Reports

Subtropical Convergence Fluctuations and Quaternary Climates in the Middle Latitudes of the Indian Ocean

Abstract. *Oxygen isotopic and microfaunal analyses and shell size variations of* Orbulina universa *in two Indian Ocean cores indicate that the position of the Subtropical Convergence has fluctuated between a northern limit north of 31°S during glacial stages and its present, maximum southern limit. The northward displacement of the Subtropical Convergence to a position off Durban, South Africa, reflects the general weakness of the Agulhas Current during glacial stages and parts of interglacial stages, representing about 65 percent of the past 540,000 years.*

Relatively sharp hydrographic and faunal contrasts occur along boundary currents (for example, the Peru Current and the Benguela Current) and in regions where different water masses meet (for example, the frontal zones in the Northern Hemisphere and the Southern Hemisphere). A recent comparison of geographic shifts in such oceanographic features in the world's oceans between the present and 18,000 years before the present (B.P.) was made as part of the CLI-MAP Project (*1*).

Strong temperature contrasts are evident today south of South Africa where the Agulhas Current terminates in the Subtropical Convergence zone and where the mean surface isotherms are displaced southward (*2*). We report here on fluctuations in the position of the Subtropical Convergence in the Indian Ocean during the late Quaternary based on isotopic and micropaleontological analyses of two midlatitude sediment cores from opposite margins of the Indian Ocean.

The first core, RC 17-69, was taken 500 km southeast of Durban, South Africa (31°30′S, 32°36′E; water depth, 3308 m). The core is 11.3 m long and contains well-preserved planktonic foraminiferal faunas. The second core, RC 9-150, comes from the continental slope 125 km northwest of Perth, Australia (31°17′S, 114°36′E; water depth, 2703 m). This highly calcareous core is 5.12 m long and consists predominantly of planktonic foraminifera and coccoliths. Cores RC 9-150 and RC 17-69 were both taken well above the $CaCO_3$ compensation depth and show little effect of dissolution. Core RC 9-150 has been studied by Conolly (*3*), who recorded a climatic change at 35 cm that took place 11,000 years B.P. Although both cores are from the same latitude (31°S), the surface water over the African site is, on the average, about 2.5°C warmer and slightly less saline than the water at the Australian location. This temperature contrast may be related to the presence of the strong Agulhas Current which transports warm waters southward along the coast of Africa, whereas off southwest Australia the eastern boundary current is weakly developed (*4*).

Stratigraphic correlation between the cores based on fluctuations in the ^{18}O contents of *Globigerinoides sacculifer* shells (*5*) (Fig. 1) indicated that core RC 9-150 has a continuous oxygen isotope record extending to the boundary between isotopic stage 7 and stage 8, according to the nomenclature introduced by Emiliani

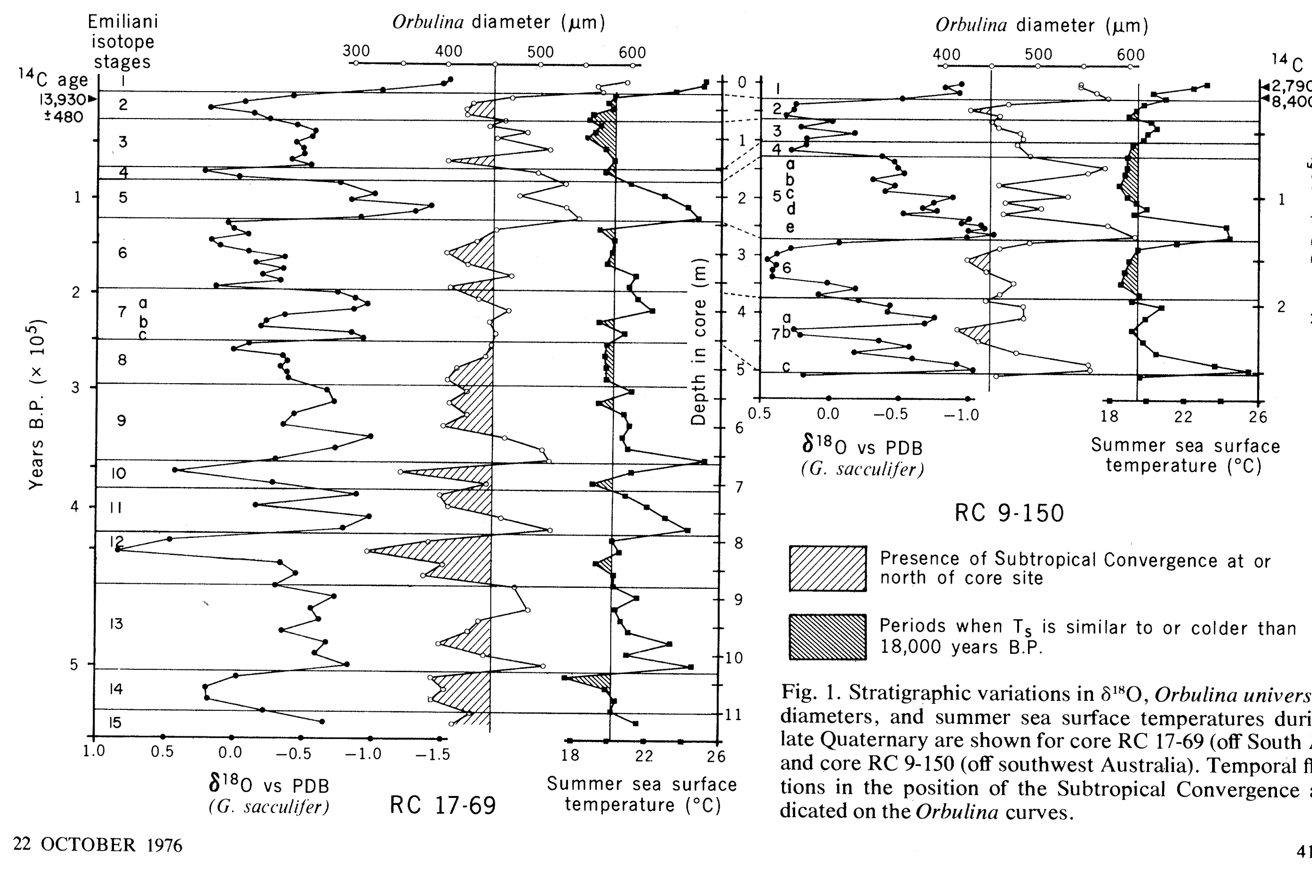

Fig. 1. Stratigraphic variations in $\delta^{18}O$, *Orbulina universa* shell diameters, and summer sea surface temperatures during the late Quaternary are shown for core RC 17-69 (off South Africa) and core RC 9-150 (off southwest Australia). Temporal fluctuations in the position of the Subtropical Convergence are indicated on the *Orbulina* curves.

Table 1. Comparison of the temperature difference (ΔT) between African (core RC 17-69) and Australian (core RC 9-150) sites, calculated by the isotopic method and the faunal transfer function method. The present measured surface temperature difference is 2.5°C.

Isotopic stage [from (*6*)]	Isotopic method			Faunal transfer method		
	$\delta^{18}O$ versus PDB, RC 17-69	$\delta^{18}O$ versus PDB, RC 9-150	ΔT (°C)	T_s RC 17-69 (°C)	T_s RC 9-150 (°C)	ΔT (°C)
2	+0.18	+0.29	+0.5	20.1	19.2	+0.9
3	−0.58	−0.18	+1.6	19.0	20.0	−0.9
4	+0.22	+0.28	+0.25	19.7	18.9	+0.8
5	−1.42	−1.19	+1.0	24.2	24.4	−0.2
6	+0.17	+0.45	+1.1	20.2	18.8	+1.4
Mean for stages 2 through 6	−0.29	−0.07	0.89	20.7	20.3	0.4
Present (core top)	−1.55	−0.95	2.5	25.1	23.2	1.9

(*6*); this boundary is equivalent in age to 250,000 years B.P. (*7*). Core RC 17-69 shows a continuous sequence to the boundary between stages 14 and 15 or 540,000 years B.P. Radiocarbon dates (*8*) for core RC 9-150 yield a sedimentation rate of 3.71 cm per 1000 years for the Holocene (stage 1). According to the time scale of Broecker and van Donk (*9*), the boundary between stages 1 and 2 at 34 cm is equivalent to 11,000 years B.P., that between stages 4 and 5 at 130 cm to 75,000 years B.P., and that between stages 5 and 6 at 260 cm to 127,000 years B.P. These dates yield sedimentation rates of 1.5 cm per 1000 years for the last glacial episode (isotopic stages 2 through 4, generally considered equivalent to the Wisconsin stage) and 2.5 cm per 1000 years for the last interglacial (stage 5). Thus, the sedimentation rate at the Australian site during the Holocene and the last interglacial (stage 5) is about twice as rapid as during the last glacial interval (stages 2 through 4).

Paleoclimatic variations were determined from the ^{18}O content and the species composition of planktonic foraminifera at various levels of the two cores. The transfer function technique of Imbrie and Kipp (*10*) makes it possible to evaluate the summer sea surface temperatures (T_s) during the geologic time represented by the two cores (Fig. 1). A multivariate regression equation was developed for the Indian Ocean [equation FI1 in (*10*)], based on the relative abundance of 29 planktonic foraminiferal species entombed in the modern seabed (*1*). The standard error of estimate for individual samples was 1.5°C. At both localities the modern species composition of planktonic foraminifera reflects a strong subtropical influence in view of the high abundance of *G. ruber*, *G. glutinata*, *G. dutertrei*, *G. menardii*, and *G. sacculifer*. Although transitional-subantarctic species such as *G. inflata* and *G. bulloides* are of secondary importance today, they dominated the region for the greater part of the late Quaternary.

Variations in the ^{18}O content of planktonic foraminifera depend on two factors: the temperature and the $^{18}O/^{16}O$ ratio of seawater (*6*). Shackleton and Opdyke (*7*) have shown that this ratio, which records the continental ice volume, is the dominant factor measured in deep-sea cores. Because a small ice volume results from global climatic warming, a general correlation between the T_s and ^{18}O curves is expected. Thus, warm temperature peaks are correlated with odd-numbered stages (depleted in ^{18}O) and cold temperature essentially with even-numbered stages (rich in ^{18}O).

However, there are differences between the details of the T_s curves and the ^{18}O curves (Fig. 1). The temperature curves show single interglacial peaks of short duration at the beginning of stage 5 (substage 5e) and stage 7 (substage 7c) in the eastern core and at the beginning of stages 5, 9, and 11 in the western core. Moreover, in the western core no T_s peaks are detectable during stages 3 and 7. Since stage 7 is known to be a full interglacial stage, the low T_s values could represent a local cool response to a general warm climate, perhaps due to the presence of a cold water mass.

At present, the strong Agulhas Current deflects the isotherms southward along Africa, whereas off Australia the eastern boundary current is very weak and there is no strong gradient of the isotherms. The measurement of the temperature difference between Africa and Australia is thus directly related to the strength of the Agulhas Current; Africa was warmer when the Agulhas Current was stronger. This temperature difference can be computed directly from the T_s curves but can also be deduced from the isotopic curves in the following way: Today the mean surface salinities are 35.5 per mil at the location of core RC 17-69 and 35.6 per mil at the location of core RC 9-150. Duplessy (*11*) has determined the relationship between $\delta^{18}O$ and the salinity of seawater in the southern Indian Ocean, showing that the difference between the two values is so small that the corresponding $\delta^{18}O$ (± 0.1 per mil) values are identical. Because a weak Agulhas Current will further lead to a stronger latitudinal dependence of the isohalines, we may assume that during

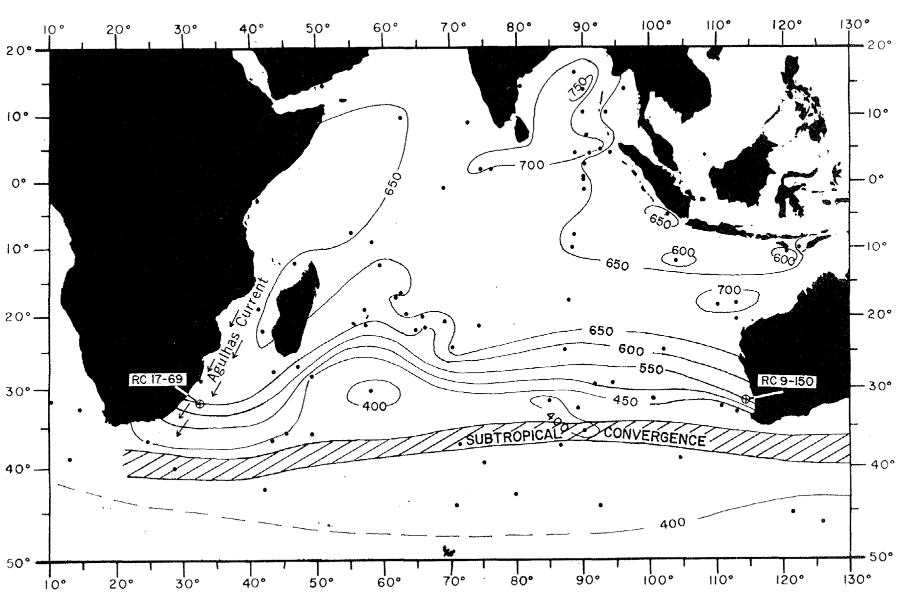

Fig. 2. Locations of cores RC 17-69 and RC 9-150 in relation to the present-day Subtropical Convergence and *Orbulina universa* shell size variations on the seabed. Isopleths indicate average shell diameters (in micrometers) for 50 or more specimens per sediment sample, as determined by Bé *et al*. (*17*).

the late Quaternary the $\delta^{18}O$ of seawater at the African and Australian sites was the same. Thus we can use the paleotemperature equation to compute stage-by-stage temperature differences between the two cores (*12*).

Table 1 presents a comparison of the temperature differences obtained by the isotopic method with those derived from the faunal analyses. Both methods lead to the conclusion that the temperature difference between the African and Australian sites was smaller during the pre-Holocene than today. During stages 2 to 6 the surface temperature in the Agulhas Current was, on the average, about 0.9°C higher (based on $\delta^{18}O$) or 0.4°C higher (based on faunal analysis) than that off the southwest Australian coast. Today, actual surface temperature measurements at the former site are on the average about 2.5°C higher than at the latter (*13*). This difference is in good agreement with the temperature differences obtained by the $\delta^{18}O$ and the faunal methods. The isotopic data indicate small temperature differences between the two cores during substages 7a and 7c, which appear as two temperature peaks separated by a pronounced temperature minimum in Fig. 1. On the contrary, the faunal data imply significant temperature differences during the same periods, that is, the African site is 1.5°C warmer than the Australian site during substage 7a, whereas the former (as a result of an anomalously low T_s value) is 2.9°C cooler than the latter during substage 7c. We cannot explain whether this is a real phenomenon or the result of a nonlinear response of the planktonic foraminiferal species to changing environmental conditions during this interval (*14*). At any rate, the isotopic and faunal evidence for an unusually cool stage 7 at the African site is also supported by the predominant occurrence of small shells of *Orbulina universa* (Fig. 1).

These results show that the present sea surface temperature difference between the two sites is much greater now than it was during most of the past 250,000 years. The modern situation reflects the influence of a strong, warm Agulhas Current (*4*), whereas the small temperature difference between the two locations during the last 250,000 years indicates that this current was generally weaker than today.

The record of core RC 17-69 (*15*) shows that present-day temperatures occurred only during four short episodes in the past 540,000 years. The modern $\delta^{18}O$ values of *G. sacculifer* are the lightest observed for the entire core and confirm that the modern conditions for the African site are exceptionally warm. Moreover, the glacial $\delta^{18}O$ conditions as observed at 18,000 years B.P. occurred six times in the past 540,000 years, with stages 10 and 12 being extraordinarily cold (*16*). According to the faunal analyses, glacial-maximum conditions similar to those at 18,000 years B.P. occurred during stages 3, 4, 6, 7, 8, 9, 10, 12, and 14. All these data indicate that during most of the past 540,000 years, surface waters off Durban, South Africa, were much cooler and hence the Agulhas Current was significantly weaker than today.

In order to further substantiate the paleolatitudinal shifts in hydrographic conditions, we studied the stratigraphic variation in the shell size of *Orbulina universa*. Bé *et al.* (*17*) have observed that the mean size of spherical shells of *O. universa* in the waters and surface sediment of the Indian Ocean varies inversely with their latitudinal occurrence. They concluded that a direct correlation exists between *Orbulina* shell size on the one hand and water temperature and density on the other (Fig. 2). Populations with the largest shells, measuring 600 to 800 μm in average diameter, are found in tropical and subtropical areas. Medium-sized *Orbulina* shells (between 450 and 600 μm in diameter) occur in the middle latitudes between about 23°S and 32°S. Shell sizes averaging less than 450 μm appear between about 32°S and 45°S. A particularly strong latitudinal gradient in shell size is observed in the middle latitudes, probably in response to the proximity of the Subtropical Convergence zone in which subtropical and subantarctic waters mix.

We have determined the stratigraphic variations in *Orbulina* shell size for cores RC 9-150 and RC 17-69 (*18*) (Fig. 1). A mean *Orbulina* shell diameter of about 550 and 600 μm represents present-day conditions at cores RC 9-150 and RC 17-69, respectively. It is possible to deduce latitudinal shifts of the Subtropical Convergence during the late Quaternary if we assume a mean shell size of 400 to 450 μm as an index for the convergence. Since both cores are well above the $CaCO_3$ compensation depth, we have ruled out the possibility that the variations in shell size are affected by selective dissolution.

Thus, by using *Orbulina* shell size as an indicator of hydrographic conditions, we deduced that the Subtropical Convergence occurred off or north of Durban during glacial stages 2, 4, 6, 8, 10, 12, and 14 as well as during parts of interglacial stages 3, 7, 9, 11, and 13 (Fig. 1). This is equivalent in duration to about 65 percent of the past 540,000 years. The predominant occurrence of *Orbulina* shells less than 450 μm in diameter is interpreted as reflecting northward displacements of the Subtropical Convergence of about 10° of latitude (relative to its present position at about 40°S). The fact that Subtropical Convergence conditions were particularly evident during the warm stages 9, 11, and 13 indicates that cold conditions prevailed for longer durations prior to rather than after 300,000 years B.P. The strong cooling during stages 10 and 12 shown by the $\delta^{18}O$ data coincided with the presence of extremely small *Orbulina* shells. On the other hand, the maximum size of *Orbulina* observed in modern populations was not evident at any time during the past 540,000 years.

At the site of core RC 9-150, Subtropical Convergence conditions occurred during stages 2, 6, and 7b. This is equivalent to about 20 percent of the past 250,000 years. By contrast, at the site of core RC 17-69, convergence conditions prevailed about twice as long for the same time interval.

Thus, northerly shifts of the Subtropical Convergence to 31°S were detected on opposite margins of the Indian Ocean during the late Quaternary. These hydrographic changes are substantiated by faunal studies in the region beneath the present Subtropical Convergence (38°S to 40°S), where Williams (*19*) has also observed repeated displacements of the convergence caused by northward migrations of the Polar Front from 48°S–50°S to 40°S during the late Quaternary. The resulting cooling is more pronounced off Africa as a result of a simultaneous weakening of the Agulhas Current, and there modern conditions occurred rarely during the late Quaternary. Present-day mean summer sea surface temperatures prevailed for only about 1 percent of the past 540,000 years off southeast Africa and for about 10 percent of the past 250,000 years off southwest Australia.

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5. Samples containing about 15 specimens (~ 0.3 mg of $CaCO_3$) were taken at 10-cm intervals for

both cores. The samples were roasted under vacuum at 400°C for 45 minutes and reacted under vacuum through the action of 100 percent H_3PO_4 at 50°C. The $^{18}O/^{16}O$ ratio is reported as $\delta^{18}O$ values (per mil) relative to the Chicago Pee-Dee belemnite (PDB-1) standard:

$$\delta^{18}O\left[\frac{(^{18}O/^{16}O)\text{sample}}{(^{18}O/^{16}O)\text{standard}} - 1\right] \times 1000$$

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8. Radiocarbon dates were obtained for five Holocene levels in core RC 9-150: 2790 ± 110 years B.P. at 5 to 5.5 cm; 6000 ± 600 years B.P. at 15 cm; 8400 ± 260 years B.P. at 24 to 26 cm; 8100 ± 600 years B.P. at 31 cm; and 10,000 ± 1000 years B.P. at 35 cm. The second and fifth dates were measured by G. S. Bien [see (*3*)] and the others by T. H. Peng and W. S. Broecker at Lamont-Doherty Geological Observatory.

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11. The relationship between $\delta^{18}O$ and the salinity of seawater in the southern Indian Ocean is based on data collected from different cruise tracks of the French M.S. *Galliéni* between Durban, Crozet Island, Kerguelen Island, New Amsterdam Island, Réunion Island, and Madagascar and the Danish M.S. *Thala Dan* between Australia and Antarctica [J. C. Duplessy, *C. R. Acad. Sci. Paris* **271**, 1075 (1970)]. For seawater with a salinity of less than 35 per mil, an increase of 0.66 per mil in $\delta^{18}O$ corresponds to an increase in salinity of 1 per mil. For higher salinities, the $\delta^{18}O$ of seawater is constant to within 0.1 per mil (at the 1 σ level, where σ is the standard deviation).

12. If the difference between the $\delta^{18}O$ values of seawater at the two sites has remained zero, the temperature difference in the past at the two sites can be calculated from the $\delta^{18}O$ of the foraminifera present at the same isotopic stage in the two cores from the formula:

$$T_2 - T_1 = -4.2\,(\delta^{18}O_{\text{foram 2}} - \delta^{18}O_{\text{foram 1}})$$

where, according to the simplified paleotemperature equation,

$$T = 16.9 - 4.2\,(\delta^{18}O_{\text{foram}} - \delta^{18}O_{\text{sea}})$$

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15. According to K. Geitzenauer (personal communication), the nannofossil *Pseudoemiliania lacunosa* boundary is at about 845 cm in core RC 17-69, which is equivalent to the lower part of stage 12 or about 460,000 years B.P.

16. Since the maximum glacial-interglacial $\delta^{18}O$ variation measured in abyssal Atlantic benthic foraminifera is 1.6 per mil, this variation is the highest possible without a change in temperature (J. C. Duplessy, unpublished results). The very large $\delta^{18}O$ variation of 2.4 per mil observed between the present and stage 12 in *G. sacculifer* of core RC 17-69 implies a strong temperature difference.

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18. We determined mean shell size by measuring the shell diameters of 50 or more specimens of spherical *Orbulina universa*. An appropriate portion is obtained by splitting sediment samples (coarser than 149 μm) through a microsplitter.

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20. We thank L. Lott, R. Free, E. Tuck, and M. Bé for laboratory assistance, W. S. Broecker and T. H. Peng for the radiocarbon dates, B. Le Coat and J. Antiqnac for help in the isotopic analysis, K. Geitzenauer for determining the *Pseudoemiliania lacunosa* datum on the basis of nannofossils, and T. L. Ku of the University of Southern California for valuable comments. The cores were obtained from the Lamont-Doherty Geological Observatory core collection, curated under NSF grant DES 72-01568. This research is an outgrowth of the CLIMAP Project and was supported under NSF (International Decade of Oceanographic Exploration) grants DES 71-04204, DES 75-21366, and DES 76-02202, Lamont-Doherty Geological Observatory Contribution No. 2385.

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Ecologic and Paleoclimatic Implications of Morphologic Variation of *Orbulina universa* in the Indian Ocean

Abstract. *Multivariate cluster analysis of various morphologic indices of* Orbulina universa *populations from the Indian Ocean indicate the existence of two major groups whose geographic distribution corresponds to the equatorial and central water masses. An abrupt change in shell porosity between populations of this planktonic foraminiferal species in plankton as well as sediment samples occurs within or near the 10°S Hydrochemical Front.* Orbulina universa *is an excellent indicator of oceanographic conditions in the Indian Ocean today, and may be used as an independent check on shifts in water masses during the last glaciation.*

Variation in the abundances and species composition of planktonic foraminifera preserved in deep-sea sediments has been shown to be valuable in reconstructing the paleoclimatic history of the oceans (*1*). This results from the fact that the geographic distribution of assemblages of living species corresponds to the distribution of major oceanic water masses. Temporal shifts in these water masses can thus be monitored by shifts in faunal zones as recorded in stratigraphic sequences (*2, 3*).

It is reasonable to expect that within a major water mass, each planktonic foraminiferal species would be characterized by distinct morphologic characters which differentiate it from neighboring populations in adjacent water masses. The existence of such morphological provinces should be most evident in areas where sharp hydrographic bound-

Table 1. Data on mean shell diameter and shell porosity of *O. universa* in plankton and sediment samples in the Indian Ocean.

Code	Sample	Latitude	Longitude	Mean shell diameter (μm)	Mean shell porosity (%)	Ocean depth (m)	Surface temperature (°C)	Surface density (g/liter)
				Central group				
Sediments								
A	V 14-81	28°26′S	43°47′E	608	5.17	3634	20.8	24.5
C	RC 11-124	36°6′S	90°13′E	417	6.19*	3775	14.0	26.5
D	V 18-222	38°34′S	140°37′E	646	5.73	1904	13.0	26.5
J	V 18-207	25°38′S	87°7′E	662*	5.17	3434	19.0	25.0
K	V 16-93	30°12′S	91°43′E	511	5.44	2769	16.0	26.0
L	Monsoon 45	18°41′S	87°51′E	624	5.71	1735	23.5	23.5
O	RC 11-123	37°59′S	86°39′E	421	5.66	3766	12.0	26.5
P	RC 11-120	43°31′S	79°52′E	413	5.10	3193	9.0	26.5
Q	V 20-170	21°48′S	69°14′E	596	4.81	2479	20.7	23.5
R	RC 8-61	46°32′S	125°34′E	385†	4.50†	4254	11.0	26.5
			Means	528.3	5.35			
Plankton								
1	V 16-131	29°52′S	62°36′E	536	3.48		23.9	
2	RC 9-111	28°27′S	101°57′E	525	5.00		23.9	
3	V 16-110	42°40′S	45°40′E	443†	3.31		14.9	
4	V 20-194	22°18′S	68°0′E	576	4.22		21.0	
5	V 19-148	12°44′S	82°1′E	681	6.79*		24.8	
7	V 14-142	13°35′S	64°39′E	697	6.08		28.0	
10	RC 8-29	35°49′S	109°57′E	723*	3.19†		18.9	
			Means	597.3	4.58			
				Equatorial group				
Sediments								
B	CH 99-64	13°18′S	46°59′E	694	7.72†	3243	24.8	23.5
E	Dodo 204	3°9′N	94°6′E	765	12.07	2150	28.4	23.5
F	RC 9-155	7°24′N	72°48′E	728	12.22	1765	28.0	23.5
G	Dodo 117	18°21′S	62°4′E	657†	9.44	3394	22.8	23.5
H	V 19-183	8°7′N	62°47′E	819*	17.35*	4451	27.3	22.5
I	V 19-200	4°13′S	41°33′E	690	9.23	2692	25.0	23.5
M	Dodo 193	2°12′S	69°15′E	724	9.98	3494	27.9	22.5
N	V 14-105	14°18′N	51°0′E	664	11.52	2120	24.8	23.0
			Means	717.6	11.19			
Plankton								
6	V 19-154	0°27′N	80°37′E	714†	9.71†		28.8	
8	V 19-168	0°29′S	53°41′E	787	10.96		27.4	
9	V 19-160	7°26′N	61°4′E	822	10.68		28.0	
11	V 20-180	17°10′S	99°12′E	860*	11.18*		24.2	
			Means	795.7	10.63			

*Maximum. †Minimum.