*Marine Geology* – Elsevier Publishing Company, Amsterdam – Printed in The Netherlands

# PLANKTONIC FORAMINIFERA: SELECTIVE SOLUTION AND THE LYSOCLINE

WOLFGANG H. BERGER[1]

*Scripps Institution of Oceanography, University of California, San Diego, Calif. (U.S.A.)*

(Received September 24, 1968)
(Resubmitted December 10, 1968)

## SUMMARY

Pacific Ocean waters appear to be undersaturated with calcium carbonate at all depths except in the uppermost few hundred meters. This leads to continuous destruction of almost all calcareous sediment exposed on the Pacific Ocean floor. Samples derived from sediment and from plankton were exposed for four months on a taut wire buoy in the central Pacific, in order to assess the effects of solution on foraminiferal death assemblages. The rate of destruction varied for different species and for different variants within species. Sediment assemblages therefore should tend to become enriched with resistant (non-spinose) species and with opaque (usually thick-shelled), zero and negative forms, i.e., specimens with small terminal chambers. Results obtained by laboratory experiments compare well with those obtained from the solution experiments in the field.

The distribution of resistant forms in surface sediment samples from the East Pacific Rise shows that there exists a level of rapid solution increase (lysocline) in this area. The surface of the lysocline is at approximately 4,000 m depth in the tropics on the western side of the East Pacific Rise. The lysocline surface slopes upward toward Antarctica and toward South America and apparently becomes less well defined in high latitudes and near the continent. The calcium carbonate compensation depth results from a balance of rates of solution and of rates of supply of calcareous matter and usually lies well below the lysocline. The existence of a lysocline implies an associated oxygen minimum roof, and is bound to both active bottom water production and excess calcite supply by planktonic organisms.

## INTRODUCTION

Planktonic Foraminifera thrive in surface waters of the open ocean. Their death assemblages provide much of the sediment accumulating on the ocean floor. Known as "*Globigerina* ooze" or "foraminiferal ooze" when sufficiently concen-

[1]Present address: Geologisches Institut, Universität Kiel (B.R.D.).

trated, foraminiferal shells form widespread pelagic deposits which store information about both the present conditions and the history of the oceans.

The processes transforming life into death assemblages and death into sediment assemblages are poorly understood, and this hampers analysis of much of the geological record. Several recent studies have been concerned with the role that solution plays in these processes (BERGER, 1967, 1968; PYTKOWICZ and FOWLER, 1967; RUDDIMAN and HEEZEN, 1967). The purpose of this study is: (*1*) to evaluate the importance of solution in the modification of sediment assemblages of planktonic foraminiferal species and variants; (*2*) to provide experimental information about the transition from death to sediment assemblages; and (*3*) to map the distribution of the intensity of destruction of foraminiferal shells in the eastern South Pacific. Such maps have important implications for physical, chemical, and ecological oceanography and for paleoclimatology.

## SATURATION OF SEA WATER WITH CALCIUM CARBONATE

The most important agent of transformation of foraminiferal death assemblages in the deep-sea probably is the gradual dissolution of calcium carbonate which selectively removes some constituents while having little effect on others (MURRAY, 1897; SCHOTT, 1935). Another agent affecting the sediment is destruction by benthonic organisms. Mixing and horizontal displacement may change the proportions of the members of an assemblage (BERGER and HEATH, 1968). It has been suggested that recrystallization also may be important (REVELLE, 1944), but this has been seriously questioned (BÉ and ERICSON, 1963).

The problem of calcium carbonate saturation and its effect upon the preservation of shell material has been studied since the "Challenger" expedition. MURRAY and RENARD (1891) observed the distribution of pteropod shells and suggested that they were attacked by solution at rather shallow depths. Wattenberg, chemist of the "Meteor" expedition, investigated the theoretical aspects of sea water saturation and applied the results to the Atlantic Ocean in a series of papers (summarized in BARTH et al., 1939). He related saturation to carbon dioxide content, pH, alkalinity, salinity, temperature and pressure. He calculated the saturation of bottom waters in the Brazil and Angola basins, obtaining undersaturation in the former and supersaturation in the latter basin. His alkalinity measurements, however, indicated that solution takes place in both basins.

It appears to be difficult to obtain reliable measurements of the variables to be entered into the thermodynamic equations for calcium carbonate equilibrium in sea water. Recent calculations of ocean water saturation (BERNER, 1965; PYTKOWICZ, 1965), however, are in remarkable agreement with actual measurements of solution rates (PETERSON, 1966). PYTKOWICZ (1965) offers several tables of calcium carbonate saturation with depth for profiles near 80°W and 15°S, based on data taken by U.S.N.S. "Eltanin" and on thermodynamic calculations. The profile he

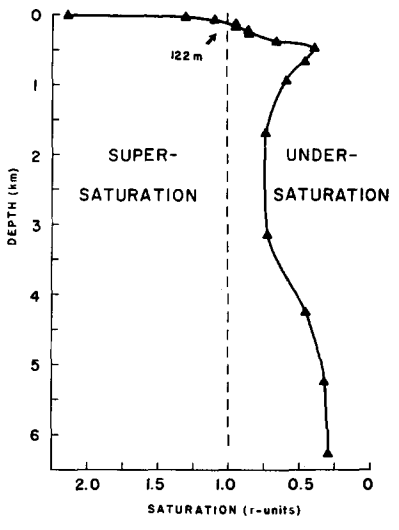
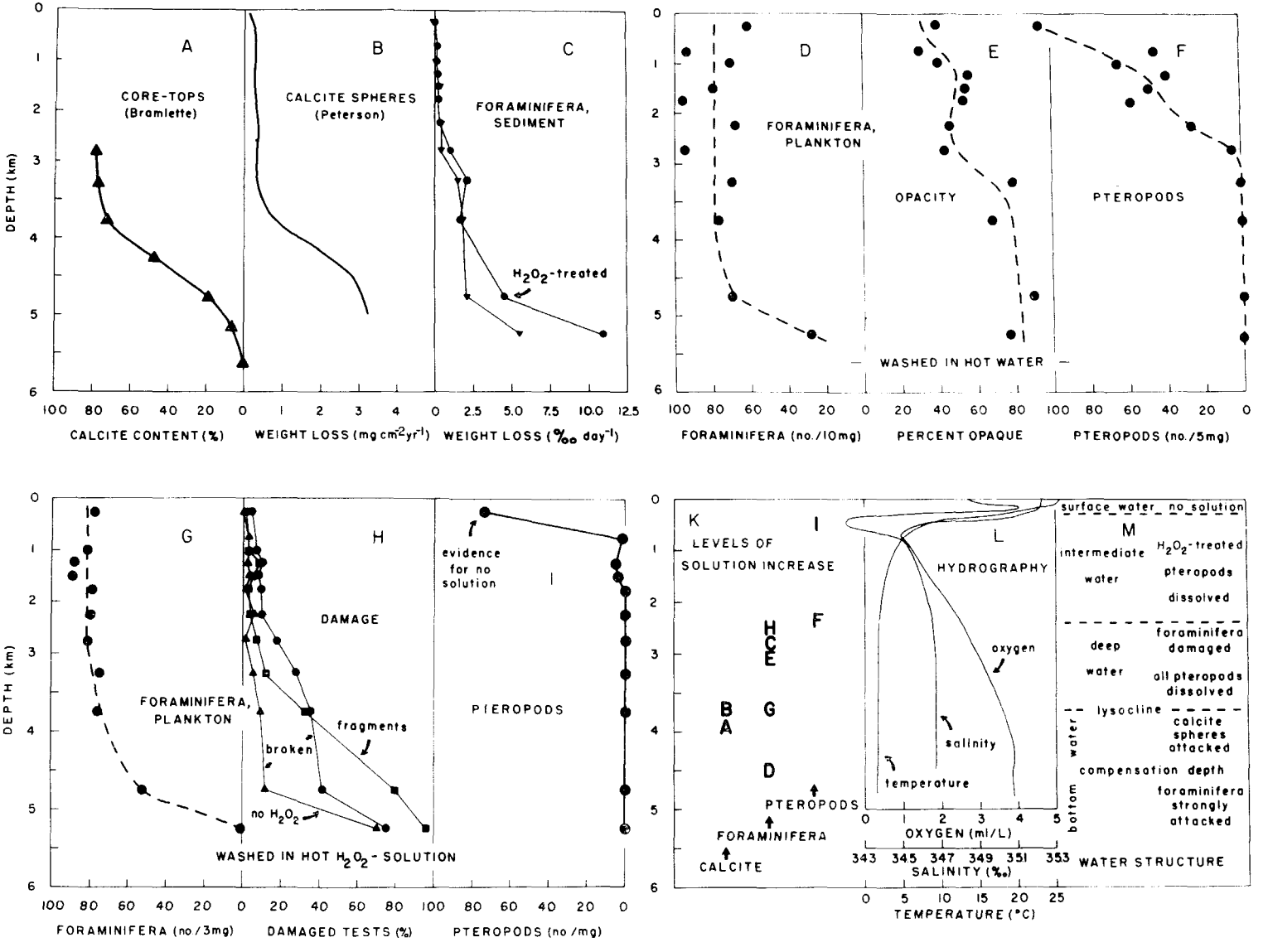



Fig.1. Calculated degrees of saturation of ocean water off Peru.
Based on PYTKOWICZ (1965, table I). The values plotted are the ratios of the observed carbonate concentration to the concentration expected if the water sample had been saturated with respect to calcite at the in situ pressure.

considers typical of the area is plotted in Fig.1. The surface water is calculated to be supersaturated with calcium carbonate, while the subsurface water appears to be undersaturated at all depths.

The area from which Pytkowicz' data were obtained is in a region of upwelling off Peru. The depth of the mixed layer is about 30–50 m (WOOSTER, 1960; WOOSTER and REID, 1962); thus, the supersaturation would appear to extend well into the thermocline. The calculated undersaturation maximum at about 400–700 m corresponds to a strong oxygen minimum (REID, 1965, p.62). Such minima are known to be associated with carbon dioxide maxima and pH minima (GRAHAM and MOBERG, 1944; PARK, 1968). From 1,000 to 3,000 m the profile indicates little change in undersaturation. From between 3,000 and 4,000 m depth the undersaturation becomes increasingly greater toward the bottom. This part of the profile is in good general agreement with geological data, summarized by BRAMLETTE (1961), and with the solution experiments by PETERSON (1966) in the central Pacific. Their profiles show that dissolution of calcium carbonate increases drastically between 3,500 and 4,000 m depth in the central Pacific (Fig.2A, B). Above this level it is difficult to detect differences in the dissolving action of sea water, even in the oxygen minimum layer, contrary to what might be expected on the basis of calculated undersaturation with respect to calcite (Fig.1). In comparing Fig.1 and Fig.2, however, it should be kept in mind that the upwelling region off Peru is certainly not representative for the whole central Pacific.


A
CORE-TOPS
(Bramlette)
B
CALCITE SPHERES
(Peterson)
C
FORAMINIFERA,
SEDIMENT
$H_2O_2$-treated
DEPTH (km)
CALCITE CONTENT (%)
WEIGHT LOSS (mg cm$^{-2}$yr$^{-1}$)
WEIGHT LOSS (‰ day$^{-1}$)
D
FORAMINIFERA,
PLANKTON
E
OPACITY
F
PTEROPODS
WASHED IN HOT WATER
FORAMINIFERA (no./10mg)
PERCENT OPAQUE
PTEROPODS (no./5mg)
G
H
DAMAGE
FORAMINIFERA,
PLANKTON
fragments
broken
no $H_2O_2$
WASHED IN HOT $H_2O_2$ - SOLUTION
FORAMINIFERA (no/3mg)
DAMAGED TESTS (%)
I
evidence
for no
solution
PTEROPODS
PTEROPODS (no/mg)
K
LEVELS OF
SOLUTION INCREASE
I
H
F
E
B
A
G
D
PTEROPODS
FORAMINIFERA
CALCITE
L
HYDROGRAPHY
oxygen
salinity
temperature
OXYGEN (ml/L)
SALINITY (‰)
TEMPERATURE (°C)
M
surface water no solution
intermediate water
$H_2O_2$-treated pteropods dissolved
deep water
foraminifera damaged
all pteropods dissolved
lysocline
calcite spheres attacked
compensation depth
foraminifera strongly attacked
bottom water
WATER STRUCTURE

EXPERIMENTS ON DISSOLUTION OF FORAMINIFERA AND PTEROPOD SHELLS

*Depth profile*

The general undersaturation of Pacific Ocean waters is responsible for a continuous destruction of exposed calcareous sediment at virtually all depths, especially below the level of rapid increase of solution rate. The effects of dissolution were studied in conjunction with PETERSON'S (1966) solution experiment using a deep-moored buoy in the central Pacific near Horizon Guyot.

Samples of foraminiferal ooze and of shelled plankton derived from tows were split into aliquots of various series. Portions of a washed sediment from the East Pacific Rise (22°07'S 115°10'W, water depth 3,190 m) were washed in buffered, hot, demineralized water. Another series of samples from the same sediment was boiled for three hours in buffered 10% hydrogen peroxide solution. Both types of aliquots weighed about 0.1 g each (Fig.2C). Plankton aliquots were derived from plankton tow samples by gravity separation. They were washed in hot water (Fig.2D, E, F). Another series of aliquots derived from plankton was of somewhat different composition. Only shells smaller than 0.5 mm were used for this series, which was treated with hydrogen peroxide (Fig.2G, H, I). The plankton aliquots weighed about 0.01 g each. All plankton used came from depths of 0–600 m between 35° and 15°N in the eastern Pacific.

The samples were placed in plastic tubes about 2.5 cm long and 2 cm wide, which were sealed with nylon gauze having openings of less than 62 $\mu$. Several samples of each series were retained in the laboratory as controls. The samples which were exposed in the ocean were protected by heavy pieces of core-liner which were open at both ends. The core-liners were fastened to the taut wire so that they could rotate vertically. The samples were recovered after four months of exposure during the summer of 1966. Further details of the procedure are given by PETERSON (1966) and by BERGER (1967).

Fig.2. Calcium carbonate solution in the central Pacific. A. Average percentage of calcium carbonate in core-top samples, after BRAMLETTE (1961). B. Difference in weight of calcite spheres before and after exposure along the taut wire of a buoy in the central Pacific. Simplified after PETERSON (1966). C. Loss of weight of foraminiferal sediment during the solution experiment, after BERGER (1967). D,E,F. Exposure effects on plankton aliquots washed in hot water only. D. Number of Foraminifera present after the experiment, divided by the original weight of each sample. E. Percentage of foraminiferal plankton having opaque tests after exposure. F. Number of (aragonitic) pteropod shells present after the experiment, per original weight of sample. G,H,I. Exposure effect on plankton aliquots washed in buffered hot hydrogen peroxide solution. G. As in D. H. Percentage of damaged shells in the foraminiferal plankton. I. As in F. K. Levels at which the diagrams A to I seem to indicate an increase in solution effects. L. Hydrography near the buoy. M. Water structure inferred from solution effects.

Values for samples at 4,250 m have been deleted. Flow through the container protecting these samples is believed to have been restricted: all samples show rather little solution of calcium carbonate. The shape of the curves drawn are considered to be of greater interest than the absolute values, which may largely depend on the experimental procedure. (See BERGER, 1967, for discussion of errors.)

Fig.2 shows the effects of exposure on the various sample series, and the inferred water structure. Fig.2C shows the weight losses of the foraminiferal sediment samples in parts per thousand per day. Above 1,000 m depth less than 2% and above 2,000 m less than 5% of each sample was lost during the four months of the experiment, corresponding to very small daily losses. This suggests that any mechanical losses through flushing of the containers were negligible in these samples, unless mechanical losses increased together with solution losses. Below 2,000 m solution becomes important in destroying foraminiferal tests from sediment samples. The ones treated with hydrogen peroxide lost more weight than the others. The treatment may have increased the surface area of the tests available to solution. Possibly the tests were cleaned of organic material, which otherwise could have protected them from solution. Between 3,000 and 5,000 m the solution rates increase by a factor of more than three, and they approximately double in the deepest 500 m, from 4,750 to 5,250 m.

Pteropods, Foraminifera, Acantharia and other shelled plankton were present in somewhat varying amounts in the plankton samples. Values are given as number of specimens per weight (Fig.2D, F, G, I), because the original number present is not known. This restricts interpretations to general trends in each category. Fig.2D shows the number of Foraminifera per 10 mg of original sample weight which were found in each aliquot after exposure. The number of Foraminifera was apparently not appreciably diminished except in the deepest sample. The Foraminifera that had been boiled in hydrogen peroxide show a greater change in no./weight below 4,000 m than do those that were not so treated (Fig.2G). Above 4,000 m, the numbers of specimens per original weight are similar in all samples. The sample at 4,750 m shows a pronounced loss and, in the deepest one, all Foraminifera were destroyed.

The relative opacity to transmitted light of the tests examined while immersed in water is plotted against depth in Fig.2E. Relative opacity (percentage black specimens) increased in samples placed deeper than 3,000 m. In the treated samples, damage to the tests is expressed as the proportion of individuals which are broken and as the proportion of foraminiferal particles which are fragments (Fig.2H). A specimen was recorded as "broken" if it had a hole, and as a "fragment" if it consisted of less than half a test. The percentage of broken specimens in the untreated samples also is plotted. The damage to foraminiferal tests, untreated and treated, is small near the surface and increases very slightly to a depth of about 2,500 m. Below this depth the percentage of test damage is distinctly greater than in the shallower samples. The untreated samples showed less damage than the treated ones.

Pteropod numbers per original weight are plotted in Fig.2F, I. Both treated and untreated pteropods showed no solution in the samples placed at 250 m. The condition of the shells in these samples was indistinguishable from that of unexposed pteropods. The next deeper pteropod samples at 750 m show marked

solution. All pteropods which were boiled in hydrogen peroxide are dissolved except for a few fragments (Fig.2I). From this depth to about 2,000 m little change in solution is observed. Solution may decrease somewhat, corresponding to the increase in pH below the oxygen minimum, but the evidence is inconclusive From 2,750 m downward practically all pteropods are dissolved, including the untreated ones, which presumably were protected by the organic coating of their shells.

The information presented in Fig.2A–I is summarized in Fig.2K and compared with the hydrography in Fig.2L and M. Diagram K shows the depths at which solution apparently increases in core tops, calcite spheres, foraminiferal ooze, foraminiferal plankton and pteropods. The levels may cluster at certain depths, although the spacing of the buoy samples is too wide for good control. The hydrography as measured at the beginning of the experiment is plotted in Fig.2L. It shows the water structure expected for this region (MUREMTSEV, 1958; REID, 1965). In Fig.2M the results of the solution experiments are tentatively related to water structure.

The surface water above the thermocline is saturated or supersaturated with respect to aragonite and calcite. The change to undersaturation with respect to aragonite occurs somewhere in the thermocline between 250 and 750 m, as shown by the solution of pteropods. The underlying intermediate water, while strongly attacking aragonite, is only slightly aggressive toward calcite. Solution rates for calcite show little change with depth in this stratum. In the deep water solution rates increase, as is indicated by the greater damage to Foraminifera and complete dissolution of pteropods. The next increase in rate of solution occurs somewhat below 3,500 m, based on the calcite spheres (PETERSON, 1966). This level possibly marks an increased influence of the Antarctic bottom water as measured by calcium carbonate dissolution. A comparable level was found in the Atlantic and was termed "lysocline" (BERGER, 1968). Solution appears to increase continuously and rapidly at depths below the lysocline. The existence of such a level in the Pacific is especially interesting in view of the very gradual changes in chemical properties with depth in waters below 2,000 m (KNAUSS, 1962). Conditions near the ocean floor await further study.

It should be emphasized that the depth limits for intermediate, deep, and bottom water as based on the solution experiments (Fig.2M) are not identical to those based upon temperature and salinity. According to MUREMTSEV (1958) North Pacific intermediate water occupies depths from 300–400 m to 1,000–1,500 m between 42° and 20°N. REID's salinity map (1965, p.51) confirms a range of approximately 300–1,000 m near 20°N. The "intermediate water" of Fig.2M, however, corresponds closely to the oxygen minimum zone. The hydrographic boundaries between North Pacific upper deep water, lower deep water, and Pacific bottom water are rather vague. MUREMTSEV (1958, p.263) states that Pacific bottom water forms in the southern part of the South Pacific Basin through mixing of Antarctic

deep and bottom waters, and that it spreads from here throughout the Pacific to depths below 3,500–4,500 m. In Fig.2M the "bottom water" as defined by calcite solution extends upward to the level at which the oxygen content rapidly decreases. The apparent importance of the oxygen profile in the solution of calcareous shells will be discussed in the concluding section.

*Selectivity of solution: species*

One important conclusion of the solution experiment is that the water at almost all depths in the central Pacific is undersaturated with calcium carbonate. Most of the ocean bottom is rather deep and hence covered by water in which undersaturation is relatively large. Most calcareous sediment in the Pacific, therefore, is probably subjected to a certain amount of solution. Different kinds of shelled plankton in a sediment where solution occurs dissolve at different rates. This leads to an enrichment of the more resistant species in the sediment.

Rankings of resistance to solution for various species of planktonic Foraminifera were obtained in several independent ways. The Foraminifera in the untreated samples of *Globigerina* ooze exposed on the central Pacific buoy were counted, and the percentage of broken specimens per species was noted in each sample. The percentages in each species were ranked and the ranks were compared with the ranks of the weight losses in the sample series (BERGER, 1967). Presumably, the weight losses reflect the degrees of solution that the various samples experienced, and the percentage of broken shells reflects the effect of this solution upon the various species. Foraminiferal shells are very strong mechanically, consequently

TABLE I

COMPARISON BETWEEN SOLUTION RESISTANCE OF FORAMINIFERA ACCORDING TO BUOY EXPERIMENT AND SUSCEPTIBILITY TO ACIDIC ALIZARIN STAIN[1]

| *Staining experiment* | *Correlation of percent broken with weight loss: buoy experiment* | |
|---|---|---|
| | *significant* ($\% < 0.05$) | *not significant* ($\% > 0.05$) |
| Easily stained | *Globigerina rubescens*<br>*Globigerinella siphonifera*<br>*Globigerinoides ruber* (medium)<br>*Globigerinoides sacculifer*<br>*Globigerinoides tenellus* | *Globigerinoides ruber* (large) |
| Not easily stained | *Globigerinoides conglobatus* | *Globorotalia crassaformis*<br>*Globigerinoides ruber* (small)<br>*Turborotalita humilis*<br>*Globorotalia truncatulinoides*<br>*Globorotalia tumida* |

[1] Probabilities of buoy experiment based on BERGER (1967, table I).

the rank difference correlations were interpreted as reflecting susceptibility to solution (Table I, A vs. B). Susceptibility to solution also can be studied in the laboratory using a weakly acidic solution of Alizarin-S. The intensity of the stain reflects the solubility of a foraminiferal surface. Foraminiferal tests with a low resistance to solution acquire a deep red stain more rapidly than resistant tests. The reasons for differential staining are not clear and may include effects of organic matter in the skeletons and varying shell porosity.

The staining experiments were done on aliquots of the same sample that provided the foraminiferal ooze for the buoy experiment. Aliquots were placed in petri dishes, covered with water, and drops of staining solution were added slowly. The staining solution consists of 1% HCl in water and contains enough Alizarin-S to color it orange and is buffered with zinc chloride. The dishes were agitated and solution was added until the sediment turned faintly red. Approximately 700 specimens were physically separated under the microscope according to whether they showed a deep or faint red stain, while keeping the view out of focus to avoid identification and hence bias. Ten species were classified into the two categories "easily stained" and "not easily stained" according to whether they had more or fewer deeply stained individuals than the average of all specimens counted.

The results are given in Table I. The species showing significant correlations of broken specimens and weight loss in the buoy experiment are relatively easily stained by Alizarin-S, and vice versa. The laboratory procedure appears to be a useful method for investigating the relative solubility of foraminiferal species. All species falling into the categories of "significant correlation" and of "easily stained" are spined forms, while all the unspined forms belong to the two other categories. This is in accord with earlier generalizations based on the inspection of core samples (PHLEGER et al., 1953; OLAUSSON, 1965).

The results from open ocean solution experiments and from laboratory experiments compare well with published information based on analysis of core-top samples (BERGER, 1968). In this earlier report fifteen common species were ranked with respect to solubility. Seven more species were introduced into this list by using the information in Table I and data collected from the Santa Barbara Basin off southern California (Table II). In the Santa Barbara Basin, Foraminifera are dissolved where the bottom is shallower than the sill depth, and hence aerated. Below sill depth conditions are anaerobic and Foraminifera are preserved. The difference in the composition of assemblages above and below sill depth reflects the different susceptibility to solution of the various species. This will be fully documented elsewhere (BERGER and SOUTAR, 1970).

The solubility ranking provides a key for the interpretation of fossil assemblages with respect to the amount of solution they have undergone. The reliability of the ranking of species in Table II is not known. Rankings of species based on core-top samples were done separately, from the data of various authors, and the

TABLE II

RANKING OF SPECIES FROM FORAMINIFERAL SEDIMENTS IN ORDER OF DECREASING SUSCEPTIBILITY TO SOLUTION; RANK 1 IS THE MOST SOLUBLE SPECIES

| *Low resistance* | *High resistance* |
|---|---|
| 1. *Globigerinoides ruber* | 12. *Globorotalia hirsuta* |
| 2. *Orbulina universa* | 13. *Globorotalia truncatulinoides* |
| 3. *Globigerinella siphonifera* | 14. *Globorotalia inflata* |
| 4. *Globigerina rubescens* | 15. *Globorotalia cultrata* |
| 5. *Globigerinoides sacculifer* | 16. *Globoquadrina dutertrei* |
| 6. *Globigerinoides tenellus* | 17. *Globigerina pachyderma*, s.l. |
| 7. *Globigerinoides conglobatus* | 18. *Pulleniatina obliquiloculata* |
| 8. *Globigerina bulloides* | 19. *Globorotalia crassaformis* |
| 9. *Globigerina quinqueloba* | 20. *Sphaeroidinella dehiscens* |
| 10. *Globigerinita glutinata* | 21. *Globorotalia tumida* |
| 11. *Candeina nitida* | 22. *Turborotalita humilis* |

results agree very well from one ranking to the other (BERGER, 1968). In most cases differences in ranks of the same species between the lists based on the various authors are less than two steps. For most sediments, therefore, if species in Table II are separated by more than two intervening steps, they are probably different in their susceptibility to solution.

*Selectivity of solution: variants*

Three sizes of "*Globigerinoides*" *ruber* show different resistances to solution (see Table I). The rank position of each species in Table II probably represents an average situation for sediment assemblages larger than 125 $\mu$, the size class usually counted. Various sizes and different variants of the same species may occupy ranks separated by several steps.

The relationship between solution effects and variant properties was studied by recording size, opacity, chamber-size increase, and state of preservation of each specimen in the foraminiferal samples exposed on the experimental solution buoy. About 10,000 specimens were classified in this manner. About 5,000 of these specimens were derived from plankton tows; of these, about 3,500 were treated with hydrogen peroxide solution. The treated specimens proved to be the most fruitful for analysis, since solution produced visible effects in these assemblages at depths of exposure greater than 2,500 m, and the additional variable of the effect of protective test coating was eliminated .

The sizes used are "small" (max. diam. $< 175$ $\mu$), "medium" (175–275 $\mu$), and "large" ($> 275$ $\mu$). The relative opacity (Fig.2E) was determined by viewing the submerged specimens in transmitted light. A specimen was classified as "opaque" if its last chamber appeared black. Specimens in which it was possible to focus on the far side of the last chamber were termed "transparent". All others were assigned the category "intermediate". The chamber-size increase is either

positive, zero, or negative, depending on whether the last chamber is larger than, equal to, or smaller than the previous chamber. The state of preservation was recorded as "whole", "little damaged", and "much damaged". Little damaged specimens were defined as having at least one hole but more than about three-fourths of a complete shell. All samples were counted as unknowns.

Table III shows the average percent distribution of these properties in the samples exposed at depths shallower than 2,500 m (A, C), where little solution took place, and in the samples below 2,500 m, where the effects of solution are appreciable. Two unexposed reference samples are included in the "shallow" set. Small discrepancies in the percentage totals are due to rounding.

Opacity, size, and state of preservation for the shallow samples are shown in Table IIIA. About one specimen in ten is damaged in all opacity groups. The samples contained an equal amount of "intermediate" and "opaque" specimens (41.7% and 41.4%, see Table IIIA), but relatively few (6.6%) "transparent" ones. Table IIIB shows the percent distributions in the deep samples, as differences from the values in the shallow samples. The proportion of whole specimens is considerably decreased, while the relative abundance of damaged specimens is correspondingly increased. The loss of whole specimens is restricted to the "transparent" and the "intermediate" group. Whole specimens in the "opaque" group actually increase in percentage.

Two reasons are suggested:

(*1*) The terminal chambers which usually are the thinnest and most transparent are the first to be destroyed by solution. The remaining test, usually indistinguishable from a smaller thick shelled individual, is then classified as opaque.

(*2*) The walls are pitted and roughened by solution so that light is scattered on the wall surfaces before entering and/or after leaving the wall. This may account for observations by MURRAY (1967), who reports that transparent benthonic Foraminifera became opaque after etching with acid.

Table IIIC presents the percentage distribution of chamber size increase, size, and state of preservation in the shallow samples. More than half of the assemblage are whole Foraminifera with the last chamber larger than the previous one (59.7%, "positive"). The other whole Foraminifera are about equally divided between "zero" and "negative". All three categories contribute toward the loss of 14.4% from whole specimens (− 14.4%, Table IIID). The contribution from the negative specimens is less than one-tenth (1.2% from 14.6%), while the positive and the zero group each lose one-sixth (10.5% from 59.7% and 2.6% from 15.4%). The losses of whole specimens and the gains in damaged specimens balance out within each group. There is no cross-over from one group to the other comparable to the transfer of transparent to opaque specimens in Table IIIA,B. A slight increase in positive specimens might be expected if last chambers dissolve first, because sometime during their growth all tests are positive. In negative and zero individuals the last chamber usually is not much thinner than the previous one.

The result is that the chamber-by-chamber removal which should transfer specimens from zero and negative to positive probably is not important enough to counteract the higher solubility of the positive group.

There are no obvious relationships between size distribution and solution effects visible in Table III. This does not necessarily mean that there are no such relationships within species. The lumping of various species with different size ranges may obscure them, or in some species small specimens may be more soluble, in others large ones.

Tables IV and V represent the percentage distributions separated for spined and unspined species. Losses of whole specimens are somewhat higher in the spined forms (− 16.3%) than in the unspined ones (− 11.0%). This difference is seen to be due mainly to the proportionally greater loss of the positive individuals of intermediate opacity of the spined Foraminifera (− 20.3%, Table IVB, vs. − 12.5%, Table VB, and − 11.6%, Table IVD, vs. − 7.4%, Table VD). The corresponding percentage gain is in the positive, opaque, little damaged group (+ 9.7%, Table IVB, vs. + 3.3%, Table VB, and + 10.7%, Table IVD, vs. + 3.2%, Table VD). The other percentages appear not much different from the general pattern of Table III.

Tables VI and VII show the distribution of the properties in the two most abundant spined species, "*Globigerinoides*" *ruber* and "*G*". *sacculifer*. Both have exactly the same large amount of whole specimens in the shallow samples (94.2%). In the deeper samples, "*G*." *sacculifer* has lost 18.1% in the whole individuals, while "*G*." *ruber* lost 15.0%. Also, relatively more "*G*". *sacculifer* appear in the "much damaged" group (5.2%, Table VIIB, D, vs. 3.5%, Table VIB, D). This suggests that "*G*." *ruber* is somewhat more resistant to solution than "*G*." *sacculifer* in these plankton samples.

In "*G*." *ruber* the specimens with small terminal chambers appear particularly vulnerable to solution, contrary to the general trend for total Foraminifera (3.5% from 8.1%, Table VID, C vs. 1.2% from 14.6%, Table IIID, C). Percentages in Table VI are based on a smaller count than those in Table III; nevertheless, this may indicate that in "*G*." *ruber* the chamber-by-chamber removal is rather important in shell destruction, even in negative specimens. In "*G*." *sacculifer* there are too few specimens with small terminal chambers to permit observations about the solution effect.

Tables VIII and IX show the distribution of properties of the two most abundant species without spines, *Globoquadrina dutertrei* and *Globigerinita glutinata*. *G. dutertrei* has 83.5% whole specimens in the shallow samples (Table VIIIA, C), *G. glutinata* has 97.2% (Table IXA, C). Almost one-sixth of the undamaged *G. dutertrei* are lost in the deeper samples (13.1% from 83.5%, Table VIIIB, D), while for *G. glutinata* the equivalent number is less than one-tenth (8.1% from 97.2%, Table IXB, D). *G. glutinata* therefore seems somewhat more resistant to solution than *G. dutertrei*. In both species the main loss of whole specimens takes place in

TABLE III

PERCENT TRANSPARENT, INTERMEDIATE AND OPAQUE INDIVIDUALS (OPACITY) AND PERCENT POSITIVE, ZERO AND NEGATIVE INDIVIDUALS (CHAMBER-SIZE INCREASE) FOR ALL FORAMINIFERA, IN SAMPLES PLACED AT DEPTHS ABOVE AND BELOW 2,500 M

| | *Opacity* | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *transparent* | | | | *intermediate* | | | | *opaque* | | | | *all* |
| | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | |
| *A. Samples, shallower than 2,500 m (2,343 counted)* | | | | | | | | | | | | | |
| Whole | 3.4 | 2.3 | 0.9 | 6.6 | 15.3 | 15.2 | 11.3 | 41.7 | 8.9 | 13.7 | 18.7 | 41.4 | 89.7 |
| Little damaged | 0.3 | 0.2 | 0.2 | 0.7 | 1.0 | 1.2 | 2.2 | 4.3 | 0.4 | 0.5 | 3.5 | 4.4 | 9.3 |
| Much damaged | 0 | 0 | 0.2 | 0.2 | 0.1 | 0.1 | 0.5 | 0.7 | 0 | 0 | 0 | 0.1 | 1.0 |
| Total | 3.7 | 2.6 | 1.2 | 7.5 | 16.4 | 16.4 | 14.0 | 46.8 | 9.3 | 14.2 | 22.2 | 45.8 | 100.0 |
| *B. Samples, deeper than 2,500 m (1,326 counted)* | | | | | | | | | | | | | |
| Whole | − 0.8 | − 1.6 | + 0.1 | − 2.3 | − 5.3 | − 5.7 | − 5.4 | −16.3 | + 0.5 | + 1.3 | + 2.3 | + 4.1 | − 14.4 |
| Little damaged | + 0.1 | 0 | 0 | 0 | + 1.3 | + 0.4 | + 1.2 | + 3.0 | + 1.8 | + 2.8 | + 1.7 | + 6.3 | + 9.3 |
| Much damaged | + 0.2 | + 0.2 | + 0.4 | + 0.8 | + 1.0 | + 0.4 | + 0.6 | + 1.9 | + 0.8 | + 0.4 | + 1.4 | + 2.4 | + 5.1 |
| Total | − 0.5 | − 1.5 | + 0.5 | − 1.5 | − 3.0 | − 4.8 | − 3.7 | −11.4 | + 3.1 | + 4.5 | + 5.4 | +12.9 | 0 |
| | *Chamber-size increase* | | | | | | | | | | | | |
| | *positive* | | | | *zero* | | | | *negative* | | | | *all* |
| | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | |
| *C. Samples, shallower than 2,500 m (2,343 counted)* | | | | | | | | | | | | | |
| Whole | 24.2 | 26.4 | 9.2 | 59.7 | 2.7 | 3.7 | 9.0 | 15.4 | 0.7 | 1.1 | 12.7 | 14.6 | 89.7 |
| Little damaged | 1.4 | 1.5 | 2.0 | 4.9 | 0.1 | 0.2 | 3.1 | 3.4 | 0.1 | 0.1 | 0.8 | 1.1 | 9.3 |
| Much damaged | 0.1 | 0.2 | 0.6 | 0.9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.0 |
| Total | 25.7 | 28.0 | 11.7 | 65.5 | 2.8 | 3.9 | 12.1 | 18.9 | 0.9 | 1.2 | 13.6 | 15.7 | 100.0 |
| *D. Samples, deeper than 2,500 m (1,317 counted)* | | | | | | | | | | | | | |
| Whole | − 4.6 | − 5.3 | − 0.7 | −10.5 | − 1.1 | − 0.4 | − 1.1 | − 2.6 | + 0.4 | − 0.3 | − 1.1 | − 1.2 | − 14.4 |
| Little damaged | + 3.2 | + 2.7 | + 0.8 | + 6.8 | + 0.1 | + 0.5 | + 0.3 | + 0.9 | 0 | + 0.1 | + 1.4 | + 1.5 | + 9.3 |
| Much damaged | + 1.9 | + 0.8 | + 1.3 | + 4.0 | 0 | + 0.2 | + 0.9 | + 1.0 | 0 | 0 | + 0.2 | + 0.2 | + 5.1 |
| Total | + 0.5 | − 1.7 | + 1.5 | + 0.3 | − 1.0 | + 0.2 | + 0.1 | − 0.8 | + 0.3 | − 0.2 | + 0.4 | + 0.5 | 0 |

TABLE IV

PERCENT TRANSPARENT, INTERMEDIATE AND OPAQUE INDIVIDUALS (OPACITY) AND PERCENT POSITIVE, ZERO AND NEGATIVE INDIVIDUAL (CHAMBER-SIZE INCREASE) FOR SPINED FORAMINIFERA SPECIES, IN SAMPLES PLACED AT DEPTHS ABOVE AND BELOW 2,500 M

| | *Opacity* | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *transparent* | | | | *intermediate* | | | | *opaque* | | | | *all* |
| | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | |
| *A. Samples, shallower than 2,500 m (1,117 counted)* | | | | | | | | | | | | | |
| Whole | 2.7 | 1.1 | 1.4 | 5.2 | 16.9 | 13.0 | 9.6 | 39.5 | 17.7 | 23.3 | 6.4 | 47.4 | 92.0 |
| Little damaged | 0.4 | 0.3 | 0.3 | 0.9 | 1.3 | 1.4 | 1.3 | 4.0 | 0.7 | 0.6 | 0.4 | 1.8 | 6.7 |
| Much damaged | 0 | 0 | 0.4 | 0.4 | 0.2 | 0.2 | 0.4 | 0.8 | 0 | 0 | 0.1 | 0.1 | 1.3 |
| Total | 3.0 | 1.3 | 2.1 | 6.4 | 18.4 | 14.6 | 11.3 | 44.3 | 18.4 | 23.9 | 6.9 | 49.2 | 100.0 |
| *B. Samples, deeper than 2,500 m (609 counted)* | | | | | | | | | | | | | |
| Whole | − 0.4 | − 0.4 | + 0.1 | − 0.6 | − 9.3 | − 6.1 | − 4.8 | −20.3 | + 0.7 | + 0.3 | + 3.6 | + 4.7 | − 16.3 |
| Little damaged | + 0.3 | − 0.1 | 0 | + 0.2 | + 1.3 | + 0.4 | + 0.2 | + 1.9 | + 3.6 | + 5.0 | + 1.2 | + 9.7 | + 11.9 |
| Much damaged | 0 | + 0.2 | + 0.4 | + 0.6 | + 0.6 | + 0.5 | + 0.3 | + 1.3 | + 1.5 | + 0.8 | + 0.2 | + 2.5 | + 4.4 |
| Total | 0 | − 0.3 | + 0.5 | + 0.2 | − 7.4 | − 5.2 | − 4.4 | −17.0 | + 5.7 | + 6.1 | + 5.1 | +17.0 | 0 |
| | *Chamber-size increase* | | | | | | | | | | | | |
| | *positive* | | | | *zero* | | | | *negative* | | | | *all* |
| | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | |
| *C. Samples, shallower than 2,500 m (1,117 counted)* | | | | | | | | | | | | | |
| Whole | 33.0 | 30.5 | 14.0 | 77.4 | 3.8 | 5.0 | 1.9 | 10.7 | 0.6 | 1.8 | 1.5 | 3.9 | 92.0 |
| Little damaged | 2.1 | 2.0 | 1.5 | 5.6 | 0.2 | 0.1 | 0.3 | 0.5 | 0.2 | 0.3 | 0.2 | 0.6 | 6.7 |
| Much damaged | 0.2 | 0.2 | 0.9 | 1.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.3 |
| Total | 35.2 | 32.7 | 16.4 | 84.2 | 3.9 | 5.1 | 2.1 | 11.2 | 0.8 | 2.1 | 1.7 | 4.6 | 100.0 |
| *D. Samples, deeper than 2,500 m (609 counted)* | | | | | | | | | | | | | |
| Whole | − 7.9 | − 3.7 | 0 | −11.6 | − 2.0 | − 1.4 | − 0.3 | − 3.6 | + 0.7 | − 1.0 | − 0.8 | − 1.1 | − 16.3 |
| Little damaged | + 5.1 | + 4.6 | + 1.0 | +10.7 | + 0.1 | + 0.7 | − 0.1 | + 0.8 | − 0.2 | − 0.1 | + 0.3 | + 0.1 | + 11.9 |
| Much damaged | + 2.1 | + 1.1 | + 1.6 | + 3.8 | 0 | + 0.3 | + 0.3 | + 0.7 | 0 | 0 | 0 | 0 | + 4.4 |
| Total | − 0.6 | + 1.9 | + 1.5 | + 3.0 | − 1.8 | − 0.3 | + 0.4 | − 1.8 | + 0.5 | − 1.1 | − 0.6 | − 1.2 | 0 |

TABLE V

PERCENT TRANSPARENT, INTERMEDIATE AND OPAQUE INDIVIDUALS (OPACITY) AND PERCENT POSITIVE, ZERO AND NEGATIVE INDIVIDUALS (CHAMBER-SIZE INCREASE) FOR NON-SPINED FORAMINIFERA SPECIES, IN SAMPLES PLACED AT DEPTHS ABOVE AND BELOW 2,500 M

| | *Opacity* | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *transparent* | | | | *intermediate* | | | | *opaque* | | | | *all* |
| | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | |
| *A. Samples, shallower than 2,500 m (1,211 counted)* | | | | | | | | | | | | | |
| Whole | 3.7 | 3.5 | 0.4 | 7.6 | 13.5 | 17.3 | 13.0 | 43.9 | 0.7 | 5.1 | 30.3 | 36.1 | 87.6 |
| Little damaged | 0.2 | 0.2 | 0.1 | 0.4 | 0.7 | 0.9 | 3.1 | 4.6 | 0 | 0.3 | 6.4 | 6.7 | 11.7 |
| Much damaged | 0 | 0.1 | 0 | 0.1 | 0 | 0.1 | 0.5 | 0.6 | 0 | 0 | 0 | 0 | 0.7 |
| Total | 3.9 | 3.7 | 0.5 | 8.1 | 14.2 | 18.3 | 16.6 | 49.1 | 0.7 | 5.5 | 36.7 | 42.8 | 100.0 |
| *B. Samples, deeper than 2,500 m (697 counted)* | | | | | | | | | | | | | |
| Whole | − 0.7 | − 2.8 | + 0.2 | − 3.3 | − 1.2 | − 5.2 | − 6.0 | −12.5 | + 1.0 | + 2.8 | + 1.0 | + 4.8 | − 11.0 |
| Little damaged | − 0.1 | − 0.1 | − 0.1 | − 0.2 | + 0.9 | + 0.5 | + 2.1 | + 3.6 | + 0.1 | + 1.1 | + 2.1 | + 3.3 | + 6.8 |
| Much damaged | + 0.1 | 0 | + 0.4 | + 0.6 | + 0.1 | + 0.2 | + 0.9 | + 1.3 | 0 | 0 | + 2.3 | + 2.3 | + 4.2 |
| Total | − 0.6 | − 2.8 | + 0.5 | − 2.8 | − 0.1 | − 4.5 | − 3.0 | − 7.6 | + 1.2 | + 3.8 | + 5.3 | +10.4 | 0 |
| | *Chamber-size increase* | | | | | | | | | | | | |
| | *positive* | | | | *zero* | | | | *negative* | | | | *all* |
| | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | |
| *C. Samples, shallower than 2,500 m (1,211 counted)* | | | | | | | | | | | | | |
| Whole | 15.4 | 22.9 | 4.9 | 43.1 | 1.7 | 2.6 | 15.7 | 20.0 | 0.8 | 0.5 | 23.2 | 24.5 | 87.6 |
| Little damaged | 0.7 | 1.1 | 2.4 | 4.1 | 0.1 | 0.3 | 5.7 | 6.1 | 0.1 | 0 | 1.4 | 1.5 | 11.7 |
| Much damaged | 0 | 0.2 | 0.3 | 0.5 | 0 | 0 | 0.1 | 0.1 | 0 | 0 | 0.1 | 0.1 | 0.7 |
| Total | 16.0 | 24.1 | 7.6 | 47.7 | 1.8 | 2.9 | 21.5 | 26.2 | 0.9 | 0.5 | 24.7 | 26.1 | 100.0 |
| *D. Samples, deeper than 2,500 m (697 counted)* | | | | | | | | | | | | | |
| Whole | − 0.6 | − 6.0 | − 0.9 | − 7.4 | − 0.3 | + 0.4 | − 2.2 | − 2.1 | + 0.1 | + 0.2 | − 1.8 | − 1.5 | − 11.0 |
| Little damaged | + 0.9 | + 1.1 | + 1.2 | + 3.2 | 0 | + 0.3 | + 0.5 | + 0.8 | 0 | + 0.3 | + 2.5 | + 2.8 | + 6.8 |
| Much damaged | + 0.3 | + 0.2 | + 2.0 | + 2.5 | 0 | 0 | + 1.3 | + 1.3 | 0 | 0 | + 0.3 | + 0.3 | + 4.2 |
| Total | + 0.6 | − 4.6 | + 2.3 | − 1.6 | − 0.2 | + 0.7 | − 0.4 | + 0.1 | + 0.1 | + 0.5 | + 1.0 | + 1.6 | 0 |

TABLE VI

PERCENT TRANSPARENT, INTERMEDIATE AND OPAQUE INDIVIDUALS (OPACITY) AND PERCENT POSITIVE, ZERO AND NEGATIVE INDIVIDUALS (CHAMBER-SIZE INCREASE) FOR *Globigerinoides ruber*, IN SAMPLES PLACED AT DEPTH ABOVE AND BELOW 2,500 M

| | *Opacity* | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *transparent* | | | | *intermediate* | | | | *opaque* | | | | *all* |
| | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | |
| *A. Samples, shallower than 2,500 m (345 counted)* | | | | | | | | | | | | | |
| Whole | 1.7 | 0.3 | 0.3 | 2.3 | 14.8 | 18.3 | 6.1 | 39.1 | 18.3 | 30.4 | 4.1 | 52.8 | 94.2 |
| Little damaged | 0.3 | 0 | 0 | 0.3 | 0.9 | 1.4 | 0.6 | 2.9 | 0.9 | 1.2 | 0.6 | 2.6 | 5.8 |
| Much damaged | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 2.0 | 0.3 | 0.3 | 2.6 | 15.7 | 19.7 | 6.7 | 42.0 | 19.1 | 31.6 | 4.6 | 55.4 | 100.0 |
| *B. Samples, deeper than 2,500 (197 counted)* | | | | | | | | | | | | | |
| Whole | − 0.7 | − 0.3 | − 0.3 | − 1.3 | − 6.2 | − 8.7 | − 0.5 | −15.2 | + 0.5 | + 2.6 | − 1.6 | + 1.5 | − 15.0 |
| Little damaged | + 0.2 | 0 | 0 | + 0.2 | + 0.6 | + 0.6 | − 0.6 | + 0.6 | − 2.6 | + 6.9 | + 0.9 | +10.6 | + 11.5 |
| Much damaged | 0 | 0 | 0 | 0 | + 1.0 | 0 | 0 | + 1.0 | + 2.5 | 0 | 0 | + 2.5 | + 3.5 |
| Total | − 0.5 | − 0.3 | − 0.3 | − 1.1 | − 4.5 | − 8.0 | − 1.1 | −13.6 | + 5.8 | + 9.5 | − 0.5 | +14.7 | 0 |
| | *Chamber-size increase* | | | | | | | | | | | | |
| | *positive* | | | | *zero* | | | | *negative* | | | | *all* |
| | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | |
| *C. Samples, shallower than 2,500 m (345 counted)* | | | | | | | | | | | | | |
| Whole | 27.0 | 32.5 | 3.2 | 62.6 | 7.2 | 12.7 | 3.5 | 23.5 | 0.6 | 3.8 | 3.8 | 8.1 | 94.2 |
| Little damaged | 1.7 | 1.7 | 0.3 | 3.8 | 0.3 | 0.3 | 0.3 | 0.9 | 0 | 0.6 | 0.6 | 1.2 | 5.8 |
| Much damaged | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 28.7 | 34.2 | 3.5 | 66.4 | 7.5 | 13.0 | 3.8 | 24.3 | 0.6 | 4.3 | 4.3 | 9.3 | 100.0 |
| *D. Samples, deeper than 2,500 m (197 counted)* | | | | | | | | | | | | | |
| Whole | − 3.6 | 0 | + 0.9 | − 2.7 | − 3.1 | − 4.1 | − 1.5 | − 8.8 | + 0.4 | − 2.3 | − 1.8 | − 3.5 | − 15.0 |
| Little damaged | + 3.9 | + 5.9 | − 0.2 | + 9.9 | − 0.3 | − 1.7 | − 0.2 | + 1.6 | 0 | − 0.1 | − 0.1 | − 0.2 | − 11.5 |
| Much damaged | + 3.5 | 0 | 0 | + 3.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | + 3.5 |
| Total | + 3.8 | + 5.9 | + 1.1 | +10.6 | − 3.4 | − 2.3 | − 1.3 | − 7.0 | + 0.4 | − 2.3 | − 1.8 | − 3.7 | 0 |

TABLE VII

PERCENT TRANSPARENT, INTERMEDIATE AND OPAQUE INDIVIDUALS (OPACITY) AND PERCENT POSITIVE, ZERO AND NEGATIVE INDIVIDUALS (CHAMBER-SIZE INCREASE) FOR *Globigerinoides sacculifer*, IN SAMPLES PLACED AT DEPTHS ABOVE AND BELOW 2,500 M

| | *Opacity* | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *transparent* | | | | *intermediate* | | | | *opaque* | | | | *all* |
| | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | |
| *A. Samples, shallower than 2,500 m (433 counted)* | | | | | | | | | | | | | |
| Whole | 3.9 | 1.4 | 0.2 | 5.5 | 19.6 | 9.0 | 1.6 | 30.3 | 27.5 | 27.0 | 3.9 | 58.4 | 94.2 |
| Little damaged | 0.5 | 0 | 0 | 0.5 | 1.8 | 0.7 | 0 | 2.5 | 1.2 | 0.5 | 0.5 | 2.1 | 5.1 |
| Much damaged | 0 | 0 | 0 | 0 | 0.2 | 0 | 0.2 | 0.5 | 0 | 0 | 0.2 | 0.2 | 0.7 |
| Total | 4.4 | 1.4 | 0.2 | 6.0 | 21.7 | 9.7 | 1.8 | 33.3 | 28.6 | 27.5 | 4.6 | 60.7 | 100.0 |
| *B. Samples, deeper than 2,500 m (222 counted)* | | | | | | | | | | | | | |
| Whole | − 1.2 | − 0.9 | − 0.2 | − 2.3 | −11.5 | − 1.8 | − 1.6 | −15.0 | + 0.9 | − 0.4 | − 1.2 | − 0.7 | − 18.1 |
| Little damaged | − 0.5 | 0 | 0 | − 0.5 | + 2.3 | + 1.6 | 0 | + 3.8 | + 5.1 | + 4.5 | 0 | + 9.6 | + 12.9 |
| Much damaged | 0 | + 0.5 | 0 | + 0.5 | + 1.2 | + 0.5 | − 0.2 | + 1.3 | + 1.8 | + 1.8 | − 0.2 | + 3.4 | + 5.2 |
| Total | − 1.7 | − 0.5 | − 0.2 | − 2.4 | − 8.2 | + 0.2 | − 1.8 | − 9.9 | + 7.9 | + 5.8 | − 1.4 | +12.3 | 0 |

| | *Chamber-size increase* | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *positive* | | | | *zero* | | | | *negative* | | | | *all* |
| | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | |
| *C. Samples, shallower than 2,500 m (433 counted)* | | | | | | | | | | | | | |
| Whole | 50.3 | 36.3 | 4.6 | 91.2 | 0.7 | 1.2 | 0.7 | 2.5 | 0 | 0 | 0.5 | 0.5 | 94.2 |
| Little damaged | 3.2 | 1.2 | 0.5 | 4.8 | 0.2 | 0 | 0 | 0.2 | 0 | 0 | 0 | 0 | 5.1 |
| Much damaged | 0.2 | 0 | 0.5 | 0.7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.7 |
| Total | 53.8 | 37.4 | 5.5 | 96.8 | 0.9 | 1.2 | 0.7 | 2.8 | 0 | 0 | 0.5 | 0.5 | 100.0 |
| *D. Samples, deeper than 2,500 m (222 counted)* | | | | | | | | | | | | | |
| Whole | −11.6 | − 2.5 | − 2.3 | −16.4 | − 0.7 | − 0.7 | − 0.2 | − 1.6 | + 0.5 | 0 | − 0.5 | 0 | − 18.1 |
| Little damaged | + 7.2 | + 6.0 | 0 | +13.2 | − 0.2 | 0 | 0 | − 0.2 | 0 | 0 | 0 | 0 | + 12.9 |
| Much damaged | + 3.0 | + 2.3 | − 0.5 | + 4.7 | 0 | + 0.5 | 0 | + 0.5 | 0 | 0 | 0 | 0 | + 5.2 |
| Total | − 1.5 | + 5.8 | − 2.8 | + 1.4 | − 0.9 | − 0.3 | − 0.2 | − 1.4 | + 0.5 | 0 | − 0.5 | 0 | 0 |

TABLE VIII

PERCENT TRANSPARENT, INTERMEDIATE AND OPAQUE INDIVIDUALS (OPACITY) AND PERCENT POSITIVE, ZERO AND NEGATIVE INDIVIDUALS (CHAMBER-SIZE INCREASE) FOR *Globoquadrina dutertrei*, IN SAMPLES PLACED AT DEPTHS ABOVE AND BELOW 2,500 M

| | *Opacity* | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *transparent* | | | | *intermediate* | | | | *opaque* | | | | *all* |
| | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | |
| *A. Samples, shallower than 2,500 m (780 counted)* | | | | | | | | | | | | | |
| Whole | 0.9 | 4.2 | 0.6 | 5.8 | 2.1 | 8.2 | 19.5 | 29.7 | 0.1 | 1.8 | 46.0 | 47.9 | 83.5 |
| Little damaged | 0.1 | 0.3 | 0.1 | 0.5 | 0.1 | 0.8 | 4.2 | 5.1 | 0 | 0.1 | 9.9 | 10.0 | 15.6 |
| Much damaged | 0 | 0.1 | 0 | 0.1 | 0 | 0 | 0.8 | 0.8 | 0 | 0 | 0 | 0 | 0.9 |
| Total | 1.0 | 4.6 | 0.8 | 6.4 | 2.2 | 9.0 | 24.5 | 35.6 | 0.1 | 1.9 | 55.9 | 57.9 | 100.0 |
| *B. Samples, deeper than 2,500 m (443 counted)* | | | | | | | | | | | | | |
| Whole | − 0.7 | − 3.3 | + 0.1 | − 4.0 | − 1.2 | 3.9 | − 8.9 | −13.9 | + 0.6 | − 1.8 | + 2.5 | + 4.9 | − 13.1 |
| Little damaged | − 0.1 | − 0.3 | − 0.1 | − 0.5 | − 0.1 | + 0.1 | + 3.5 | + 3.5 | 0 | + 1.3 | + 3.4 | + 4.7 | − 7.6 |
| Much damaged | 0 | + 0.1 | + 0.2 | + 0.4 | 0 | 0 | + 1.5 | + 1.5 | 0 | 0 | + 3.6 | + 3.6 | − 5.5 |
| Total | − 0.8 | − 3.5 | + 0.1 | − 4.1 | − 1.3 | − 3.8 | − 4.0 | − 9.0 | + 0.6 | + 3.1 | + 9.6 | +13.2 | 0 |
| | *Chamber-size increase* | | | | | | | | | | | | |
| | *positive* | | | | *zero* | | | | *negative* | | | | *all* |
| | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | |
| *C. Samples, shallower than 2,500 m (780 counted)* | | | | | | | | | | | | | |
| Whole | 2.3 | 10.9 | 6.2 | 19.4 | 0.5 | 2.7 | 24.1 | 27.3 | 0.3 | 0.6 | 35.9 | 36.8 | 83.5 |
| Little damaged | 0.3 | 0.6 | 3.2 | 4.1 | 0 | 0.5 | 8.8 | 9.4 | 0 | 0 | 2.2 | 2.2 | 15.6 |
| Much damaged | 0 | 0.1 | 0.5 | 0.6 | 0 | 0 | 0.1 | 0.1 | 0 | 0 | 0.1 | 0.1 | 0.9 |
| Total | 2.6 | 11.7 | 9.9 | 24.1 | 0.5 | 3.2 | 33.1 | 36.8 | 0.3 | 0.6 | 38.2 | 39.1 | 100.0 |
| *D. Samples, deeper than 2,500 m (443 counted)* | | | | | | | | | | | | | |
| Whole | − 0.9 | − 4.8 | − 1.0 | − 6.8 | 0 | − 0.7 | − 2.9 | − 3.6 | − 0.3 | − 0.1 | − 2.5 | − 2.7 | − 13.1 |
| Little damaged | − 0.3 | − 0.8 | − 2.0 | − 2.4 | 0 | 0 | − 0.9 | + 0.8 | 0 | − 0.5 | − 3.9 | − 4.3 | − 7.6 |
| Much damaged | 0 | + 0.1 | + 2.7 | + 2.8 | 0 | 0 | − 2.2 | + 2.2 | 0 | 0 | + 0.6 | − 0.6 | − 5.5 |
| Total | − 1.2 | − 4.0 | + 3.6 | − 1.5 | 0 | − 0.7 | + 0.1 | − 0.7 | − 0.3 | − 0.5 | + 2.0 | − 2.2 | 0 |

TABLE IX

PERCENT TRANSPARENT, INTERMEDIATE AND OPAQUE INDIVIDUALS (OPACITY) AND PERCENT POSITIVE, ZERO AND NEGATIVE INDIVIDUALS (CHAMBER-SIZE INCREASE) FOR *Globigerinita glutinata*, IN SAMPLES PLACED AT DEPTHS ABOVE AND BELOW 2,500 M

| | *Opacity* | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *transparent* | | | | *intermediate* | | | | *opaque* | | | | *all* |
| | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | |
| *A. Samples, shallower than 2,500 m (389 counted)* | | | | | | | | | | | | | |
| Whole | 8.5 | 2.3 | 0 | 10.8 | 36.5 | 36.2 | 1.3 | 74.0 | 1.8 | 9.8 | 0.8 | 12.3 | 97.2 |
| Little damaged | 0.3 | 0 | 0 | 0.3 | 1.8 | 0.8 | 0 | 2.6 | 0 | 0 | 0 | 0 | 2.8 |
| Much damaged | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 8.7 | 2.3 | 0 | 11.1 | 38.3 | 37.0 | 1.3 | 76.6 | 1.8 | 9.8 | 0.8 | 12.3 | 100.0 |
| *B. Samples, deeper than 2,500 m (230 counted)* | | | | | | | | | | | | | |
| Whole | − 1.5 | − 1.9 | + 0.4 | − 3.0 | − 1.7 | − 8.4 | − 0.9 | −11.0 | + 2.1 | + 4.1 | − 0.4 | + 6.0 | − 8.1 |
| Little damaged | + 0.1 | + 0.4 | 0 | + 0.6 | + 3.0 | + 1.8 | 0 | + 4.8 | + 0.4 | + 0.9 | 0 | + 1.3 | + 6.8 |
| Much damaged | + 0.4 | 0 | 0 | + 0.4 | + 0.4 | + 0.4 | 0 | + 0.9 | 0 | 0 | 0 | 0 | + 1.3 |
| Total | − 0.9 | − 1.4 | + 0.4 | − 2.0 | + 1.7 | − 6.1 | − 0.9 | − 5.3 | + 2.5 | + 5.0 | − 0.4 | + 7.3 | 0 |
| | *Chamber-size increase* | | | | | | | | | | | | |
| | *positive* | | | | *zero* | | | | *negative* | | | | *all* |
| | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | *small* | *medium* | *large* | *total* | |
| *C. Samples, shallower than 2,500 m (389 counted)* | | | | | | | | | | | | | |
| Whole | 40.4 | 45.8 | 1.3 | 87.4 | 4.4 | 2.3 | 0.5 | 7.2 | 2.1 | 0.3 | 0.3 | 2.6 | 97.2 |
| Little damaged | 1.5 | 0.8 | 0 | 2.3 | 0.3 | 0 | 0 | 0.3 | 0.3 | 0 | 0 | 0.3 | 2.8 |
| Much damaged | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 41.9 | 46.5 | 1.3 | 89.7 | 4.6 | 2.3 | 0.5 | 7.5 | 2.3 | 0.3 | 0.3 | 2.8 | 100.0 |
| D. *Samples, deeper than 2,500 m (230 counted)* | | | | | | | | | | | | | |
| Whole | − 0.8 | − 9.7 | 0 | −10.4 | − 0.9 | + 2.9 | − 0.5 | + 1.5 | + 0.5 | + 0.6 | − 0.3 | + 0.9 | − 8.1 |
| Little damaged | + 3.3 | + 2.2 | 0 | + 5.5 | + 0.1 | + 0.9 | 0 | + 1.0 | + 0.1 | 0 | 0 | + 0.1 | + 6.8 |
| Much damaged | + 0.9 | + 0.4 | 0 | + 1.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | + 1.3 |
| Total | + 3.3 | − 6.9 | 0 | − 3.6 | − 0.7 | + 3.8 | − 0.5 | + 2.5 | + 0.7 | + 0.6 | − 0.3 | + 1.1 | 0 |

medium and large, non-opaque, positive specimens (Tables VIIIB,D and IXB,D, greatest negative numbers in the first rows). In *G. dutertrei* the zero and negative specimens also contribute toward the loss (− 3.6% and − 2.7%, Table VIIID). In *G. glutinata* these groups do not contribute (+ 1.5% and 0.9%, Table IXD). Gains appear in the whole, opaque specimens in both species (+ 4.9%, Table VIIIB, and + 6.0%, Table IXB). The relative gains in the damaged categories concentrate in the non-transparent groups in both species (Tables VIIIB and IXB, second rows). In *G. glutinata* these gains are mainly in the positive group (+ 5.5%, Table IXD), while in *G. dutertrei* both the positive and the negative groups receive damaged specimens (+ 2.4% and + 4.3%, Table VIIID).

The results given in Tables III–IX are difficult to evaluate because the classifications are subjective to some degree and small differences in percentages are not statistically significant. The following conclusions are tentative, therefore:

(*1*) Various phenotypes of the same species possess different resistances to solution. In general, the thin-shelled, transparent forms with the last chamber larger than the previous one are destroyed most rapidly.

(2) The phenotypic composition of a foraminiferal death assemblage is changed by the effects of solution. The assemblage tends to become enriched with opaque (usually thick shelled), zero and negative forms, i.e., specimens with small terminal chambers.

(*3*) The pattern of change is not necessarily identical for all species; layer-by-layer removal, chamber-by-chamber solution, and overall etching may be of relatively different importance.

Tables VI and VII indicated that "*Globigerinoides*" *sacculifer* may be somewhat less resistant than "*G.*" *ruber* and Tables VIII and IX suggested that *Globoquadrina dutertrei* is less resistant than *Globigerinita glutinata*. There is an apparent contradiction with the ranking given in Table II, where "*G*". *ruber* is shown as being more soluble than "*G.*" *sacculifer* and *G. glutinata* more than *G. dutertrei*. The ranking given in Table II, however, is based on specimens from sediment assemblages. Such assemblages are expected to be enriched in the more resistant phenotypes of each species, partly because the assemblages almost invariably have experienced some solution and hence selective destruction. Support for this contention comes from comparing the proportions of variants in the plankton samples here discussed, which were collected at various times and various localities, with the proportion of variants in a typical sediment assemblage, such as figured by PARKER (1962). Parker illustrated seventeen specimens of *Globoquadrina dutertrei* to show the range in variation of this species. It is interesting that twelve of the figured specimens, i.e., 70%, are negative, and that the plankton samples only had half as many (36.8%) negative variants. A similar situation is indicated for most other species.

The ranking in Table II, therefore, probably reflects the relative solution susceptibility of the resistant variants in each species. Plankton samples, on the

other hand, may contain less resistant and more resistant variants in various proportions; consequently it is not surprising that the rankings derived from solution experiments on plankton samples should be different from those in Table II. The concentration by solution of negative and zero individuals, termed "kummerform" elsewhere, has important implications for paleoecological interpretation, since kummerforms may represent environmentally stressed members of species populations. These implications will be discussed in another study.

## GEOGRAPHIC DISTRIBUTION OF SOLUTION PATTERNS

### *Solution-induced changes in sediment assemblages*

Selective solution can change species composition and variant composition of a foraminiferal sediment assemblage. Except for one brief paper on distributions on the shelf and upper slope in the Gulf of Mexico (ORR, 1967), variant characteristics have not been mapped. The usefulness of variant distributions on the ocean floor for determining solution patterns can, therefore, not be evaluated at the present time. RUDDIMAN and HEEZEN (1967) correlated percentages of several species in core-top samples with the 4,000 m depth contour in the equatorial Atlantic, and interpreted changes in species proportions across this depth as being due to solution.

Observations by PHILIPPI (1910) and by members of the "Meteor" Expedition suggested that calcium carbonate solution in the South Atlantic is related to the flow of Antarctic bottom water. BERGER (1968) used all species counted in sediment samples, ranked them with respect to solution resistance, and calculated the average weighted rank for each sample, as a basis for forming "solution indices". The depth level below which the indices markedly increased for the various samples was found to correlate with the boundary between North Atlantic deep water and Antarctic bottom water and with areas of upwelling near the African continent. Changes of the solution indices within cores were interpreted as reflecting a lowering of the upper surface of Antarctic bottom water by about 500 m since the Last Glacial.

If this interpretation is correct, Antarctic bottom water may have had a shallower level and greater flow velocities in the area surrounding the Antarctic continent. There is a possibility that the resulting increase in calcium carbonate solution on the southern parts of the ocean floor may have been partly balanced by decreased solution in the North Pacific. Support for this suggestion comes from findings by NAYUDU (1964) and by SAIDOVA (1965). Both authors report fewer calcareous Foraminifera in the Holocene sections of cores from the North Pacific than in underlying Pleistocene sediments. Nayudu proposes a decrease in foraminiferal sediment supply due to a decrease in productivity to account for his observations. Waning productivity alone, however, would appear to be insufficient, because radiolarians and diatoms also should indicate lower production rates.

This, apparently, is not indicated by Nayudu's data. Also, a decrease in calcareous sediment supply may not necessarily lead to less calcareous sediment on the ocean floor, because the parallel decrease in supply of organic matter enhances preservation of calcite. SAIDOVA (1965) suggests tectonic deepening of various parts of the North Pacific ocean floor by 200–2,000 m during post-Glacial time to account for the decrease in calcareous deposits. The increase in solution in the North Pacific since the Last Glacial, which is here proposed, may have resulted from the postulated decrease in solution in the southern ocean. Such a decrease in calcium carbonate uptake could have led to a lowering of the saturation level of the bottom water that flows into the North Pacific (WOOSTER and VOLKMANN, 1960). Alternatively, or in addition, parts of the bottom water may have become near stagnant if derived during maximum cooling, because later influx had to wait till any climax bottom water was sufficiently warmed by mixing and by geothermal heatflow to permit its displacement (WORTHINGTON, 1968).

*Lysocline versus calcium carbonate compensation depth*

The level of rapid solution increase which apparently is correlated with the top of the Antarctic bottom water in the central Atlantic has been termed "lysocline" (BERGER, 1968). Data from the southeast Pacific (BLACKMAN, 1966) were

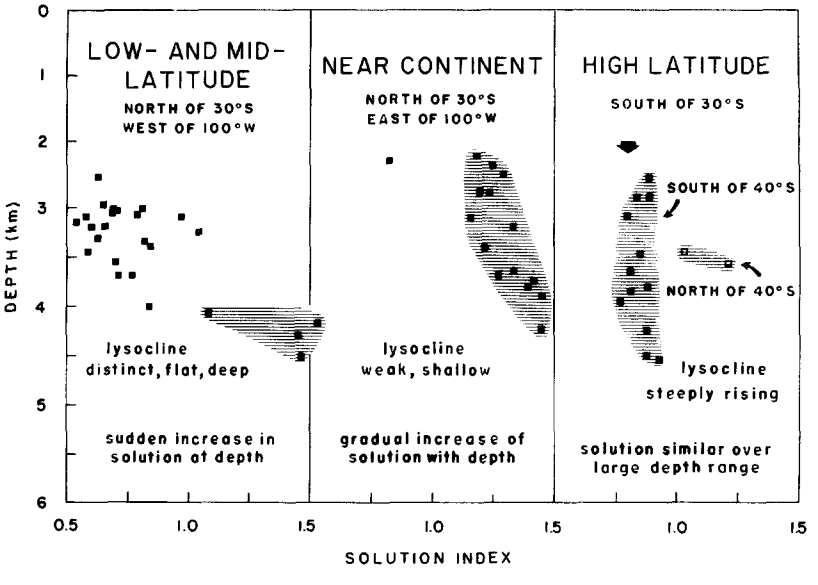



Fig.3. Distribution of solution indices in the southeast Pacific. The solution indices of individual samples, counted by BLACKMAN (1966) are calculated according to BERGER (1968), without correction for latitude. Solution indices of assemblages at different latitudes are not directly comparable. Ruled areas: assemblages are enriched in resistant species. The arrow in the high latitude diagram points to the index value believed to correspond to a mildly attacked high latitude assemblage. The lysocline interpretations are tentative.

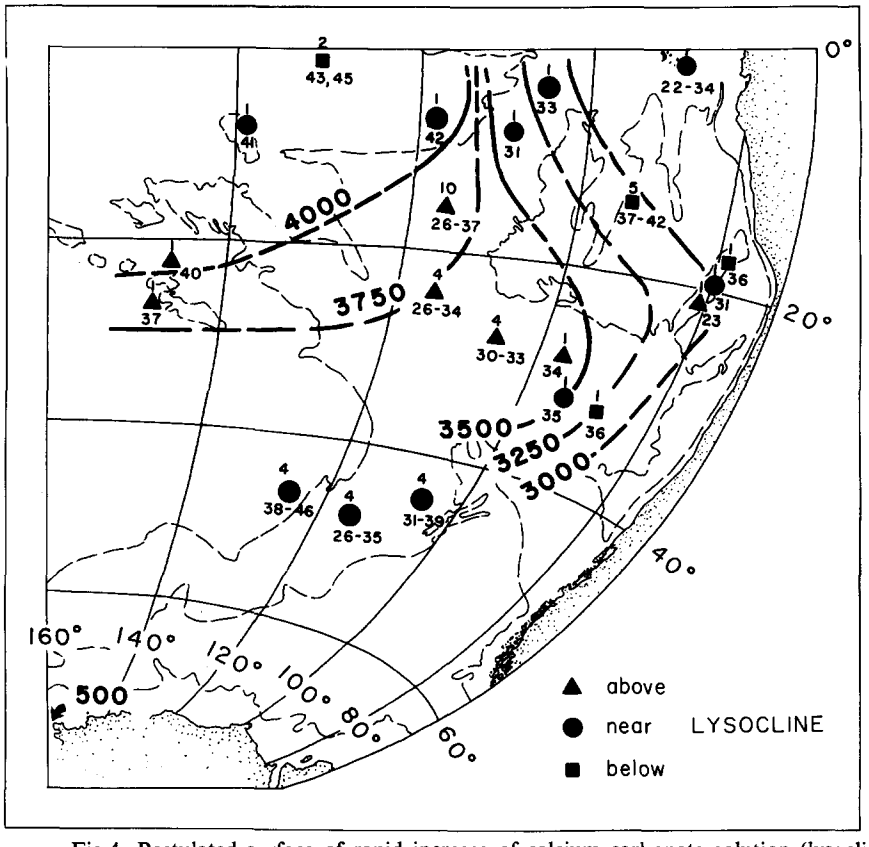



Fig.4. Postulated surface of rapid increase of calcium carbonate solution (lysocline) in the southeast Pacific, inferred from the distribution of resistant Foraminifera in the core-top data from BLACKMAN (1966). Numbers above symbols indicate the number of samples in each control point. Numbers below symbols indicate the depths in 100 m intervals. Calcite solution boundary of 500 m near Antarctica based on KENNETT (1966). Bottom contour given is at 4,000 m depth[1].

analyzed in the same fashion as were those from the Atlantic, in order to find out whether a lysocline exists over the East Pacific Rise, and if so, how the surface is distributed (Fig.3, 4). Blackman studied faunal distributions and tended to avoid samples which obviously had been attacked by solution. A surface separating small solution indices from large ones, where present, therefore is less well documented for the southeast Pacific than is the lysocline in the central Atlantic. Also, such a surface may be less well defined, because of the more uniform hydrography in the deep Pacific. Nevertheless, the general shape of a lysocline zone as a quarter bowl intersected by the bottom topography of the East Pacific Rise probably is correct. The proposed bowl shape is consistent with the distribution of the "critical depth" (LISITZIN, 1969), marking the level where 10% of the sediment consists of

[1] A much improved map of the lysocline will be given in PARKER and BERGER (1970).

calcite. The lysocline, of course, is generally shallower than this level and is independent of supply and dilution rates.

Correlations with water structure are more difficult in the Pacific than in the Atlantic where the boundary between deep waters of different origins provide convenient markers. The distribution of in situ temperatures at 3,500 m (KNAUSS, 1962; fig.4) is consistent, however, with the hypothesis that the influence of Antarctic bottom water plays an important role in determining the level of the lysocline. Of special interest is the possible upward diffusion of deep water at 3,500 m near the South American continent between 20°S–40°S, which may be partly responsible for the upward slope of the lysocline at that place.

Of even greater importance, however, is the great fertility of the Peru Current, which causes delivery of much organic matter to the ocean floor near the continent. This should lead to greater than average solution, since it is expected that the increased benthonic activity provides for increased exchange of interstitial water with bottom water and for high carbon dioxide production in the sediment.

BRAMLETTE (1961) put the calcium carbonate compensation depth at about 4,500 m in the central Pacific. The tentative lysocline map of Fig.4 shows a depth range of approximately 4,000 m near the equator at 140°W to 3,000 m near the continent at 20°S. If this is correct, the lysocline and the carbonate compensation depth cannot be identical. The proposed relationship between the two

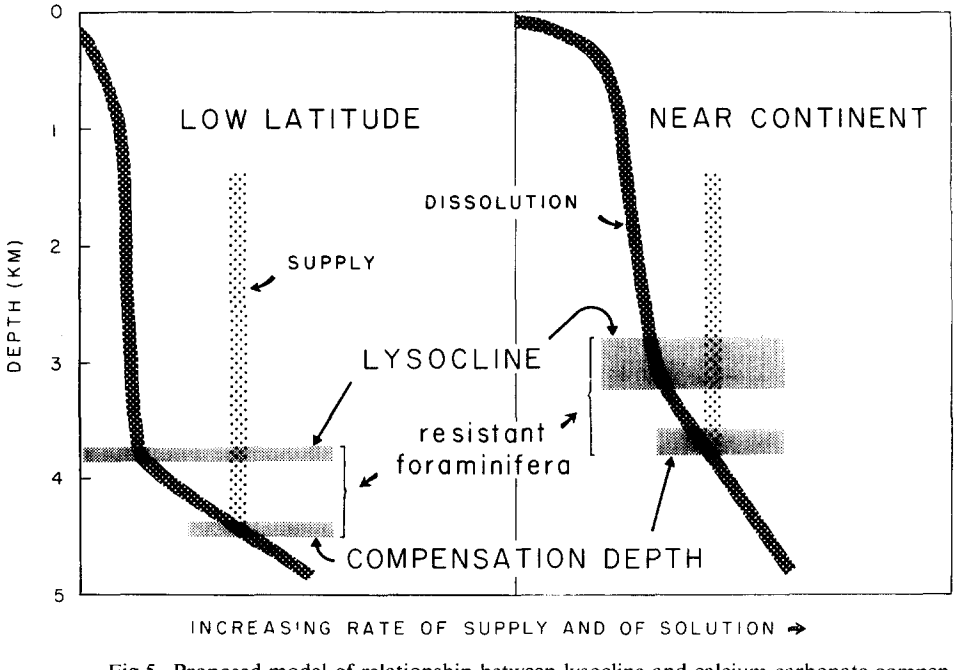



Fig.5. Proposed model of relationship between lysocline and calcium carbonate compensation depth in the southeast Pacific.

levels is illustrated in Fig.5. At any one place, the calcium carbonate compensation depth is a function of both the solution rate depth profile in the area and the rate of supply of calcium carbonate to the ocean floor. It is defined as the level at which these rates are equal and virtually no calcite is deposited (BRAMLETTE, 1961). It is mapped on the basis of calcite content in sediments. The lysocline is not dependent upon the rate of supply in this manner, although on a very large scale a positive correlation between a shallow lysocline and high productivity would be expected, since the deep water circulation apparently responsible for the lysocline position also controls the large scale nutrient supply. In addition, delivery of organic matter to the ocean floor provides for benthonic activity and carbon dioxide production which increase solution of calcium carbonate.

The lysocline level cannot be mapped on the basis of calcite content because a sediment consisting entirely of calcite may have undergone more solution than one containing very little. However, any solution should have the effect of concentrating resistant phenotypes and species in a foraminiferal assemblage, regardless of their concentration.

*Origin of the lysocline*

The reasons for the existence of a lysocline are as yet unknown. Relating this level to the influence of Antarctic bottom water does not solve the chemical problems involved. The usually cited properties presumed to be responsible for solution of calcium carbonate in the ocean appear to change too gradually across this level to warrant a sudden increase in solution rate. Possibly other factors also contribute to the sharp decrease in calcite deposition below the lysocline, such as benthonic activity (MENARD, 1964, p.161) or changes in the rate of bottom water flow.

Recently OLAUSSON (1965; 1967), TUREKIAN (1965) and PYTKOWICZ (1967) reemphasized the mass balance concept in explaining calcium carbonate distribution patterns. River influx of calcium ultimately determines the amount deposited (KUENEN, 1950, p.393; REVELLE and FAIRBRIDGE, 1957) and any excess shell production by planktonic organisms, therefore, must be redissolved. Thus, oceanic circulation controls the calcium carbonate distribution through the patterns of shell supply and of deep water flow (BROECKER et al., 1968).

A recent ocean model by SILLÉN (1967) is of special interest in this context. Assuming that the ocean water is in equilibrium with the sediments, he argues that a stagnant ocean would show little difference in saturation throughout its depth, with respect to a compound whose solubility increases with pressure, such as calcite (SILLÉN, 1967; Fig.3). When stirred, however, this ocean becomes supersaturated in shallow water and undersaturated in deep water. The reason is that deep water, being under high pressure, contains more calcium carbonate when saturated than does shallow water. Pressures are lowered for upward displaced water parcels and are increased for downward displaced water parcels. The con-

centrations of calcium carbonate are then too low for pressurized water and too high for depressurized water with respect to the previous equilibrium condition.

In the Pacific, the recent downward displacement of the bottom water is evident from its high oxygen content (WOOSTER and VOLKMANN, 1960). The active flow of the bottom water possibly hinders the development of saturated microenvironments near and within the sediment, and the continuous carbon dioxide production resulting from combustion of organic material keeps the water aggressive on its way north, despite the uptake of calcite. In contrast, the oxygen-depleted older water above the bottom water is largely derived from rising and hence depressurized water (MUREMTSEV, 1958). Because it took up calcite while being under higher pressure as bottom water, this deep water is now closer to saturation.

The lysocline level, then, may be located at a boundary between: (*1*) bottom water containing a substantial proportion of recently downward displaced water; and (*2*) overlying older, oxygen-depleted water which has been recently displaced upward. The existence of a lysocline, therefore, implies an associated oxygen minimum roof, which in turn implies the active production of bottom water in polar areas.

ACKNOWLEDGEMENTS

This work was supported by the Office of Naval Research (Nonr. 2216-23) and the American Chemical Society (PRF 2068-A2), and by the National Science Foundation (GB 5262). I am grateful to F. B. Phleger for generous advice and encouragement throughout the project. M. N. A. Peterson led the expedition during which the solution experiments were made, and I am indebted to him for discussions on calcium carbonate solution. E. W. Fager, J. D. Isaacs, H. W. Menard, and W. S. Wooster read the manuscript and made helpful suggestions.

REFERENCES

BARTH, T. W. F., CORRENS, C. W. and ESKOLA, P., 1939. *Die Entstehung der Gesteine*. Springer, Berlin, 422 pp.

BÉ, A. W. H. and ERICSON, D. B., 1963. Aspects of calcification in planktonic Foraminifera (Sarcodina). *Ann. N.Y. Acad. Sci.*, 109(1): 65–81.

BERGER, W. H., 1967. Foraminiferal ooze: solution at depths. *Science*, 156(3773): 383–385.

BERGER, W. H., 1968. Planktonic Foraminifera: selective solution and paleoclimatic interpretation. *Deep-Sea Res.*, 15(1): 31–43.

BERGER, W. H. and HEATH, G. R., 1968. Vertical mixing in pelagic sediments. *J. Marine Res.*, 26(2): 134–143.

BERGER, W. H. and SOUTAR, A., 1970. Preservation of plankton shells in an anaerobic basic off California. *Geol. Soc. Am., Bull.*, 81 (in press).

BERNER, R. A., 1965. Activity coefficients of bicarbonate, carbonate and calcium ions in sea water. *Geochim. Cosmochim. Acta*, 29(8): 947–965.

BLACKMAN, A., 1966. *Pleistocene Stratigraphy of Cores from the Southeast Pacific Ocean*. Thesis, Univ. of California, San Diego, Calif., 200 pp.

BRAMLETTE, M. N., 1961. Pelagic sediments. In: M. SEARS (Editor), *Oceanography — Publ. Am. Assoc. Advan. Sci.*, 67: 345–366.

BROECKER, W. S., HOROWITZ, R., TAKAHASKI, T. and LI, Y.-H., 1968. Factors influencing the $CaCO_3$ compensation levels in the ocean. *Geol. Soc. Am., Progr. Ann. Meeting*, 1968: 38.

GRAHAM, H. W. and MOBERG, E. G., 1944. Chemical results of the last cruise of the "Carnegie." *Carnegie Inst. Wash. Publ.*, 562: 1–58.

KENNETT, J. P., 1966. Foraminiferal evidence of a shallow calcium carbonate solution boundary, Ross Sea, Antarctica. *Science*, 153(3732): 191–193.

KNAUSS, J. A., 1962. On some aspects of the deep circulation of the Pacific. *J. Geophys. Res.*, 67(10): 3943–3954.

KUENEN, PH. H., 1950. *Marine Geology*. Wiley, New York, N.Y., 568 pp.

LISITZIN, A. P., 1969. Distribution of carbonate microfossils in suspension and in bottom sediments. In: B. M. FUNNELL and W. R. RIEDEL (Editors), *The Micropaleontology of Oceans*. Cambridge Univ. Press, Cambridge, in press.

MENARD, H. W., 1964. *Marine Geology of the Pacific*. McGraw-Hill, New York, N.Y., 271 pp.

MUREMTSEV, A. M., 1958. The principal hydrological features of the Pacific Ocean. *U.S. Dept. Comm., Office Tech. Serv., P.B. Rept.*, 63-11065: 1–417. (Transl. from Russian by Israel Program for Sci. Transl.)

MURRAY, J., 1897. On the distribution of the pelagic Foraminifera at the surface and on the floor of the ocean. *Natl. Sci.* 11(65): 17–27.

MURRAY, J. and RENARD, A. F., 1891. *Deep-sea Deposits based on the Specimens Collected during the Voyage of H.M.S. 'Challenger' in the Years 1872–1876. Rept. Voy. 'Challenger'*. Longmans, London, 525 pp. (Reprint Johnson, London, 1965.)

MURRAY, J. W., 1967. Transparent and opaque foraminiferid tests. *J. Paleontol.* 41(3): 791.

NAYUDU, Y. R., 1964. Carbonate deposits and paleoclimatic implications in the northeast Pacific Ocean. *Science*, 146(3643): 515–517.

OLAUSSON, E., 1965. Evidence of climatic changes in North Atlantic deep-sea cores, with remarks on isotopic paleotemperature analysis. In: M. SEARS (Editor), *Progress in Oceanography*. Pergamon, London, 3: 221–252.

OLAUSSON, E., 1967. Climatological, geoeconomical, and paleooceanographical aspects on carbonate deposition. In: M. SEARS (Editor), *Progress in Oceanography*. Pergamon, London, 4: 245–265.

ORR, W. N., 1967. Secondary calcification in the foraminiferal genus *Globorotalia*. *Science*, 157(3796): 1554–1555.

PARK, P. K., 1968. Seawater hydrogen-ion concentration: vertical distribution. *Science*, 162(3851): 357–358.

PARKER, F. L., 1962. Planktonic foraminiferal species in Pacific sediments. *Micropaleontol.*, 8(2): 219–254.

PARKER, F. L. and BERGER, W. H., 1970. Faunal and solution patterns of planktonic Foraminifera in surface sediments of the South Pacific. *Deep-Sea Res.* (in press).

PETERSON, M. N. A., 1966. Calcite: rates of dissolution in a vertical profile in the central Pacific. *Science*, 154(3756): 1542–1544.

PHILIPPI, E., 1910. Die Grundproben der Deutschen Südpolar-Expedition 1901–1903. *Deutsche Südpolar Expedition, 1901–1903*, 2(6): 415–616.

PHLEGER, F. B., PARKER, F. L. and PEIRSON, J. F., 1953. North Atlantic Foraminifera. *Rept. Swedish Deep-Sea Expedition, 1947–1948*, 7(1): 1–122.

PYTKOWICZ, R. M., 1965. Calcium carbonate saturation in the ocean. *Limnol. Oceanog.*, 10(2): 220–225.

PYTKOWICZ, R. M., 1967. Carbonate cycle and the buffer mechanism of recent oceans. *Geochim. Cosmochim Acta*, 31: 63–73.

PYTKOWICZ, R. M. and FOWLER, G. A., 1967. Solubility of Foraminifera in seawater at high pressures. *Geochem. J.*, 1: 169–182.

REID, J. L., 1965. *Intermediate Waters of the Pacific Ocean*. Hopkins, Baltimore, Md., 85 pp.

REVELLE, R., 1944. Marine bottom samples collected in the Pacific Ocean by the 'Carnegie' on its seventh cruise. *Carnegie Inst. Wash. Publ.*, 556, 2(1): 1–133.

REVELLE, R. and FAIRBRIDGE, R., 1957. Carbonates and carbon dioxide. *Geol. Soc. Am., Mem.*, 67(1): 239–296.

RUDDIMAN, W. F. and HEEZEN, B. C., 1967. Differential solution of planktonic Foraminifera. *Deep-Sea Res.*, 14(6): 801–808.

SAIDOVA, H. M., 1965. Sediment stratigraphy and paleogeography of the Pacific Ocean by benthonic Foraminifera during the Quaternary. In: M. SEARS (Editor), *Progress in Oceanography*. Pergamon, London, 4: 143–152.

SCHOTT, W., 1935. Die Foraminiferen in dem äquatorialen Teil des Atlantischen Ozeans. *Deut. Atlant. Expedition 'Meteor', 1925–1927, Wiss. Erdch.*, 3(3B): 43–134.

SILLÉN, L. G., 1967. The ocean as a chemical system. *Science*, 156 (3779): 1189–1197.

TUREKIAN, K. K., 1965. Some aspects of the geochemistry of marine sediments. In: J. P. RILEY and G. SKIRROW (Editors), *Chemical Oceanography*. Academic Press, London, pp.81–126.

WOOSTER, W. S., 1960. El Niño. *Calif. Coop. Oceanog. Fish. Invest., Rept.*, 7: 43–45.

WOOSTER, W. S. and REID, J. L., 1962. Eastern Boundary Currents. In: M. N. HILL (Editor), *The Sea*. Interscience, New York, N.Y., 2: 253–280.

WOOSTER, W. S. and VOLKMAN, G. H., 1960. Indications of deep Pacific circulation from the distribution of properties at five kilometers. *J. Geophys. Res.*, 65(4): 1239–1249.

WORTHINGTON, L. V., 1968. Genesis and evolution of water masses. *Meteorol. Monographs*, 8(30): 63–67.