glassware used in the procedure was combusted