

AN ABSTRACT OF THE THESIS OF

Paul Loubere for the degree of Doctor of Philosophy in Oceanography
presented on April 18, 1980

Title: PROPERTIES OF THE OCEANS REFLECTED IN THE SEA-BED DISTRIBUTION
OF QUATERNARY PLANKTONIC FORAMINIFERA: including a study of the
limits of empirical paleo-oceanographic models and the recogni-
tion and interpretation of faunal assemblages lacking modern
counterparts.

Redacted for privacy

Abstract Approved: _____

Hans J. Schrader

The floor of the deep world ocean is, in most places, being covered by a slowly accumulating blanket of fine sediments. Part of this sediment is comprised of the skeletons of minute planktonic, free-floating, organisms. It has been known since the nineteenth century, from the work of Murray and his predecessors, that the geographic distribution of the fossils of individual species of the plankton in the sediments reflects the shape, location and temperature of the major surficial current systems of the oceans. Thus, the mosaic of species relative abundances in deep sea sediments paints, age after geologic age, a picture of ocean circulation. The hope of the geologist interested in the history of the oceans, and their relations to changing global land forms and climate, is to be able to "peel back" the sediment layers and discover, from the paleo-geographic distribution of species, how ocean systems have evolved to their present state. The fossil plankton distribution and relative abundances in the deep sea, however, reflect a great many biological processes interacting with physical events on time scales of months (seasonal cycles of ocean warming, etc.) to centuries (forming and melting of an ice cap). Hence, understanding the fossil data is not easy. The problem becomes an ecological one projected over long time spans and confused by the many geologic processes normal to the deep

ocean.

The first section of this thesis attempts to define some of the hydrographic features of the upper ocean that can be deciphered from the sea-bed relative abundances of species of planktonic Foraminifera. It is clear that more than sea-surface temperature (the oceanic parameter that has received the most attention in paleo-oceanographic studies) is reflected in these data and the second thesis section examines the disrupting effects of species responses to non-thermal factors on certain empirical temperature estimating faunal equations (e.g. Imbrie and Kipp transfer functions).

The empirical approach to paleo-oceanographic work depends on finding a modern day analog to some down-core faunal assemblage and then inferring past hydrography following actualistic reasoning. This is true whether one uses a simple correlation coefficient to compare down core to surface sediment assemblages, or constructs "standard assemblages" (statistical factors) for the same purpose. What can be done when no obvious analog is to be found? The interpreting of such data requires an understanding of the principles that govern the relative abundances of species in sediments. The mechanisms responsible for the sediment assemblages fall into two categories: (a) physical syn- and post-depositional ; and (b) ecological. The former has been given much attention but the latter is less well understood, particularly when it comes to explaining the annual integration of species production. The annual species production is what governs, in large part, the sediment species relative abundances when no significant physical (e.g. dissolution, sorting) processes are operating. Part 1 of this thesis attempts to observe and define some of the Foraminifera ecology reflected in the sea-bed assemblages. Part 3 of the thesis uses these observations to decipher 18,000 Y.B.P., glacial age, western Mediterranean planktonic Foraminifera assemblages for which no exact modern analogs could be found in an extensive surface sediments data set from the North Atlantic and Mediterranean. It may be that the hydrography of the glacial age western Mediterranean cannot be matched by any oceanographic system operating in the present world ocean. Still, the study incorporated in part 1 of this thesis offers a means of recognizing and interpreting such a "no-analog" situation. The western Mediterranean work shows how this can be done.

PROPERTIES OF THE OCEANS REFLECTED IN THE SEA-BED DISTRIBUTION OF
QUATERNARY PLANKTONIC FORAMINIFERA: including a study of the limits
of empirical paleo-oceanographic models and the recognition and
interpretation of faunal assemblages lacking modern counterparts

by
Paul Loubere

A THESIS
submitted to
Oregon State University

in partial fulfillment of
the requirements for the
degree of
Doctor of Philosophy
Completed April 1980
Commencement June 1981

APPROVED:

Redacted for privacy

Professor of Oceanography in Charge of Major

Redacted for privacy

Dean of the School of Oceanography

Redacted for privacy

Dean of the Graduate School

Thesis presented on April 18, 1980

Typed by Nancy Kneisel for Paul Loubere

ACKNOWLEDGEMENTS

Specific acknowledgements for the work done in this thesis are given at the end of each thesis section. I owe general debts of gratitude to Dr.'s Vern Kulm and Hans Schrader for showing confidence in me at times when I was less than convinced of my own abilities. Dr. Bill Hutson went to bat for me in the money game more often than he should have been required to. I am very grateful for his efforts on my behalf. The School of Oceanography supported my efforts as a student and researcher generously. My committee, Hans Schrader, Bill Hutson, Erwin Suess, Bob Smith and Arthur Boucot, aided me with my thesis and guided my education as a marine geologist. They, and my fellow students, helped create the positive atmosphere in which the following work was done.

I owe to my parents, Leo and Lynn, the greatest debt of all for they helped me realize my abilities and gave me the confidence to pursue my ambitions.

FOR MY WIFE FRANCES AND MY BROTHER PHILIP:

we are all seeking for a truth

FOR MY FATHER-IN-LAW FRANK:

who guided me when geology was more an adventure than a science

THE SCENE: Deep in the sea there is no motion, no sound, save that put there by the insane humors of man. The slow, smooth stirring of the deep ocean currents, the high-frequency snapping or popping of ocean life, even the occasional snort or burble of a porpoise are all in low key, subdued, responsive to the primordial quietness of the deep.

E. L. Beach - Run Silent, Run Deep

THE CAVEAT: " There was once upon a time ... a world of seas and continents and islands ---" " Like the earth", she murmured, bitterly. " Yes, what else could you expect from sending a man made of our common, tormented clay on a voyage of discovery? What else could he find? What else could you understand or care for, or feel the existence of even? There was the comedy of it, and the slaughter."

Joseph Conrad - The Tale

TABLE OF CONTENTS

The thesis is presented as three papers in publication format.

PAPER 1: Oceanographic Parameters Reflected in the Sea-bed Distribution
of Planktonic Foraminifera from the North Atlantic and Mediter-
ranean Sea

	<u>Page</u>
ABSTRACT	1
INTRODUCTION	3
Data preparation	3
Approach to data analysis	5
Studying the relative abundance of species	6
Species relationships to oceanography	7
Species sensitive to temperature and salinity	7
Species showing T/S patterns reflecting temperature and seasonality	18
Species showing a response to either temp. or salinity alone	29
Species showing a distribution reflecting productivity	32
Summary	35
References	37
Table 1- Summary of sites and data	43
Table 2- Sites used for Figure 7(b)	48
Figures:	
1- Data points in February T/S field	4
2- <u>G. ruber</u> in summer and winter T/S fields	8
3- Salinity influenced species in T/S field	12
4- <u>G. sacculifer</u> in T/S field	16
5- <u>G. inflata</u> in T/S and T/ seasonality fields	19
6- <u>G. inflata</u> in the W. Mediterranean	22
7- Left coiling <u>N. pachyderma</u> vs. temperature	26
8- <u>Pachyderma-dutertrei</u> complex in T/S field	30
9- <u>G. bulloides</u> , <u>G. quinqueloba</u> in T/S field	33

PAPER 2: Quantitative Paleoceanography: Data Base Limitations to Temper-
ature Estimates.

ABSTRACT	49
INTRODUCTION	51

CONTENTS CONT:	<u>Page</u>
Abundance no-analogs	53
Ratio no-analogs	62
Conclusions	70
References	71
Table 1- Summary of Kipp sites with Com. 0.8 in M.C.T. model	73
Table 2- Group 2 sites with large T. estimate error	75
Table 3- Group 2 sites with small T. estimate error	76
Table 4- Medit. sites with mixed assemblages	77
Figures:	
1- Temperature estimates at Kipp sites with M.C.T. model	54
2- T. estimate error vs. Communality and excess species %	56
3- Histogram of M.C.T. site number vs. Feb. temperature	59
4- Percent <u>G. ruber</u> vs. Feb. surface water T/S	66
6- Thunell model applied to Atlantic, M.C.T. model applied to Mediterranean	68
<u>PAPER 3: The Western Mediterranean during the Last Glacial: Solution to a No-analog Problem</u>	
ABSTRACT	78
INTRODUCTION	80
Cores studied	81
Dating the cores	83
The faunal data	85
Definition of 18,000 Y.B.P. assemblages	86
The last Glacial at core TR173-16	87
The Glacial age at core 35326	94
Summary of the model	100
References	102
Table 1- Species percents at TR173-16	107
Table 2- Species percents at 35326	108
Figures:	
1- Core locations and dating	82
2- Principal component 1 and T. estimates for the cores	88
3- Important species in Feb. T/S field	90
4- <u>G. inflata</u> in the W. Mediterranean	92
5- Scanning electron micrographs of species	109

OCEANOGRAPHIC PARAMETERS REFLECTED IN THE SEA-BED DISTRIBUTION
OF PLANKTONIC FORAMINIFERA FROM THE NORTH ATLANTIC AND MEDITERRANEAN SEA

Paul Loubere

Department of Oceanography
Oregon State University
Corvallis, Oregon 97331

ABSTRACT:

Sediment surface (modern) planktonic Foraminifera assemblages from 234 cores taken in the North Atlantic and western Mediterranean have been analyzed to determine the relationships between species relative abundance and oceanographic characteristics such as temperature, salinity, seasonality (annual thermal contrast in the upper ocean), water density and phytoplankton productivity. The relative abundances of the most common species have been plotted on temperature-salinity diagrams, using average conditions in surface waters above the coring sites as plotting coordinates. These species are shown to fall into distinct groups. G. ruber (white form), G. falconensis, and left coiling G. truncatulinoides are related to higher salinities, G. sacculifer and the pink form of G. ruber are related to moderate salinities; and N. dutertrei and G. menardii probably are related to lower salinities. N. pachyderma is shown to occur over a wide range of salinities, but has distinct temperature limits, contrasting with G. glutinata which shows opposite sensitivities. G. inflata and left coiling N. pachyderma relative abundances show a relationship to seasonality with the former becoming more abundant and the latter less abundant as annual thermal contrast increases. In addition, G. inflata abundances reflect the upper water column density structure. The distribution of G. bulloides may also be related to upper water column densities, but, along with G. quinqueloba, may also in part reflect phytoplankton productivity in the open ocean. In general, the species represented winter oceanographic conditions much better than summer ones. This is shown diagrammatically for the major species G. ruber and G. bulloides. It is thought that this is due to the peak test production occurring at the seasons of significant phytoplankton blooming,

times when hydrography has a more winter than summer aspect. Also, the T/S diagram relative abundance distributions of the dominant species do not appear to be closely associated to any of the major water masses and current systems of the study area. This work emphasizes the seasonal nature of living Foraminifera production and the limitations this imposes on the paleo-oceanographic information to be extracted from sea bed assemblages.

INTRODUCTION:

The purpose of this paper is to examine the relationship of surface sediment planktonic Foraminifera species distributions to several important oceanic surface water properties. These are: temperature, salinity, seasonality (annual thermal contrast) and productivity.

The study area selected was the North Atlantic and the western Mediterranean. The North Atlantic is a well-known body of water for which a great deal of oceanographic data is available. Also, there is a considerable body of information in the literature on sediment surface Foraminifera distributions for this area. The species counts assembled for the North Atlantic by Kipp (1976) are used here (see Table 1). Figure 1 shows the temperature and salinity range covered by these data (Figure 6(d) shows the geographic distribution of the samples). To increase the salinity range of this study (see Figure 1), species counts from the western Mediterranean were made by the author (see Table 1) and supplemented with counts provided by Dr. Thunell (personal comm.) and Todd (1958). A total of 234 core top samples were used as listed in Table 1.

DATA PREPARATION:

The material from the Mediterranean was prepared so as to be taxonomically consistent with the North Atlantic data. The Foraminifera species recognized are those listed by Kipp (1976), based on a classification developed by Parker (1962), Bradshaw (1959), and others as summarized in Bé (1967, 1977). The category of pachyderma-dutertrei intergrade is somewhat subjective, but the author has attempted to follow Kipp's use of the term. Thunell did not recognize this category, but the samples he provided which are used in this work contain only

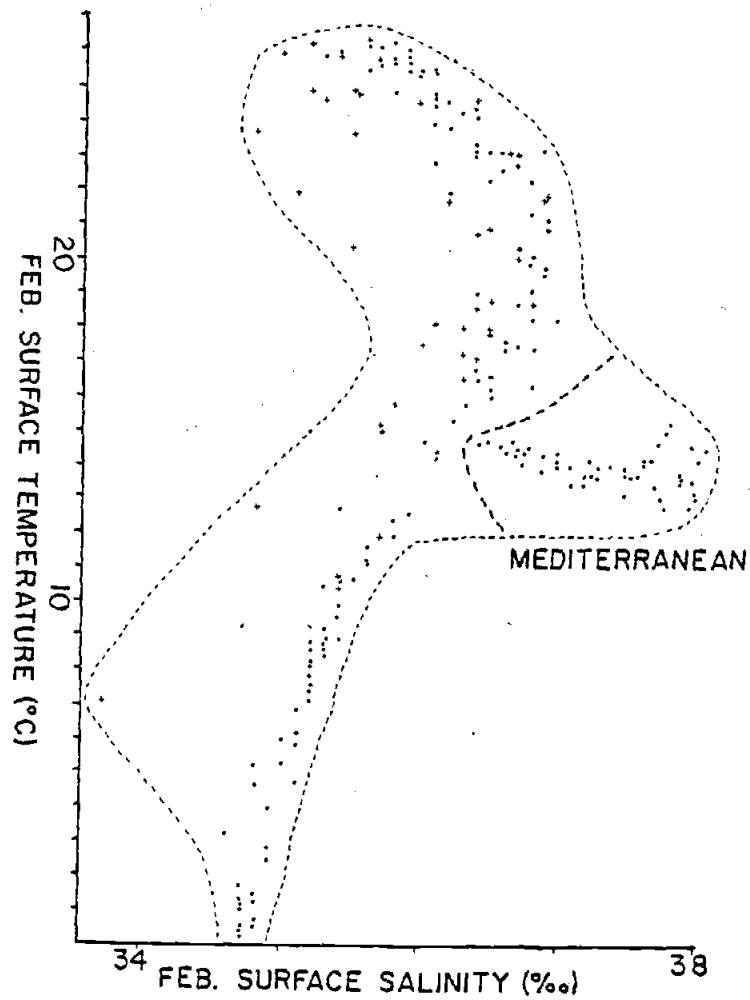


FIG. 1- Distribution of data points in average February surface water T/S field. Each surface sediment sample location is plotted against mean conditions in surface waters directly above the coring site. T/S data from Kipp (1976) and U.S. Naval Oceanographic Atlas (1967). Crosses mark samples listed as showing signs of moderate to severe dissolution.

small quantities of either end-member species. The size fraction used (greater than 149 microns) is that selected by Kipp. The necessity for consistency on this score has been demonstrated by Vincent (1972).

APPROACH TO DATA ANALYSIS:

The method used for examining the data was to plot individual species percents against the mean February temperatures and salinities of the surface waters directly above the sites where the sediment samples were collected. Each sample was plotted on a February T/S diagram using the average surface conditions for coordinates, as shown in Figure 1. T/S - species percent diagrams were created by then plotting individual species percents for each sample and contouring the results. An example of this for Globigerinoides ruber (d'Orbigny) is shown in Figure 2(a). The contour intervals have been selected to best present the relationship between species abundances and temperature and salinity.

The conditions for particular months, rather than averaging annual hydrography, were used because the work of Bé (1960), Tolderlund and Bé (1971) and Vergnaud-Grazzini (1975) has shown that, for the area being studied, planktonic Foraminifera are seasonal in their production. The seasonal extremes of February and August have been of most interest to paleo-oceanographers (Imbrie and Kipp, 1971; CLIMAP, 1976) and February conditions are used extensively below as species distributions show a better correspondence to the hydrography of the colder times of the year (see below for documentation of this). This would be expected as the authors listed above have shown that, outside the tropics, most species have major abundance peaks in the early spring and can have a minor peak in the fall. Examples of seasonal bias in the sea-bed data will be given below for two major species, G. ruber

and Globigerina bulloides (d'Orbigny).

Mean sea surface conditions, as recorded in the U.S. naval oceanographic Atlas (1967) and Kipp (1976), have been used since the quantity of surface information far exceeds that at depth. We may expect the surface conditions to be well correlated to those surrounding the Foraminifera as the mixed layer is considerably thickened in the winter and early spring (Sverdrup, Johnson and Fleming, 1942), the times of the year apparently most important to the Foraminifera. A cold season mixed layer of better than 100 meters is common for the study area and this covers the productive layer of the planktonic Foraminifera (Lohman, 1920; Schott, 1935; Bradshaw, 1959; Bé, 1960; Berger, 1969, 1976).

STUDYING THE RELATIVE ABUNDANCE OF SPECIES:

Two influences are recorded in the T/S-species percent diagrams. The first is the relationship of that species with the physical conditions of overlying surface waters and the second is the changes in abundances of the other species present in the samples used (this dependence is created by using a relative abundance measure with the data; Chayes, 1971, 1975). The degree to which changes in the other species influences a particular species diagram is inversely proportional to: the number of species present, the true covariance among the species and the absolute magnitude of their relative abundances. It has long been observed with Foraminifera that one or two species tend to dominate each region of the ocean. For these species, disturbance by changes in the percentages of other species will be reasonably small. Hence, we may expect a certain degree of independence among more common species so that we have a better chance of studying directly their relationship to surface water oceanography.

For less common species we may expect more difficulty as small changes in other species abundances can create a relative abundance shift that is a significant part of the total percentage range of the lesser taxa.

SPECIES RELATIONSHIPS TO OCEANOGRAPHY:

The species, once plotted on the T/S diagrams, tend to show five types of oceanographic responses. These are; sensitive to: temperature and salinity, temperature alone, temperature and seasonality, salinity alone, and temperature and productivity. Below, the more abundant Foraminifera species will be discussed within these five categories.

SPECIES SENSITIVE TO TEMPERATURE AND SALINITY:

Species Representative of High and Low Salinities:

Globigerinoides ruber (white var.): This species was selected for first consideration as it is abundant in the North Atlantic and Mediterranean, is a near surface dweller (Bé and Tolderlund, 1971), is reported to be sensitive to salinity (Bé, 1977), and shows a shift in season of maximum abundance, from peaks in the spring and fall in the subtropics to summer peaks in the tropics (Tolderlund and Bé, 1971). This latter is important as it suggests we should see a progressive decrease in the correlation of species percent to winter oceanographic conditions as temperature increases on our February T/S plot.

Figure 2(a) shows that G. ruber sediment surface distribution has a good over-all relationship to February temperatures and salinities for the North Atlantic and western Mediterranean. The distribution of G. ruber on the T/S diagram cannot be explained by dissolution as most of the data points used in the figure show little sign of carbonate loss

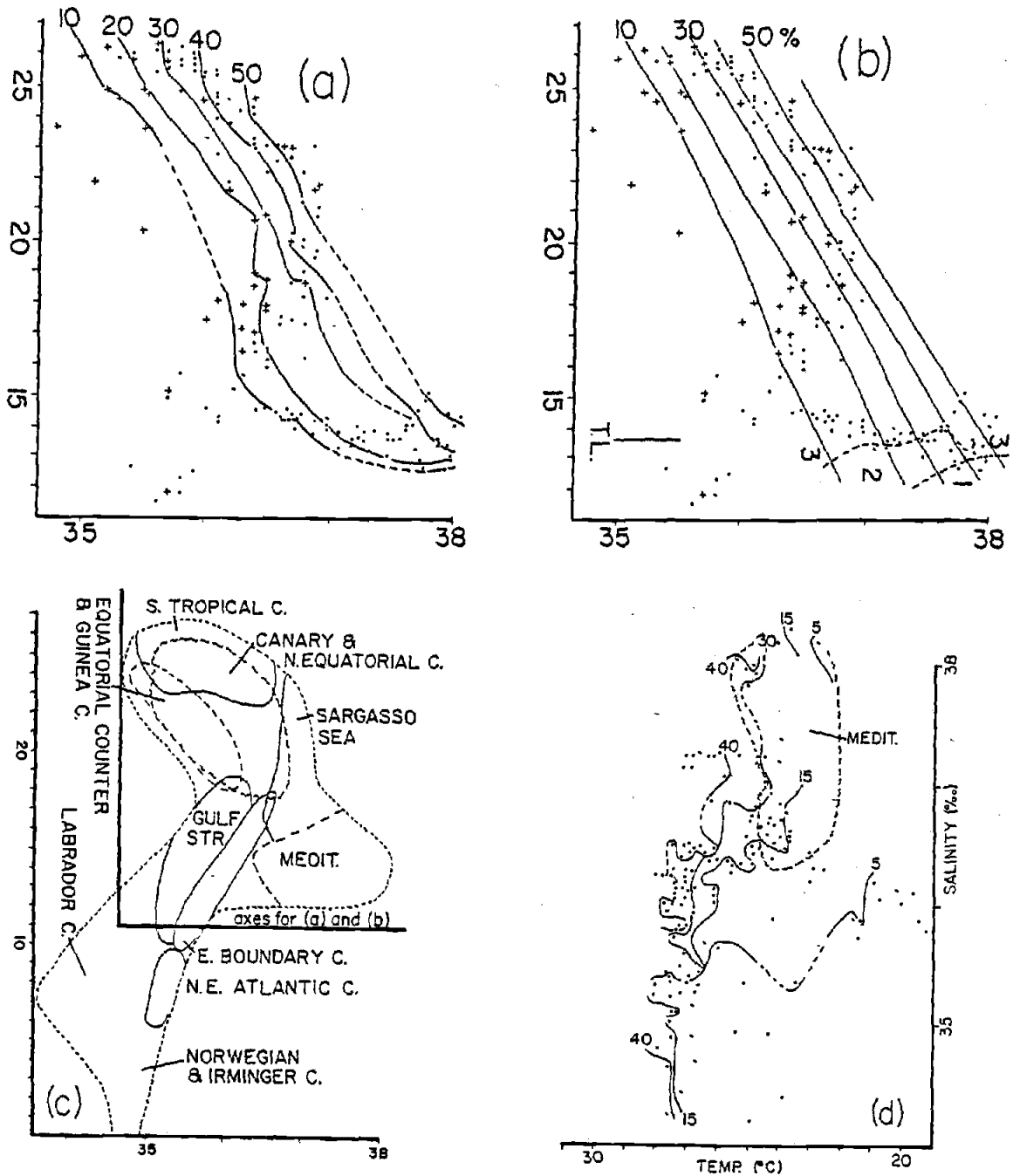


FIG. 2- (a) percent contours of *G. ruber* (white var.) plotted in mean surface water February T/S field. (b) polynomial regression of *G. ruber* percent on February T. and sal. (see text). T.L. = lower temperature limit to production; 1 = absolute values of regression residuals greater than 20%, 2 = residuals from 7-15%, 3 = residuals less than 7%. (c) the sample T/S field divided generally into the water masses and currents which the samples underlie, C = current. (d) contours of *G. ruber* (white var.) percent plotted against summer surface water T. (from Kipp, 1976) and sal. (see Table 1). Note that the pattern is less interpretable than (a). For all diagrams save (d) T. is vertical scale.

(see Figure 1, crosses on Figure 2(a)).

A quadratic least squares regression of this species on the oceanographic parameters for the North Atlantic gives:

$$\% \text{ ruber} = 10,524 - 188.19 (\text{Feb. } T) - 507.89 (\text{Feb. sal.}) + .431 (\text{Feb. } T.^2) + 6.08 (\text{Feb. sal.}^2) + 4.83 (\text{Feb. } T. * \text{Feb. sal.})$$

$$R^2 = .91 \qquad 113 \text{ samples used (see Table 1)}$$

- physical oceanographic data from Kipp (1976).

Figure 2(b) shows this equation applied to both the North Atlantic and Mediterranean data. The distribution of residuals forms a coherent pattern which implies that the western Mediterranean lies on the edge of the G. ruber range. These data suggest there is a temperature limit for this species at about 13.5°C. (T.L. on Figure 2(b)) below which test production and contribution to the sediments decreases drastically. The lower temperature limit on production, here indicated by increasing residuals, cuts across the well-defined species response to salinity.

The hypothesis that G. ruber is sensitive to both temperature and salinity is given support by Bá's (1977) observation on the higher salinity preferences of the species in the Atlantic ocean and Jones' (1967) demonstration that Foraminifera distribution in the water column can be sensitive to both temperature and salinity.

The regression model presented above has several implications. The relative abundance of G. ruber in surface sediments shows a fairly regular response to temperature and salinity across several water mass and current boundaries on the T/S diagram (see Figure 2(c) showing water mass and current locations on the T/S diagram). This represents a constancy of response over a wide range of physical oceanographic conditions, sedimentary environments and biotic primary production

zones (Bé and Tolderlund, 1971; Bé, 1977; Cifelli, 1962). The relative abundance of G. ruber appears to reflect winter surface temperatures and salinities much better than other oceanographic features and seems not to show any water mass or geographic endemism. These features indicate that G. ruber will serve as an excellent paleo-oceanographic tool as long as the marked salinity responses can be separated from the control of temperature on the species.

The relationship of G. ruber to winter conditions does not worsen as temperature increases on the T/S plot; as was suggested it should above due to shifts in its season of maximum abundance. Indeed, the plotting of percent G. ruber in the sediments against summer conditions (see Figure 2(d)) does not produce an easily interpretable result for any temperature range. As there is no reason to suppose that the physical oceanographic data is less accurate for summer than winter conditions, it is apparent that G. ruber reflects the winter season much better than the summer season. Such a result was not expected, but its explanation may lie in a combination of biotic production and sample preparation factors.

G. ruber may reach its highest standing stock during summer months in more tropical areas (Tolderlund and Bé, 1971), but standing stock does not necessarily equate to biomass production. The greatest quantity of shell production may accompany the spring phytoplankton blooms (see Menzel and Ryther, 1960; Ryther and Menzel, 1960) and this would be the predominant season reflected in the sediments.

We may also selectively examine only the Foraminifera tests reflecting a season of fairly rapid production when we sieve our material at 149 microns. We look at only whole tests of fairly large size and

the possibility of these arriving undamaged by zooplankton depredations could be enhanced at times of higher reproductive rates. Berger (1976, p. 282) has suggested that predation would be heavier on small Foraminifera than large ones, and that the sediment record is biased towards deeper living, cortified, specimens (Bé and Ericson, 1963; Bé, 1965). As Berger and Soutar's (1967) rates of turnover for Foraminifera in the water column are high, the time to create an adult form which could reproduce (leaving the test intact so as to contribute to the sediment we examine) could be very rapid during times of high phytoplankton abundance. Quick passage to larger size, thus avoiding destructive predation, would enhance the Foraminifera record of the phytoplankton bloom season and limit our view of oceanographic conditions at other times of the year. Also, if the highly productive times of the year see the generation of greater numbers of heavily calcified individuals (as suggested by Bé's, 1979, observation of calcification during gametogenesis), the representation of these seasons in the fossil record would be enhanced by selective solution at the sediment-water interface.

Globorotalia truncatulinoides (d'Orbigny) of the left coiling form can be expected to show a good relationship to winter temperature and salinity. Bé (1960) and Tolderlund and Bé (1971) have shown this species to be restricted to the winter season. Thiede (1971) has previously suggested that the left coiling form of G. truncatulinoides is responsive to salinity. This species distribution on the T/S diagram is shown in Figure 3(a). Here a higher salinity and temperature range is indicated. The picture is clouded somewhat by the depth preference of the more cortified (more likely to be preserved form of the species (Bé, 1977)). This is especially true for the northwestern Mediterranean where the species has been recorded over a great range

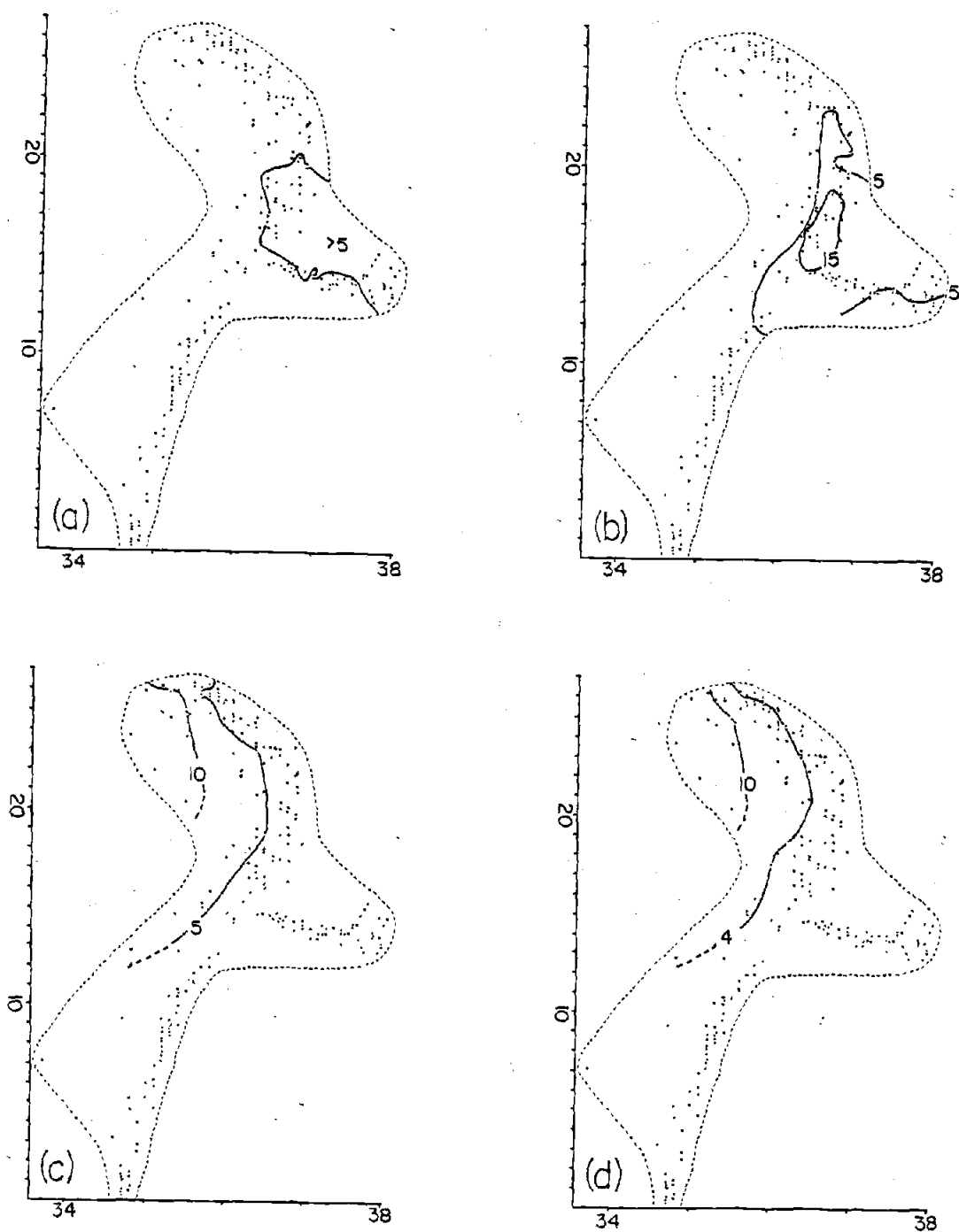


FIG. 3- (a) contours of percent left coiling *G. truncatulinoides* plotted against the February surface water T/S field. (b) percent *G. falconensis*. (c) percent *M. dubertrei*, (d) percent *G. senardi* all contoured against the same conditions as (a). T. is on the vertical scale.

of depths (Vergnaud-Grazzini, personal comm., in prep.). Also, the lesser abundances of G. truncatulinoides makes its percent values more susceptible to disturbance due to changes in other species abundances.

Another species showing a distribution related to higher salinity is Globigerina falconensis (Blow), see Figure 3(b). This may be compared to Figure 9(a) showing the disposition of G. bulloides on a T/S diagram. These distinctly different species ecological ranges support the hypothesis that G. falconensis is a separate ecotype from G. bulloides (Bé and Tolderlund, 1971; Kennett, 1976).

Species indicative of lower marine salinities have been of particular interest in tracing the melt water of ice sheets during past glacial epochs. Areas particularly well studied are the Gulf of Mexico and the eastern Mediterranean. Neogloboquadrina dutertrei (d'Orbigny) has received the most attention as a salinity sensitive species (for the Gulf of Mexico: Kennett and Shackleton, 1975; Thunell, 1976; for the Mediterranean sea: Kullenberg, 1952; Ryan, 1972; Thunell, 1978). Bé and Tolderlund (1971) and Ruddiman (1971) record N. dutertrei as most abundant at lower marine salinities in the Atlantic ocean. Thunell (1978) reports finding increased quantities of N. dutertrei in Mediterranean surface sediments below both high ($38.2^{\circ}/\text{oo}$ -N.W. Mediterranean) and low (30 to $35^{\circ}/\text{oo}$ -N.E. Aegean Sea) salinity surface waters. The author has investigated the sediments below the high salinity region (cores listed in Table 1) and has found that most of the Neogloboquadrinid forms are attributable to N. pachyderma or pachyderma-dutertrei intergrade (see Kipp, 1976, for references to photographs of the intergrade). The latter was not recognized as a taxonomic form by Thunell. The intergrade differs substantially from the N. dutertrei photographed in Thunell (1978), Bé (1977) or Cifelli (1974). Planktonic Foraminifera in the

water column of the northwest Mediterranean have been investigated by Vergnaud-Grazzini (1975, personal comm.) and Cifelli (1974). Neither of these authors report N. dutertrei in quantities exceeding 1%. Hence, if N. dutertrei (s.s.) is abundant anywhere in the Mediterranean, it is probable that this will only be in the lower salinity N.E. Aegean.

Figure 3(c) shows the percentage of N. dutertrei plotted against average February temperature and salinity for the data included in this work. This figure lends support to the contention that N. dutertrei s.s. is indicative of warmer temperatures and lower salinities. A drawback of the present work is that many of the low salinity data points are represented by faunal assemblages showing signs of dissolution (see Figure 1, Kipp, 1976). N. dutertrei is relatively solution resistant (Berger, 1970; Adelseck, 1978), hence it will tend to be disproportionately represented in the above samples. It should be noted that dissolution points do not strictly control the contours on Figure 3(c) leading the author to suspect that chemical erosion may enhance the N. dutertrei abundance, but does not create it. Kipp (1976) remarks that dissolution may be responsible for the abundance of N. dutertrei in her "gyre margin" assemblage.

Globorotalia menardii (d'Orbigny) is another species that shows a relationship to salinity, see Figure 3(d). This species is found in sub-tropical to tropical waters (Bé and Tolderlund, 1971; Bé and Hutson, 1977; Bé, 1977) and has been extensively used as a stratigraphic-climatic indicator in the tropical Atlantic (Ericson and Wollin, 1956 and 1968; Ericson et al., 1961, 1964). Review of this work, along with further research, has lead several authors (Emiliani, 1964; Prell and Damuth, 1978) to question G. menardii's strict temperature dependence. A more complex ecologic response has been suggested and it seems likely from

Figure 3(d) that salinity is important in bounding G. menardii abundances in the sediments. As with N. dutertrei the evaluation of the T/S diagram is hampered by dissolution. G. menardii is a resistant species (Berger, 1970; Adelseck, 1978) and can be sensitive to dissolution (Hutson, 1977). Carbonate erosion might explain the highest abundances of this species in Figure 3(d), but it fails to explain the general trend of species decrease as salinity increases. It is significant that G. menardii is absent from the Mediterranean surface sediments (Parker, 1958; Todd, 1958) and is found in only small quantities in the water column (Cifelli, 1974) as the Mediterranean represents a high salinity environment that otherwise supports such tropical species as G. ruber and G. sacculifer (Parker, 1958; Thunell, 1978). Bé (1977) and Berger (1969) have published salinity ranges for G. menardii for the Indian and Pacific Oceans. The range of conditions sampled are not broad enough to test the salinity diagram developed here, but Bé's data suggest a preference for less saline waters. Imbrie and Kipp (1971) defined a "gyre margin" assemblage for the North Atlantic containing G. menardii which they were able to show had some correlation to both temperature and salinity.

Species Representative of Mid-range Salinities:

Globigerinoides sacculifer (without terminal sac-like chamber), (Brady) is an example of a species that appears to prefer a mid-range of salinities, see Figure 4(a). The warm water preference of this species has been previously discussed by Bradshaw (1959), Parker (1962), Bé and Tolderlund (1971), Berger (1969) and Bé (1977). A possible difficulty with the interpretation of salinity preference is that the T/S zone of greater G. sacculifer abundance is bounded above by increasing

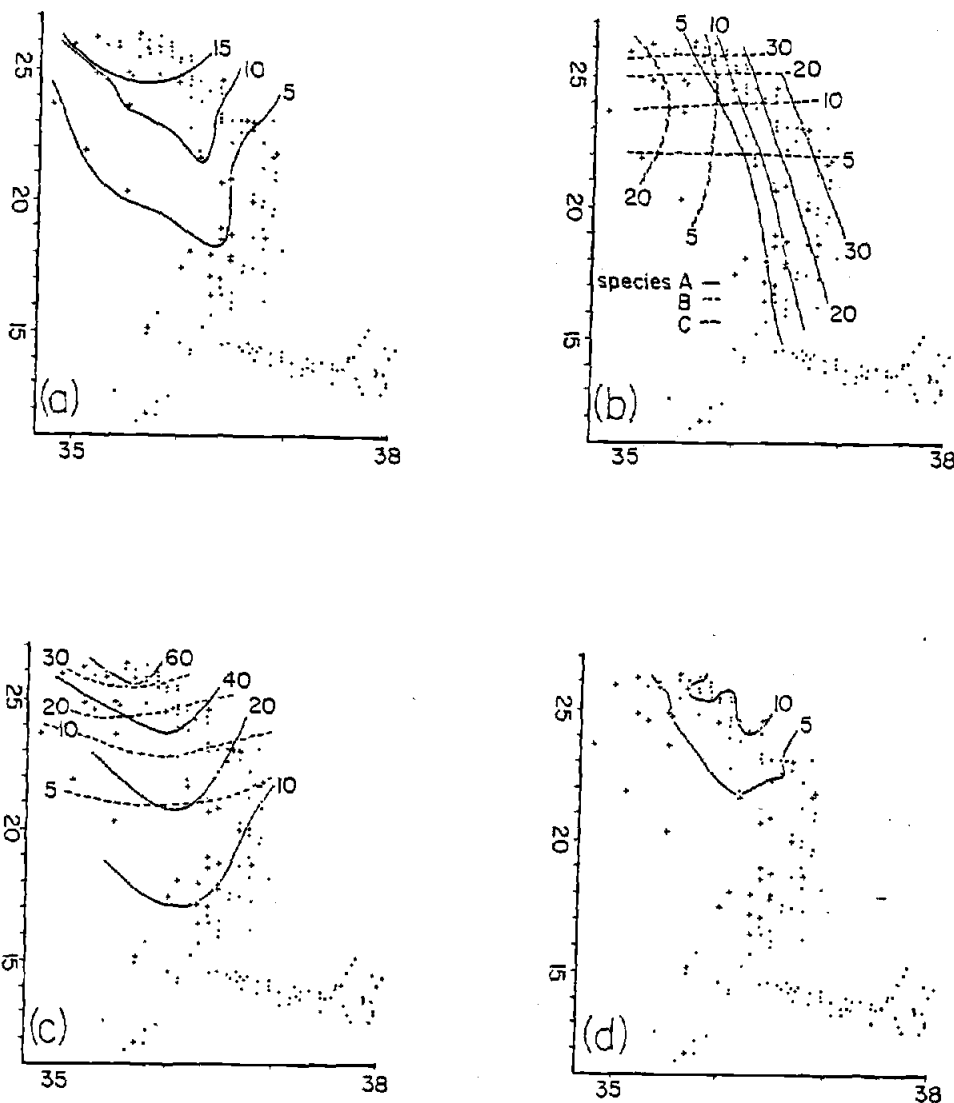


FIG. 4- (a) contours of *G. saeculifer* (non-ssc like finel chamber) percent plotted against surface water February T/S field. (b) 3 species accumulation rate model (see text)- species and contoured values are arbitrary. (c) solid line-percent contours of species B of (b) using model from (b); dotted line-percent contours of species B after modifying model from (b) to include additional species (see text). (d) contours of percent of pink form *G. ruber* plotted against February conditions. For all figures T. is on the vertical scale.

quantities of G. ruber (Figure 2(a)) and bounded below by data points showing signs of dissolution (see Figure 1, G. sacculifer is susceptible to dissolution, Adelseck, 1978). The dissolution factor is not sufficient to explain the trend of G. sacculifer contours on Figure 4(a), but it might enhance the sharpness of abundance decreases as salinity drops.

The difficulty lies in the fact that we are using relative abundances of species. This means that, as previously discussed, a species percent for a sample is dependent in the accumulation rates of all the species in that sample. As G. ruber abundance increases it may cause an artificial decrease in the abundance of G. sacculifer, thus creating an "upper salinity" limit. Figure 4(b) shows a simple accumulation rate model (units are arbitrary) for three species. Species A, mimicking G. ruber, is responding to temperature and salinity; species B, an analogue for G. sacculifer, responds only to temperature; and species C mimicks the lower salinity, dissolution enhanced, species such as N. dutertrei. Converting the "accumulation rates" to percent, as in Figure 4(c) (solid lines), shows how species B might then appear to have a salinity response. This figure bears a similarity to that constructed from actual G. sacculifer percentages.

The percentaging difficulty becomes less noticeable if more species are added to the model. To illustrate this, a value of 50 was added to accumulation rate totals for each point in Figure 4(b) and percentages were recalculated, see Figure 4(c)-dotted lines. Adding the constant above merely increases the number of individuals used to find the percent and makes the total abundance of the species A to C a sub-set of a larger total "accumulation rate" for Foraminifera in the sample. As can be seen in Figure 4(c) the distorting effect of using relative abundance data has been greatly reduced.

In reality, we are dealing with a fairly large number of species and a reasonable diversity for the data points in Figure 4(a). Few sites in the higher temperature realm are completely dominated by only two or three species (Stehli, 1965). Hence, it seems a reasonable hypothesis that the abundance of G. sacculifer is sensitive to salinity and the highest accumulation rates of this species, other things being equal, occur in the mid-range of salinities in the Atlantic Ocean. This theory should be tested using cores, located under appropriate temperature and salinity clines where dissolution is not a factor. The G. sacculifer form with a terminal sac-like chamber shows a diagram pattern similar to that of the form just discussed.

G. ruber of the pink variety shows a T/S-species percent pattern which is very different from the white form of G. ruber, but similar to G. sacculifer, see Figure 4(d). The discussion for G. sacculifer, therefore, applies to the pink G. ruber.

SPECIES SHOWING T/S PATTERNS REFLECTING TEMPERATURE AND SEASONALITY:

Seasonality is defined here as the difference between average August and average February temperatures for surface waters above the sampling sites. Figure 5(a) shows seasonality plotted on a February average T/S diagram. Winter-summer temperature differences reach their highest values in the Gulf Stream and in the Mediterranean Sea.

Globorotalia inflata (d'Orbigny) seems to reflect seasonality. The biogeographic role and temperature range of G. inflata have been summarized by Bradshaw (1959), Parker (1962), Bé and Tolderlund (1971) and Bé (1977). This species marks the boundary between subpolar and subtropical or central water masses. On the February T/S diagram G. inflata shows a distribution pattern, Figure 5(b), which is obviously

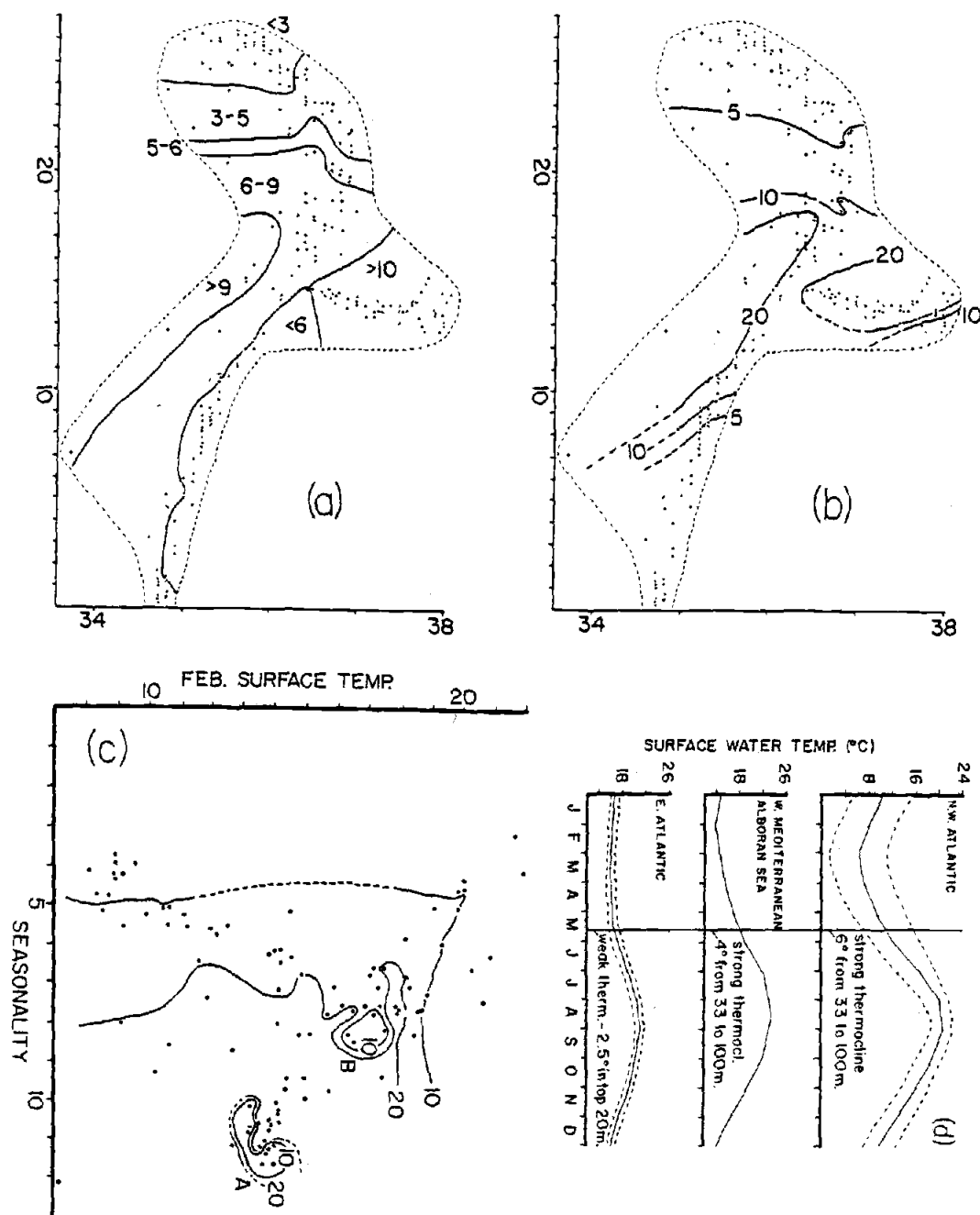


FIG. 5- (a) site seasonality (Aug. T.-Feb. T.) plotted on the February surface water T/S field. (b) contours of percent *G. inflata* on the February T/S field, note similarities to (a). For (a) and (b) Temp. is on the vertical scale. (c) plot of *G. inflata* percent on a February T. - seasonality diagram, A and B are anomalies where species percent does not increase with seasonality. (d) comparison of average surface water temperature records for two areas of high seasonality (N.W. Atlantic, W. Medit.) and one area of low seasonality (E. Atlantic). Data from U.S. naval oceanographic Atlas (1967).

controlled mainly by temperature, but shows a secondary modulation reminiscent of Figure 5(a), showing the summer to winter temperature difference.

The relationship of the sediment surface percent distribution of G. inflata to surface water seasonality can be tested by plotting the data points on a temperature-seasonality diagram just as they were plotted on the T/S diagrams discussed above. Figure 5(c) shows the species percent on temperature-seasonality plot. It is evident that G. inflata relative abundance has a relationship to seasonality, with species percent increasing as annual thermal contrast does. However, there are two major anomalies in this pattern, labelled "A" and "B" on Figure 5(c). Region A is comprised of samples from the northwestern Mediterranean which have only small quantities of G. inflata inspite of being taken below waters of high seasonality with a temperature range near optimum for the species. Thunell (1978) and Figure 6(a) show the surface sediment distribution of G. inflata in the western Mediterranean. The species has an abundance maximum in the Alboran Sea (south of Spain) and rapidly diminishes in importance to the north and east of the basin. This pattern cannot be attributed to temperature as there is only a small average gradient across the western Mediterranean (about 2°C - U.S. Naval Oceanographic Atlas, 1967) and the range of temperatures lies well within the species limits. The species distribution is more likely to be related to upper water column stratification for it is in this physical parameter that the western and northern parts of the basin differ most.

LaCombe and Tchernia (1971) describe the Alboran Sea as permanently stratified due to the sharp difference in characteristics between mid-depth Levantine water (250-500 m.) and the surface water entering from

the Atlantic Ocean. In the northwest Mediterranean, however, stratification is seasonal, with vertical mixing occurring during the winter (Wüst, 1961; Sankey, 1973) and stability only during the summer. The difference between the Alboran Sea and the northwestern region is summarized in Figure 6 (a, b) showing monthly average density profiles for these two areas given in the U.S. Naval Oceanographic Atlas (1967). Vergnaud-Grazzini (1974) presents data showing that the most important production of Foraminifera in the western Mediterranean occurs in the colder months of the year (times of high phytoplankton production). Hence, during the production period, the Alboran Sea is stratified while the northwestern Mediterranean is not. It seems plausible that G. inflata, being a mesopelagic species (Bé and Tolderlund, 1971; Be, 1977), uses the density gradient to position itself in the water column. Without a gradient the species might get carried by vertical mixing into regions of the water column where there is no food, conditions are otherwise unacceptable or its population is so dispersed that reproduction is difficult.

The oceanography of the sites in anomalous Region "B" of Figure 5(c) lends support to the hypothesis that G. inflata is associated with upper water column density gradients. The data points at the core of the anomaly all lie in the eastern Atlantic at the southern margin of the G. inflata range, as shown in Figure 6(d). In this region the pycnocline is seasonal and only weakly developed during all but the summer months (see U.S. Naval Oceanographic Atlas, 1967; P. 80, 132-212). Figure 5(d) helps illustrate this. The bottom graph of the figure shows that the summer increase in surface temperature occurs relatively late in the year for the eastern Atlantic. Thus, the spring thermocline, hence pycnocline, is weak and high in the water column. This can be

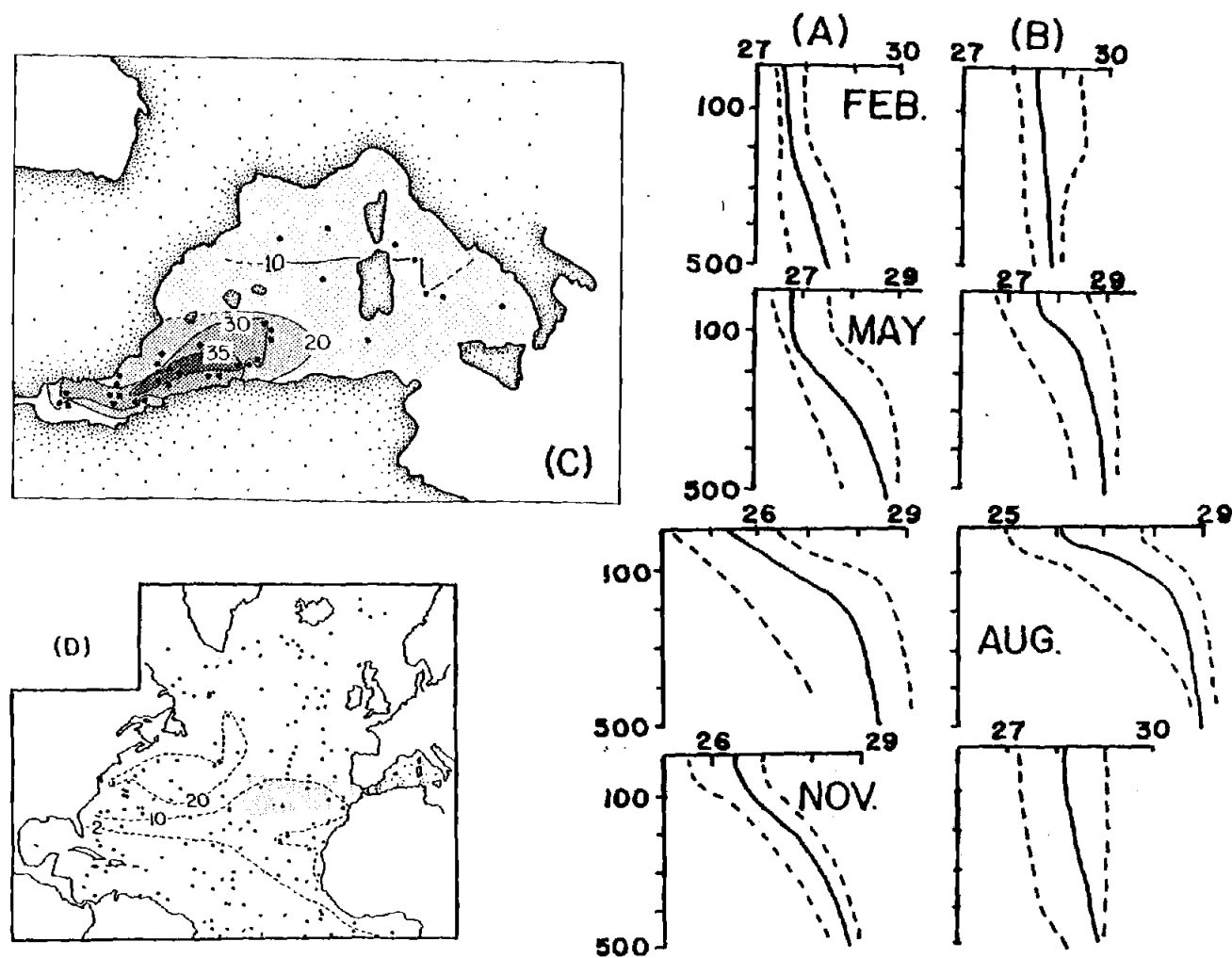


FIG. 6- Water column density over the year for the southwestern Mediterranean (A) and the north and eastern parts of the western basin (B). Data from U.S. naval oceanographic Atlas (1967). Horizontal axis = sigma-t, vertical axis = depth (meters). (c) shows the sediment surface percent of *G. inflata* - data from Table 1. (D) location of sites used in this study, contours are of percent *G. inflata* (from Kipp, 1976), shaded area are sites in anomaly "B" of Figure 5(c).

compared to the N.W. Atlantic, along the Gulf Stream, and to the Alboran Sea, both shown in Figure 5(d). These are both areas where the sediments abound in G. inflata (for the N.W. Atlantic distribution of the species see Figure 6(d) and Kipp, 1976, P. 16). The Gulf Stream is permanently stratified (Stommel, 1966) as is the Alboran Sea (see above).

In the eastern Atlantic most of the biological production probably occurs in the spring (see below) when the area is not stratified below about 50 meters. Hence, the physical situation is analogous to the N.W. Mediterranean and we can once again associate the relative scarcity of G. inflata in sediments to the absence of a permanent upper water column density gradient.

An explanation of the influence of seasonality on G. inflata abundance in deep sea sediments may be found in the composite nature of our surface sediment samples. These may represent an average of Foraminifera test production for several thousands of years. If we assume that oceanic conditions over that period of time have been fairly constant, then this average would generally represent one year's production. However, biological production in ocean waters is not constant through all seasons (McGill, 1966). Rather, certain conditions lead to spring and autumn phytoplankton blooms which are followed by marked increases in zooplankton production. The period of high phytoplankton production is initiated in the spring by increasing surface water stability and photoperiod (Steeman-Nielsen, 1958, Steele and Menzel, 1962). It lasts until depleted nutrients and increasing surface water temperature inhibit high rates of cell division (Riley, 1946). Nutrient regeneration is a function of surface water stratification which depends on the rate of change in surface water temperatures. In Figure 5(d) it can

be seen that, in the spring, areas of high seasonality in the Atlantic and the Mediterranean develop a shallow thermocline more strongly and earlier in the year than do areas of lower seasonality (eastern Atlantic). Also, the range and rate of change in temperature is greatest in the high seasonality regions. This means that the period of time when conditions of production are optimal for any one of the shallower dwelling Foraminifera species will be shorter in a high than in a low seasonality region. By contrast G. inflata lives at greater depth in the water column (Bé and Tolderlund, 1971), where seasonal events are subdued. Therefore, it might have a more regular annual production rate, less dependent on surface physical events. Other, globogerinid, species living closer to the surface might have production rates curtailed by rapidly changing oceanography in areas of high seasonality. The result of this scheme would be to increase the relative abundance of G. inflata in sediments of more seasonal regions. The driving mechanism of the model would be variations in the lengths of periods of peak production in the more surface dwelling Foraminifera species.

Tolderlund and Bé (1971) provide some information suggesting that G. inflata abundances may be less sensitive to seasonality than other Foraminifera. At station Delta (op. cit., p. 303), a region of moderate seasonality in the "transition zone", G. inflata shows a more continuous presence than do most of the other species recorded, which tend to have sharp peaks in abundance.

In summary, the relative abundance of G. inflata in deep sea sediments appears to reflect three parameters. These are temperature, seasonality and upper water column density structure. The latter acts as a "limiting factor" in the species response to temperature and seasonality.

Left-coiling Neogloboquadrina Pachyderma (Ehrenberg):

The temperature-related coiling directions in N. pachyderma were first discussed by Ericson (1959) and Bandy (1960). The geologic history of coiling directions in this species has been further elaborated by Jenkins (1967) and Kennett (1968). The biogeographic distribution of the coiling variants of N. pachyderma in surface sediments and the water column of the North Atlantic has been reviewed by Bé and Tolderlund (1971), Tolderlund and Bé (1971), Kipp (1976), and Be (1977). Cifelli (1961) has argued that the coiling forms are actually different species, calling the right-coiling type Globigerina incompta.

Kipp (1976) provides data points from cores located in polar regions of the North Atlantic where the sinistral N. pachyderma is abundant and with which we may examine its relationship to temperature and seasonality. Figure 7(a) shows the result of regressing the percent of left-coiling N. pachyderma against average February surface water temperature (sites used listed in Table 1). Samples plotting below 2°C tend to be mono- or bi-specific, so that changes in relative abundances of species are hard to interpret (see section above dealing with the study of relative abundance data). Above 8°C samples have too few left-coiling N. pachyderma for variations in relative abundance to be evaluated. Between 2 and 10°C the left-coiling form composes an important, but not totally dominant, part of the fauna. It is in this range that the relative abundance of sinistral N. pachyderma is seen to be sensitive to seasonality. As shown in Figure 7(a), those samples with a seasonality of greater than 5.5°C lie below the regression line, while those with a seasonality of less than 5.5°C lie above it. We can use the residuals of the regression to "partial out" the temperature influence on the abundance of N. pachyderma in a "group distance" test to see if seasonality

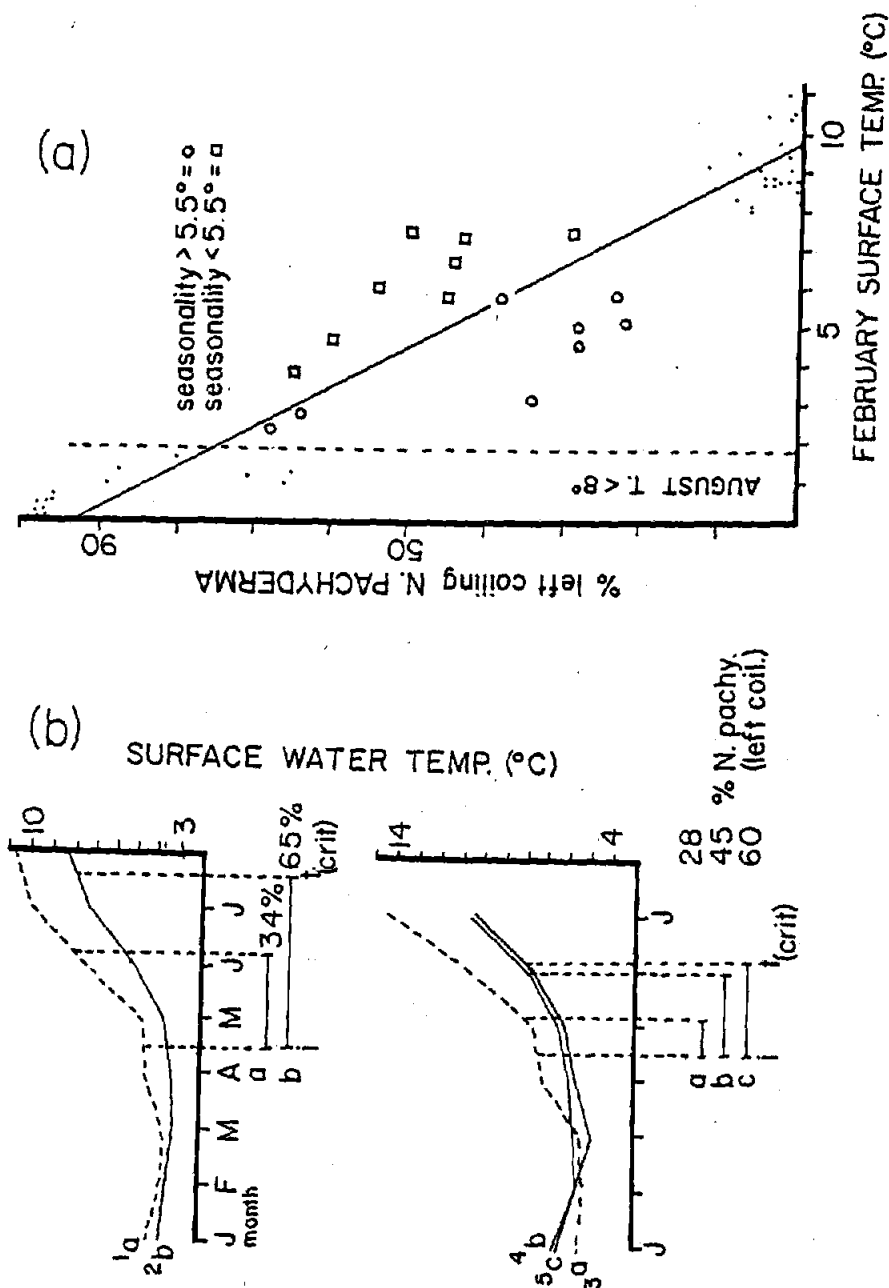


FIG. 7- (a) cold water samples percent of left coiling *N. pachyderma* plotted against mean surface water February temperature. Regression line is shown (see Table 1 for samples used). Note that samples of low seasonality plot above the line while those with high seasonality plot below it, for samples with abundant *N. pachyderma* and summer temperatures greater than 3°C. (b) comparison of mean annual temperature cycles for surface waters of high (dotted line) and low (solid line) seasonality sites with similar February temperatures. 1 = general time of increased production in waters due to phytoplankton blooms; t(crit) = time when sinistral *N. pachyderma* production is curtailed by rising temperature—fig. 7a suggests 3°C. as a limit. Note that low seasonality sites have the longest hypothetical period of production and contain the largest quantities of sinistral *N. pachyderma*, as indicated by the percent values given.

is a significant factor influencing the species. Using the seasonality of 5.5°C or greater as a selector criterion, we can divide the 16 data points, lying between 2 and 8°C in Figure 7(a), into two groups. Their properties are listed below:

	GROUP 1 SEASONALITY 5.5°	GROUP 2 SEASONALITY 5.5°
Mean residual	-13.84	14.24
Group variance	116.84	56.64
d.f.	7	7

- Calculated "t" for group distance = 5.728
- Critical "t" for significance level of .05 at d.f. = 14 is 2.145
- The means of the residuals for the two groups are statistically different.

Hence, sites having a higher seasonality have fewer sinistral N. pachyderma than expected, while those sites with a lower seasonality have more of this species than expected.

This phenomenon can be explained using a model in which zooplankton reproduction is linked to phytoplankton production and in which N. pachyderma has an upper temperature limit to its reproduction of about 8°C . At and beyond this limit reproduction would drop off steeply. We shall concentrate on spring as Tolderlund and Bé (1971) have shown that the major abundances of left-coiling N. pachyderma occur in this season. In the North Atlantic polar regions phytoplankton spring blooms occur when solar incidence and surface water structure permit it (Corlett, 1953; Riley, 1942, 1943; Steeman-Nielsen, 1958; Holmes, 1956). This is roughly from the end of April to the end of July. On Figure 7(b) seasonal temperature profiles for regions of low and high seasonality are presented. See Table 2 for cores used. Profiles have been selected

to compare high and low seasonality sites, used in the above regression, that have similar February temperatures. Assuming that phytoplankton production begins fairly simultaneously over the North Atlantic, it can be seen that sinistral N. pachyderma will encounter its upper temperature limit much earlier in the year at high seasonality sites than at low seasonality locations. Hence, the period of active production will be shorter at more seasonal locations and the relative abundance of left-coiling N. pachyderma will decrease in the sediments below. That the abundance of the species does decrease as the hypothesized production period decreases is shown in Figure 7(b). Tolderlund and Bé's (1971) seasonal Foraminifera observations at polar station Bravo show that N. pachyderma has sharp seasonal limits, unlike other major species at that location, and that the species abundance decline occurs around June when surface water temperatures approach 7.5 to 8°C (extrapolated from the U.S. Naval Oceanographic Atlas of the North Atlantic, 1967). It should be noted that the effect of seasonality on the above species should become less apparent as peak summer temperatures drop towards 8°C, and when minimum winter temperatures go above this limit.

It is interesting to observe that smaller quantities of left-coiling forms are not accompanied by marked increases in the right-coiling variant for core locations in the N.W. Atlantic (the higher seasonality zone, see Kipp, 1976) as one would expect if the two forms represented a physiological cline within one population. This might indicate that the right and left-coiling forms of N. pachyderma are genetically separated populations, or even separate species as suggested by Cifelli (1961).

SPECIES SHOWING A RESPONSE TO EITHER TEMPERATURE OR SALINITY ALONE:

The right-coiling form of N. pachyderma (N. incompta?): Bradshaw (1959) presents a T/S diagram for this species based on plankton tows from the North Pacific Ocean during different years and summer months. This diagram tends to suggest that the species is associated with cooler temperatures and lower salinities. This hypothesis is supported by data presented in both Berger (1969) and BÉ (1977). The T/S diagram presented in Figure 8(a) is constructed using sediment samples, so it represents, generally, the long range averaging of N. pachyderma production over hundreds or thousands of years. Also, the range of salinities examined is greater than that for the above studies. The data suggest that N. pachyderma abundance represents largely temperature variations and is not sensitive to salinity. The February 7 to 12°C isotherms seem to delimit the zone of maximum abundance for the species in surface sediments. It will be noted that this figure does not include individuals classed as pachyderma-dutertrei intergrades.

The morphological gradations of N. dutertrei have been discussed by Zobel (1968) and are reviewed in Kennett (1976). Parker (1958, 1962) and others have commented on the intergradation of form between N. pachyderma and N. dutertrei. This continuous sequence of forms has given rise to the category of P.D. intergrade used by Kipp (1976). Figure 8(b) shows a T/S diagram for the intergrade and demonstrates that it has a coherent pattern of distribution. Kipp (1976) observed this and placed it in a "gyre margin" group. Figure 8(b) suggests that the quantity of intergrade forms increases as salinity reaches high and low values, or when temperature increases. Figure 8(c) shows the overlapping zones of concentration of dextral N. pachyderma, the P.D. intergrade and

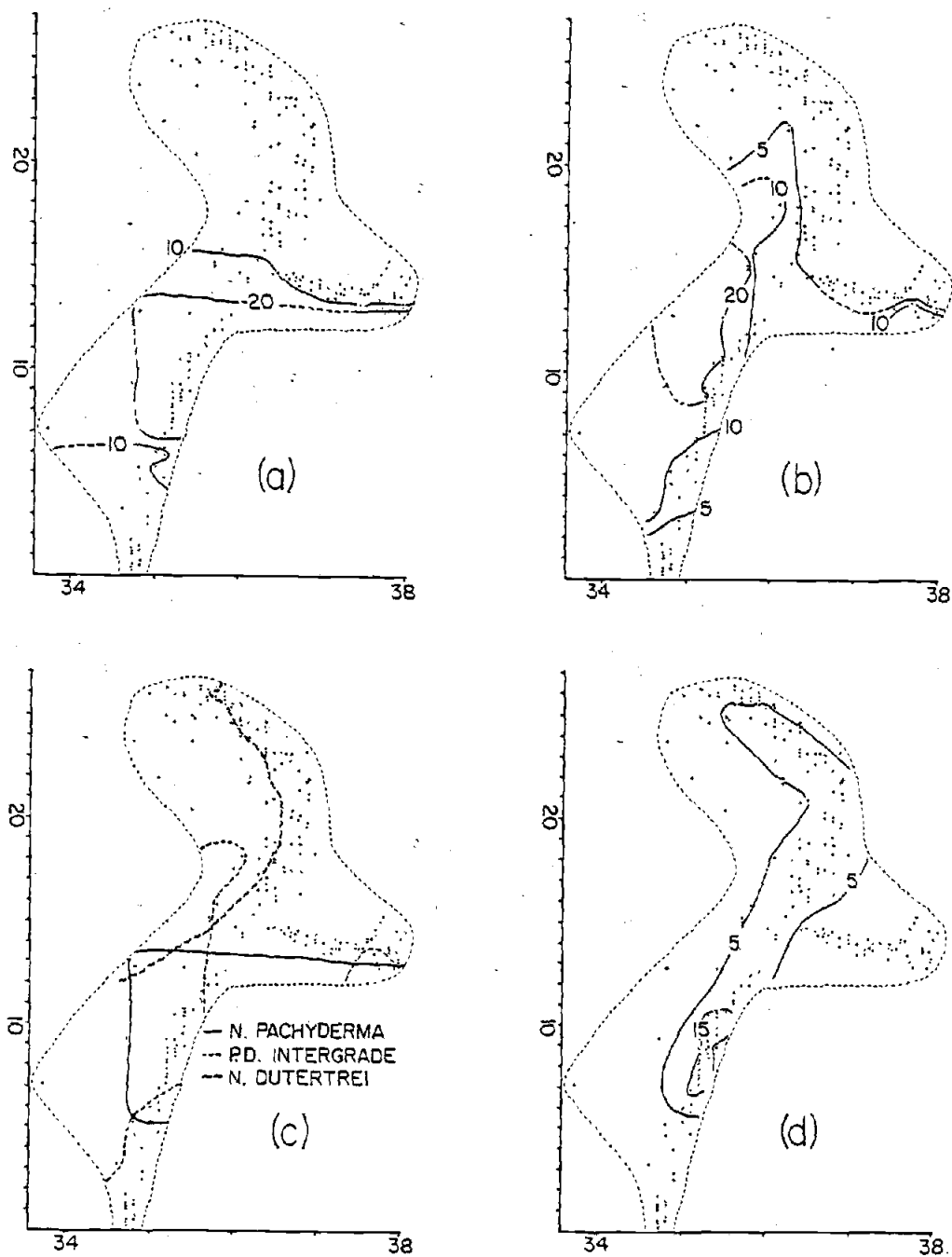


FIG. 8- (a) contours of percent right coiling *N. pachyderma* against mean surface water February T/S field, (b) contours of P-D intergrade percent against the same conditions. (c) comparison of T/S areas of highest concentration for dextral *N. pachyderma*, *N. dutertrei* and their intergrade. (d) contours of percent *G. glutinata* against the February conditions. For all figures T. is on the vertical scale.

N. dutertrei (see above for a discussion of the latter species). This suggests that the "intergrade" forms are sensitive to salinity and temperature and may indicate zones of "ecologic stress" for either or both of the end member species. The T/S diagram of P.D. intergrade does not show a satisfactory relationship to seasonality (see Figure 5(a)). Also, dissolution would not account for its abundance (see Figure 1, abundant pteropods in the sediments of the Mediterranean indicates that little dissolution occurs there - Herman, 1971). Hence, as indicated by Zobel (1968) and Bé and Tolderlund (1971), distribution of this intermediate form may represent oceanic regimes not entirely favorable to either N. dutertrei or N. pachyderma. The differing salinity relationships of the latter taxa indicates that they are distinct species, rather than an ecological cline in morphology of N. dutertrei, as suggested by Parker and Berger (1971).

Globigerinata glutinata (Egger): Tolderlund and Bé (1971) remarked that this is an enigmatic species with a cosmopolitan distribution. Such an impression is supported by data presented in Berger (1969). Figure 8(d) shows a T/S diagram for G. glutinata for surface sediments, illustrating a broad temperature range. Kipp (1976) figures a bi-modal biogeography for this species with general occurrence at all latitudes in the North Atlantic, but peaks in abundance for sub-arctic and sub-tropical waters. Figure 8(d) suggests the bi-modality can be resolved into a mid-range salinity preference. Certainly, G. glutinata is not abundant in the Mediterranean surface sediments (Parker, 1958; Thunell, 1978) or water column (Vergnaud-Grazzini, 1974, 1975; Cifelli, 1974). G. glutinata might appear to be absent from low salinity environments due to dissolution, but the data points showing corrosion will not entirely

explain the reduced percentage under less saline waters. A difficulty in interpreting the data arises from the fact that the relationship of G. glutinata to dissolution is complex (Adelseck, 1978) and is not completely understood.

SPECIES SHOWING A DISTRIBUTION REFLECTING PRODUCTIVITY:

Globigerina bulloides (d'Orbigny): G. bulloides has been associated with the more productive areas of the ocean (Bé and Tolderlund, 1971; Bé, 1977). Furthermore, Tolderlund and Bé (1971) have shown that G. bulloides seasons of high standing stock vary as do the seasons of phytoplankton bloom in the North Atlantic. That is, from a variable saw-tooth pattern, including spring, summer and autumn maxima, near the Labrador Sea (Holmes, 1956; Riley, 1946) to a pattern with peaks in the spring and autumn for the central North Atlantic (Corlett, 1953; Menzel and Ryther, 1960). Such a relationship to productivity would lead us to expect that, on the T/S diagram, G. bulloides percentages would reflect summer and winter conditions nearly equally well in the low temperature regions of the diagram, but would progressively become biased towards winter conditions as we move up the temperature axis. Figures 9(a,b) show that this is what is observed in the sea-bed data. G. bulloides shows a diachronous oceanographic signal, with winter conditions better represented than summer conditions in the higher temperature field.

Looking at Figure 9(a), we see that the upper limits of G. bulloides abundance lie along two boundaries. For salinities higher than 36⁰/oo percentage contours run generally parallel to isotherms. At 36.1⁰/oo salinity there is a lobe of higher percentages which corresponds to sites containing abundant G. falconensis, see Figure 3(b). This is probably

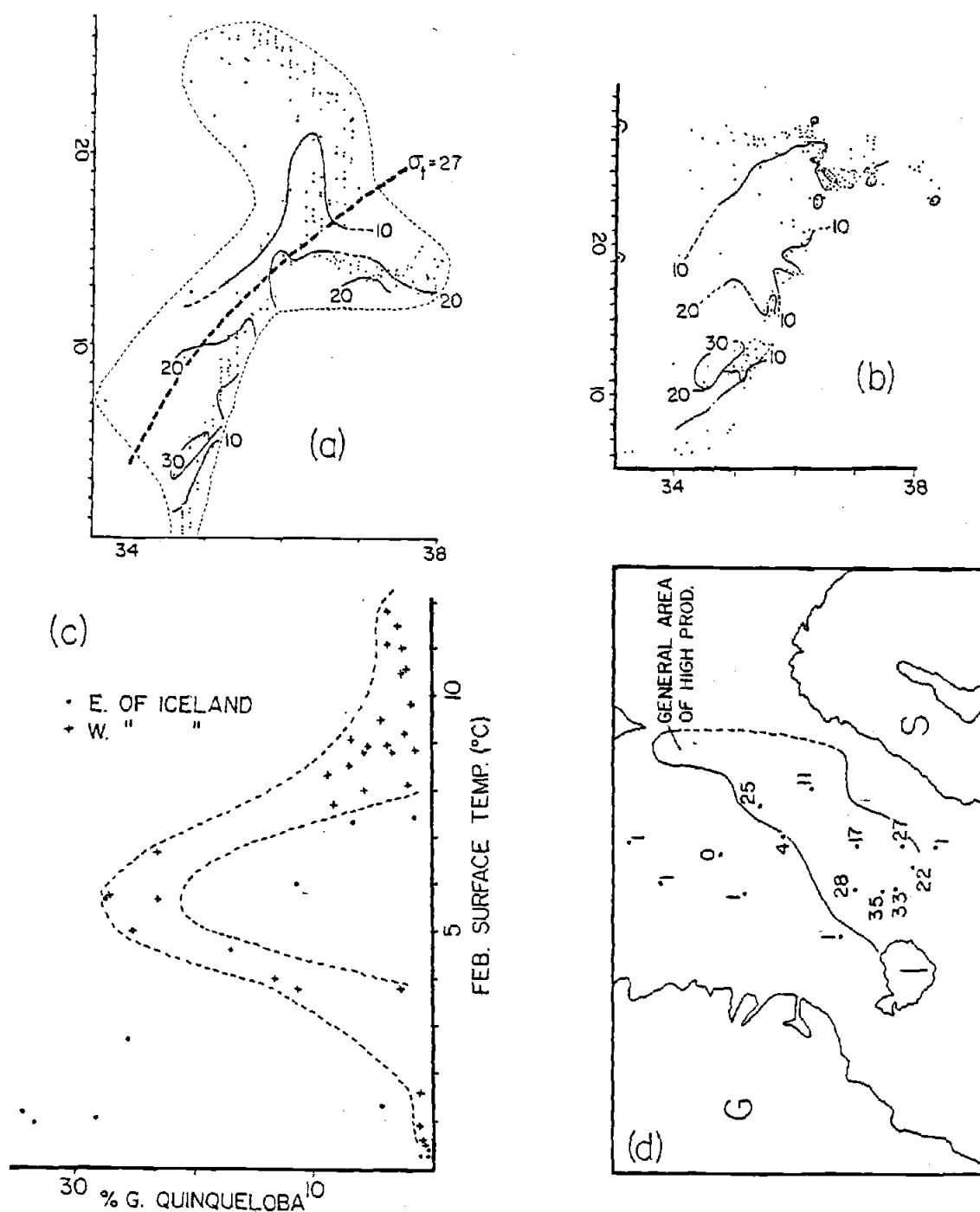


FIG. 9 - (a) contours of percent *G. quinqueloba* against surface water February T. (vertical axis), and salinity. Note that the contour pattern may generally follow the 27 sigma-t density line. (b) contours of percent *G. quinqueloba* against average summer surface water T. and Sal. (Table 1). Note that the contouring becomes clearer at lower temperatures. (c) percent *G. quinqueloba* plotted against average February surface water T. (samples used indicated on Table 1). Note that samples west of Iceland show a classic distribution of % vs. T. while those east of Iceland do not. (d) samples east of Iceland plotted by percent of *G. quinqueloba*. Note that higher percentages are found under the area of increased biological production reported by Serge (1952).

due to the gradation in morphology between these two species.

Below 36 ‰ salinity the upper abundance limit of G. bulloides seems to be sensitive to changes in the salt content of the water. This observation is based on eight data points (see Figure 9(a)) of which only two are free from signs of dissolution (Kipp, 1976). G. bulloides is moderately susceptible to solution (Berger, 1970), and tends to occur in assemblages whose important members (N. pachyderma, P.D. intergrade, G. inflata, N. dutertrei) are more resistant than it is. Therefore, the salinity response must be viewed with suspicion. It is interesting to note that the contours of G. bulloides in Figure 9(a) are parallel to the $27^{\circ} \sigma_T$ isoline up to about 15°C where a temperature limit seems to become operative. It is intriguing to speculate that the species is sensitive to water density.

Globigerina quinqueloba (Natland): G. quinqueloba is a common epipelagic sub-arctic species (Bé and Tolderlund, 1971). In the North Atlantic it shows a continuous distribution from south of Spitzbergen to Newfoundland (Kipp, 1976). The biogeographic zone of this species tends generally to follow the isotherms, but plotting percent data against temperature shows two types of behavior. Figure 9(c) presents such a plot in which data points have been divided into those west and those east of Iceland. The number of data points is low, but it does seem that these two groups show distinctly different relationships to the temperature parameter. The western group seems to have a regular parabolic response with a maximum at about 5.5°C . The eastern group shows a much more irregular response with peak values near 1°C . It is interesting to note that those eastern sites with higher percentages of G. quinqueloba lie below the regions of highest phytoplankton production in the Norwegian Sea (Berge, 1958; Koblenz-Mishke et al., 1970;

see Figure 9(d)). At the high latitudes of the Norwegian Sea, the phytoproduction season is short and closer to the summer season. As G. quinqueloba is a surface dweller, it might be more sensitive to this period of production than G. bulloides and N. pachyderma, the species it most commonly occurs with. Hence, its abundance fluctuations would reflect ocean fertility, as well as temperature.

SUMMARY:

Despite limitations due to dissolution and to the restricted span of temperatures and salinities represented by the available Foraminifera assemblages, certain coherent species responses to environmental parameters can be deduced from the data examined above. In addition to the well-documented relationship of species distributions to temperature, several forms show distinct salinity preferences. This has been demonstrated for G. ruber, G. sacculifer and N. dutertrei; all occurring in warmer waters where the data cover a reasonable span of salinities. Salinity response in low temperature species has not been discussed as data are not available to test this possibility (see Figure 1).

It has been shown, using two major species, that the species examined reflect winter oceanographic conditions better than summer conditions, suggesting that major test input to the sediments, for the greater than 149 micron fraction, occurs during the times of phytoplankton bloom. That is, at times better correlated to the winter than summer season.

In addition to the above general physical responses, the effect of annual cycles of upper water column temperature change and the intersection of these with annual phytoplankton production cycles appears to be of importance in determining species abundances in the sediments.

Seasonality probably is important in controlling the Foraminiferal assemblage recorded in the sediments as it may accentuate the differences in food supply and average production rate between meso and more epipelagic species, or between steno- and more eurythermal species.

The vertical density structure of the water column has been shown to affect the sediment record of one major deeper dwelling species, G. inflata, and may well control the distribution of the meso-pelagic Foraminifera.

ACKNOWLEDGMENTS:

My main debt is to Dr. N. Kipp, who, by putting her raw data in the public domain, afforded me many happy hours trying to understand Foraminifera and made the present work possible. I am very grateful to Dr. H. Schrader for his cheerful psychological and financial support; I thank Dr.'s W. Hutson and L. Kulm for their support and encouragement. Thanks also to my academic siblings Gretchen Schuette and Bob Karlin, who helped develop the atmosphere in which this work was done. Dr. R. Thunell very kindly shared his data and views of Mediterranean micropaleontology with me. A short conversation with Dr. A. McIntyre several years ago inspired me to pursue the subject of seasonality recorded in fossil data. The author was supported by N.S.F. grants, OCE 7808522, OCE 77-23162 A01.

REFERENCES:

- Adelseck, C., 1978, Dissolution of deep-sea carbonate: preliminary calibration of preservational and morphologic aspects, *Deep Sea Research*, 25: 1167-1185
- Bandy, O., 1960, The geologic significance of coiling ratios in the Foraminifera *Globigerina pachyderma* (Ehrenberg), *J. of Paleont.*, 34: 671-681
- Bé, A., 1960, Ecology of recent planktonic Foraminifera, Part 2, Bathymetric and seasonal distributions in the Sargasso Sea off Bermuda, *Micropaleont.*, 6(4): 373-392
- , 1965, The influence of depth on shell growth in *Globigerinoides sacculifer* (Brady), *Micropaleont.*, 11(1): 81-97
- , 1967, Foraminifera, Families Globigerinidae and Globorotaliidae. Fiche No. 108, In: (Fraser, J.H. ed) *Fiches d'identification du zooplankton*, Conseil International pour l'Exploration de la Mer, Charlottenlund, Denmark
- , 1977, Recent planktonic Foraminifera, In: (Ramsay, A., ed.), *Oceanic Micropaleontology*, Vol. 1, p. 1-100 Academic Press, London
- , 1979, Planktonic Foraminifera: Ultrastructural changes caused by calcification during gametogenesis in *Globigerinoides sacculifer* (Brady), *Geol. Soc. Amer. abstracts for national meetings*, 11(7): 385-386
- , and D. Ericson, 1963, Aspects of calcification in planktonic Foraminifera, In: *Comparative Biology of Calcified Tissues*, N.Y. Academy of Sciences, Ann. 109(1): 65-81
- , and W. Hutson, 1977, Ecology of planktonic Foraminifera and biogeographic patterns of life and fossil assemblages in the Indian Ocean, *Micropaleont.*, 23(4): 369-414
- , and D. Tolderlund, 1971, Distribution and ecology of living planktonic Foraminifera in surface waters of the Atlantic and Indian Oceans, in: (Funnell, B., and Riedel, W., eds.) *The Micropaleontology of Oceans*, p. 105-149, Cambridge U. Press
- Berge, G., 1958, The primary production in the Norwegian Sea in June, 1954, measured by an adapted C-14 technique, in: *Reports of the International Council for the Exploration of the Sea*, 144: 79-91
- Berger, W., 1969, Ecologic patterns of living planktonic Foraminifera, *Deep Sea Research*, 16: 1-24
- , 1970, Planktonic Foraminifera: selective solution and the lysocline, *Mar. Geol.*, 8: 111-138

- , 1976, Biogenous deep-sea sediments: production, preservation and interpretation, In: (Riley, J., and Chester, R., eds.) Chemical Oceanography, 5: 265-388, Academic Press, London
- , and A. Soutar, 1967, Planktonic Foraminifera: field experiment on production rate, Science, 156 (3781): 1495-1497
- Bradshaw, J., 1959, Ecology of living planktonic Foraminifera in the North and Equatorial Pacific Ocean, Cushman Found., Foram. Res., Contr., 10(2): 25-64
- Chayes, F., 1971, Ratio Correlation, University of Chicago Press, Chicago, 99p.
- , 1975, Apriori and experimental approximation of simple ratio correlations, In: (McCammon, R., ed.), Concepts in Geostatistics, Springer-Verlag, New York, p. 106-137
- Cifelli, R., 1961, Globigerina incompta, a new species of pelagic Foraminifera from the North Atlantic, Cushman Found. Foram. Res. Contr. 12(3): 83-86
- , 1962, Some dynamic aspects of the distribution of planktonic Foraminifera in the western North Atlantic, J. Mar. Res., 20(5): 201-213
- , 1974, Planktonic Foraminifera from the Mediterranean and adjacent Atlantic waters (cruise 49 of the Atlantis II, 1969), J. of Foram. Res., 4(4): 171-183
- CLIMAP, Project members, 1976, The surface of the ice age Earth, Science, 191: 1131-1137
- Corlett, J., 1953, Net phytoplankton at ocean weather stations "I" and "J", Cons. Perm. Internat., Expl. Mer., Jour., 19(2): 178-190
- Emiliani, C., 1964, Paleotemperature analysis of the Caribbean cores A254-BR-C and CP-28, Geol. Soc. Amer. Bull., 75: 129-144
- Ericson, D., 1959, Coiling direction of Globigerina pachyderma as a climatic index, Science, 130 (3369): 219-220
- , and Wollin, G., 1956, Correlation of six cores from the equatorial Atlantic and the Caribbean, Deep-Sea Research, 3(2): 104-125
- , 1968, Pliocene climates and chronology in deep-sea sediments, Science, 162: 1227-1234
- , and M. Ewing, G. Wollin, B. Heezen, 1961, Atlantic deep-sea sediment cores, Geol. Soc. Amer. Bull., 72: 193-276
- , and M. Ewing, G. Wollin, 1964, the pleistocene epoch in deep-sea sediments, Science, 146: 723-732

- Herman, Y., 1971, Vertical and horizontal distribution of pteropods in Quaternary sequences, In: (Funnel, B., and Riedel, W., eds.), The micropaleontology of Oceans, p. 463-486, Cambridge University Press
- Holmes, R., 1956, The annual cycle of phytoplankton in the Labrador Sea, 1950-51, Bulletin of the Bingham Oceanographic Collection, 16:3-73
- Hutson, W., 1977, Variations in planktonic Foraminifera assemblages along North-South transects in the Indian Ocean, Marine Micropaleo., 2: 47-66
- Imbrie, J., and N. Kipp, 1971, A new micropaleontological method for quantitative paleoclimatology, application to a Late Pleistocene Caribbean core, In: (Turekian, K., ed.) The Late Cenozoic Glacial Ages: 71-181, Yale University Press
- Jenkins, D., 1967, Recent distribution, origin and coiling ratio changes in *Globorotalia pachyderma* (Ehrenberg), Micropaleontology 13(2): 195-203
- Jones, J., 1967, Significance of the distribution of planktonic Foraminifera in the Equatorial Atlantic undercurrent, Micropaleontology, 13(4): 489-501
- Kennett, J., 1968, Latitudinal variation in *Globigerina pachyderma* (Ehrenberg) in surface sediments of the South-West Pacific Ocean, Micropaleontology, 14(3): 305-318
- , 1976, Phenotypic variation in some recent and late Cenozoic planktonic Foraminifera, In: (Hedley, R., Adams, G., eds.), Foraminifera, vol. 2, p. 111-170
- , and N. Shackleton, 1975, Laurentide ice sheet melt water recorded in Gulf of Mexico deep sea cores, Science, 188: 147-150
- Kipp, N., 1976, New transfer function for estimating past surface conditions from sea-bed distribution of planktonic Foraminiferal assemblages in the North Atlantic, In: (Cline, R., and Hays, J., eds.) Investigation of Late Quaternary Paleoceanography and Paleoclimatology, p. 3-42, Geol. Soc. Amer. Mem. 145
- Koblentz-Mishke, O., Volkovinsky, V., and J. Kabanova, 1970, Plankton primary production of the world ocean, In: (ed. Wooster W.S.), Scientific Exploration of the South Pacific, National Academy of Sciences, Washington D.C., 257p.
- Kullenberg, B., 1952, On the salinity of the water contained in marine sediments, Medd. Oceanogr. Inst. Gotesborgs., 21: 1-38
- LaCombe, H., and P. Tchernia, 1971, Caracteres hydrologiques et circulation des eaux en Mediterranee, In: (Stanley, D., ed.) The Mediterranean Sea: A natural sedimentation laboratory, Dowden, Hutchinson and Ross, Inc., p. 25-36

- Lohman, H., Die Bevölkerung des Ozeans mit Plankton nach den Ergebnissen der Zentrifugenfänge während der Ausreise der Deutschland, 1911, Zugleich ein Beitrag Zur Biologie des Atlantischen Ozeans. Archiv. Biontol. Ges. Naturf. Freunde, Berlin, vol. 4(3): 1-617
- McGill, D., 1966, Fertility of the Oceans, In: (Fairbridge, R.), The Encyclopedia of Oceanography, p. 268-272, Van Nostrand Reinhold Co., 1021 p.
- Menzel, D., and J. Ryther, 1960, The annual cycle of primary production in the Sargasso sea off Bermuda Deep Sea Research, 6(4): 351-367
- Parker, F., 1958, Eastern Mediterranean Foraminifera, Rept. Swed. Deep Sea Exped., 8(4): 217-283
- , 1962, Planktonic Foraminiferal species in Pacific sediments, Micropaleont., 8(2): 219-254
- , and W. Berger, 1971, Faunal and solution patterns of planktonic Foraminifera in surface sediments of the South Pacific, Deep Sea Res., 18(1): 73-107
- Prell, W., and J. Damuth, 1978, The climate related diachronous disappearance of Pulleniatina obliquiloculata in late Quaternary sediments of the Atlantic and Caribbean, Marine Micropaleont., 3: 267-277
- Riley, G., 1942, The relationship of vertical turbulence and spring diatom flowerings, J. of Mar. Res., 5(1): 67-87
- , 1943, Physiological aspects of spring diatom flowerings, Bull. Bing. Oceanogr. Coll., 8(4): 1-53
- , 1946, Factors controlling Phytoplankton populations on Georges Bank, J. of Marine Res., 6(1): 54-73
- Ruddiman, W., 1971, Pleistocene sedimentation in the equatorial Atlantic-stratigraphy and faunal paleoclimatology, Geol. Soc. Amer. Bull., 82: 283-302
- Ryan, W., 1972, Stratigraphy of Late Quaternary sediments in the Eastern Mediterranean, In: (Stanley, D., ed.), The Mediterranean Sea: a natural sedimentation laboratory, p. 149-169, Dowden, Hutchinson and Ross, Inc., Stroudsburg, Pa.
- Ryther, J. and D. Menzel, 1960, The seasonal and geographic range of primary production in the western Sargasso Sea, Deep Sea Research, 6: 235-238
- Sankey, T., 1973, The formation of deep water in the Northwestern Mediterranean, In: (B. Warren, ed.) Progress in Oceanography pp. 159-180. Pergamon Press, New York

- Schott, W., 1935, Die Foraminiferen in dem äquatorialen Teil des Atlantischen Ozeans, Deutsch. Atlant. Exped. "Meteor", 1925-1927, Wiss. Ergebn., 3(3): 43-134
- Steele, J. and D. Menzel, 1962, Conditions for maximum primary production in the mixed layer, Deep Sea Res., 9: 39-49
- Stehli, F., 1965, Paleontologic technique for defining ancient ocean currents, Science, 148: 943-946
- Steeman-Nielsen, E., 1958, Light and the organic production in the sea, Reports of the International Council for the Exploration of the Sea, 144: 141-147
- Stommel, H., 1966, The Gulf Stream: A physical and dynamical description, 2nd ed., University of California Press, Berkeley and Los Angeles, 248p.
- Sverdrup, H., M. Johnson and R. Fleming, 1942, the Oceans, Prentice-Hall, 1087p.
- Thiede, J., 1971, Variations in coiling ratios of Holocene planktonic Foraminifera, Deep Sea Res., 18: 823-831
- Thunell, R., 1976, Calcium carbonate dissolution history in late Quaternary deep-sea sediments, western gulf of Mexico, Qt. Res., 6: 281-297
- , 1978, Distribution of recent planktonic Foraminifera in surface sediments of the Mediterranean Sea, Marine Micropaleo., 3: 147-173
- Todd, R., 1958, Foraminifera from western Mediterranean deep-sea cores, Swedish Deep-sea Exped. Rept., 8(3): 169-215
- Tolderlund, D., and A. Bé, 1971, Seasonal distribution of planktonic Foraminifera in the western North Atlantic, Micropaleont., 17(3): 297-329
- U.S. Naval Oceanographic Atlas of the North Atlantic Ocean, 1967, Section 2: Physical Properties, U.S. Naval Oceanographic Office, Washington, D.C.
- Vergnaud-Grazzini, C., 1974, Les Foraminifères planctoniques de mer Ligure, distribution saisonnière et caractéristiques thermiques, Union des Oceanographes de France, 6(1): 30-35
- , 1975, Seasonal distribution pattern of Foraminifera in the Mediterranean plankton, Rapp. Comm. int. Mer Médit., 23: 161-162
- Vincent, E., 1972, Oceanography and Late Quaternary Planktonic Foraminifera, southwestern Indian Ocean. unpubl. Ph.D. Thesis, University of Southern California, 353 p.

- Wüst, G., 1962, On the vertical circulation of the Mediterranean Sea, Journal of Geophysical Research, 66: 3261-3271
- Zobel, B., 1968, Phänotypische Varianten von Globigerina dutertrei Orbigny (Foram.), Ihre Bedeutung für die Stratigraphie in quartären Tiefsee-Sedimenten, Geol. Jahrb., 85: 97-122

TABLE 1 - SUMMARY OF SITES AND DATA USED IN THIS STUDY

FROM KIPP (1976):

Core	R*	I*	L*	Sum.* Sal.	Core	R	I	L	Sum. Sal.	Core	R	I	L	Sum. Sal.
A152-84	X	X		36.08	V7-68		X		34.43	V23-82		X		35.50
A153-154	X	X		37.27	V9-31	X			34.90	V23-83		X		35.56
A157-3		X		34.95	V10-80	X	X		36.43	V23-84				35.77
A164-13	X	X		36.26	V10-88	X	X		37.14	V23-96	X	X		36.81
A164-15	X			36.11	V10-89	X			37.15	V23-101	X			36.58
A164-16	X	X		36.13	V10-98	X	X		36.49	V23-105	X			36.49
A164-17	X	X		36.25	V12-4	X			37.15	V23-107	X			36.48
A164-23	X	X		36.07	V12-80	X			35.27	V24-8	X			36.20
A167-1		X		34.20	V12-99				33.00	V25-24	X			37.27
A167-12	X	X		36.25	V12-122	X			36.00	V25-46	X			35.74
A167-13	X			37.17	V14-4	X			36.25	V26-50	X			35.25
A167-18	X			36.30	V14-5	X			35.83	V26-51	X			35.32
A179-6	X			36.15	V16-20	X			36.45	V26-53	X			35.29
A179-13	X			36.52	V16-21	X			36.45	V27-10		X		33.00
A179-15	X			36.51	V16-23	X			35.95	V27-15	X	X		35.90
A179-20	X			36.43	V16-200	X			35.83	V27-16		X		35.75
A179-24	X	X		36.26	V16-205	X			36.29	V27-17		X	X	35.05
A180-13	X	X		36.36	V16-206	X			37.25	V27-20			X	34.46
A180-15	X	X		35.38	V16-209	X			37.09	V27-21			X	34.50
A180-20	X	X		36.72	V16-227			X	34.00	V27-22			X	34.19
A180-39	X	X		36.87	V17-1	X			36.47	V27-23			X	33.13
A180-69	X			35.27	V17-158	X	X		34.92	V27-24			X	34.96
A180-70	X			35.34	V17-162	X			37.25	V27-25			X	34.22
A180-72	X			35.40	V17-163	X			37.27	V27-28			X	34.52
A181-7	X			33.80	V17-164	X	X		37.20	V27-30			X	34.64
A181-9	X			36.25	V17-165	X	X		36.85	V27-32			X	34.84
KM1-41	X			36.47	V17-192			X	34.51	V27-33			X	35.06
R9-7		X	X	35.20	V17-196			X	34.08	V27-38			X	35.27
RC9-61	X			35.60	V18-16	X			36.25	V27-104			X	35.02
RC9-212		X		35.88	V18-21	X			36.05	V27-111		X		35.27

TABLE 1 (continued):

	<u>Core</u>	<u>R*</u>	<u>I*</u>	<u>L*</u>	<u>Sum.*</u> <u>Sal.</u>	<u>Core</u>	<u>R</u>	<u>I</u>	<u>L</u>	<u>Sum.</u> <u>Sal.</u>	<u>Core</u>	<u>R</u>	<u>I</u>	<u>L</u>	<u>Sum.</u> <u>Sal.</u>
	RC9-222		X		35.79	V18-373		X		34.95	V27-114		X		34.92
	RC9-225		X		35.41	V19-296				35.06	V27-122		X	X	35.68
	RC10-22	X			36.12	V19-308	X			37.25	V27-137	X	X		35.92
	RC10-49	X			36.15	V19-310	X	X		36.71	V27-143	X	X		36.20
	RC11-10	X			36.05	V20-7	X			34.26	V27-144	X	X	X	36.12
	RC11-11	X			36.10	V20-233	X			35.80	V27-162	X	X		36.75
	RC11-12	X			36.10	V20-234	X			35.37	V27-164	X	X		37.02
	RC11-13	X			36.00	V20-242	X			37.25	V27-167	X	X		37.27
	RC13-158	X			36.05	V20-253		X		34.95	V27-172	X	X		36.36
	RC13-196	X			34.70	V22-24	X			36.11	V27-178	X			35.47
	SP9-3		X		35.43	V22-26	X			35.50	V27-234	X			34.44
	SP10-5			X	35.19	V22-188	X			35.45	V27-250	X			35.26
	V2-9		X		34.05	V22-202		X		35.65	V27-266	X	X		36.60
	V3-128	X			36.50	V22-204	X			36.02	V28-25			X	--
	V4-8	X	X		36.50	V22-211	X			36.87	V28-28			X	--
	V4-12	X	X		36.41	V22-219	X			37.27	V28-29			X	--
	V4-32	X	X		36.66	V22-230	X	X		36.77	V28-30			X	--
	V5-1	X	X		36.33	V22-232	X	X		36.50	V28-34			X	34.96
	V5-31	X			36.39	V23-13	X	X		35.90	V28-36			X	--
	V5-40	X			36.40	V23-16			X	33.91	V28-41			X	--
	V6-5	X			34.66	V23-22			X	34.51	V29-167	X		X	35.37
	V7-13	X			36.02	V23-29			X	34.94	V29-170	X		X	36.68
	V7-42	X	X		36.14	V23-38			X	35.09	V29-176	X	X		36.20
	V7-53	X	X		36.38	V23-60			X	--	V29-177	X	X		36.15
	V7-67				36.36	V23-81		X		35.44	V29-178	X	X		36.06
	V29-179		X		35.95	V29-198				35.30	V29-211			X	--
	V29-180		X		35.57	V29-200				35.20	V29-214			X	--
	V29-183		X		35.57	V29-202				35.16	V29-215			X	--
	V29-184		X		35.57	V29-203		X		35.13	V29-220			X	35.10
	V29-189		X		35.51	V29-204				35.10	V29-222			X	35.20
	V29-190		X		35.52	V29-205		X		35.14	V29-223			X	35.07
	V29-193		X		35.36	V29-209			X	34.86					
	V29-194				35.30	V29-210			X	34.87					

TABLE 1 (continued):

* R = used in G. ruber regression model

I = used in *G. inflata* studies

L = used in Left-coiling *N. pachyderma* and *G. quinqueloba* studies.

Sum. Sal. = Summer salinity for surface waters above the site, as recorded in the U.S. Naval Oceanographic Atlas of the North Atlantic (1967), sites beyond the area coverage of this atlas have no values listed, but are unimportant to the work included in this study that uses the summer conditions.

WESTERN MEDITERRANEAN CORES - surface sediment samples

	O Lat. (N)		O Long.		Surf. T. Feb. Aug.		Surf. Sal. Feb. Aug.		% G. Ruber	% G. Inflata
V10-3	36	41.2	00	06.3W	14.1	24.4	37.20	36.90	15.0	35.0
V10-4	38	41.0	04	33.3E	13.7	24.9	37.25	37.30	25.5	25.5
V10-5	40	18.3	06	47.3E	13.2	24.0	37.50	37.75	18.2	10.9
V10-6	41	32.2	09	46.4E	13.1	23.8	38.00	38.10	12.1	1.0
V10-9	40	58.3	10	46.0E	13.2	24.1	38.00	37.95	20.4	4.9
V10-21	39	19.5	14	25.3E	14.0	25.6	37.90	38.00	39.1	16.2
V10-72	39	37.0	11	54.0E	13.8	25.1	37.90	38.10	42.9	9.1
V10-73	38	18.2	8	40.2E	14.0	25.1	37.50	37.70	25.8	15.7
V10-74	37	31.0	4	01.2E	14.0	24.6	37.10	36.90	23.3	32.9
V10-76	37	03.0	0	22.5E	13.5	24.4	37.20	37.00	11.5	44.9
V10-78	35	51.0	4	15.0W	14.6	22.6	36.60	36.30	14.9	25.9
V14-143	41	39.0	5	00.0E	12.8	22.9	37.95	38.10	2.1	6.7
RC9-197	41	57.7	6	57.8E	12.8	22.9	37.95	38.10	7.6	4.6
RC9-203	36	08.3	1	57.7W	14.4	23.8	37.00	36.80	13.3	34.5
TR173-1	40	13.0	12	14.0E	13.6	25.0	37.90	38.00	39.2	9.2
TR173-3	38	45.3	4	27.8E	13.7	24.9	37.30	37.30	21.2	28.7
TR173-4	38	12.6	4	42.2E	13.8	24.8	37.20	37.20	23.4	30.2
TR173-5	37	23.0	3	50.0E	14.2	24.4	37.00	36.85	21.8	20.2

TABLE 1 (continued:

Core	0° Lat. (N)		0° Long.		Surf. T.		Surf. Sal.		% G. Ruber	% G. Inflata
					Feb.	Aug.	Feb.	Aug.		
TR173-6	37	22.0	3	09.0E	13.9	24.4	36.90	36.80	14.1	39.9
TR173-7	36	56.0	2	25.0E	14.1	24.3	36.75	37.75	12.0	20.3
TR173-8	36	55.9	2	08.3E	14.1	24.3	36.80	37.75	19.8	--
TR173-9	38	00.0	1	44.0E	13.7	24.7	37.55	37.15	23.8	24.4
TR173-10	37	34.9	0	09.4E	13.8	24.5	37.50	37.10	21.0	25.2
TR173-11	37	19.0	0	08.0E	13.9	24.5	37.20	37.00	17.2	39.2
TR173-12	36	58.9	0	45.6E	13.5	24.4	37.10	36.75	9.5	54.0
TR173-13	36	30.0	0	24.0E	14.3	24.3	36.90	36.70	10.0	17.9
TR173-15	35	55.1	1	50.0W	14.5	23.8	36.75	36.60	8.9	39.6
TR173-16	36	10.1	1	51.4W	14.4	23.8	36.85	36.80	8.2	27.3
TR173-19	35	49.3	3	58.2W	14.7	23.0	36.50	36.40	9.4	29.5
TR173-14K	35	56.8	1	05.5W	14.4	24.0	36.70	36.70	7.1	37.5

CORES FROM THUNELL (1978, pers. comm.):

Core	Feb. T.	Feb. Sal.	% G. Ruber	% G. Inflata
TR171-7	14.1	37.00	19.0	28.0
TR171-8	14.1	37.25	20.0	19.0
TR171-9	14.0	37.40	28.0	18.0
TR171-10	13.8	37.60	25.0	11.0
TR171-11	14.2	37.70	28.0	19.0
TR171-12	14.2	37.70	23.0	17.0
TR171-13	14.1	37.65	20.0	31.0
TR171-14	14.2	37.65	26.0	23.0
V10-73	14.0	37.30	27.2	10.1

TABLE 1 (continued):W. MEDITERRANEAN CORE TOPS FROM TODD (1958) USED IN G. RUBER STUDY:

<u>Core</u>	<u>% G. Ruber</u>	<u>Feb. T.</u>	<u>Feb. Sal.</u>
02	15	14.4	36.75
06	8	14.4	36.75
08	11	14.4	36.80
07	17	14.4	36.80
018	3	12.8	37.80
211	5	14.4	36.70
205	42	13.6	38.00

TABLE 2
SITES USED FOR FIGURE 7(b)

<u>Figure No.</u>	<u>Site</u>	<u>LAT(N)</u>		<u>LONG.</u>	
		<u>o</u>	<u>'</u>	<u>o</u>	<u>'</u>
1	V27-21	54	03	46	52 W
2	V27-30	59	09	41	04 W
3	V23-16	46	00	45	03 W
4	V29-220	65	10	00	04 W
5	V28-41	67	41	00	14 E

QUANTITATIVE PALEOCEANOGRAPHY: DATA BASE LIMITATIONS
TO TEMPERATURE ESTIMATES

Paul Loubere and William Hutson

Department of Oceanography
Oregon State University
Corvallis, Oregon 97331

ABSTRACT:

Paleoecologic estimation equations, as developed by Imbrie and Kipp, are mathematical models designed to predict hydrographic parameters from relative abundances of fossil species in deep sea sediments. The equations are derived empirically from a modern data base. Therefore, they should not be applied to samples representing oceanographic conditions outside those found in the derivational data set. Such samples are called "no-analog" and may be difficult to recognize in fossil material. The effects of no-analog conditions have been tested on three planktonic Foraminifera oceanographic estimation equations from the North Atlantic and the Mediterranean Sea. The no-analog conditions used were (a) abundance no-analogs: where species in a sample occur in proportions greater than the maximum for those species in the source data of the equation (excess species percentages); and (b) ratio no-analogs: where the ratios of species abundances in a sample are not encompassed in the derivational data set. Both of these no-analogs can be created by post-depositional processes (i.e. dissolution) or by species response to ecologic conditions not represented in the equation source data. Both types of no-analogs can lead to large temperature estimation errors which may be indicated by the presence of species excess percentages, lowered communality or unusual mixes of factor loadings. However, the relationships among temperature estimate error, communality and the no-analogs are not simple and can be confused by the polynomial temperature regression model used.

It is shown that the completeness of sampling over the temperature range of paleo-ecological equation has significant effects on the equation's ability to properly evaluate non-source data samples. The error producing effect of non-temperature related ecologic responses in the fauna is demonstrated using Atlantic equations applied to Mediterranean samples and the recognition of these responses is discussed.

INTRODUCTION:

Hutson (1977) has reviewed the concept of no-analog samples in quantitative paleo-oceanography and discussed the no-analog problem using dissolution affected assemblages of planktonic Foraminifera as examples. This paper expands upon his work by examining the results of applying paleo-temperature transfer functions (as developed by Imbrie and Kipp, 1971) to surface sediment samples from geographic locations not represented in the transfer function's source data. These samples will be associated to oceanographic conditions not found in the transfer function calibration data and may be conveniently divided into two groups: (a) abundance no-analogs where species occur in abundances greater than those found for the species in any sample of the calibration data; and (b) ratio no-analogs where species relative abundance ratios do not follow trends established in the calibration data set ($d_i:d_j \not\approx c_i:c_j$, of Hutson, p. 359, op. cit.). Both these varieties of no-analogs may be encountered in downcore work or in applying a transfer function from one ocean to another (e.g. Thiede, 1978; Berger and Gardner, 1975). It is therefore important to examine how they will effect the transfer function. It will be useful to establish how sensitive a paleo-temperature equation can be to disturbance by no-analogs and to see if signs of the disturbance can be detected in the equation results. The factor model approach of Imbrie and Kipp (op. cit.) provides three outputs that may be of use in evaluating no-analogs, these are: the site factor

loadings, the site communality¹ and the temperature estimate. Each of these will be examined in relation to the two types of no-analog described above.

The North Atlantic and the Mediterranean Sea are adjacent oceans in open communication with one another that differ greatly in their oceanography (Sverdrup, Johnson and Fleming, 1942). They offer us an ideal opportunity to study the effects of no-analog conditions on paleo-ecologic prediction equations. We can take equations derived in one area, apply them to surface sediment assemblages of the other region and see how well they predict the area's present day hydrography. The equations and surface sediment data of Kipp (1976) for the North Atlantic and Thunell (1979) for the Mediterranean will be used below. In addition the Northeast Atlantic equation of Molina-Cruz and Thiede (1978) will be used to examine the effects of no-analogs in the Atlantic Ocean. Also, Thiede (1978) has used this paleo-ecologic transfer function to predict glacial age surface water temperatures for the western Mediterranean. Therefore, the equation should be included in our examination of no-analogs in the Atlantic and Mediterranean.

February surface water temperature alone will be considered as this is the variable best estimated by the Kipp study, which is the most geographically comprehensive of the paleo-ecological equations used here.

¹ The communality is a measure of the extent to which the composition of a sample may be accounted for by analysis into a given set of reference assemblages (Imbrie and Kipp, 1971).

ABUNDANCE NO-ANALOGS:

The effects of species over-abundances on the complicated model represented by a transfer function are not easily predicted. To illustrate this the paleo-ecologic equation derived for the N.E. Atlantic by Molina-Cruz and Thiede (1978) (hereafter shortened to M.C.T.) was applied to the N. Atlantic samples of Kipp (1976). The N.E. Atlantic data base was comprised of 84 samples. Of these 60 were taken from Kipp's (1976) work and all were located east of 41°W longitude. Figure 1(a) shows the M.C.T. predicted temperatures plotted against the observed values for the Kipp data. A considerable amount of the scatter resides in points with a communality less than 0.8, as can be seen from figure 1(b). There are 45 samples (25% of Kipp's 191 sites) in the lower communality group. Of these, 33 are listed by Kipp as showing moderate to severe dissolution. In the entire North Atlantic data set, 50 sites are given as showing signs of dissolution.

Many of the samples with a communality less than 0.8 contain one or several species whose abundances are greater than the maxima allowed in the M.C.T. equation. The relationships of species over-abundance, communality and temperature estimation error are shown in figure 2. The species over-abundance for the diagram was assessed by finding, for each site, the sum of the "excess" percentages for all species. Excess is defined as the percentage of individuals in a species that exceeds the maximum abundance of that species in the M.C.T. data set. Communality could easily be related to excess species percent as these parameters have a

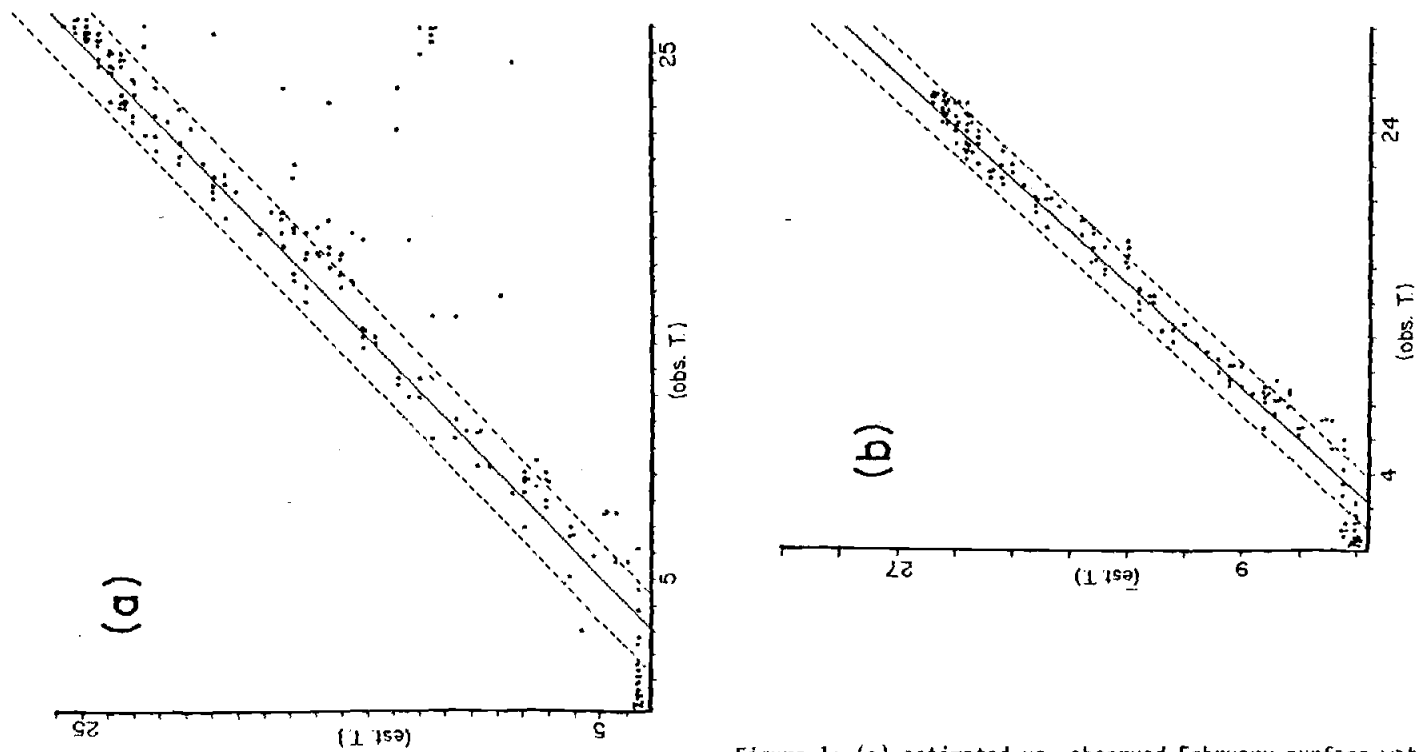


Figure 1: (a) estimated vs. observed February surface water temperature of Kipp sites using the M.C.T. estimation model (see text for explanation of model); (b) same data using only sites with a communality greater than 0.8

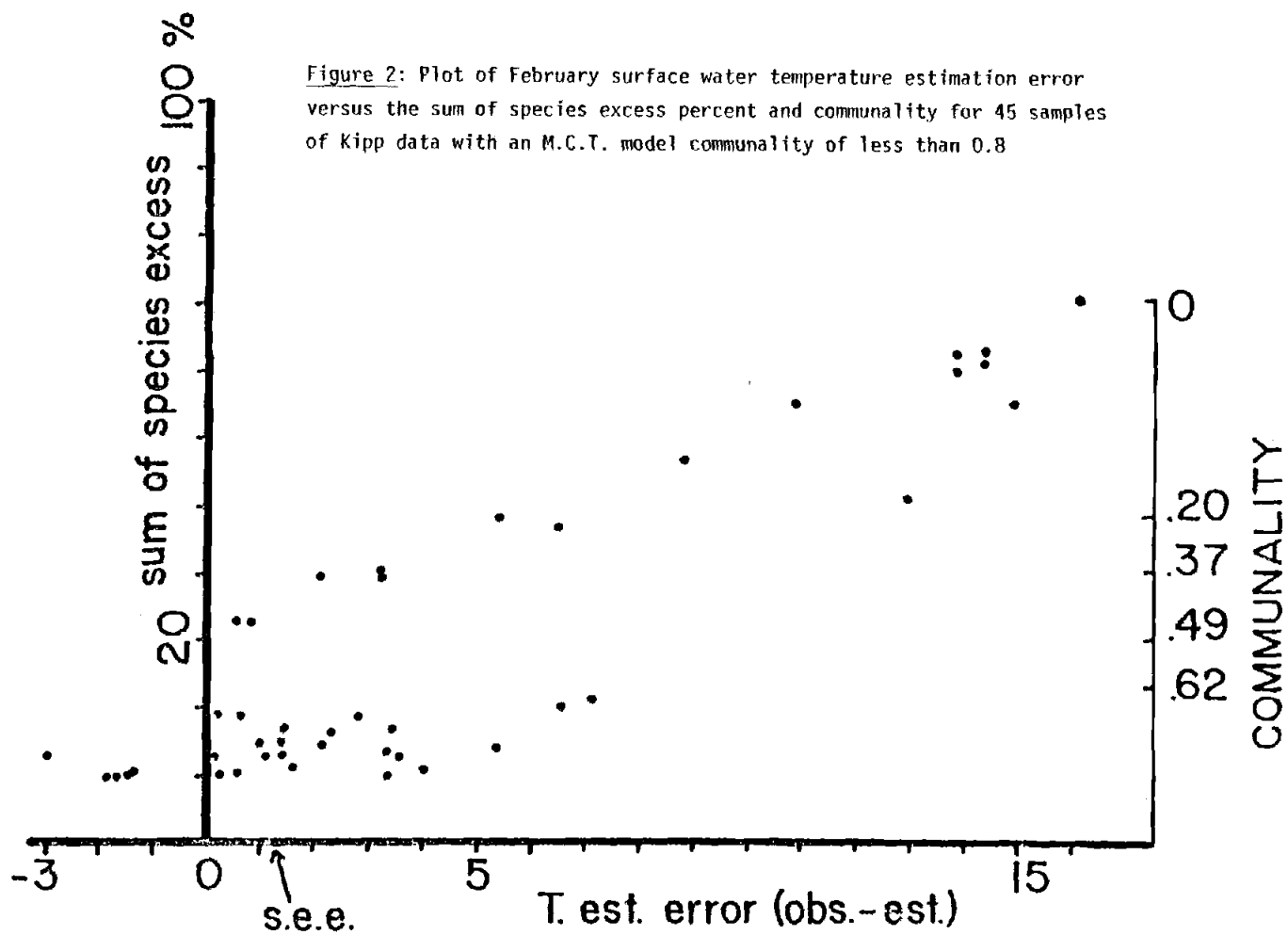
correlation of $-.96$ for this particular group of sites.

In general, one would expect that the temperature estimate error would increase as communality drops since a low communality would mean that all factor loadings would be small. As these loadings are the independent variables for the transfer function's temperature estimating regression equation, their diminishing values would drive temperature estimates to the regression intercept. This would lead to considerable error save at sites whose temperatures are near to the intercept value. For the M.C.T. equation this is 6°C .

It is also to be expected that communality would drop as the sum of excess species percents increases. Generally, this increase would tend to create assemblages with low values for all the species of importance to the factor model. This would lead to low factor loadings and low communality. Such a result is not inevitable, but is likely for a sample which contains significant excesses of species that are of small importance to a factor solution being applied to that sample. For the example being developed here we shall see that the sites in Kipp's data having the lowest communality in the M.C.T. factor space are those with important quantities of species that are rare in the M.C.T. source data.

The logical extension of the statements above is that the transfer function should increasingly under-estimate temperature as the sum of excess species percents increases.

Looking at figure 2, we see that this is generally true, but



relationships of sum of excess species percents, communality and temperature estimate error are not simple. The data show three groupings: (1) in which the sum of excess species percents is less than 12 and temperature estimate errors range from less than 0.3° to more than 7° ; (2) in which the sum of excess species percents is greater than 20 and the temperature estimate errors range from less than 0.6° to greater than 16° ; (3) in which temperatures are over-estimated inspite of lower communalities. The samples in question are presented in Table 1.

The first group is comprised of 23 samples of which fifteen are recorded as showing signs of moderate to severe dissolution. There is no pattern between species excess percents and temperature estimate error. Further, those species with excesses show only small (mostly less than 5%) over-abundances. Also, none of the over-abundant species in any of the samples is of major importance to the M.C.T. factor calculations. Hence, lowered communality is the result of species proportions being alien (a ratio no-analog) to the M.C.T. model. The unusual species proportions may be the result of dissolution in certain cases, but not in all of them and other, ecological, factors must be acting to cause the drops in communality. This will be discussed in detail below when we look at Mediterranean samples.

The degree of temperature estimation error within Group 1 is not related to dissolution, rather it appears to be due to instability in the M.C.T. temperature regression equation resulting from large coefficients (this problem is discussed in Hutson, 1977).

For instance, the two sites within the group with the largest temperature estimation error are not listed as having suffered significant dissolution. These sites, summarized in Table 2, serve as examples of the complex operation of a regression equation containing polynomial terms. In both cases it can be seen that the sums of both the positive and the negative terms are large compared to the intercept. Furthermore, two factors, the tropical and subtropical, dominate these sums. This situation makes the regression very sensitive to relatively small changes in the warmer temperature factor loadings. For our two examples, we have considerable perturbation of the regression model since the warmer factor loadings are somewhat lower than expected for the observed February temperature. The reason for the regression sensitivity can be seen in figure 3, showing a histogram of the number of samples used by Molina-Cruz and Thiede in their temperature regression plotted against the observed February temperature for each sample. It can be seen that the bulk of the data fall into the mid-temperature range with little representation of the temperature extremes. As the regression solution gave a relatively low intercept value, great weight had to be given to the higher temperature factors so that warmer sites could be correctly evaluated. This is the reason for the sensitivity to these factors. At the other extreme, it will be noted that in figure 1(b), showing temperature estimates of Kipp sites with M.C.T. communalities greater than 0.8, considerable error is found at very low temperatures. These are sites dominated by left coiling Neogloboquadrina

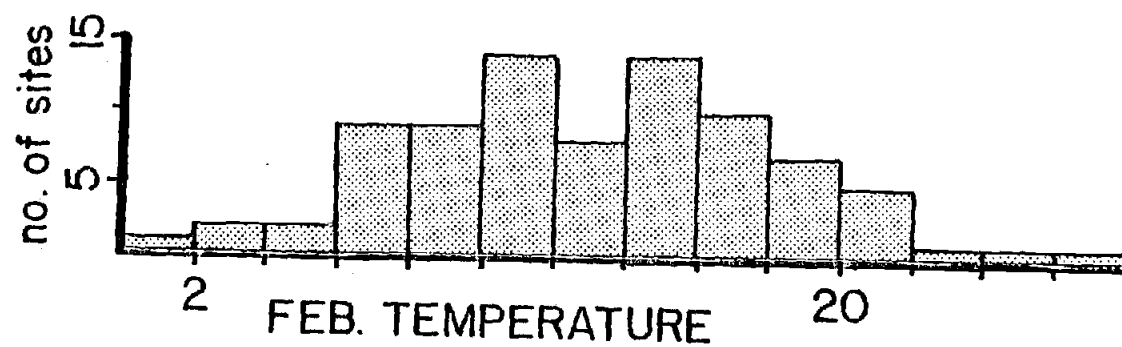


Figure 3: Number of sites per February temperature interval in the M.C.T. derivational data base

pachyderma (Ehrenberg) for which the M.C.T. study has only one example. The M.C.T. model cannot properly extrapolate beyond its lower temperature limit due to its limited source data. The ideal regression would have equal numbers of samples in each temperature interval and an intercept value near the median of the temperature range.

For Group 2, those samples with greater than 20% excess species percentages, we would have expected large temperature errors due to low factor loadings. For these samples, we may expect that low communalities are due to over-abundances of species unimportant to the M.C.T. factor model. This group is comprised of 16 sites all of which are listed as showing moderate to severe dissolution. All of them show significant quantities of some or all of the following species: Neogloboquadrina dutertrei (d'Orbigny), Globorotalia menardii (d'Orbigny), Pulleniatina obliquiloculata (Parker and Jones) and Globorotalia tumida (Brady). This group of species is dissolution resistant (Berger, 1968; Adelseck, 1978) and has been labelled by Kipp (1976) as a possible dissolution assemblage. Hence, the Group 2 sites probably represent the effects of chemical corrosion. However, it has been argued (Kullenberg, 1952 ; Ryan, 1972; Kennett and Shackleton, 1975; Thunell, 1976; 1978) that N. dutertrei is indicative of lowered salinities and that the ecological response of G. menardii (Emiliani, 1964; Prell and Damuth, 1978) is complex, being sensitive to other factors than temperature. If this is the case, then these samples also represent an environment not included in the M.C.T. study. It is important to differentiate dissolution from ecologic variation,

as the addition of dissolution marked samples to the M.C.T. (or any other) data set in the hopes of dealing with sites having low communality for ecological reasons would only lead to confusion.

The tremendous variability in temperature estimate errors for Group 2 sites can also be attributed to the sensitivity of the M.C.T. regression equation. In table 3, the two group 2 sites with the least temperature error are summarized and it is shown that regression sensitivity to the tropical factor loading is responsible for the unexpectedly high temperature estimates. Hence, we cannot assume a simple increase in temperature estimate error with decreasing communality. The response of the error to communality is complex and depends on the polynomial regression model used.

The Group 3 samples over-estimate temperatures inspite of lowered communality. These sites show only small or no species excess percentages, hence the problem lies in the relative proportions of species in the samples. More specifically, the lowered communality and the error in temperature estimation can be attributed to the fact that the M.C.T. study covers only part of the range of two dominant species with broad temperature ranges: Globigerina bulloides (d'Orbigny) and Globorotalia inflata (d'Orbigny). In the M.C.T. factor model these two species are used principally to define subtropical and Gulf Stream assemblages, while in the Kipp (1976) model they define sub-polar and transitional assemblages. The difference between the models is probably due to the limited M.C.T. sampling at lower temperature areas. This would lead to a model weighting of G. bulloides and G. inflata

to higher temperatures, hence the over-estimate of temperature when the M.C.T. equation is applied to samples from colder parts of the G. bulloides-G. inflata biogeographic zones.

The lowered communalities of Group 3 sites are due to a species proportion problem caused by the above species being found in the company of colder water fauna than expected by the M.C.T. model.

In summary, the application of the Molina-Cruz and Thiede temperature transfer function to the Kipp data set illustrates three important aspects of transfer functions and no-analogs: (1) increasing abundances of species that are rare in the model source data leads to decreasing communality, but (2) there is not a simple relationship between decreasing communality and temperature estimate error; (3) incomplete coverage of the temperature range of important species will lead to biased estimates when the temperature estimating function is applied to samples representing the part of the species range not sampled. However, lowered communality may serve as an indication of this problem, even when species excess percentages are not observed.

The possibility of non-temperature related ecological responses in species leading to temperature estimate errors has also been raised.

RATIO NO-ANALOGS:

The Mediterranean study of Thunell (1979) was used to further investigate the effects of ecology on transfer functions. It was anticipated that a marginal basin, such as the Mediterranean, would present some extreme conditions to the fauna and that non-temperature

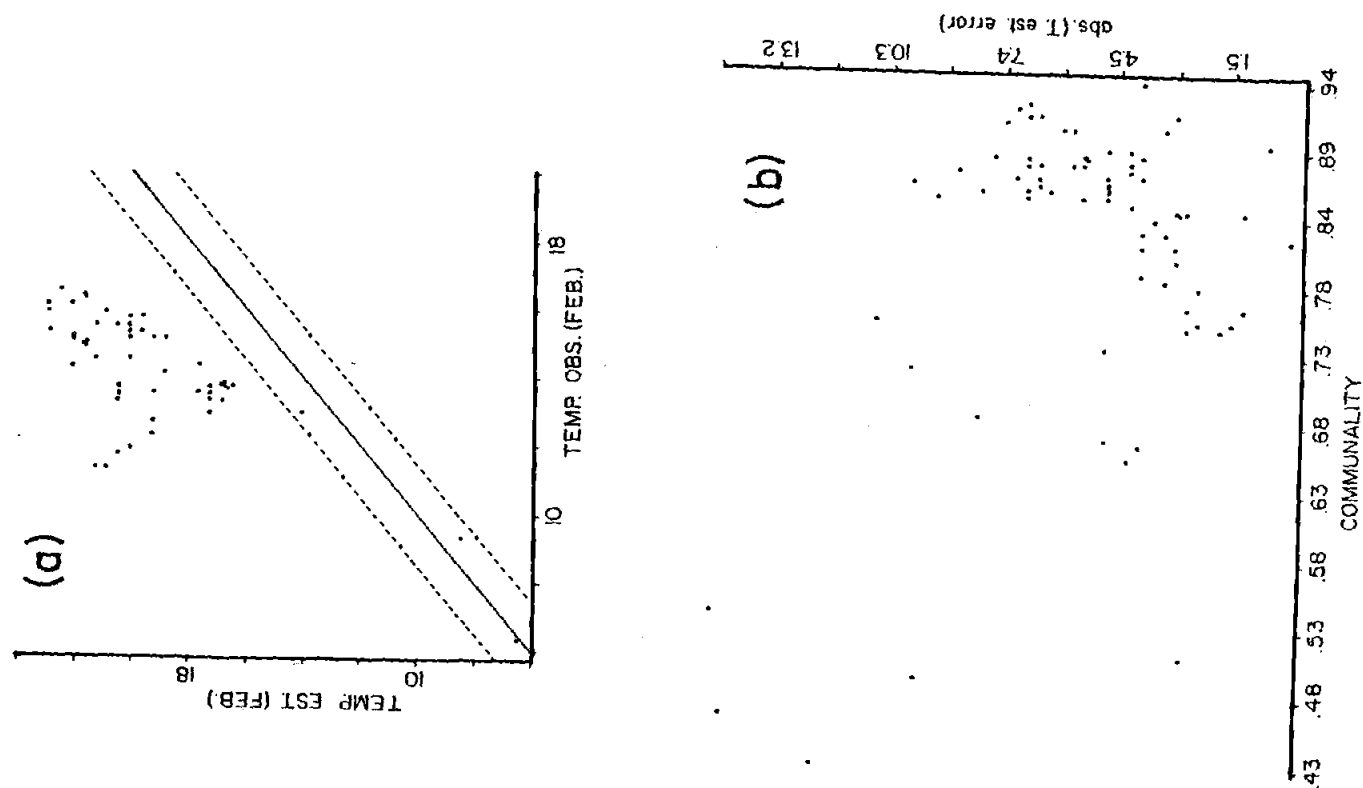


Figure 4: (a) February surface water temperature estimates versus observed values for Thunell data sites with a communality greater than 0.8 for the Kipp factor model. (b) communality versus the absolute value of the estimation error of Kipp factor model on all Mediterranean data.

related ecologic responses would be noticable. Further, carbonate preservation in the Mediterranean is generally excellent (frequent pteropod remains in surface sediments- Herman, 1972) so the effects of dissolution would be minimal.

The Thunell data is comprised of 74 trigger weight surface sediment samples. The Kipp (1976) February transfer function was applied to this data and 52 sites were found to have a communality of 0.8 or better. From the review of the Molina-Cruz-Thiede equation above, we may hope that these sites will give accurate temperature estimates (see fig. 1(b)). In fact, in figure 4, we find that the Kipp function increasingly overestimates temperature as the observed value for the samples goes up. Insert figure 4(b) shows that estimation errors can be considerable even when communalities are fairly high. The principal source for error appears to lie in the abundances of Globigerinoides ruber (d'Orbigny) of the white variety. This form is abundant in the Mediterranean (Parker, 1955; Thunell, 1978) representing winter temperatures much colder than expected for its Atlantic ocean distribution. We can see this by comparing the Kipp (1976) data set weighted mean specie's February temperature with that of the Thunell data. This weighted mean was calculated as:

$$\text{Feb. mean } T. = \frac{\sum_{i=1}^n (p_i * T_i)}{\sum_{i=1}^n p_i}$$

where: p = percent of G. ruber in a sample

T = February surface water temperature for that site

n = number of sites in the data set

Results:

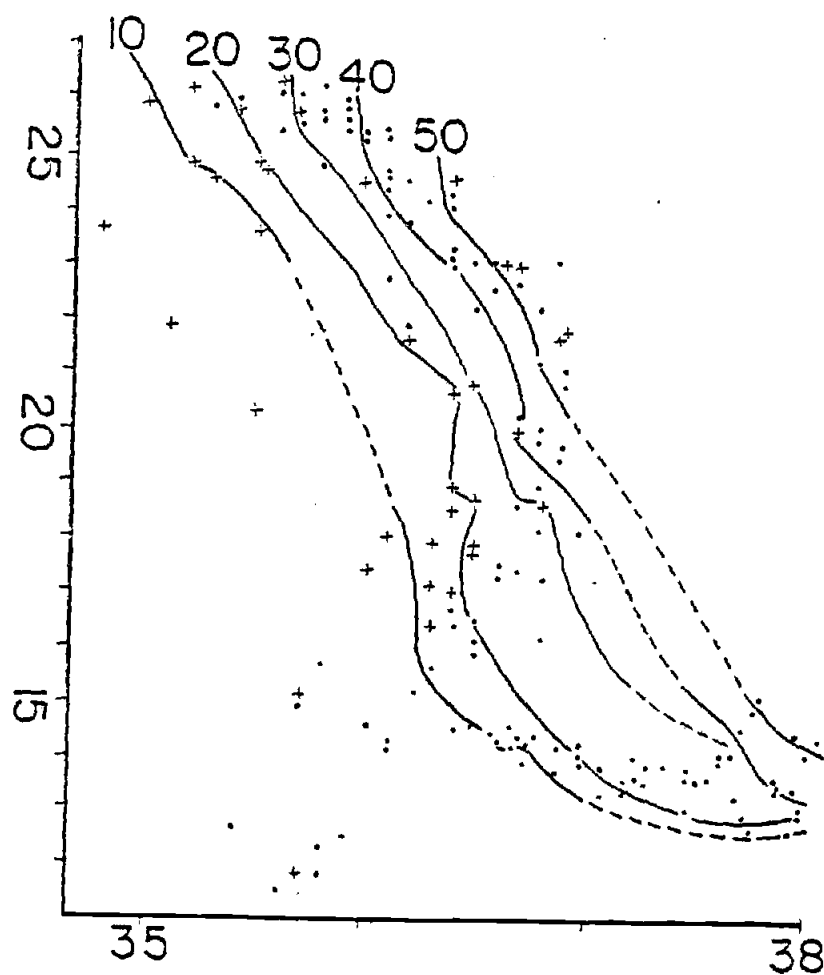
for the N. Atlantic; mean T. = 22.3°C

for the Mediterranean; mean T. = 14.4°C

Since G. ruber is given considerable weight in the Kipp solution as the dominant component of the tropical factor, its abundance in the Mediterranean leads to higher communalities and erroneously high temperature estimates. The reason for the important quantities of G. ruber in the Mediterranean may be found in figure 5, taken from Loubere (in prep.). This shows the percentage of white G. ruber in 139 surface sediment samples from the N. Atlantic and western Mediterranean plotted against the average surface water February temperatures and salinities above each sampling site. From the diagram it seems that this species shows a marked response to salinity or a salinity correlated factor (for the N. Atlantic, February T. and salinity show a polynomial regression r^2 of .91 on white G. ruber percent, Loubere, in prep.). Thus, salinity and temperature can act as the transfer function controlling parameters of Luz and Bernstein (1976, p. 319). As the Mediterranean is a high salinity basin, G. ruber is present in greater abundances than expected for equivalent temperature conditions in the N. Atlantic. Hence, the N. Atlantic transfer function was "fooled" into predicting overly high temperatures.

This sort of ecologic effect may not be indicated by species excess percentages (for the Mediterranean data relative to the Kipp study there are no excess percentages) and, as we have seen above,

FIGURE 5 - Percent white form *G. ruber* in N. Atlantic and western Mediterranean surface sediments plotted against mean February temperatures and salinity for surface waters directly above the sediment sampling sites. Temperature is the vertical axis, crosses mark samples showing moderate to severe dissolution.



communality may not be a good indicator of the problem either. This is because the Imbrie and Kipp (1971) factoring approach places great emphasis on numerically abundant species, hence the communality depends on these species and tends to be high when they are abundant. The Mediterranean problem, revealed above, may however be indicated by ratio no-analogs. This means that the proportions of species in a Mediterranean sample may be unusual when compared to the North Atlantic data set. For instance, if a salinity related factor allows G. ruber to appear abundantly in sediments beneath waters of intermediate temperatures we might expect to find it mixed with some accepted intermediate temperature fauna. This would be an unexpected situation in the N. Atlantic, but it is found in the Mediterranean, as shown in Table 4. Here two sites are examined in detail showing a factor mix of tropical and sub-polar elements, as can be seen in the species abundance data. Altogether, 14 of the 52 Thunell samples with reasonably high communalities showed distinct mixing of warm and cold fauna. This is also summarized in Table 4 as a composite sample. Hence, the factor loadings serve in some cases to indicate a ratio no-analog, and this should make us wary of temperature estimates derived from such data.

It is interesting to apply the Thunell transfer function to the Kipp data, as done in figure 6(a). The result shows the reverse trend to the above, as expected given the already discussed G. ruber problem. It is also interesting to note that the Molina-Cruz-Thiede

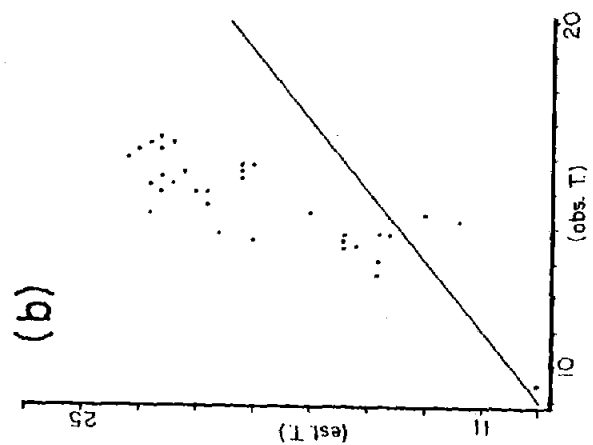
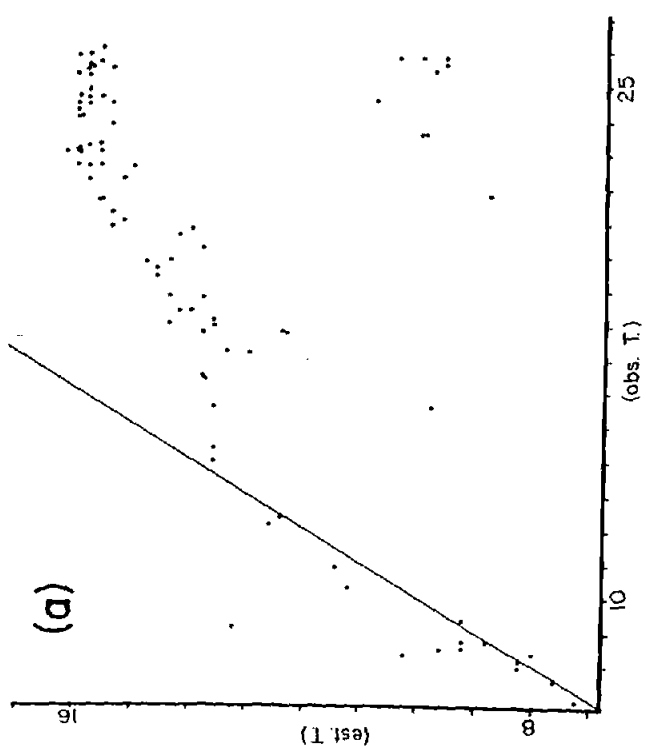


Figure 6: (a) Estimated versus the observed February surface water temperatures for Kipp data sites with a communality of greater than 0.8 for the Thunell factor model; (b) estimated versus the observed February temperatures for Thunell sites with a communality greater than 0.8 for the M.C.T. factor model

function is unsuccessful in the Mediterranean, see figure 6(b), inspite of the fact that it was geared towards nearer shore faunal assemblages (Molina-Cruz and Thiede, 1978).

A final point of interest is to compare the transfer function estimates of seasonality (winter-summer temperature difference) since this is important to nearer shore studies and a matter of controversy for the glacial age eastern Mediterranean (compare Thiede, 1978 with Thunell, 1979). The application of N. Atlantic transfer functions to the Mediterranean, and visa versa, is summarized below:

<u>Equation</u>	<u>Mean source data seas.</u>	<u>applied to*</u>	<u>Mean est. seas.</u>	<u>Mean obs. seas.</u>
Kipp	5.03	Medit. (52)	6.7	10.2
M.C.T.	5.44	Medit. (33)	4.8	10.0
Thunell	10.5	N. Atlant.(90)	9.58	4.5

* using only samples with a communality >0.8; no. of sites
in ()

It appears that the transfer functions simply predict the seasonality of their source data sets. This must bring into question the appropriateness of predicting temperatures for several seasons of the year, often highly correlated with one another, from the faunal data (which may really only represent one season, see Tolderlund and Bé, 1971) and it raises questions concerning the application of a transfer function to localities other than that where the function was originally generated.

CONCLUSIONS:

- (1) The error of estimation for a paleo-ecologic transfer function cannot be related in a simple way to communality. Communality is the indicator of how applicable a transfer function is to a sample.
- (2) The use of polynomial regression equations can lead to instability of temperature estimations, especially when the maximum and minimum temperature intervals in the derivational data base are represented by only a few samples.
- (3) Before a paleo-environmental transfer function can be generally applicable, the complete temperature range of the species it depends on must be represented in the function's derivational data base.
- (4) Paleo-ecological transfer functions cannot extrapolate beyond the ecological limits of the function's derivational data base. Calculations of site communality will not necessarily identify ecologic no-analogs, though "mixed" assemblage factor loadings may indicate their presence. A better measure of the applicability of a transfer function to a data set needs to be devised.
- (5) No-analogs generated by ecologic and physical post-depositional processes must be distinguished from one another before a paleo-ecological transfer function can be devised to overcome a no-analog problem.

REFERENCES:

- Adelseck, C., 1978, Dissolution of deep sea carbonate: preliminary calibration of preservational and morphologic aspects, *Deep Sea Research*, 25:1167-1185
- Berger, W., 1968, Planktonic Foraminifera: selective solution and paleoclimatic interpretation, *Deep Sea Research*, 15: 31-43
- , and J. Gardner, 1975, On the determination of Pleistocene temperatures from planktonic Foraminifera, *J. of Foram. Res.*, 5:102-113
- Emiliani, C., 1964, Paleotemperature analysis of the Caribbean cores A254-BR-C and CP-28, *Geol. Soc. Amer. Bull.*, 75: 129-144
- Herman, Y., 1972, Vertical and horizontal distribution of pteropods in Quaternary sequences, In: (Funnell, B. and W. Riedel, eds.), *The Micropaleontology of Oceans*, p. 463-486, Cambridge U. Press
- Hutson, W., 1977. Transfer functions under no-analog conditions: experiments with Indian Ocean planktonic Foraminifera, *Quaternary Research*, 8(3):355-367
- Imbrie, J., and Kipp, N., 1971, A new micropaleontological method for quantitative paleoclimatology, application to a late Pleistocene Caribbean core, In: (Turekian, K., ed.) *The Late Cenozoic Glacial Ages*, pp. 71-181, Yale University Press
- Kennett, J., and Shackleton, N., 1975, Laurentide ice sheet melt water recorded in Gulf of Mexico deep sea cores, *Science*, 188: 147-150
- Kipp, N., 1976, New transfer function for estimating past surface conditions from sea-bed distribution of planktonic Foraminiferal assemblages in the North Atlantic, In: (Cline, R., and J. Hays, eds.) *Investigation of Late Quaternary Paleoceanography and Paleoclimatology*, pp. 3-42, *Geol. Soc. Amer. Mem.* 145
- Kullenberg, B., 1952, On the salinity of the water contained in marine sediments, *Medd. Oceanogr. Inst. Gotesborgs*, 21: 1-38
- Luz, B. and M. Bernstein, 1976, Planktonic Foraminifera and quantitative paleoclimatology of the eastern Mediterranean, *Marine Micropaleontology*, 1: 307-323
- Molina-Cruz, A., and J. Thiede, 1978, The glacial eastern boundary current along the Atlantic Eurafrian continental margin, *Deep Sea Research*, 25: 337-356
- Parker, F., 1955, Distribution of planktonic Foraminifera in some Mediterranean sediments, *Papers in Mar. Biol. and Oceanogr.*, *Deep Sea Research suppl.*, 3: 204-211

REFERENCES (cont.)

- Prell, W., and J. Damuth, 1978, The climate related diachronous disappearance of Pulleniatina obliquiloculata in late Quaternary sediments of the Atlantic and Caribbean, Marine Micropaleontology, 3: 267-277
- Ryan, W., 1972, Stratigraphy of Late Quaternary sediments in the eastern Mediterranean, In: (Stanley, D., ed.) The Mediterranean Sea: a natural sedimentation laboratory, pp. 149-169, Dowden, Hutchinson and Ross, Inc., Stroudsburg, Pa.
- Sverdrup, H., M. Johnson and R. Fleming, 1942, The Oceans, Prentice-Hall, 1087 p.
- Thiede, J., 1978, A glacial Mediterranean, Nature, 276: 680-683
- Thunell, R., 1976, Calcium carbonate dissolution history in late Quaternary deep-sea sediments, western Gulf of Mexico, Quaternary Research, 6: 281-297
- , 1978, Distribution of recent planktonic Foraminifera in surface sediments of the Mediterranean sea, Marine Micropaleontology, 3: 147-173
- , 1979, Eastern Mediterranean Sea during the Last Glacial maximum; an 18,000-Years B.P. reconstruction, Quaternary Research, 11: 353-372
- Tolderlund, D., and A. Bé, 1971, Seasonal distribution of planktonic Foraminifera in the western North Atlantic, Micropaleontology, 17: 297-329

TABLE 1

Summary of Kipp sites having a communality of less than 0.8 in Molina-Cruz-Thiede factor space

<u>GROUP 1:</u> <u>CORE</u>	<u>Kipp</u> <u>ref. no.</u>	<u>Comm.</u>	<u>T. est.</u> <u>error[†]</u>	<u>Σ% species</u> <u>excess</u>	<u>obs. T.</u>
A167-18	14	.74	0.12	2.9	22.9
V12-99	75	.68	7.18	11.0	23.0
RC13-196	48*	.72	0.57	0.0	24.8
V25-46	149	.72	0.24	8.8	26.0
A164-13	4*	.70	3.45	6.5	20.6
V5-31	59	.79	0.24	0.0	18.2
V22-232	125	.67	1.41	4.3	18.1
V7-53	64*	.78	5.33	4.1	17.9
A167-1	10*	.63	4.00	0.9	15.0
V20-253	115*	.70	3.26	2.7	14.9
V18-373	101	.62	6.53	10.3	15.7
V7-42	63	.63	2.28	6.2	17.4
V7-68	66*	.71	1.13	3.2	12.7
V22-230	124*	.59	1.60	6.2	17.0
A180-13	24*	.75	3.58	2.9	17.8
V2-9	52*	.67	0.60	8.8	10.6
V23-29	131	.73	0.25	0.0	5.8
A164-15	6*	.75	2.79	8.8	18.7
A164-17	8*	.78	2.12	4.3	18.4
A179-24	22*	.74	1.04	4.9	18.6
V29-167	199*	.76	3.29	0.0	18.0
KM1-41	34*	.69	1.40	3.0	16.4
V7-13	62	.71	1.36	6.4	23.7

GROUP 2: sites with species excess greater than 20%

V18-16	99*	.19	5.48	38.0	25.7
RC11013	46*	.49	0.85	22.9	26.1
V20-235	113*	.02	14.34	60.9	25.9
V22-202	120*	.04	8.86	46.7	21.9
V17-158	88*	.14	3.25	31.2	20.3
V26-51	151*	.28	3.24	30.0	25.9
V26-52	152*	.02	14.90	55.1	25.7
A180-69	30*	.01	15.84	70.0	24.6
A180-70	31*	.03	13.79	59.8	25.9
V19-298	105*	.02	13.76	62.0	25.4
V12-80	74*	.31	2.1	28.7	25.1
V26-53	153*	.48	0.51	22.4	24.9
V27-250	190*	.03	12.94	40.8	24.9
V19-296	104*	.04	10.79	55.2	23.7
V27-234	187*	.11	6.23	36.2	23.7
V26-50	150*	.02	14.38	62.9	25.9

TABLE 1 (cont.)

GROUP 3: sites with comm. greater than .8 which over estimated T.

V23-22	130	.67	-1.57	15.1	5.1
V27-20	159	.78	-1.78	0.0	4.5
V27-21	160	.72	-2.93	3.5	3.1
V23-16	128	.70	-1.49	0.0	5.0
RC9-212	37*	.76	-1.68	0.0	10.3

*showing moderate to severe dissolution.

TABLE 2: Two group 1 sites (see table 1) with large temperature estimation error - showing the sensitivity of the regression equation to "warm" factor loadings

<u>Factor</u>	<u>site 75</u>	<u>site 101</u>	<u>Factor</u>	<u>coeff. of regress.</u>	<u>site 75</u>	<u>site 101</u>
1 Temperate	.3456*	.1965	2 x 44.839	=	<u>16.653</u>	<u>6.049</u>
2 Tropical	.3714	.1349	3 x 3 -2.930		-0.013	-0.035
3 Polar	-.0658	.1092	1 x 5 -12.629		-2.284	1.080
4 Subtrop.	.3758	.6041	1 x 4 9.238		1.199	1.097
5 Gulf Str.	.5233	-.4352	2 x 4 -16.599		<u>-2.317</u>	<u>-1.352</u>
			4 x 5 10.698		2.104	<u>-2.813</u>
			2 x 2 -27.394		<u>-3.779</u>	<u>-0.499</u>
			1 x 2 -13.658		-1.753	-0.362
			constant 6.008			
			$\Sigma(+)$ terms		19.957	8.225
			$\Sigma(-)$ terms		-10.145	-5.061
			T. estimate		15.82	9.17
			T. obs.		23.0	15.7

* Kipp sites in Molina-Cruz and Thiede factor space

TABLE 3 - Two group 2 sites (see table 1) with small temperature estimation errors - showing the sensitivity of the regression equation to "warm" factor loadings

<u>Factor</u>	<u>site 46</u>	<u>site 153</u>	<u>Factor</u>	<u>coeff. of regress.</u>	<u>site 46</u>	<u>site 153</u>
1 Temperate	-.0107*	.0301	2	x 44.839	= <u>30.769</u>	<u>30.509</u>
2 Tropical	.6862	.6804	3 x 3	-2.930	-0.001	-0.002
3 Polar	.0112	.0230	1 x 5	-12.629	0.006	-0.042
4 Subtrop.	-.1150	-.0890	1 x 4	9.238	0.011	-0.025
5 Gulf Str.	.0454	.1094	2 x 4	-16.599	1.310	1.005
			4 x 5	10.698	-0.056	-0.104
			2 x 2	-27.394	<u>-12.899</u>	<u>-12.682</u>
			1 x 2	-13.658	0.100	-0.279
			constant	6.008		
			$\Sigma(+)$ terms		32.1096	31.514
			$\Sigma(-)$ terms		-12.956	-13.134
			T. estimate		25.249	24.388
			T. obs.		26.1	24.9

* Kipp sites in Molina-Cruz and Thiede factor space

TABLE 4 - Mediterranean sites showing mixed assemblages in Kipp factor space

<u>Factor loading*</u>	<u>RC9-200</u>	<u>V10-022</u>	<u>composite of 14 samples</u>
Tropical	.6751	.7467	.5595
Subpolar	.3161	.4994	.4187
Polar	.0154	.0311	.0276
Gyre Marg.	-.0001	.0069	.0266
Transition	-.1807	.1618	-.0211
Subtrop.	.5588	.2760	.5403
Communal.	.9009	.9103	.8424
%G. ruber	29.6	30.0	
%G. inflata	21.1	1.6	
%G. bulloides	17.2	18.6	
%N. pachyder.	2.1	10.0	
%G. glutin.	3.5	11.9	
T. est. error (obs. - est.)	-3.58	-3.15	-3.38

* Thunell sites in Kipp factor space

The Western Mediterranean During the Last Glacial:
Solution to a No-Analog Problem

Paul Loubere
School of Oceanography
Oregon State University
Corvallis, Oregon 97331

ABSTRACT:

Assemblages of planktonic Foraminifera representing oceanographic conditions in the western Mediterranean during the last ice volume maximum (18,000 y.b.p.) are presented for two rapid sedimentation rate deep-sea cores, one from the northern and one from the western part of the basin. The locations permit monitoring of hydrography in the Alboran Sea, where exchange occurs with the Atlantic, and in the northern Balearic Sea, where the warm Mediterranean outflow to the world ocean is generated by a unique vertical mixing process. This latter makes a significant contribution to the heat budget of the global deep sea. Thus the assemblages reflect western Mediterranean oceanography and interaction with the Atlantic during the last ice age. Quantitative empirical paleoceanographic interpretation of the fauna is not possible because they occur in relative abundances not seen in the North Atlantic or Mediterranean of today. However, some more general deductions of paleohydrography are possible. The fauna indicate that the western Mediterranean was considerably colder 18,000 y.b.p. and highly seasonal (large annual thermal contrast), reflecting the seas' nearly land-locked position. Climate over the basin appears to have been quite variable over periods of less than 500 years. The fauna also indicate that the vertical stratification seen in the southwestern part of the study area, which is the product of warm, saline water injection from the eastern Mediterranean, was not present during the last ice age. This means that interchange

between the eastern and western Mediterranean systems was much altered during the glacial and that the character of the water returned to the Atlantic from the Mediterranean was quite different, probably colder, from the present. The deep world ocean would then have been lacking a significant heat source 18,000 y.b.p.

INTRODUCTION

The western Mediterranean exists at the junction of major oceanic and continental climatic systems (Butzer, 1960; British Air Ministry Office, 1962). Its present oceanography reflects this (LaCombe and Tchernia, 1972), and the intersection of oceanic and continental influences is well seen in the unusual vertical mixing zone developed in the northwestern part of the basin. The mixing zone controls the properties of the waters which the Mediterranean returns to the Atlantic (Wüst, 1961; MEDOC, 1970; Sankey, 1973). This water is important as it makes up about 10% of the heat budget of the deep world ocean (Gordon, 1972). The western Mediterranean also serves as the oceanic transition zone between the Atlantic and the Eastern Mediterranean. The late Quaternary quantitative paleo-oceanography of the latter has received much attention (Ryan, 1972; Vergnaud-Grazzini et al., 1977; Thunell et al., 1977; Thunell, 1979) but the same cannot be said for the western Mediterranean where little work has been done to establish how its water temperatures, structure and sources have changed with climate variations.

The Quaternary record of planktonic Foraminifera in deep sea cores of western Mediterranean has been extensively examined beginning with the survey studies of Phleger (1960), Parker (1955) and Todd (1958). Much work has been directed towards deriving paleo-climatic curves for individual or groups of cores (for example: Vergnaud-Grazzini and Bartolini, 1970; Herman, 1971; Blanc-Vernet et al., 1969; Rotschy et al., 1972; Blanc et al., 1976).

Questions of interest now are: (a) Can discrete fossil assemblages of western Mediterranean Foraminifera be interpreted paleoceanographically, if so, (b) what effect did the ice ages have on exchange of water between the basins of the Mediterranean and (c) what effect did the ice ages have on the Mediterranean as a heat supply to the deep world ocean?

The present work is directed towards defining and interpreting hydrographically the faunal assemblages representing the last glacial maximum (about 18,000 y.b.p.) from two high sedimentation rate cores taken from the north and western reaches of the western Mediterranean. Thiede (1978) presented an initial attempt at estimating paleotemperatures for the last glacial Mediterranean, but his study was somewhat hampered by faunal assemblages not well modelled into factor loadings by his paleo-ecologic transfer function. The research presented below is aimed at expanding on Thiede's work and deriving some general characteristics of western Mediterranean glacial age hydrography which can be used to answer the questions raised above.

The Cores Studied

The first core examined was TR173-16 [$36^{\circ}10.1'N$; $1^{\circ}51.4'W$; 1904 m. of water] taken in the central Alboran Sea (south of Spain) so as to be able to monitor in time the flow of water between the Atlantic and Mediterranean (see Figure 1). The core lithology is uniformly fine grained, uninterrupted by turbidites, and two carbon-14 dates show that its sedimentation rate is quite high. The second core is 35326 [$41^{\circ}24.8'N$; $5^{\circ}57.8'E$; 2480 m. of water] taken

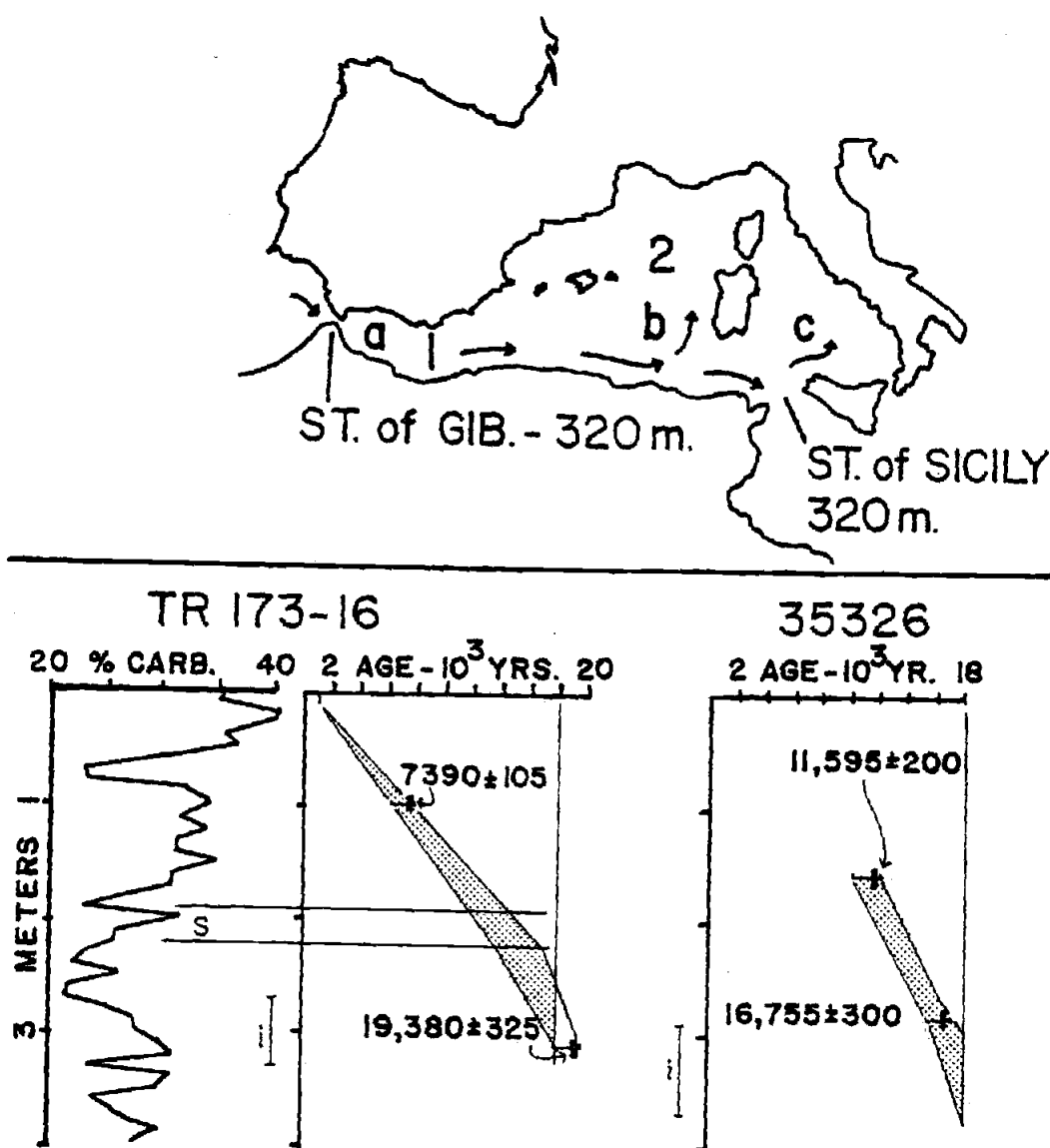


FIG. 1- TOP- core location in western Mediterranean, 1=TR176-16, 2=35326. Arrows show generally cyclonic surface circulation of present day. TR176-16 intervals dated: 92-107 cm., 305-320 cm. CARB = carbonate % in core, S = zone of pre-Holocene drop in carbonate content. Shaded area is zone of uncertainty for the age-depth curve of the core (see text). i = interval in which faunal counts were made to cover the intersection of the age-depth curve with the 18,000 Y.B.P. isochron. 35326 intervals dated: 150-165 cm., 275-290 cm. Shaded area and "i" as for TR176-16 (see text). For TOP diagram a = Alboran Sea, b = Balearic Sea, c = Tyrrhenian Sea.

in the northwest Mediterranean from the top of a salt dome for the purpose of monitoring in time the activities of the vertical mixing region in the western basin mentioned above. This core is also uniformly fine-grained and rapid in sedimentation rate (see Figure 1).

Dating the Cores

Eriksson and Olsson (1965) have shown that total carbon dating of Mediterranean sediments can lead to considerable errors in age determination. In this study, their recommendation has been followed and only the greater than 61 micron fraction was analyzed for carbon-14. This material consisted almost entirely of planktonic Foraminifera with lesser amounts of pteropod shell fragments, echinoderm remains and pelagic bivalves. About ten grams of carbonate were extracted for each of two samples per core (Figure 1) after the sediment had been repeatedly sieved and cleaned ultrasonically. Microscopic examination showed that a large part of the fine matter clinging to the fossil shells had been removed. Carbon-14 dating was done by Beta Analytic with the Benzene method and liquid scintillation counting (a description of the technique is available from Beta Analytic, University Branch, P.O. Box 248113, Coral Gables, Florida, 33124, U.S.A.). The levels analyzed and the C-14 ages are given in Figure 1. The probable non-analytical errors in this dating are summarized below for each core:

<u>Type of Error</u>	<u>TR173-16</u>	<u>35326</u>
10% contamination "dead" C.	-800 yrs	-800 yrs
water age, half life uncertainty	+300 yrs	+300 yrs
total interval to examine for		
18,000 y.b.p. sample	270 to 330 cm	290 to 370 cm

The contamination value is included above as it was impossible to completely remove all the fine material from the dated samples. Ten percent seemed to be a very generous estimate of the quantity of "dead", fine-grained, carbon possible in any of the samples. The influence of this on the age date was taken from Eriksson and Olsson (op. cit.), as was the water age and half-life uncertainty estimates.

Huang and Stanley's (1972) observations that surface sediments in the Alboran Sea have a C-14 age between 800 and 1000 y.b.p. and that carbonate concentration in Alboran Sea cores decreases as late Pleistocene sediment rate increases, were used to help interpolate an 18,000 y.b.p. level for TR173-16. An age-depth curve was established for the core, see figure 1, by drawing a line between the surface age (assumed constant to a depth of about 15 cm. due to bioturbation, Berger, 1976) and the error bounded first C-14 age estimate. This line was continued until a significant, late Pleistocene age, decrease in carbonate was observed in the core. Here the slope of the line was changed to connect it to the error bounded second C-14 date. The uncertainty limits of the age-depth curve are given by the error limits of the C-14 analyses. The most likely depth for the 18,000 y.b.p. level of core TR173-16 is taken to be the zone where the age-depth curve, and its error bounds, intersect the 18,000 y.b.p. isochron of figure 1.

In core 35326 an 18,000 y.b.p. level was found by linearly extrapolating from the two C-14 dates and their error limits. For all the C-14 ages error limits were found by combining analytical

and non-analytical (given above) error.

The Faunal Data

Samples 10 cm apart were taken from the interval containing the 18,000 y.b.p. material for each core [spacing is less than 500 years]. For each sample planktonic Foraminifera larger than 149 microns were extracted from about 7.5 cc of sediment by wet sieving. The sieve residue was split and the relative abundance of species determined as shown in Tables 1 and 2. The taxonomy used is that of the Kipp (1976) based on the work of Parker (1962) and Bé (1967, 1977). This allows a direct comparison of Mediterranean assemblages to the extensive CLIMAP (NOAA, 1976) data base and aids in the standardization of faunal data for global paleo-oceanographic studies. The category of pachyderma-dutertrei intergrade is somewhat subjective, but the author has endeavoured to follow the guidelines of Kipp (1976, p. 8-9). Photographs of representative species types for this study are shown in Figure 5. Five samples in the data base were re-split and recounted to see if the laboratory procedures and taxonomy were consistent and to see if sufficient numbers of individuals were being counted for reproducible results. As can be seen from the first to second count correlations on Tables 1 and 2, the numbers are adequate and the procedures acceptable.

The paleo-oceanographic interpretations of the samples used here will not be hampered by dissolution as they all contained frequent pteropod remains. This indicates good carbonate preservation.

Definition of Typical 18,000 y.b.p. Assemblages

It is interesting to note that the samples, for each core, are often significantly different one from the other (see correlations on Table 1 and 2). This suggests that important changes occurred in Mediterranean ice-age climate over periods of less than 500 years. Nevertheless, all the samples within a core have a basic similarity and a representation of the fundamental assemblage was found using principal components analysis of sample correlations. The numerical techniques used are those reviewed in Cooley and Lohnes (1971). Computations were performed with programs written by the author using the IMSL (1979) mathematical computer subroutine package.

The first principal component of each core accounts for a large part of the sample variance (Tables 1 and 2) and can be used to estimate a representative faunal assemblage. The component was found, for each core, using standard techniques therefore it had a mean of zero and a variance equal to the first eigenvalue. To find the assemblage estimate this component must be transformed so as to have a mean and standard deviation comparable to the faunal percentage data. This was done by regressing (least squares) the component against the sample to which it is best correlated. The regression predicted values offer a good estimate (due to the generally very high sample correlations to the component) of the fundamental 18,000 y.b.p. Foraminiferal assemblage. This is what is listed as P.C. 1 on Tables 1 and 2; it should be noted that since only a linear regression was used, the correlations of P.C. 1 to

the samples were not altered by the transformation. These assemblage estimates represent the faunal associations that must be interpreted if we are to understand western Mediterranean glacial oceanography.

The Last Glacial Age at Core TR173-16

Listed next to the P.C. 1 assemblage estimate on Table 1 is the surface sediment (representing modern conditions) Foraminifera abundances. As can be seen, the glacial age and recent fauna have little in common. This indicates that considerable oceanographic change has occurred along the western Mediterranean margin of Africa over the last 18,000 years. The glacial sample is nearly completely dominated by only four species categories of which Neogloboquadrina pachyderma (Ehrenberg) and its intergrade are most important. We can begin to examine the glacial paleo-oceanography of core TR173-16 by applying the paleo-temperature estimating transfer functions of Kipp (1976) and Molina-Cruz and Thiede (1978) to the ice age fauna. This follows Thiede's (1978) suggestion that functions based on the wide range of oceanographic conditions in the Atlantic can interpret the 18,000 y.b.p. Mediterranean hydrography. Figure 2a presents the computed communalities and temperature estimates. The communalities¹ are not very satisfactory as both Hutson (1977) and Loubere (paper 2, this thesis) have shown that values less than 0.8 can indicate significant temperature estimate error. This

¹The communality is a measure of the extent to which the composition of a sample may be accounted for by analysis into a given set of reference assemblages (Imbrie and Kipp, 1971).

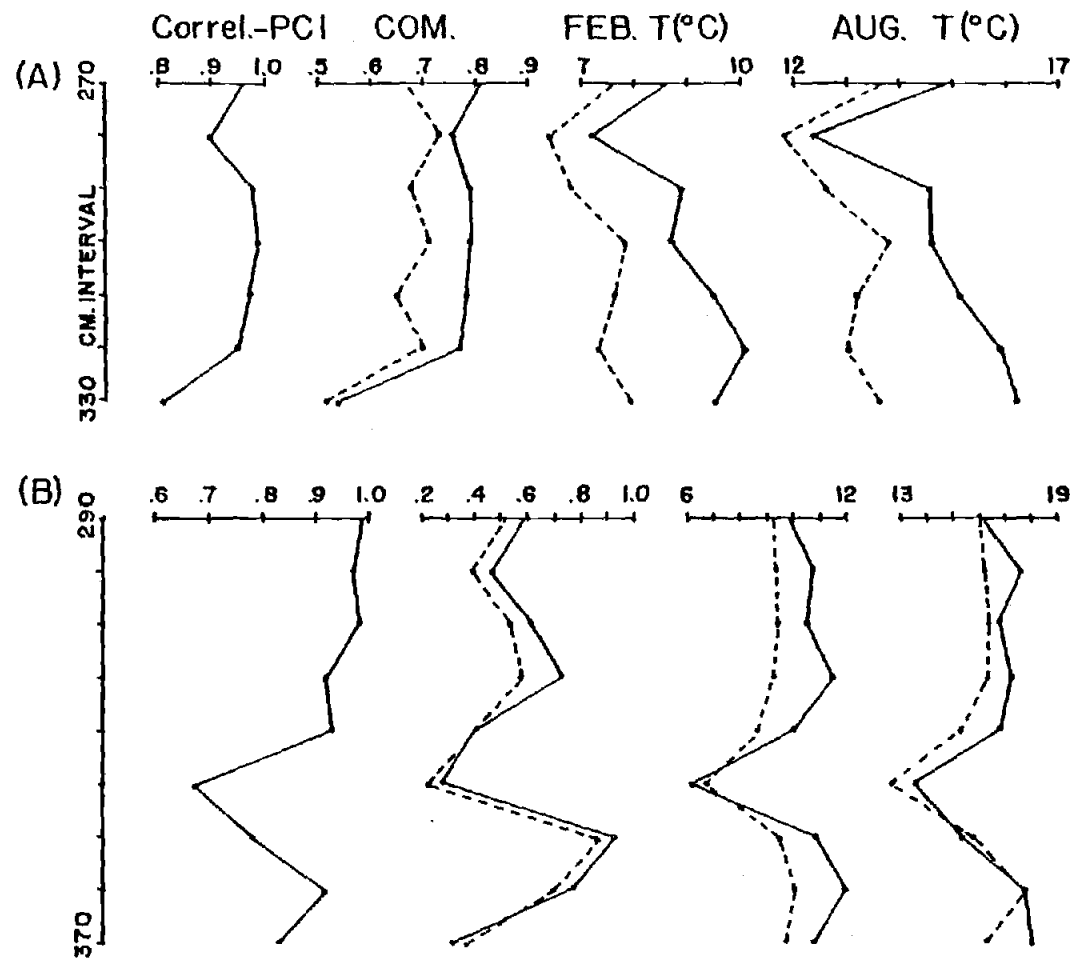


FIGURE 2: (A) correlation of TR173-16 counts to the first principal component of sample correlations. Also shown are the communality (COM), estimated February and August surface water temperature estimates for the counts using Kipp's (1976, solid line) and Molina-Cruz and Thiede (1978, dashed line) pole-to-temperature transfer functions.
(B) same information in the same order for core 35326

problem indicates that there is something unusual about the relative abundances of species in the 18,000 y.b.p. interval.

Using the P.C. 1 assemblage as a guide line it is possible to define the unusual features of the abundances. Loubere (1st paper - this thesis) has shown that the right coiling N. pachyderma form used by Kipp (1976) is a good temperature indicator, unaffected by other oceanographic parameters. Figure 3a shows a mean surface water February temperature-salinity diagram for samples in the North Atlantic and Mediterranean on which the sediment surface percent of dextral N. pachyderma has been plotted using conditions in surface waters directly above the sampling sites as plotting coordinates. The diagram is discussed in detail by Loubere (op. cit.). It shows that right coiling N. pachyderma abundances are greater than 20% for February temperatures between 13 and 7°C. Figures 3(b) and (c) show similar T/S plots (also reviewed in detail by Loubere (op. cit.)) for Globigerina bulloides (d'Orbigny) and the P.D. intergrade. These indicate that abundances of greater than 20% P.D. intergrade and less than 20% G. bulloides are to be found at temperatures greater than 9°C. Figure 3(d) shows a major problem exists in the abundance of Globorotalia inflata (d'Orbigny). For temperatures between 9 and 13°C we would expect to find more than 10% of this species. Indeed, Kipp's (1976) species biogeographic maps show that G. inflata and right coiling N. pachyderma overlap considerably in their distribution. Yet, the former species is nearly absent in the TR173-16 18,000 y.b.p. samples. Loubere (op. cit.) has reviewed the North Atlantic

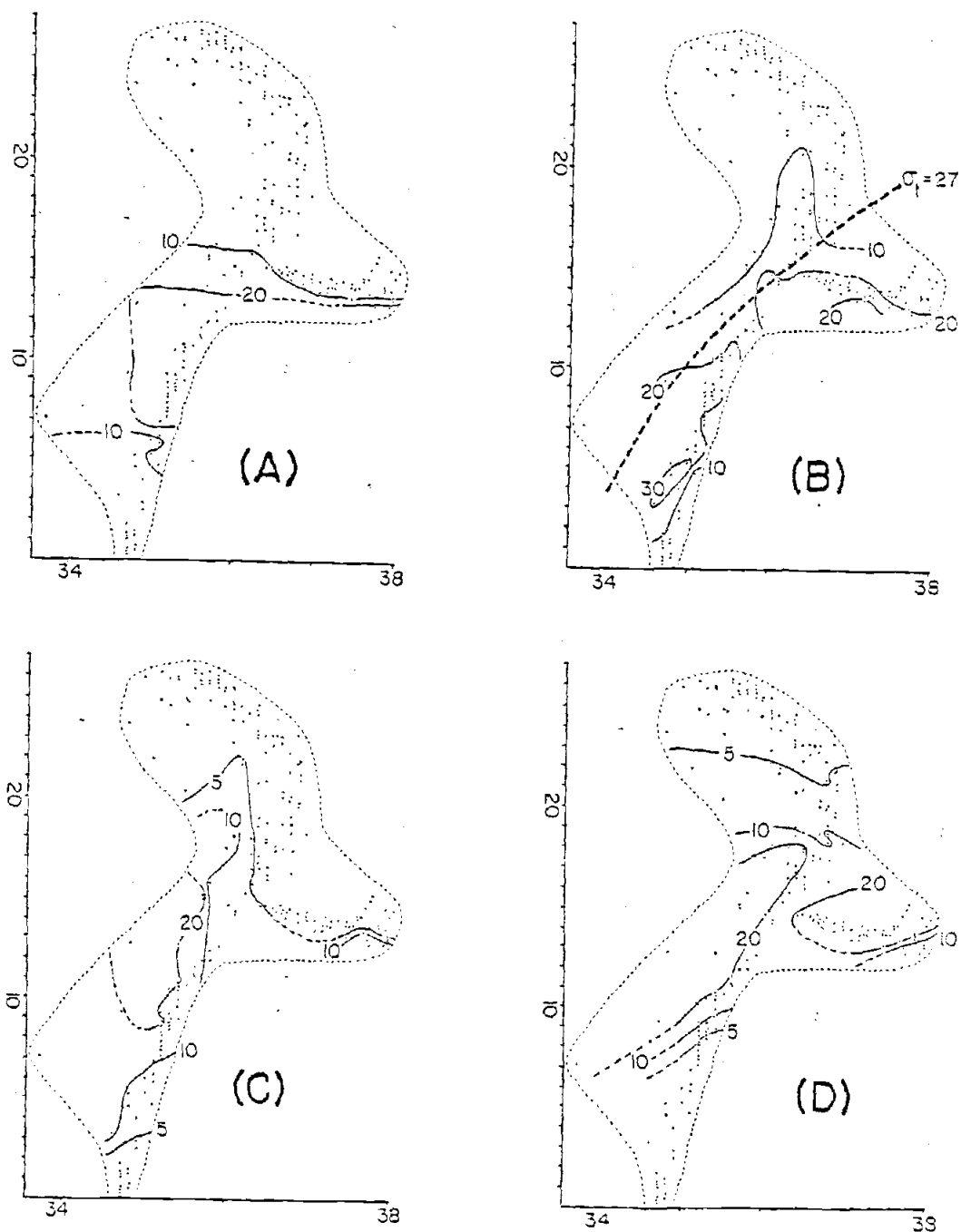


FIGURE 3: Species percent in surface sediments from the Atlantic and Mediterranean plotted against mean February temperature and salinity for surface waters directly above the sampling site. A = right coiling *N. pachyderma* as defined by Kipp (1976), B = *G. bulloides* (*G. falconensis* excluded), C = *P.D.* intergrade, D = *G. inflata*. Diagrams explained in Loubere (1980, paper 1 this thesis). Temp. (°C) on vertical axis, salinity (‰) on horizontal axis.

and Mediterranean G. inflata distribution and observed that the species was most abundant beneath the year-round stratified waters of the Gulf Stream and the Alboran Sea [south of Spain]. This point can be amplified for the Mediterranean. LaCombe and Tchernia (1972) describe the Alboran Sea as permanently stratified due to the sharp difference in characteristics between mid-depth Levantine water (250-500 m) and the surface water entering from the Atlantic Ocean. In the Northwest Mediterranean however, vertical stratification is seasonal, with vertical mixing occurring during the winter (Wüst, 1961; Sankey, 1973) and stability present only during the summer. The difference between the Alboran Sea and the northwestern region is summarized in Figure 4 showing monthly average density profiles for these two areas as presented in the U.S. Naval Oceanographic Atlas (1967). Vergnaud-Grazzini (1974) presents data showing that the most important production of Foraminifera in the western Mediterranean occurs in the colder months of the year (times of high phytoplankton production). Hence, during the production period, the Alboran Sea is stratified while the northwestern Mediterranean is not. This difference is reflected in G. inflata abundances in the sediments for the western Mediterranean, as shown in Thunell (1978) and Figure 4. The species is very abundant in the Alboran Sea, but infrequent in the sediments of the northwestern basin. The difference is not attributable to temperature as there is only a small gradient in winter (about 2°C - see U.S. Naval Oceanographic Atlas, 1967), also the salinity gradient in the western basin is not likely to explain the faunal distribution as Loubere (1st paper,

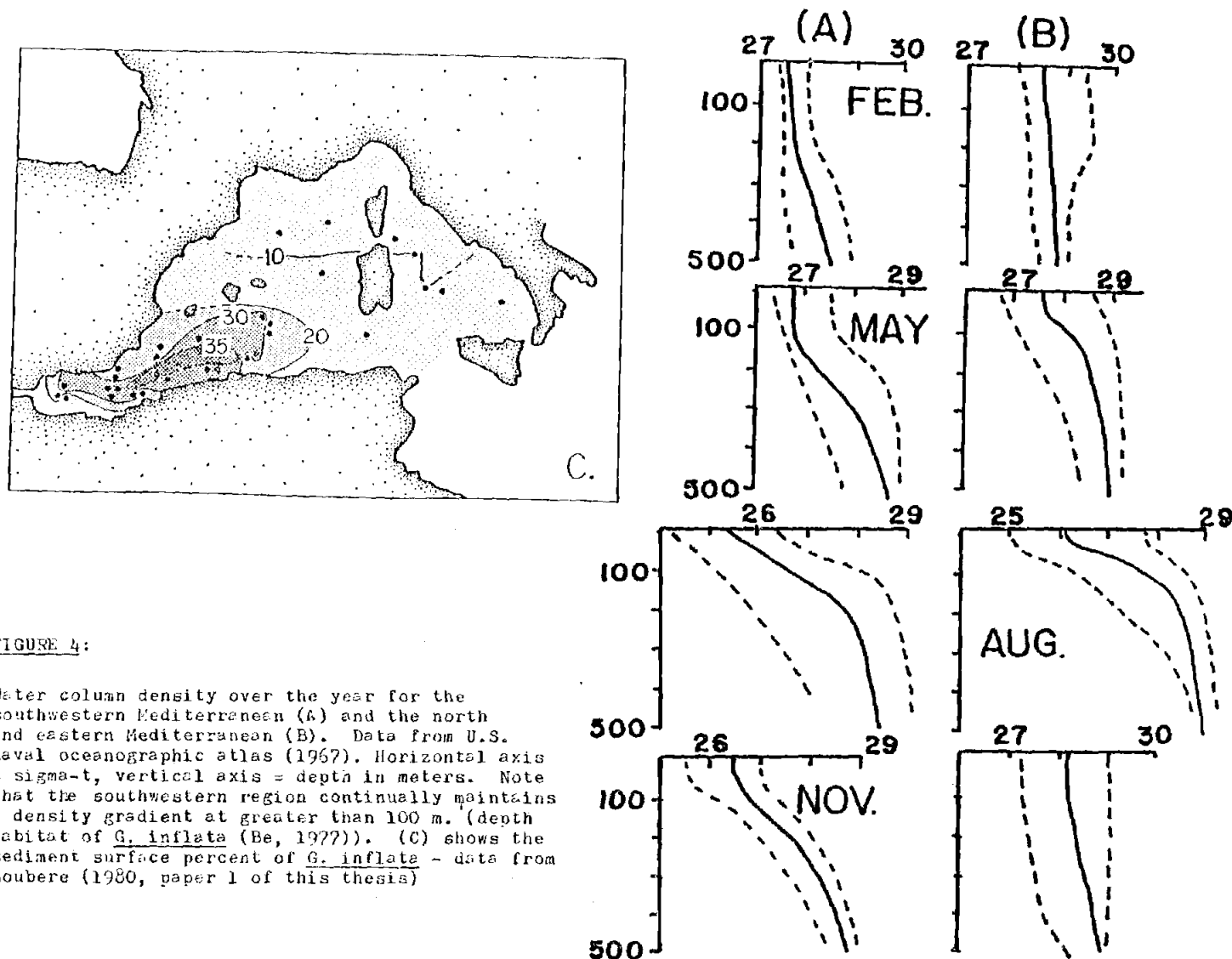


FIGURE 4:

Water column density over the year for the southwestern Mediterranean (A) and the north and eastern Mediterranean (B). Data from U.S. naval oceanographic atlas (1967). Horizontal axis = sigma-t, vertical axis = depth in meters. Note that the southwestern region continually maintains a density gradient at greater than 100 m. (depth habitat of *G. inflata* (Be, 1977)). (C) shows the sediment surface percent of *G. inflata* - data from Loubere (1980, paper 1 of this thesis)

this thesis) has shown that G. inflata does not respond to oceanic salinity changes. It seems plausible that G. inflata, being a mesopelagic species (Bé and Tolderlund, 1971; Bé, 1977), uses the density gradient to position itself in the water column. Without a gradient the species might get carried by vertical mixing into regions of the water column where there is no food, conditions are otherwise unacceptable or its population is so dispersed that reproduction is difficult.

The above discussion strongly suggests that the absence of G. inflata in the TR173-16 glacial age samples represents a lack of upper water column stratification during the productive times of the year in the Alboran Sea of 18,000 y.b.p. This indicates a major change in the water column structure of the western Mediterranean during the ice age.

The winter 18,000 y.b.p. paleo-temperature represented by the TR173-16 assemblage is probably not more than 10°C as Loubere (1st paper of this thesis, Figure 8c) has shown that Globigerina guinqueloba (Natland) is not abundant in sediments beneath warmer waters. The samples being discussed here have considerable quantities of this species. Thus, there was about a 4°C change between the last ice age and the present. It is important that there are also significant amounts of warmer water species such as Globigerina falconensis (Blow) and Neogloboquadrina dutertrei (d'Orbigny) to be found in the samples. This suggests a high seasonality with part of the productive season spanning to warmer times of the year. One would expect this for a land enclosed sea like the Mediterranean and it

is seen during the present. High seasonality is also indicated by the high abundance of P.D. intergrade in the TR173-16 samples. The intergrade seems to reflect conditions not ideal for the end-member species (Zobel, 1968; Bé and Tolderland, 1971; and Loubere, paper 1, this thesis) which could result from rapid water temperature changes during the productive season.

The Glacial Age at Core 35326

Table 2 presents the 18,000 y.b.p. fundamental assemblage (P.C. 1) for core 35326 and it can readily be seen that it is unusual compared to surface sediment Mediterranean and North Atlantic Assemblages (Todd, 1958; Parker, 1955; Thunell, 1978; Kipp, 1976). This is evident from the application of the Kipp (op. cit.) and Molina-Cruz and Thiede (1978) paleo-temperature equations to the samples, as shown in Figure 2(b). The communalities are generally poor and quite variable. In only one case (350 cm) is there a good communality but the sample shows significant loadings to cold and warm water factors simultaneously (.73 subpolar, .43-transitional, .42 subtropical for Kipp; .54 temperate, .48 subtropical, .59 Gulf stream for Molina-Cruz and Thiede). Loubere (paper 2, this thesis) has demonstrated that this situation can indicate a no-analog sample and large temperature estimate errors.

Generally, the 35326 glacial age samples are dominated by species whose ecology is not well understood or are not strictly associated to temperature limitations, indicating unusual oceanographic conditions. A reasonable initial premise we may use is that, since it

is surrounded by glacial age tundra (Frenzel, 1968; Bonatti, 1966; van der Hammen et al., 1971) the water in the northwestern Mediterranean should be colder than that in the Alboran sea, as represented by core TR173-16. Figure 3a shows that the February surface water temperature must then be less than 6°C for there to be less than 10% right coiling N. pachyderma in the assemblage. Figure 3b shows that this temperature range can accomodate the required percentage of G. bulloides, but raises some important questions concerning several other species in the 35326 data. Most notably, at such low temperatures, North Atlantic data (Kipp, 1976) indicates we should see at least 20% left coiling N. pachyderma (see Loubere, first paper, this thesis; e.g. Figure 7a). It is the absence of this pachyderma phenotype that leads to the low communalities in the Kipp and Molina-Cruz and Thiede factorings of core 35326 fauna. Both factor models are heavily weighted to the left coiling pachyderma form. Another problem is raised by the presence, in noticable quantities, of such warm and temperate water species as G. falconensis, Globorotalia scitula (Brady) and Globigerinoides ruber (d'Orbigny).

The above conflicting evidence can be reconciled using a model of a vertically unstratified upper water column that is highly seasonal (sees a large thermal contrast) and has an irregular, warmer season period of biological production.

It has been noted (Tolderlund and Bé, 1971; Bé and Tolderlund, 1971; Loubere, paper one, this thesis), that G. bulloides responds

well to increased phytoplankton production. For instance, the species is often a major element in upwelling zone faunas. Loubere (op. cit.) has shown that G. quinqueloba also seems to respond to increased production. So these species are less constrained by temperature and more by food availability. This idea agrees well with the observation that both species are among the fauna that occur in near-shore, highly seasonal but productive, waters (Boltovskoy and Wright, 1976; p. 171-172). Further, Globiginita glutinata (Egger) is well known for its eurythermy (Bé and Tolderlund, 1971; Loubere, paper one, this thesis; Figure 6d) and is abundant in 35326 samples. Hence, three of the four important species we must account for are likely to be able to thrive in a quite variable oceanic environment. Left coiling N. pachyderma on the other hand has been shown by Loubere (op. cit.) to be sensitive to seasonality, with species abundance decreasing as thermal contrast increases. This suggests that the period of major production was not in the winter or early spring for the glacial age western Mediterranean but was later in the year, as it is in the subpolar or polar regions of the north Atlantic today (McGill, 1966; Holmes, 1956; Berge, 1958). Thus, a high seasonality and a late production season would lead to a very short period of time when left coiling N. pachyderma was able to produce significant test material. A warmer season production period and high seasonality would also explain the unexpected presence of the warmer water species.

One difficulty with the above model is that a production period in moderate temperature waters should include considerable numbers

of G. inflata (see Figure 3d). Again the absence of this species may be attributed to the lack of permanent water stability and the presence of vertical mixing. Such a situation would enhance biological production and encourage G. bulloides and G. quinqueloba population growth. In relation to this, it is interesting to note that Kipp (1976) shows G. scitula as having a maximum in sediment distribution in the N.E. Atlantic, where the water column is only stratified in the summer (see the U.S. Naval Oceanography Atlas, 1967, p. 132-212) as compared to the adjacent permanent central water mass and continually stratified Gulf Stream (Stommel, 1966). G. scitula is abundant in the 35326 samples. It shows an unusual morphology with the spiral side of the test completely flattened or even depressed and the umbilical side much inflated (see Figure 5). This is anomalous when compared to the pictured specimens of Parker (1962) or Bé (1977). The meaning of this morphotype is not understood.

In summary, the above interpretation depicts the glacial age of the northwestern Mediterranean as considerably colder than it is presently with a large seasonal variation in upper water column temperature and a biological production cycle similar to that seen in polar waters of the North Atlantic today.

There is independent support for the hypothesis that the northwestern basin waters were much colder during the last ice age. Vergnaud-Grazzini (1975) has found large positive shifts in the planktonic Foraminifera δO^{18} for 18,000 y.b.p. samples of the region.

These are much larger than any change expected for glacial ice volume growth. Also, core TR173-1 [40°13'N, 12°14'E, in 2493 m of water] from the central Tyrrhenian basin (between Sardinia and Italy) has a down core transition from a G. ruber dominated fauna to a left-coiling N. pachyderma assemblage, as shown in the table below:

cm depth	%G. ruber	%N. pachy L.	%N. pachy R.	%G. inflata
0	38.7	0.0	6.2	9.2
10	2.5	0.9	17.8	5.0
40	14.9	3.2	23.0	15.4
70	2.3	21.4	3.8	5.9
90	5.7	18.8	4.9	10.8
110	0.0	35.6	7.5	13.7
120	0.0	32.7	2.1	6.7

Although this core is undated, the samples listed must extend into the last glacial age. They show that, in the Tyrrhenian basin, a winter production season existed and that a dramatic temperature drop occurred during the ice age. It is notable that G. inflata, nearly absent in our other two cores, is present in moderate amounts in the company of very cold water fauna. This indicates high seasonality and upper water column stratification; a circumstance that would enhance winter season biological production (see below) which in turn would help explain the abundance of left coiling N. pachyderma.

To be completely consistent, the model of glacial age western

Mediterranean hydrography must explain the delayed onset of biological production represented by the samples of core 35326. Phytoplankton productivity has been linked to the onset of some vertical water stability due to the development of the spring shallow thermocline (Riley, 1942; Steele and Menzel, 1962). The associated pycnocline helps maintain the plant population in the lighted environment of the upper water column. The onset of rapid upper water column temperature change in the glacial northwestern Mediterranean would undoubtedly have depended on the continental climate that surrounded it. It was mentioned above that this was arid and cold. As with tundra environments today, the arrival of spring was probably late but very rapid. If the Eurasian continent supplied cold, dry winds to the northwestern basin during the winter it may well be that evaporation raised the winter surface water salinity, a circumstance that would enhance the already discussed upper water column instability. Such a mechanism operates in the northwestern Mediterranean today (Sankey, 1973) and it would have delayed the onset of stability in glacial age times as increased salinity offset the density lowering effects of rising temperature. The result would have been a very short colder water period of production. Further, if summer evaporation, along with early autumn cooling, led to some increases of surface water density and instability in the water column or led to only a weak pycnocline, vertical mixing would have continued to provide enough nutrients to the upper waters to supply a warmer season period of production. This is a situation

not found in the northwestern basin today, but is analogous to the average autumnal phytoplankton production system (McGill, 1966).

Summary of the Model for a Glacial Age Western Mediterranean

Three main elements of glacial age hydrography have been stressed above, these are: (a) a considerable drop in annual water temperatures, also shown by Thiede (1978), (b) an absence of the vertical stability seen in the Mediterranean today, (c) a high seasonal thermal contrast and rapid changes in oceanographic conditions, annually and in the longer term.

The decrease in temperature and the high seasonality are to be expected from the dramatic changes in climate on the continents surrounding the western Mediterranean (Frenzel, 1968; Bonatti, 1966; Livingstone, 1975; Sarnthein, 1978). The continental effect would have been enhanced by the glacial age drop in sea level which would have much restricted the flow of water into and out of the Mediterranean (sill depths at the Straits of Gibraltar and Sicily are only about 320 m., Sankey, 1973). Variability in the climate is to be expected as the western Mediterranean would have been at the junction of the major atmospheric systems associated with the cooling of Eurasia, the major southward shift of the North Atlantic polar front (CLIMAP, 1976) and the climatic shifts seen on the African continent. Lamb and Woodroffe (1970) illustrate the potential glacial climatic situation.

Vertical stability in the western Mediterranean presently is the result of inflow of saline, warm Levantine intermediate water

from the eastern Mediterranean (LaCombe and Tchernia, 1972). This water is formed by winter cooling of high salinity water south of Crete and Cyprus. Glacial conditions could have reduced the formation rate of this water (Thunell, 1979, shows lowered glacial salinities and temperatures for most of the eastern basin), and lowered sea level could have inhibited its entry into the western basin. The data from core TR173-1 listed above indicates stability in the Tyrrhenian Sea, so it may be that some intermediate water entered the western Mediterranean during the last glaciation, but its flux was probably too small to create a basin wide mid-depth lense similar to that seen today. Such a situation would have had profound effects on ice age western Mediterranean bottom water which must have been colder and less saline than it is presently, reflecting the characteristics of the surface waters from which it formed. It seems likely that the modern Mediterranean bottom water 10% contribution to the deep world ocean heat budget (Gordon, 1972) was much reduced during the ice age. This must have had an impact on the development and maintenance of the global ice age.

Acknowledgements

The author is much indebted to Dr. H. Schrader for his help in financing carbon-14 dates used in this paper. Thanks also to Dr. W.H. Hutson for his support and encouragement. The research reported above was supported by NSF grants, OCE 7808522 and OCE 77-23162 A01.

References

- Bé, A., 1967. Fiches d'identification du zooplancton, Zooplankton Sheet 108, Foraminifera, Consul Permanent International pour l'exploration de la Mer, also: Lamont-Doherty Geological Observatory, Contribution 982, 9 p.
- Bé, A. 1977. An ecological, zoogeographic and taxonomic review of recent planktonic Foraminifera, IN: (A. Ramsay, ed.) *Oceanic Micropaleontology*, 1:1-100, Academic Press, N.Y.
- Bé, A. and Tolderlund. 1971. Distribution and ecology of living planktonic Foraminifera in surface waters of the Atlantic and Indian Oceans, IN: (B. Funnell, and W. Riedel, eds.) *The Micropaleontology of Oceans*, p. 105-149, Cambridge, Univ. Press, England.
- Berge, G. 1958. The primary production in the Norwegian Sea in June 1954, measured by an adapted C-14 technique, IN: *Reports of the International Counsel for the Exploration of the Sea*, 144: 79-91.
- Berger, W., 1976. Biogenous Deep Sea Sediments: Production, Preservation and Interpretation, IN: (Riley, J. and R. Chester, eds.) *Chemical Oceanography*, 5, p. 266-372, 2nd edition, Academic Press, London.
- Blanc, Blanc-Vernet, Laurec, Le Campion et Pastouret. 1976. Application paleoecologique de la methode d'analyse Factorielle encomposantes principales: interpretation des microfaunes de Foraminifera planktoniques Quaternaires en Mediterranee III, *Paleogeography, Paleoclimatology, Paleoecology*, 20: 277-296.
- Blanc-Vernet, Chamley and Froget, 1969. Analyse paleoclimatique d'une carotte Mediterranee nord-occidentale: comparaison enter les resultats de trois etudes: Foraminifera, pteropods, Fraction sedimentaire issue du continent, *Paleogeography, Paleoclimatology, Paleoecology*, 6: 215-235.
- Boltovskoy, E. and R. Wright. 1976. Recent Foraminifera, Dr. W. Junk b.v. Publ., The Hague, 515 pp.
- Bonatti, E. 1966. North Mediterranean climate during the last Wurm glaciation, *Nature* 209:984-985.
- British Air Ministry Met. Office. 1962. Weather in the Mediterranean, v. 1, General Meteorology, H.M. Stationary Office, London.

- Butzer, K. 1960. Dynamic climatology of large scale European circulation patterns in the Mediterranean area, *Meteorologische Rundschau* 13: 97-105.
- CLIMAP, Project Members. 1976. The surface of the Ice Age earth, *Science*, 191:1131-1144.
- Cooley, W. and P. Lohnes. 1971. *Multivariate Data Analysis*, John Wiley and Sons, Inc., New York, 364 pp.
- Eriksson, K. and Olsson. 1965. Some problems in connection with C-14 dating of tests of Foraminifera, *Bulletin Geol. Inst. Univ. of Uppsala*, 42(7):1-13.
- Frenzel, B. 1968. The Pleistocene vegetation of northern Eurasia, *Science*, 161:637-649.
- Gordon, A. 1972. General Ocean Circulation. IN: *Proceedings of the Symposium on Numerical Models of Ocean Circulation*. p. 212-252, Durham, New Hampshire.
- Herman, Y. 1971. Vertical and horizontal distributions of pteropods in Quaternary sequences, IN: (B. Funnell and W. Riedel, eds.) *The Micropaleontology of Oceans*, Cambridge Univ. Press, pp. 643-486.
- Holmes, R. 1956. The annual cycle of phytoplankton in the Labrador Sea, 1950-1951. *Bulletin of the Bingham Oceanographic Collection*, 16:3-73.
- Huang, T. and D. Stanley. 1972. Western Alboran Sea: Sediment dispersal, ponding and reversal of currents. IN: (D. Stanley, ed.), *The Mediterranean Sea: A Natural Sedimentation Laboratory*, pp. 521-560.
- Hutson, W. 1977. Transfer functions under no-analog conditions: Experiments with Indian Ocean planktonic Foraminifera, *Quaternary Research*, 8:335-367.
- Imbrie, J. and N. Kipp. 1971. A new micropaleontological method for quantitative paleoclimatology, application to a late Pleistocene Caribbean core, IN: (K. Turekian, ed.) *The Late Cenozoic glacial ages*: 71-181, Yale University Press.
- IMSL. 1979. *The IMSL Library: Fortran subroutines in the areas of mathematics and statistics*, v. 1: International Mathematical and Statistical Libraries, Inc., GNB building, 7500 Bellaire Blvd., Houston, Texas.

- Kipp, N. 1976. New transfer function for estimating past surface conditions from sea bed distribution of planktonic Foraminiferal assemblages in the North Atlantic, IN: (R. Cline and J. Hays, eds.), Investigation of Late Quaternary Paleocceanography and Paleoclimatology, p. 3-42, Geol. Soc. Amer. Mem., 145.
- LaCombe, H. and P. Tchernia. 1972. Caracteres hydrologiques et circulation des eaux en Mediterranee, IN: (D. Stanley, ed.) The Mediterranean Sea: A natural sedimentation laboratory, pp. 25-36. Dowden, Hutchinson and Ross, Inc., Pennsylvania.
- Lamb, H. and A. Woodroffe. 1970. Atmospheric circulation during the last Ice Age, Quaternary Research, 1:29-58.
- Livingstone, D., 1975, Late Quaternary Climatic Change in Africa, Ann. Rev. of Ecol. and Systematics, 6:249-280.
- Loubere, P. 1980. Oceanographic parameters reflected in the seabed distribution of planktonic Foraminifera from the North Atlantic and Mediterranean Sea, paper 1, Ph.D. Thesis, 42 pp.
- Loubere, P. and W. Hutson. 1980. Quantitative paleoceanography: Data base limitations to temperature estimates, Paper 2 - Ph.D. Thesis, 25 pp.
- McGill, D. 1966. Fertility of the Oceans, IN: (Fairbridge, R., ed.) The Encyclopedia of Oceanography, pp. 268-272. Van Nostrand Reinhold Co., 1021 pp.
- MEDOC, MEDOC Group. 1970. Observation of formation of deep water in the Mediterranean Sea, 1969, Nature, 227:1037-1040.
- Molina-Cruz, A. and J. Thiede. 1978. The glacial eastern boundary current along the Atlantic Eurafrian continental margin, Deep-Sea Research, 25:337-356.
- NOAA, U.S. Dept. of Commerce. 1976. Environmental Data Service Announcement of Marine Geology Data, National Geophysical and Solar Terrestrial Data Center, Boulder, Colorado.
- Parker, F. 1955. Distribution of planktonic Foraminifera in some Mediterranean sediments, Papers in Marine Biology and Oceanography, Deep-Sea Research, Suppl. v. 3:204-211.
- Parker, F. 1962. Planktonic Foraminiferal species in Pacific sediments, Micropaleontology, 8(2):219-254.
- Phleger, F. 1960. Foraminifera of three submarine cores from the Tyrrhenian Sea, K. Vet. O. Vitterh. Samh. Handl., F.6., Series B, Bd. 5, N:05:7-19.

- Riley, G. 1942. The relationship of vertical turbulence and spring diatom flowerings, *J. of Marine Research*, 5(1):67-87.
- Rotschy, F., Vergnaud-Grazzini, Bellaiche et Chamley, 1972. Etude paleoclimatique d'une carotte prelevee sur un dome de la plaine abyssale lique ("Structure Alinat"), *Paleogeography, Paleoclimatology, Paleoecology*, 11:125-245.
- Ryan, W. 1972. Stratigraphy of Late Quaternary sediments in the eastern Mediterranean, IN: (D. Stanley, ed.) *The Mediterranean Sea: A Natural Sedimentation Laboratory*, pp. 149-169, Dowden, Hutchinson and Ross, Inc., Stroudsburg, Pa.
- Sankey, T. 1973. The formation of deep water in the northwestern Mediterranean, IN: (B. Warren, ed.) *Progress in Oceanography* pp. 159-180. Pergamon Press, New York.
- Sarnthein, M. 1978. Sand deserts during glacial maximum and climatic optimum, *Nature*, 271(5648):43-46.
- Steele, J. and D. Menzel. 1962. Conditions for maximum primary production in the mixed layer, *Deep Sea Research*, 9:39-49.
- Stommel, H. 1966. *The Gulf Stream: A physical and dynamical description*, 2nd ed., University of California Press, Berkeley and Los Angeles, 248 p.
- Thiede, J. 1978. A glacial Mediterranean, *Nature*, 276:680-683.
- Thunell, R. 1978. Distribution of recent planktonic Foraminifera in surface sediments of the Mediterranean Sea, *Marine Micropaleontology* 3:147-173.
- Thunell, R. 1979. Eastern Mediterranean Sea during the Last Glacial maximum, An 18,000 y.b.p. reconstruction, *Quaternary Research*, 11:353-372.
- Thunell, R., D. Williams and J. Kennett. 1977. Late Quaternary paleoclimatology, stratigraphy and sapropel history in eastern Mediterranean deep-sea sediments, *Marine Micropaleontology*, 2:371-388.
- Todd, R. 1958. Foraminifera from western Mediterranean deep-sea cores, *Swedish Deep-Sea Exped., Rept.*, 8(3):169-215.
- Tolderlund, D. and A. Be. 1971. Seasonal distribution of planktonic Foraminifera in the western North Atlantic, *Micropaleontology* 17(3):297-329.

- U.S. Naval Oceanographic Atlas of the North Atlantic. 1967. Section 2. Physical Properties, U.S. Naval Oceanographic Office, Washington, D.C.
- van der Hammen, T., T. Wijmstra and W. Zagwijn. 1971. The floral record of the late Cenozoic of Europe, IN: (Turekian, K., ed.) The late Cenozoic Glacial Ages, p. 391-424, Yale University Press, New Haven and London.
- Vergnaud-Grazzini, C. 1974. Les Foraminifères Planctoniques de Mer Ligure, Distribution saisonnière et caractéristiques terminiques, Union des Oceanographes de France, v. 6, bulletin no. 1:30-35.
- Vergnaud-Grazzini, C. 1975. $\delta O-18$ changes in Foraminifera carbonate during the last 10 x 5 years in the Mediterranean Sea, Science, 190(4211):272-274.
- Vergnaud-Grazzini, C. and Bartolini, 1970. Evolution paleoclimatique des sédiments Wurmiens et post-Wurmiens en Mer d'Alboran, Revue de Géographie Physique et de Géologie Dynamique, 12(2):325-334.
- Vergnaud-Grazzini, C., W. Ryan, and M. Cita. 1977. Stable isotope fractionation, climate change and episodic stagnation in the eastern Mediterranean during the late Quaternary, Marine Micropaleontology, 2:343-370.
- Wüst, G. 1961. On the vertical circulation of the Mediterranean Sea, Journal of Geophysical Research, 66:3261-3271.
- Zobel, B. 1968. Phänotypische Varianten von Globigerina dutertrei (d'Orbigny) (Foraminifera). Ihre Bedeutung für die Stratigraphie in quartären Tiefsee-Sedimenten, Geol. Jahrb., 85:97-122.

TABLE 1
SPECIES PERCENTS FOR POTENTIAL 18,000 Y.B.P. LEVELS IN CORE TR173-16

Species	270cm.	280cm.	290cm.	300cm.	310cm.	320cm.	330cm.	*PC-1	surface assembl.
G. ruber	0.0	0.0	0.3 (0.6) ¹	1.2	1.3	1.2	1.8 (1.0)	0.4	11.4
G. saccul.	0.0	0.4	0.0 (0.3)	0.0	0.2	0.3	0.0 (0.0)	0.0	1.9
N. pachy R	33.7	22.3	31.3 (31.8)	31.4	27.1	26.9	22.4 (24.9)	29.1	5.6
N. pachy L	1.9	4.4	0.8 (1.8)	2.3	0.7	0.6	2.1 (2.2)	1.5	0.3
G. glutin.	3.9	5.7	6.9 (5.9)	3.1	7.1	2.4	5.4 (6.2)	4.8	0.6
G. scitula	0.8	1.6	1.5 (1.8)	1.9	1.1	0.9	3.1 (1.0)	1.1	0.0
G. bulloid.	7.6	17.2	8.7 (8.0)	8.9	9.1	18.1	8.0 (6.9)	11.4	37.9
G. falcon.	3.8	5.5	3.9 (4.5)	2.3	3.8	4.1	5.4 (3.7)	3.9	9.2
G. quin.	7.0	21.9	9.1 (11.9)	14.7	10.6	7.1	28.9 (32.1)	14.9	1.7
N. dutert.	3.8	1.1	4.6 (4.2)	3.1	3.3	5.6	5.9 (3.5)	3.6	0.0
G. inflata	4.2	0.2	0.5 (1.2)	3.5	2.4	1.2	0.8 (0.7)	1.4	27.3
P.D. int.*	32.1	18.9	31.5 (27.6)	27.1	32.2	31.1	15.5 (17.3)	28.1	1.1
No. ind. counted =	529	453	607 (337)	258	451	338	390 (405)		359
Correl. of 1st. & 2nd. count =			.991				.995		
Correl. to PC 1 =	.961	.900	.978	.990	.979	.949	.808		

¹ = results from a second split of the same sample

+ = pachyderma-dutertrei intergrade, see text for explanation

* = first principal component of the correlation matrix for the samples, it accounts for 88% of the sample variance and has been converted to an assemblage estimate using least squares regression (see text).

Sample Correlations:	First Eigenvector
270cm. 1.0	.3856
280cm. .757 1.0	.3621
290cm. .989 .800 1.0	.3932
300cm. .970 .867 .970 1.0	.3982
310cm. .978 .813 .991 .966 1.0	.3936
320cm. .941 .815 .951 .923 .952 1.0	.3817
330cm. .647 .900 .696 .801 .704 .624 1.0	.3250

First Eigenvalue = 6.18168, Eigenvalue Sum = 7.0

TABLE 2

SPECIES PERCENTS FOR POTENTIAL 18,000 Y.B.P. LEVELS IN CORE 35326

Species	290cm.	302cm.	310cm.	320cm.	330cm.	340cm.	350cm.	360cm.	370cm.	*PC-1
G. ruber	0.9 (0.5) ¹	1.4	1.0	1.2 (1.3)	0.0	0.0	0.0	0.0	0.0 (0.0)	0.7
G. saccul.	0.0 (0.3)	0.9	1.0	0.2 (1.7)	0.0	0.0	0.0	0.3	0.0 (0.4)	0.5
G. humil.	0.6 (0.0)	0.0	0.0	0.2 (0.5)	0.0	0.5	0.0	0.0	0.2 (0.2)	0.3
N. pachy R	6.0 (5.4)	5.0	4.5	3.7 (4.5)	6.5	8.9	8.6	1.7	3.3 (1.8)	5.2
N. pachy L	2.1 (1.6)	0.5	2.7	0.5 (0.7)	1.2	8.7	1.1	0.8	0.8 (0.6)	1.8
G. glutin.	13.5 (17.9)	12.8	13.3	10.2 (11.8)	18.5	11.0	18.9	18.6	29.3 (32.9)	16.2
G. scitu.	21.9 (23.3)	28.3	25.0	15.1 (17.2)	30.0	16.9	9.6	21.3	27.6 (28.9)	22.3
G. bulloid.	22.2 (22.7)	18.7	25.0	30.3 (25.1)	14.7	5.8	35.4	30.3	7.5 (7.1)	22.0
G. falcon.	7.5 (10.8)	6.9	7.5	8.8 (7.6)	6.8	0.7	11.1	12.9	10.2 (7.6)	8.4
G. quin.	23.4 (20.6)	23.3	19.2	26.2 (27.9)	17.7	45.3	11.1	13.2	20.2 (19.5)	20.9
G. inflata	1.5 (0.5)	0.0	0.0	0.5 (0.0)	0.3	0.3	0.0	0.0	0.0 (0.0)	0.5
P.D. int.+	0.3 (1.1)	0.5	0.7	0.7 (0.7)	2.7	1.2	2.9	0.3	1.0 (0.6)	1.2
No. ind. counted =	333 (369)	219	292	432 (447)	340	426	280	403	689 (496)	
Correl. of 1st. & 2nd. count =	.987			.983					.994	
Correl. to PC 1 =	.991	.971	.985	.921	.935	.674	.786	.925	.835	

*,+,1 = symbols as in Table 1, PC-1 accounts for 80% of data variance

Sample Correlations:

	290cm	302cm	310cm	320cm	330cm	340cm	350cm	360cm	370cm	First Eigenvector:
290cm	1.0									.3685
302cm	.970	1.0								.3609
310cm	.980	.967	1.0							.3659
320cm	.940	.860	.918	1.0						.3423
330cm	.910	.958	.918	.730	1.0					.3474
340cm	.720	.714	.598	.644	.617	1.0				.2503
350cm	.760	.638	.791	.840	.604	.243	1.0			.2920
360cm	.890	.845	.939	.878	.827	.365	.909	1.0		.3436
370cm	.790	.833	.765	.586	.923	.610	.490	.720		.3102

First eigenvalue = 7.2409, Eigenvalue sum = 9.0

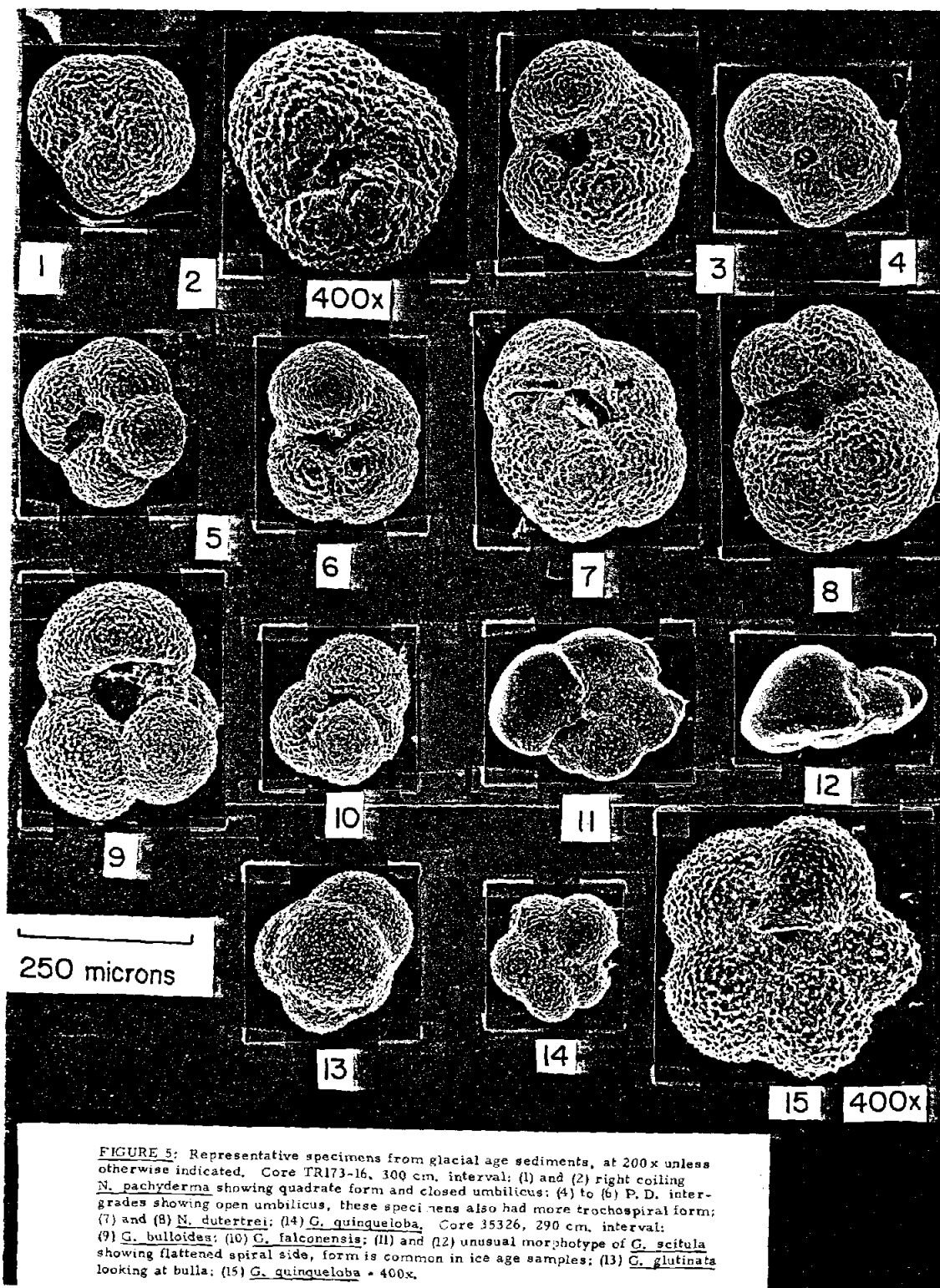


FIGURE 5: Representative specimens from glacial age sediments, at 200x unless otherwise indicated. Core TR173-16, 300 cm. interval: (1) and (2) right coiling *N. pachyderma* showing quadrate form and closed umbilicus; (4) to (6) P. D. intergrades showing open umbilicus, these specimens also had more trochospiral form; (7) and (8) *N. dutertrei*; (14) *G. quinqueloba*. Core 35326, 290 cm. interval: (9) *G. bulloides*; (10) *G. falconensis*; (11) and (12) unusual morphotype of *G. scitula* showing flattened spiral side, form is common in ice age samples; (13) *G. glutinata* looking at bulla; (15) *G. quinqueloba* - 400x.

EPILOGUE:

The work in this thesis is based on the observations of patterns in faunal data from only a part of the world ocean. All conclusions presented are the product of inductive reasoning from the data patterns and are not founded on very much theoretical understanding of the biological mechanisms in Foraminifera. Thus, while the ideas described in this work are hopefully consistent with the data available, it cannot be said that they are scientifically exclusive. The number of explanations for a set of observations is limited only by a certain degree of common sense and the imaginations of the observers. Thus, a number of questions have been raised by this thesis. Some of these are:

(1) Is the production of species such as G. ruber limited by salinity? If so, what is the ecologic advantage in this? It is interesting to note that a salinity response was seen only in sub-tropical and tropical species. It is only in the lower latitudes that a broad range of oceanic salinities are consistently maintained.

(2) A major difference in ecology probably exists between the globorotaliid (deep dwelling) and globigerinid species. This has been discussed in detail for G. inflata above. For the latter it seems possible that its production depends on water column density structure below 100 m. depth in the ocean. It will live in an unlit environment quite different from such surface dwellers as G. ruber. What is the history of this dichotomy? What are the ecologically important factors operating on deep dwelling species?

(3) Certain species, such as G. quinqueloba or G. glutinata have sediment distributions that seem to transcend temperature barriers. If this is so, how is it done biologically? It is well known, for instance, that metabolic enzymes operate well under a limited thermal range. As Foraminifera are in no way homeothermic, how can they escape this limitation?

My thesis, hopefully, serves to show that planktonic Foraminifera are an ecologically heterogenous bunch. I am tantalized by the thought of how much paleo-oceanographic information they could provide, if we could only understand.