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Globorotalia truncatulinoides as a Paleo-oceanographic Index

Abstract. In Recent surface sediments of the ocean floor *Globorotalia truncatulinoides* (d'Orbigny) grades from highly conical forms in tropical areas to rather compressed forms in cold-water areas. An interdependence exists between temperature of the surface water and form ratios as defined by mean ratio of width to height and mean ratio of width to the height from keel to ventral extremity. Values of these ratios serve to identify various water masses and thus constitute a potentially useful method in determining paleo-temperatures in Quaternary marine sediments. Subpolar populations, as end members of the cline, are found only in the Southern Hemisphere.

Distributions of planktonic foraminiferal tests in marine sediments generally reflect their living patterns within given water masses. As a result of this, the distribution of planktonic tests in fossil marine sediments are being used increasingly for paleo-oceanographic reconstructions.

In addition to exhibiting changes in relative abundance with latitude, a number of planktonic species have been found to undergo morphological changes with latitude, apparently constituting clines (1, 2). The value of these clines in establishing greater precision in the interpretation of past climates is well demonstrated by the stratigraphic application of changes in coiling direction in *Globigerina pachyderma* (1, 3).

Examination of *Globorotalia truncatulinoides* populations in 50 surface sediment samples from all the major oceanic areas revealed that distinctly different morphological types occur in polar and tropical areas. [The presence of different forms has been reported only briefly before by Blair (4) and by Boltovskoy (5).] Furthermore, a complete gradation in morphology occurs with latitude between the respective end members. I found that northward from

Antarctic waters in the Southern Hemisphere there is a gradual increase in mean test height and decrease in convexity of the dorsal side until it becomes flattened or concave in tropical-northern subtropical waters.

Samples examined are mostly calcareous oozes containing abundant specimens of *G. truncatulinoides* and were mainly from the upper 3 cm of cores obtained from depths between 1000 and 4000 m, with an average depth of about 2000 m. Samples in the Northern Hemisphere are located between 43° and 16°N and those in the Southern Hemisphere between 59° and 21°S. The

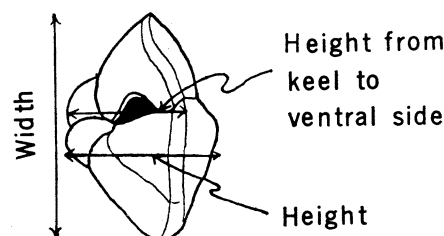


Fig. 1. Side view of a specimen of *Globorotalia truncatulinoides* (d'Orbigny) showing the parameters that were measured. This is a biconvex, relatively compressed form typical of subantarctic areas.

following specific areas were studied: south Pacific, Drake Passage, Peru-Chile Trench, Mozambique Channel, off Hong Kong, Gulf of Mexico and Caribbean, western Mediterranean, and the Atlantic Ocean near France and Florida.

In order to quantify the change in test height, the samples of *G. truncatulinoides* were analyzed in terms of mean ratio of width to height (ratio A) and mean ratio of width to the height from keel to ventral extremity (ratio B) (Fig. 1). Fifty specimens from each sample were measured with an ocular micrometer, except for seven samples in which there were fewer numbers available for measurements. Only mature specimens with a maximum diameter of more than 450 μ were measured. Multivariate analyses have been conducted on these and other parameters, including coiling direction, and a detailed account will be presented elsewhere.

Bé (6) has shown from studies of planktonic tow samples that *G. truncatulinoides* deviates from the usual bipolar nature of planktonic species distributions. He showed that in the Northern Hemisphere it does not extend north of subtropical waters (surface temperatures less than 14°C), but in the Southern Hemisphere it flourishes in subantarctic waters (surface waters as low as 4°C). Thus a discussion of its latitudinal changes relates mainly to the Southern Hemisphere, but it is important to note that reciprocal morphological changes occur in tropical-subtropical populations of both hemispheres.

An interdependence between surface water temperatures and the calculated average ratios is evident from Figs. 2 and 3. A general and somewhat gradational decrease in average ratio of width to height (Fig. 2) from northernmost Antarctic to tropical areas reflects a change from rather compressed forms in cold water to highly conical forms in tropical waters. Ranges of these ratios within certain areas in the Southern Hemisphere in turn serve to identify the following water masses: tropical-northern subtropical (1.30 to 1.38), southern subtropical-northern subantarctic (1.40 to 1.52), and southern subantarctic-northernmost Antarctic (1.48 to 1.55).

Likewise, the average ratios of width to the height from keel to ventral side (ratio B, Fig. 3) show a gradational decrease from the northernmost Antarctic to tropical areas. This ratio, al-

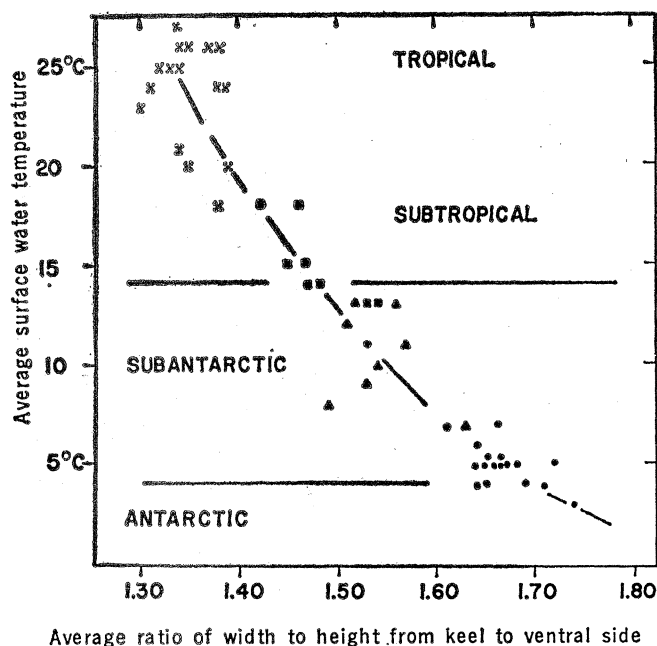
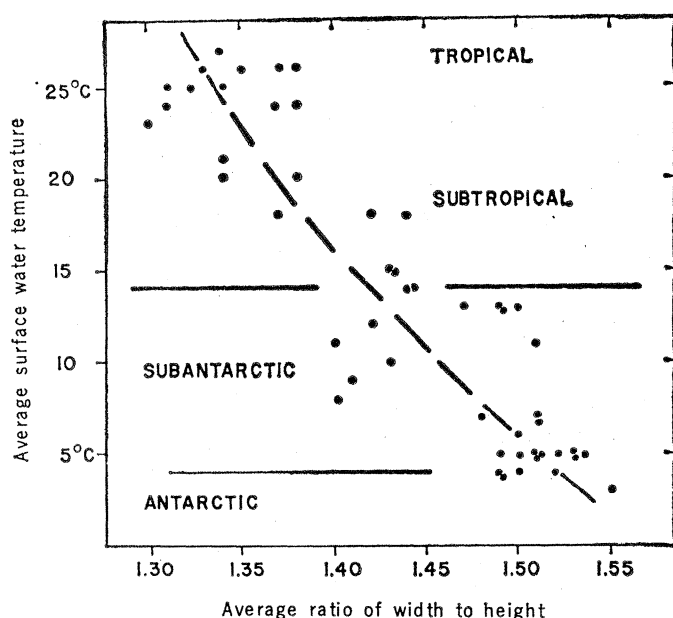


Fig. 2 (left). Graph showing that as the average surface water temperature increases samples of *G. truncatulinoides* show a general decrease in the average ratio of width to height (ratio A), reflecting a decrease in compression. Fig. 3 (right). Graph showing that as the average surface water temperature increases there is a general decrease in average ratio of width to the height from keel to ventral side (ratio B) in samples of *G. truncatulinoides*. Sample symbols represent difference in values between ratios A and B, reflecting the degree of convexity of spiral side, and are: X, 0 to .01; ■, .02 to .04; ▲, .05 to .12; and ●, .13 to .20.

though also reflecting the change to highly conical forms toward tropical areas, is characterized by a wider range of values from high to low latitudes. This results from the fact that *G. truncatulinoides*, although becoming less conical from tropical to polar areas, at the same time tends to become biconvex. The determination of ratio B therefore eliminates the influence that the convexity of the dorsal side has on the values of ratio A. Values of ratio B serve to identify the following water-mass areas in the Southern Hemisphere: tropical-northern subtropical (1.30 to 1.39), southern subtropical (1.38 to 1.48), northern subantarctic (1.49 to 1.57), and southern subantarctic to northernmost Antarctic (1.61 to 1.74).

It has yet to be demonstrated whether *G. truncatulinoides* exhibits significant morphological changes in deep-sea cores, in turn reflecting a response to changing oceanographic conditions during the Quaternary. If the statistical procedure described represents a valid tool for paleo-oceanographic interpretations, it will also serve as a check against methods already in use, such as changes in coiling direction of *G. pachyderma*.

Globorotalia truncatulinoides has extended its geographic range into water masses with temperatures less than 14°C, and as low as 4°C, in the Southern Hemisphere, but not in the Northern Hemisphere. The subantarctic populations, representing end members of the

cline, are morphologically and statistically distinguishable from, although completely gradational with, southern subtropical populations. Because of the apparent absence of any morphological breaks within the species geographic range, the observed latitudinal variation probably represents a cline, rather than the presence of distinct geographic subspecies.

There is considerable disagreement as to the time of the first development of *G. truncatulinoides* in the stratigraphic record. Some authors have reported its first appearance in sediments designated as Pliocene in age (7), while others (8, 9) have hypothesized its development from *G. tosaensis* at the Pliocene-Pleistocene boundary [base of zone N22 of Banner and Blow (8)]. Regardless of which belief is preferred it does appear from the literature that *G. truncatulinoides* first developed in tropical-subtropical areas as a highly conical form. If so, at what time did the development of the cline characteristic of present day *G. truncatulinoides* take place and what was the nature of its development? Furthermore, at what time did the subantarctic "race" evolve and what form did it have when it migrated into subantarctic waters? It is highly probable that *G. truncatulinoides* first appeared in subantarctic areas sometime after its appearance in lower latitude areas and thus marks a separate and younger "datum plane" than its

initial appearance in subtropical-tropical areas. Studies of Upper Pliocene-Pleistocene sediments within cores from various latitudes should disclose an interesting distributional and morphological history of this species. This information should in turn be valuable as a further guide to deciphering oceanographic conditions during the Quaternary.

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Amino Acid Flux in an Estuary

Abstract. Dissolved organic matter in York River estuary included 38 micrograms of free amino acids per liter. The highest concentrations were of glycine, serine, and ornithine. Of the 14 amino acids studied for uptake by planktonic bacteria, glycine, methionine, and serine had the greatest flux rates. The total amino acid flux represented from 1 to 10 percent of the daily photosynthetic carbon fixation.

A few hundredths of a milligram of dissolved free amino acids (DFAA) per liter has been reported for the open ocean (1, 2), estuaries (3), and lakes (4). However, data on concentrations of the individual amino acids must be supplemented with flux data before the importance of these compounds in community energetics can be evaluated and their varying concentrations explained. Webb and Johannes (5) calculated a maximum replenishment time of 1 month from net zooplankton-excretion rates, but it is likely that the bacteria are removing the free amino acids even more rapidly (6). This uptake of substrates by bacteria has been studied in pure cultures (7), and the same general techniques have been modified for measurements of uptake of glucose and acetate by planktonic bacteria in natural waters (6, 8). Flux estimates of amino acids that we report are calculated from analyses of the DFAA and from simultaneous measurements of the uptake of 14 C¹⁴-amino acids by the plankton of York River estuary, Virginia.

The methods of analysis of DFAA are those of Webb and Wood (3); the sample was desalted with a chelating resin in the Cu⁺⁺ form, and the Technicon AutoAnalyzer system was used (Fig. 1). The bacterial uptake methods (Fig. 1) resemble those of Wright and Hobbie (6). The sample came from York River estuary (salinity, 20 per mille; 24.5°C); the control subsample was killed with 2 drops of Lugol's acetic acid solution. For each of the 14 amino acids, the subsampling procedure (Fig.

1) was done in duplicate. Amino acids were added in four concentrations: for example, 9, 18, 26, and 35 µg of alanine per liter; the highest concentration was also added to the killed blank. These bottles were incubated for 2.0 hours on a shaking table at 23°C—in the dark to prevent photosynthetic fixation of respired C¹⁴O₂. Finally the plankton was filtered with HA Millipore filters (0.45 µ), and the activity was counted with a proportional counter.

Calculations were based on a modified Lineweaver-Burk equation:

$$(S_n + S_a)/v = (K/V) + [(S_n + S_a)/V]$$

The substrate concentrations S_n and S_a (micrograms per liter) are the natural quantities and the experimental added amounts, respectively; v is the measured velocity of uptake (micrograms per liter per hour), V is the maximum velocity of uptake (micrograms per liter per hour), K (micrograms per liter) is a constant indicating the affinity of the transport system for the substrate (7), and v equals the quantity $(S_n + S_a)$ times the fraction of the isotope taken up by the plankton per hour.

When plotted as $(S_n + S_a)/v$ versus $S_n + S_a$, the points fell along a straight line resembling the results of uptake experiments with glucose and acetate (6). The slope of the line was drawn from a calculation by least-squares regression; its inverse equals V . The K is calculated from the ordinate intercept (K/V), while the v at natural substrate concentrations, hereafter called v_n , is calculated from the equation when S_a equals zero. The turnover time T (hours), or the time required for the plankton to remove all the substrate, equals S_n/v_n .

Dissolved free amino acids were found in small quantities (Table 1), with glycine, serine, and ornithine in relatively high concentrations. Aspartic acid, threonine, alanine, and methionine were at intermediate levels, and the remainder were at low concentrations. The levels of concentration and the general order of abundance agree with results from York River estuary (3), Buzzards Bay (2), the Irish Sea

Table 1. Free amino acid concentrations (S_n), flux (v_n), removal time (T), and transport affinity constant (K) of the bacterial population in York River estuary, 6 September 1967. Surface samples (24.5°C) taken from the pier of Virginia Institute of Marine Science were incubated at 23°C. P-ala, phenylalanine.

Amino acid	S_n (µg/liter)	T (hr)	K (µg/liter)	v_n (µg/liter hr ⁻¹)
Gly	16.85	39.8	9.2	0.423
Met	1.31	7.6	0.6	.171
Ser	4.91	36.9	81.4	.133
Ala	1.49	15.4	7.7	.096
Asp	1.92	33.9	69.7	.056
Val	0.86	17.4	12.4	.050
Thr	1.50	51.0	32.3	.029
Leu	0.63	28.0	27.5	.023
Glu	1.00	42.9	56.0	.023
Ile	0.57	46.5	24.9	.012
Lys	.95	82.2	86.5	.012
Tyr	.75	81.8	230.5	.009
Pro	.58	63.3	34.3	.009
Arg	.55	93.5	158.4	.006
His	.95			
Orn	3.17			
P-ala	0.18			

(1), and certain lakes of northern Germany (4).

Aquatic bacteria in estuaries appear to have transport systems for every amino acid tested. The uptake kinetics of a mixed population can be measured only if all the uptake systems have similar characteristics (8); for example, a low K , or one dominant species. In the York River experiment, in other runs in Pamlico River estuary (salinity, 12 per mille), and in freshwater ponds near Raleigh, North Carolina, the kinetics of uptake of the isotopes were similar to uptake by transport systems in pure cultures of bacteria (6, 7). The specificity of the amino acid transport systems has not been extensively tested, but the uptake of aspartic acid was unaffected by additions of the other common amino acids; glutamic acid did interfere to some extent.

Glycine, methionine, and serine have the highest flux, with valine, alanine, and aspartic acid in an intermediate group. The importance of the DFAA flux, rather than concentration alone, as a measurement of ecological significance is illustrated by data on methionine and threonine. Although they were present in similar concentrations, me-

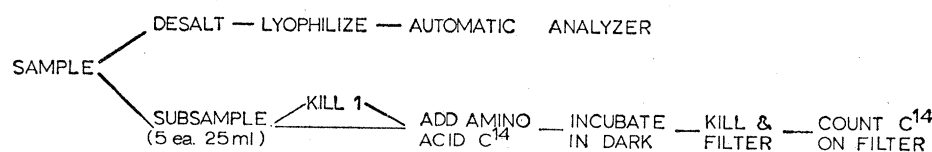


Fig. 1. Flow diagram for the measurement of dissolved free amino acids and their flux in York River estuary, 6 September 1967.