Stable isotope fractionation and differential dissolution in recent planktonic foraminifera from Pacific box-cores

Oxygen isotopes
Carbon isotopes
Planktonic foraminifera
Test ultrastructure
Deep-sea carbonates

Isotopes de l'oxygène
Isotopes du carbone
Foraminifères planctoniques
Ultrastructures du test
Carbonates pélagiques.

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ABSTRACT

Stable isotope analyses and scanning electron micrographs have been carried out on six planktonic forminifera species, *Pulleniatina obliquiloculata*, *Globorotalia tumida*, *Sphaeroidinella dehiscens*, *Globigerinoides ruber*, *Globigerinoides sacculifer* and *Globigerinoides quadrilobatus* from eleven box-cores taken at increasing depths in the equatorial Ontong-Java Plateau (Pacific). This allows us to describe the way dissolution affects the microstructures of the tests of the different species and to quantify the changes of isotopic composition. We may conclude that:

1) dissolution effects on test morphology and stable isotope compositions are species dependent, species with a similar habitat showing a similar trend;

2) the shallow water, thin-shelled species are the first to disappear: scanning electron microscope (SEM) work shows alteration of outer layers. Deep water, thick-shelled species are present in all samples: SEM work shows breakdown and disparition of inner layers;

3) for all species there is a similar trend towards increasing $\delta^{18}O$ values with increasing water depths and increasing dissolution. This effect may be as high as 0.6 °/$_{oo}$ per thousand meters for *Globorotalia tumida*;

4) below the lysocline, around 3 500 m, it appears that $^{13}C/^{12}C$ ratios slightly increase towards equilibrium values for thick shelled species: *G. tumida*, *P. obliquiloculata* and *S. dehiscens*.

^{14}C dates and isotope stratigraphy of two box-cores show that all samples are recent in age, and exclude upward mixing of glacial deposits as an important factor.

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RÉSUMÉ

Compositions isotopiques de l'oxygène et du carbone et dissolution sélective de foraminifères planctoniques des sédiments récents du Pacifique

L'étude couplée de la composition isotopique ($^{18}O/^{16}O$ et $^{13}C/^{12}C$) et de l'aspect morphologique de la dissolution (microscope électronique à balayage : MEB) a été effectuée sur six espèces de foraminifères planctoniques : *Pulleniatina obliquiloculata*, *Globorotalia tumida*, *Sphaeroidinella dehiscens*, *Globigerinoides ruber*, *Globigerinoides sacculifer* et *Globigerinoides quadrilobatus*. Les échantillons ont été prélevés par carottier-boîte à des profondeurs croissantes sur le Plateau d'Ontong-Java (Pacifique Ouest équatorial). On est ainsi en mesure de préciser de quelle manière la dissolution altère la microstructure des tests calcitiques, et l'on peut quantifier les variations de composition isotopique en fonction d'une profondeur et d'une dissolution croissantes. Les conclusions sont :

1) l'altération par dissolution de la morphologie des tests calcitiques et de leur composition isotopique est fonction de l'espèce, les espèces d'habitat semblables montrant des tendances similaires;

2) on distingue deux cas : les *espèces à test mince* vivant près de la surface en eaux chaudes sont les premières à disparaître : l'étude au MEB montre des altérations de la face externe du test; les *espèces à carapace* migrant au cours de la phase adulte à des profondeurs plus grandes en eaux plus froides sont préservées dans tous les échantillons : l'étude au MEB montre la disparition préférentielle des couches les plus internes du test;

3) pour toutes les espèces, la composition isotopique de l'oxygène augmente avec la profondeur et avec l'intensité de la dissolution. Cet effet peut atteindre 0,6 $°/_{oo}$ par 1 000 m pour *Globorotalia tumida;*

4) au-dessous de la lysocline, à environ 3 500 m, la composition isotopique de l'oxygène augmente légèrement, et se rapproche des valeurs d'équilibre pour les espèces à test épais : *G. tumida, P. obliquiloculata* et *S. dehiscens.*

Des datations au radiocarbone et la stratigraphie isotopique de l'oxygène de deux carottes ont prouvé que tous les échantillons étudiés (0-3 cm) étaient récents, et permettent d'exclure toutes contaminations par des niveaux glaciaires.

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INTRODUCTION

Oxygen and carbon isotopic ratios of planktonic foraminifera are dependent on a number of environmental factors, the most commonly cited being temperature, salinity, and depth habitat of the species. Intensity of primary production also appears to play a rôle. The relationships between stable isotopes and environmental factors have recently been summarized by Berger, Killingley and Vincent (1978).

Dissolution effects on isotopic composition have generally been over-looked, although it had been pointed out that they must exist (Berger, 1971 b; Savin, Douglas, 1973; Berger, Gardner, 1975). Conclusive evidence for the existence of a dissolution effect on oxygen isotope records was presented by Shackleton and Opdyke (1976), who used a pair of well-dated cores from different depths, one less extensively dissolved than the other (see also Duplessy, 1977). The magnitude of the effect was established by Berger and Killingley (1977) for both oxygen and carbon isotopes. They used a pair of box-cores, one of which had no signs of dissolution of calcite, while the other was raised from just below the lysocline. Berger and Killingley showed that the average oxygen isotope value of *Globigerinoides sacculifer* was changed by 0.3 °/oo through dissolution, at the lysocline level, whereas *Pulleniatina obliquiloculata* was unaffected by dissolution at the same level. Similarly, the $\delta^{13}C$ values were found to differ by about 0.3°/oo, between *G. sacculifer* from shallow and deeper levels. Changes are toward heavier values for oxygen and toward lighter values for carbon as the extent of dissolution increases.

Here we report additional observations on box-cores from the Ontong-Java Plateau which provide evidence for the effect of dissolution on foraminiferal isotopic compositions and for the magnitude of the effect in the entire dissolution range. The pertinent conditions of sedimentation in this area were summarized by Johnson, Hamilton and Berger (1977).

MATERIALS AND METHODS

Six foraminiferal taxa *Globorotalia tumida, Sphaeroidinella dehiscens, Pulleniatina obliquiloculata, Globigerinoides sacculifer, Globigerinoides quadrilobatus* and *Globige-rinoides ruber* were selected from surface samples of eleven box cores (50 x 50 cm) from the Ontong-Java Plateau, in the Western Equatorial Pacific (Eurydice Expedition, Leg 9, April-May 1975) taken at increasing depths (Table 1). The first five species were separated from the fraction coarser than 400 µm, and the sixth (*G. ruber*) was picked from a smaller size fraction, between 250 and 315 µm.

All surface samples studied were dated by ^{14}C (Berger, Johnson, 1978; Peng, Broecker, Berger, 1979; Krishnamurthy *et al.*, in press; and unpublished).

Natural dissolution effects on test morphology and the isotopic composition of foraminifera were studied using scanning electron microscopy and stable isotope analyses. Stratigraphy was established in La Jolla for four box cores based on isotopic analyses of *Pulleniatina obliquiloculata*. Two of these stratigraphies (ERDC 92, ERDC 123) have been published previously (Berger, Johnson, Killingley, 1977).

Stable isotope analysis of surface samples were done in Paris and followed standard procedures (Shackleton, 1965, 1974). Sediments were subjected to a few seconds of ultrasonic treatment to disaggregate the particles, and

Table 1

Location and depths of the box-cores studied.

Localisations et profondeurs de depôt des échantillons analysés, prélevés par carottier-boîte.

Box-cores number	Water depth (m)	Latitude	Longitude
ERDC Bx 92*	1 598	2°13.5'S	156°59.9'E
ERDC Bx 88	1 924	0°02.9'S	155°52.1'E
ERDC Bx 120	2 247	0°01.0'S	158°41.6'E
ERDC Bx 79	2 767	2°47.1'N	156°13.8'E
ERDC Bx 123*	2 948	0°01.3'S	160°24.9'E
ERDC Bx 125	3 368	0°00.2'S	160°59.9'E
ERDC Bx 128	3 732	0°00.3'S	161°25.6'E
ERDC Bx 136	3 848	1°06.0'N	161°36.3'E
ERDC Bx 139*	4 118	1°21.7'N	162°23.6'E
ERDC Bx 129*	4 169	0°00.4'S	161°58.5'E
ERDC Bx 141	4 324	2°21.7'N	163°42.4'E
ERDC Bx 131	4 441	0°01.6'S	162°41.1'E

* *Cores for which isotope stratigraphies are given. ERDC BX 139 was not included in the study of surface samples.*

* Carottes pour lesquelles la stratigraphie isotopique a été établie. L'étude des six espèces de foraminifères dans l'échantillon de surface (0-3 cm) n'a pas été faite pour le prélèvement ERDC BX 139.

Table 2

Oxygen and carbon isotope ratios for six planktonic species from eleven different depths. All samples are surface sediment. Globigerinoides quadrilobatus *is a variety of* Globigerinoides sacculifer.

Composition isotopique de l'oxygène et du carbone pour six espèces de foraminifères planctoniques prélevées à onze profondeurs différentes. Tous les échantillons représentent l'interface eau-sédiment. *Globigerinoides quadrilobatus* est une variante de *Globigerinoides sacculifer.*

Water depth (m)	Globorotalia tumida (>400 μm)		Sphaeroidinella dehiscens (>400 μm)		Pulleniatina obliquiloculata (>400 μm)		Globigerinoides ruber (250 to 315 μm)		Globigerinoides sacculifer (>400 μm)		Globigerinoides quadrilobatus (>400 μm)	
	$\delta^{18}O$	$\delta^{13}C$	$\delta^{18}O$	$\delta^{13}C$	$\delta^{18}O$	$\delta^{13}C$	$\delta^{18}O$	$\delta^{13}C$	$\delta^{18}O$	$\delta^{13}C$	$\delta^{18}O$	$\delta 13C$
1 598	−0.76	+1.54	−1.09	+1.77	−1.40	+0.97	−2.53	+1.06	−2.15	+1.90	−2.26	+1.77
1 924	−0.36	+1.65	−1.38	+1.89	−1.56	+0.94	−2.27	+1.25	−2.37	+2.46	−2.97	+1.19
2 247	−0.78	+1.39	−1.45	+1.67	−1.51	+1.16	−2.28	+1.28	−1.80	+1.96	−2.75	+1.26
2 767	−0.35	+1.60	−1.13	+1.72	−1.01	+1.29			−2.16	+2.18	−1.95	+1.69
2 948	−0.47	+1.62	−1.19	+1.57	−1.31	+0.84			−2.02	+2.17		
3 368	−0.39	+1.39	−1.23	+1.56	−1.45	+1.17			−1.88	+1.15		
3 732	+0.19	+1.74	−1.03	+1.71	−1.20	+1.26						
3 848	+0.06	+1.73	−1.00	+1.75	−0.96	+0.63						
4 169	−0.52	+1.91	−1.09	+1.62	−1.29	+1.12						
4 324	+0.56	+1.93	−1.13	+1.53	−0.89	+1.04						
4 441	+0.15	+2.05	−0.85	+1.72	−1.17	+1.35						

then they were wet sieved. Only empty specimens were analysed. Working reference gas was extracted from a white marble and calibrated against standard NBS 20 limestone treated as the other samples. The standard gave $\delta^{18}O = +1.91$, and $\delta^{13}C = +3.41$ versus NBS 20.

The standard deviation calculated from fifty repeated analyses of different samples of the same carbonate powder, calibrated against NBS 20 was: $\sigma = 0.13$ for $\delta^{18}O$; and $\sigma = 0.06$ for $\delta^{13}C$.

The standard deviation of thirty analyses of the same foraminiferal species in recent surface sediment is $\sigma \approx 0.14$ to 0.16 for $\delta^{18}O$. The average difference between duplicate or triplicate foraminiferal analyses is around $0.15°/_{oo}$ for $\delta^{18}O$.

RESULTS AND DISCUSSION

Isotopic compositions of surface samples are shown in Table 2. Oxygen and carbon isotopic compositions of the different species have been plotted against increasing water depths (Fig. 1). Oxygen isotope stratigraphies
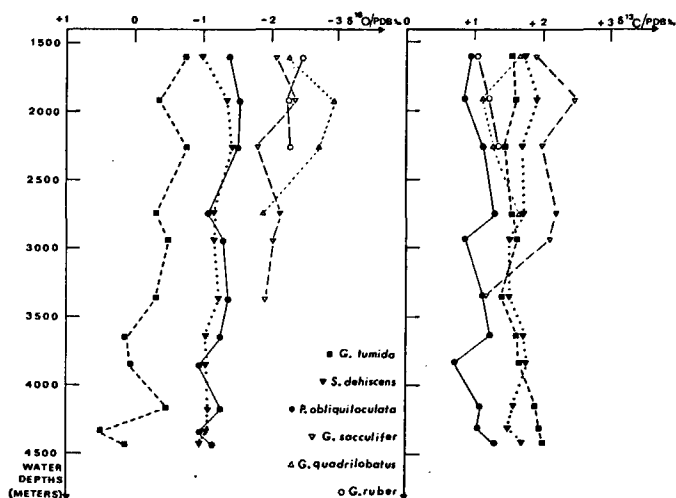

Figure 1

Oxygen and carbon isotope composition of selected foraminiferal species of surface sediments as a function of water depths.

Composition isotopique de l'oxygène et du carbone des foraminifères sélectionnés dans des échantillons de surface en fonction de la profondeur de dépôt.
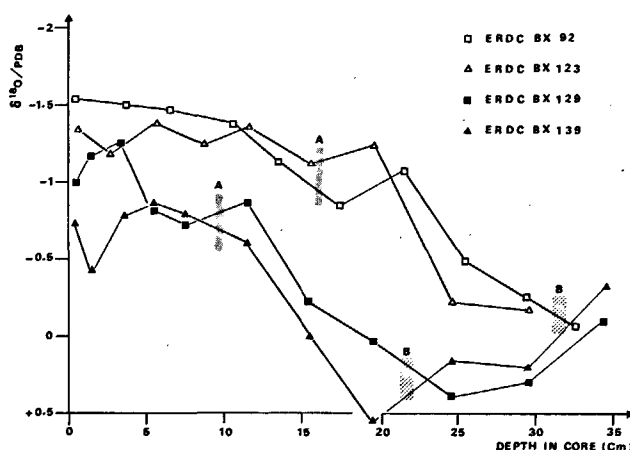

Figure 2

Oxygen isotope stratigraphy of Pulleniatina obliquiloculata *from four box-cores,* ERDC BX 92, ERDC BX 123 *are well above the lysocline;* ERDC BX 129, ERDC BX 139 *are below that level. A and B represent equivalent stratigraphic levels.*

Composition isotopique de l'oxygène de *Pulleniatina obliquiloculata* pour quatre carottes. ERDC BX 92, ERDC BX 123 sont bien au-dessus de la lysocline actuelle, ERDC BX 129 et ERDC BX 139 sont bien en-dessous de ce niveau. A et B représentent des niveaux stratigraphiques semblables.

based on analyses of *Pulleniatina* in four box cores are shown in Figure 2.

Figure 1 clearly illustrates the effect on the different species of increasing extent of dissolution of carbonate with depth.

● The shallow water species, thin-walled and porous, are the first to disappear from foraminiferal assemblages. Specimens of *Globigerinoides* are rare at depths greater than 3 500 m. Deeper-water species, thick-walled and dense, are present in all samples.

● It appears that isotopic effects due to natural dissolution depend mainly on the species: species with a similar habitat show a similar trend.

● For all species there is a similar tendency towards increasing $\delta^{18}O$ values with increasing water depth (that is, increasing dissolution). The change is not entirely linear with depth.

● For thick-shelled species (*Globorotalia tumida, Pulleniatina obliquiloculata* and *Sphaeroidinella dehiscens*),

there appears to be an increase of $^{13}C/^{12}C$ ratios towards equilibrium values. For the thin-shelled forms (*Globigerinoides ruber*, *Globigerinoides sacculifer* and *Globigerinoides quadrilobatus*), there is an indication that the ratios decrease with dissolution.

Differential dissolution of the calcite layers of the tests

SEM studies of undissolved and dissolved specimens clearly show increasing destruction of tests with increasing depth. Dissolution removes parts of the walls.

It has been established by several authors (Oba, 1969; Vergnaud-Grazzini *et al.*, 1973; Hecht, Savin, 1970, 1972; Bé, Van Donk, 1971; Emiliani, 1971) that different parts of a planktonic foraminifera shell could be secreted in different environments (essentially different water depths), thus yielding a range of isotopic values for both oxygen and carbon on the same shell. Tests of different sizes may have different $^{18}O/^{16}O$ ratios (Oba, 1969; Vergnaud-Grazzini, 1976; Berger *et al.*, 1978).

A careful study of dissolved specimens by scanning electron microscopy allows us to propose an explanation for the changes observed in the $^{18}O/^{16}O$ and $^{13}C/^{12}C$ ratios with increasing destruction of the test. We must distinguish two cases (A and B).

Case A. Thick-shelled species (Globorotalia tumida, Pulleniatina obliquiloculata, Sphaeroidinella dehiscens)

$\delta^{18}O$ values of all three species increase with depth ($0.58\,°/_{oo}$ per thousand meters for *G. tumida* and about $0.14\,°/_{oo}$ per thousand meters for *P. obliquiloculata* and *S. dehiscens*. There are small increases in $\delta^{13}C$ ($0.16\,°/_{oo}$ per thousand meters for *P. obliquiloculata* and less than $0.1\,°/_{oo}$ per thousand meters for the other two species. For the last two species, this increase is significant for a depth range over 1 km.

One of us has shown by detailed SEM studies that dissolution of the test starts at the *inner* part of the wall for these species (Bonneau, 1978; see Plate 1). At depths well below the lysocline, the outer surface is not or only slightly damaged, while sections show that one or more inner layers have disappeared; these layers correspond to the early stages of growth.

The apparent increase in the stable isotope ratios may be simply explained by the fact that the calcite layers which are first dissolved were depleted in ^{18}O. This implies, in turn, that the various calcitic layers of a single test have different isotopic compositions: the (early) inner layers should be enriched in ^{16}O and ^{12}C, while the (late) outer layer secreted during downward migration of the foraminifera, should be enriched in ^{18}O and ^{13}C. Thus, an *isotopic stratification* of the test is likely to exit. The $\delta^{18}O$ "lighter" layers would have formed in warmer water (at these locations we can exclude seasonal effects); the lower $\delta^{13}C$ values probably reflect high desequilibrium in carbon isotope fractionation during early growth stages. The outer and "heavier" layers would have formed in deeper and colder waters, nearer thermodynamic equilibrium. That heavier shells of the same species occur in deeper waters is supported by
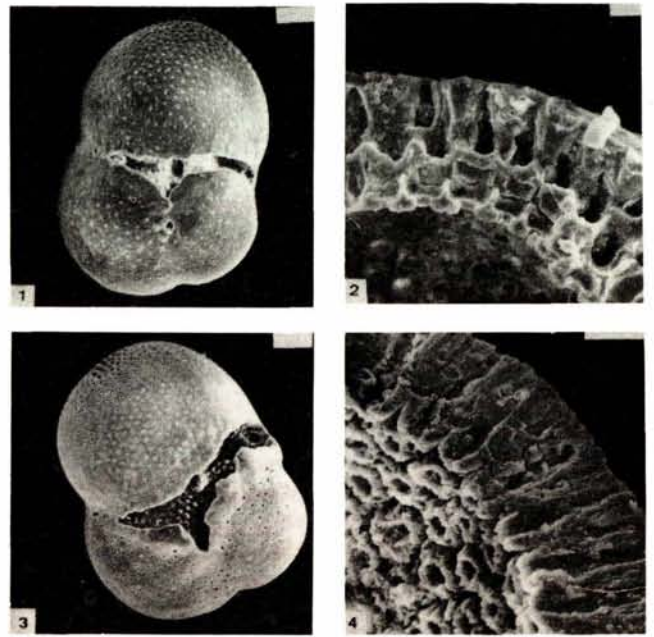

Plate 1

1) *Undamaged* Sphaeroidinella dehiscens (1 598 *m*) (*bar scale equal* 100 µm).
2) *Section of* Shaeroidinella dehiscens *wall* (1 598 m). *Test is composed by several layers. Inner wall has smooth aspect* (bar scale equal 25 µm).
3) Sphaeroidinella dehiscens (4 441 m) *with small traces of etching* (*bar scale equal* 100 µm).
4) *Section of* Sphaeroidinella dehiscens *wall* (4 441 m). *Inner layers have disappeared with dissolution. Inner wall has lost smooth aspect* (*bar scale equal* 25 µm).

1) *Sphaeroidinella dehiscens* intacte (profondeur de dépôt : 1 598 m) (la barre d'échelle représente 100 µm).
2) Vue de l'épaisseur du test de *Sphaeroidinella dehiscens* (profondeur de dépôt 1 598 m). Le test comporte plusieurs couches. La face interne a un aspect lisse (la barre d'échelle représente 25 µm).
3) *Sphaeroidinella dehiscens* présentant de légères traces de dissolution (profondeur de dépôt 4 441 m) (la barre d'échelle représente 100 µm).
4) Vue de l'épaisseur du test de *Sphaeroidinella dehiscens* (profondeur de dépôt 4 441 m). Les couches les plus internes ont disparu sous l'effet de la dissolution. La face interne du test a perdu son aspect lisse et présente des figures de dissolution caractéristiques (aspect en « balannes ») (la barre d'échelle représente 25 µm).

plankton tow results (Bé, 1960; Bé, Ericson, 1963; Berger, 1971 *a*; Vergnaud-Grazzini, 1976).

Why dissolution should occur first on the inner side of the test is still an unsolved problem. Is there a selective dissolution owing to a loose structure of the microgranular inner layer, or a difference in the crystalline arrangement of the inner and outer layers; or a difference in magnesium content of the calcite (Savin, Douglas, 1973) forming the different layers.

Case B. Thin-walled forms (Globigerinoides ruber, Globigerinoides sacculifer *and* Globigerinoides quadrilobatus

Owing to the fragility of their tests (which are commonly relatively thin and break easily), these forms disappear quite quickly from deeper sediments, the fragments of their tests becoming constituents of the fine fraction. The trends in Figure 1 suggest parallel behavior for these two species: the $\delta^{18}O$ content increases with depth and with dissolution. For *Globigerinoides ruber*, the $\delta^{18}O$ increase is about $0.4\,°/_{oo}$ per thousand meters, and about $0.2\,°/_{oo}$ per thousand meters for *Globigerinoides sacculifer*. The trends in $\delta^{13}C$ are not clear due to the scarcity of the species as the lysocline is approached.

SEM observations show that (Plate 2) dissolution affects mainly the *outer* surface, between the pores; holes may be formed by the removal of some parts of the test; the final chamber may completely disappear at the same time as parts of the outer layers of the test.

Given these differences in the mode of dissolution, why should the $\delta^{18}O$ response be in the same direction as for *G. tumida*, *P. obliquiloculata* and *S. dehiscens*, and why should the $\delta^{13}C$ response display an opposite trend?

At any one level, different individuals of *Globigerinoides* will not be affected to the same degree by dissolution. It is clear that the thin-walled forms of this genus will be the first to disappear as dissolution increases. Thus, the remaining individuals are the more resistant ones, those with a thicker test. The thinner tests are secreted at the shallower depths, and the thicker ones at greater depths. Thus, in undissolved samples we analyze a mixture of "thin" and "thick"-shelled variants; while in partially dissolved samples we find only the thicker variants and a higher $^{18}O/^{16}O$ ratio and a lower $^{13}C/^{12}C$ ratio. In this case, the higher ^{13}C content of the shells built in shallower water must reflect the high $^{13}C/^{12}C$ ratios reported from surficial waters (see Kroopnick *et al.*, 1977).
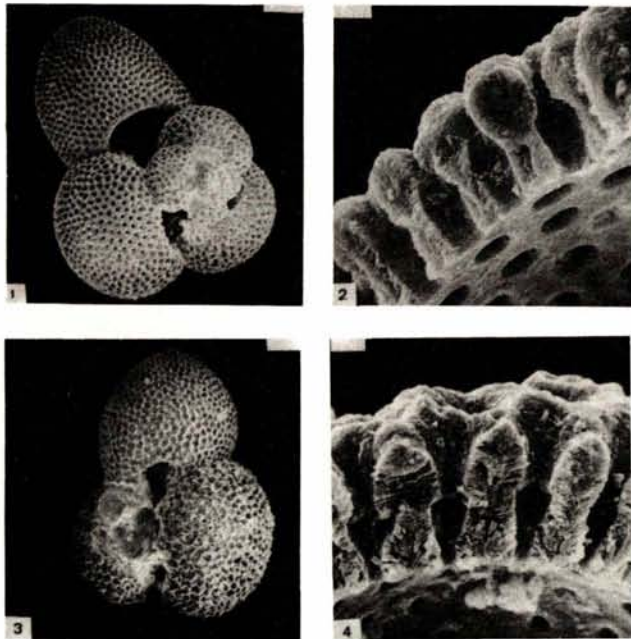

Plate 2

1) *Undamaged* Globigerinoides sacculifer (1 598 m) (*bar scale equal 100 μm*).

2) *Section of* Globigerinoides sacculifer wall (1 598 m). *Test is billamelar* (*bar scale equal 10 μm*).

3) *Damaged* Globigerinoides sacculifer (3 368 m). *Notice hole and removal of parts of the test* (*bar scale equal 100 μm*).

4) *Section of* Globigerinoides sacculifer wall (3 368 m). *Inner wall does not present evidence of dissolution* (*bar scale equal 10 μm*).

1) *Globigerinoides sacculifer* intacte (profondeur de dépôt 1 598 m). Le test est perforé et gaufré (la barre d'échelle représente 100 μm).

2) Vue de l'épaisseur du test de *Globigerinoides sacculifer* (profondeur de dépôt 1 598 m). Le test est bilamellaire. La face interne du test est lisse (la barre d'échelle représente 10 μm).

3) *Globigerinoides sacculifer* présentant un test endommagé (profondeur de dépôt 3 368 m) (la barre d'échelle représente 100 μm).

4) Vue de l'épaisseur du test de *Globigerinoides sacculifer* (profondeur de dépôt 3 368 m). Il ne manque aucune couche. La face interne du test ne présente aucune trace de dissolution (la barre d'échelle représente 10 μm).

Oxygen isotope stratigraphy

An effect of dissolution on the oxygen isotope composition of planktonic foraminifera was identified previously by Savin and Douglas (1973), who compared the isotope values for surface samples taken at different water depths in the South Pacific. A weakness in their data base is that the surface samples are not dated. If they include glacial material (as suggested by the work of Broecker and Broecker (1974) for certain areas on the East Pacific Rise), then the differences in isotope values may be at least in part due to such stratigraphic complications rather than entirely to dissolution effects (Berger, Killingley, 1977). To avoid this possible complication, we have dated the surface samples, making sure they are of Holocene age. We also consider four typical isotope stratigraphies, two for depths above the lysocline and two for depths below that level (Fig. 2).

The two pairs of isotope curves show the dissolution effect in two ways: 1) the difference in sedimentation rates is reflected in a difference in stratigraphic position of equivalent stratigraphic levels (A and B); and 2) the absolute values for $\delta^{18}O$ differ between the stratigraphies by about $0.35°/_{oo}$, with the samples from greater depth showing the heavier values at equivalent levels. The ratio of sedimentation rates between "shallow" cores and "deep" ones is between 1.5 and 2; thus, between 25 and 50% of the carbonate has been dissolved in the deeper cores, producing the isotope shift of $0.35°/_{oo}$.

To what degree does benthic mixing influence these results? Are Holocene (Recent) sediments significantly mixed with deposits of glacial ages?

The overall validity of a simple box model for mixing (Berger, Heath, 1968) has been established for two of these cores by ^{14}C dating (Peng, Broecker, Berger, 1979; Krishnamurthy *et al.*, in press). The mixed layer thickness is 8.5 cm ± 1 cm in this region (Berger, Johnson, 1978). The concentration of *Pulleniatina* slightly increases upward in the cores (Berger, 1977 a), a fact that is favorable for excluding contamination effects in these species.

We can therefore now estimate the magnitude of the effect as follows: assume the $\delta^{18}O$ is a step function at the glacial-Holocene transition, then the amount of glacial material above the transition is given by:

$$G = G_0 . e^{-L/M}, \tag{1}$$

where G_0 is the value at the last stratigraphic level of the core which has full glacial conditions (= one mixed layer depth below the actual transition), L is the distance between that level and the level at which G is found, and M is the mixed layer depth (Berger, Heath, 1968) (for $L = M$, the term $e^{-L/M}$ becomes 0.37, or 37 %). For the "shallow" cores, G_0 is at B, that is, near 32 cm depth in the cores. A sample taken at the "surface", therefore, is 30 cm above this level. According to Equation (1), the expected contamination for $L = 30$ cm and $M = 8.5$ is $e^{-3.5}$. This is 3 %. Thus, the $\delta^{18}O$ values of the "shallow" cores would be too heavy by 3 % of the difference between Holocene and glacial values, that is, by less than $0.045°/_{oo}$, which is well within the precision

of the measurements. The contamination for the "deep" cores can be reckoned similarly (L=20 cm; M=8.5; $e^{-2.35}$). It is 10 % maximally; that is, it corresponds to $0.15°/_{oo}$ at the most. On the basis of sedimentation rate difference alone, therefore, we do expect a certain difference in the isotope values of Recent samples, due to a difference in contamination by glacial material. The effect is $0.1°/_{oo}$, that is, the "deep" cores will show values this much heavier independent of a dissolution effect.

The actual difference is near $0.35°/_{oo}$; thus, it cannot be explained by contamination. In addition, the difference is also observed within the glacial sediments, where contamination from older sediments should *decrease* the effect produced by dissolution alone.

The observation that the $\delta^{18}O$ differences which are due to dissolution are about the same at Holocene and glacial levels is surprising in view of the fact that dissolution greatly increased during the Holocene (Berger, 1977 b). It appears, therefore, that the dissolution effect on oxygen isotope composition is fully established at a certain level of intensity of dissolution. A further increase in this intensity does not necessarily correlate with an increase in the isotope shift.

Acknowledgments

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