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Micropaleontology and Ocean Surface Climate

The interpretation of planktonic microfossils requires a drifting reference frame.

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Planktonic microfossils preserved in oceanic sediments record the climatic conditions of the ocean surface layer. They not only permit us to study the ocean of the past, but they also document the present climate. In contrast to the case for the deeper ocean, the conditions of the surface layer are highly variable in space and time. In addition to seasonal variations, there are variations from year to year and spatial variations produced by eddies with scales up to several hundred kilometers in diameter. Because of this variability, a description of the surface ocean climate requires that seasonal data be averaged over many years. As a result of sediment mixing by benthic organisms, a layer in the sediment normally represents the deposition of microfossils averaged over a few thousand years. Thus, the proper interpretation of planktonic marine microfossils can fill important gaps in our knowledge of the average ocean surface climate during the last millennia. Recently deposited sediments are thus not only a clue to the past, but they also can provide us with measures of present long-term averages. Because of the needs of climatology and paleoclimatology, it is important to improve our methods for interpreting planktonic microfossils.

Summary. The interpretation of micropaleontological data based on the fossil remains of planktonic organisms requires an appropriate reference frame. The environmental changes that the plankton experience are a combination of geographic and seasonal factors, correlated by the average drift trajectories. Appropriate methods have been developed to study two drifts in the North Atlantic, one from the west-central Sargasso Sea to the Norwegian Sea and another around the subtropical Sargasso Gyre. The data on planktonic foraminifera from core tops can be used to relate the relative species distribution to the characteristics of the present sea surface. At any one location, the fossil assembly results from a superposition of plankton that have had varied time-temperature histories. To interpret the climatic and geologic history from downcore data will require an iterative technique. One assumes a surface climatology, determines the fossil record this would produce, and then compares this inference with available core data. The climatological assumptions are then modified until a satisfactory agreement is reached.

In his review of estuarine nekton, McHugh (*1*) pointed out that the coordinate system of the "land animal" man is not appropriate to studies of life in the ocean. The need for an oceanic frame of reference is even more important, if we consider the plankton in the major oceanic drifts and gyre systems. The plankton does not experience the seasonal cycle at one place fixed with respect to the solid earth. Rather temperature, salinity, nutrients, food supply, and predators change as the assemblage of organisms drifts along. The changing seasons are related to changing location as a result of the average drift of the surface water. To interpret the fossil record of the plankton, we must discard our land-based prejudices and "think along with the plankton." My purpose in this article is to suggest how this can be done, and to explore possible improvements in interpretation that might result from the use of a drifting frame of reference. To this end, I use the extensive core-top data on planktonic foraminifera that have recently become available for the North Atlantic (*2*). I shall consider two major drifts: The first is a drift path of almost 10,000 kilometers from the tropical west-central Sargasso Sea to the Norwegian Sea. This drift, ranging from tropical to polar conditions, is unique to the interglacial North Atlantic. The second example is the circulation around the subtropical Sargasso Gyre.

Earlier Work

Early studies of planktonic foraminifera resulted from the collections of the great oceanographic expeditions, the *Challenger* expedition (1873 to 1876) by Brady (*3*), the *Meteor* expedition (1925 to 1927) by Schott (*4*), and the Swedish Deep-Sea Expedition (1947 to 1948) by Phleger *et al.* (*5*). The methods used in marine biogeography traditionally have consisted of associating key species or groups of species with broad climatic zones in the ocean. Fager and McGowan used quantitative methods to define groups of planktonic species and associate them with particular water masses in the North Pacific (*6*). More recently, Imbrie and Kipp (*7*) have used a special mathematical procedure known as Q-mode factor analysis to resolve micro-

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Table 1. Core locations for the drift track.

Core number	Core	Latitude	Longitude	Depth (m)
1	V 12-4	24°16′N	53°04′W	5009
2	V 17-1	28°29′N	65°03′W	5024
3	V 5-1	32°36′N	69°30′W	5323
4	A 164-15	36°08′N	68°55′W	4481
5	V 7-53	36°54′N	54°02′W	5427
6	A 180-13	39°08′N	42°39′W	4880
7	V 28-89	44°32′N	32°35′W	3643
8	V 29-183	49°08′N	25°30′W	3643
9	V 23-82	52°35′N	21°56′W	3974
10	V 29-193	55°24′N	18°44′W	1326
11	V 29-198	58°43′N	15°33′W	1139
12	V 27-38	61°22′N	11°29′W	1317
13	V 28-60	64°05′N	4°02′W	3244
14	V 29-220	65°10′N	00°04′W	2873
15	V 23-60	70°03′N	8°19′E	2974
16	V 27-60	72°11′N	8°35′E	2525

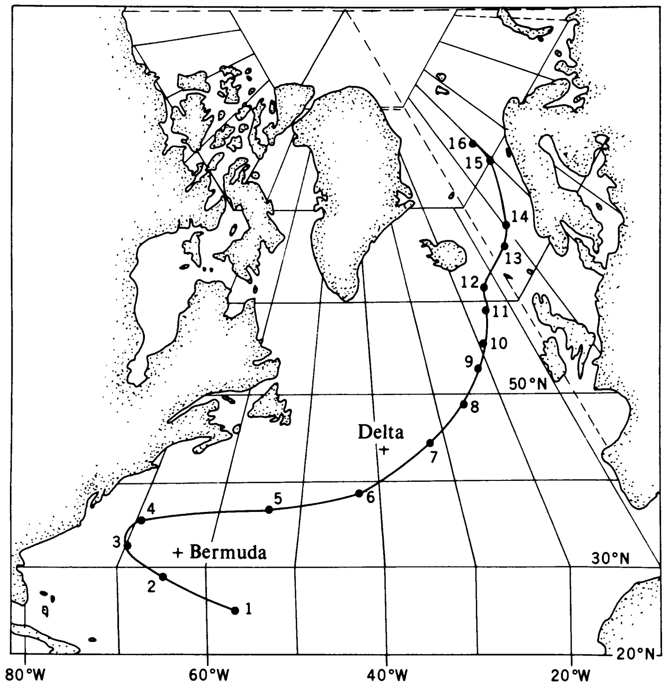
paleontological data on planktonic foraminifera. The concentrations of the factors are then quantitatively related to appropriate environmental variables such as surface summer or winter temperature. By developing quantitative relationships for present conditions, one can then map these parameters for paleoclimates, using correlated downcore data. Using this method, the members of the Climate: Long-Range Investigation, Mapping, and Prediction (CLIMAP) project of the International Decade of Ocean Exploration have produced maps of the global surface temperature for the ocean of 18,000 years ago (*8*).

Four kinds of problems arise with climatic interpretation of micropaleontological data. First, there are problems associated with taxonomy and sample preparation. To produce consistent data, the taxonomy and sample preparation must be standardized (*9*). The second problem concerns time correlation. To generate a climatic synthesis of the present or any previous time, it is necessary that the data correspond to the appropriate time horizon. The third problem arises from differential preservation of the microfossil assemblage. Differential dissolution on passing through predators, on sinking to the ocean floor, and at the sediment-water interface can significantly alter the species composition (*10*). The final problem is how to interpret the resulting "noisy" information provided by the microfossil assemblage. Here I deal primarily with the problem of interpretation. However, the limitations imposed by the other problems cannot be ignored.

A Planktonic Frame of Reference

The usual way to depict species distributions and environmental variables is to plot them on a map. This is appropriate for organisms that are stationary with respect to the solid earth or those whose excursions are small compared to the gradients of environmental variables. When one deals with the plankton communities in the major gyre and drift systems of the world ocean, however, such a method can be misleading. As the plankton drifts along with the water, spatial and temporal changes in the environment are correlated. The drifting assemblage of organisms experiences changing conditions that result both from the seasonal progression and from the change in location.

Except for the rather limited areas of major strong currents such as the Gulf Stream, ocean currents are irregular. The motion of the plankton can be further altered by vertical migration. Thus it



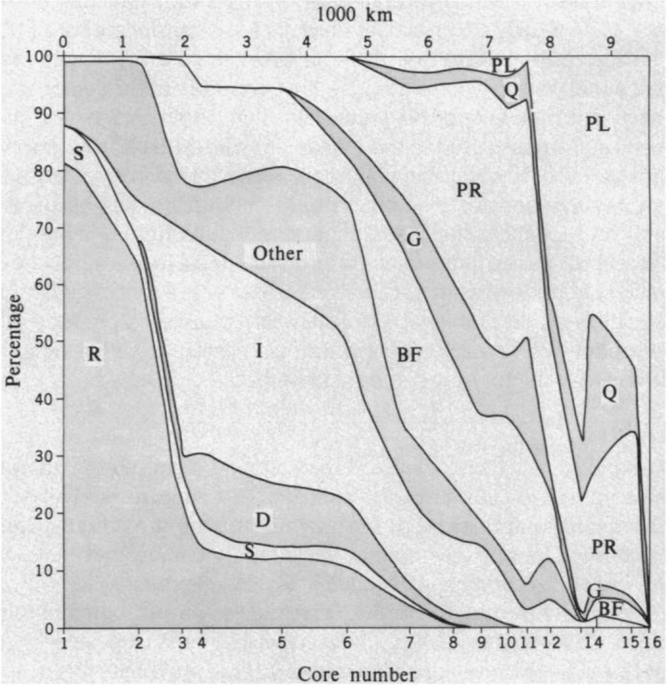


Fig. 1 (left). Location of cores 1 through 16 in the North Atlantic Ocean [Bradley equal area projection (*20*)]. Fig. 2 (right). Relative species composition of planktonic foraminifera along the track shown in Fig. 1 (distances on the upper abscissa are in thousands of kilometers): *R*, *Globigerinoides ruber*; *S*, *G. sacculifer*; *BF*, *Globigerina bulloides* and *G. falconensis*; *Q*, *G. quinqueloba*; *PL*, *G. pachyderma* (left-coiling); *PR*, *G. pachyderma* (right-coiling); *D*, *Globoquadrina dutertrei*; *I*, *Globorotalia inflata*; *G*, *Globigerinita glutinata*; *Other*, all other species.

is not possible to develop an exact frame of reference that is stationary relative to a drifting community of plankton. No "oceanic theory of relativity" can transform the coordinates of latitude, longitude, and depth into a planktonic reference frame. Rather, we must use an average drift relative to which the planktonic community is dispersed by irregularities in the currents. Differences in habitat within the water column may lead to different average drifts for various species. Thus, the situation is complex and the potential value of a drifting reference frame can only be evaluated in terms of a consideration of specific situations.

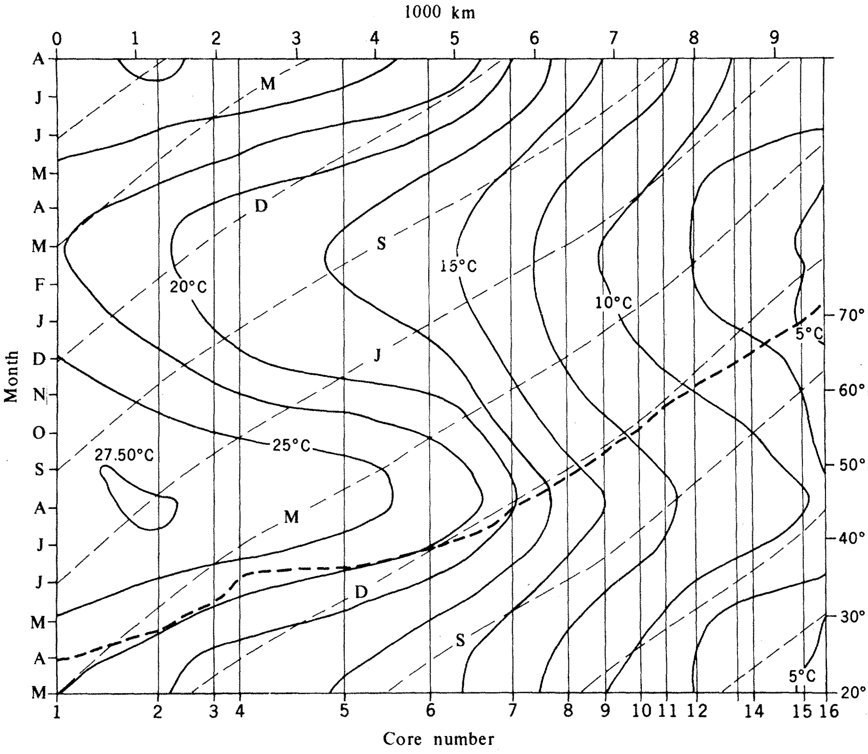


Fig. 3. Mean monthly surface temperatures along the drift track from the Sargasso Sea to the Norwegian Sea.

The Data

The data used are the species compositions of planktonic foraminifera from core tops in the North Atlantic Ocean developed by the CLIMAP team (*2*). The CLIMAP workers used a consistent taxonomy and a uniform system for sample preparation. They introduced a category of "intergrades" between the species *Globoquadrina dutertrei* and *Globigerina pachyderma* (right-coiling), which I have allocated to the separate species in the proportion that those species were identified in the same sample. Because of the low degree of overlap in the distribution of the two species, this procedure introduces relatively little uncertainty. Since one is dealing with core tops, uncertainty in correlation can be due to the loss of surface sediment by erosion or by coring and to differences in the time average due to differences in the rates of sedimentation and the depth of bioturbation. Dissolution may have affected the species composition of the deeper samples considered.

First, I consider a series of cores ranging from the central Sargasso Sea to the Norwegian Sea that fall approximately along the average drift trajectory. Then I consider the environmental conditions in an elliptical drift around the Sargasso Sea and use them to interpret the faunal data from this area.

Sargasso Sea to Norwegian Sea

The cores chosen for this approximate drift trajectory are listed in Table 1 and their locations are shown in Fig. 1. The relative species composition of planktonic foraminifera along the track is shown in Fig. 2. The composition changes from a dominance of *Globigerinoides ruber* at core 1 to a complete dominance of *Globigerina pachyderma* (left-coiling) at core 16. The annual cycle of surface temperatures along the track is shown in Fig. 3. The distance along the track is shown on the horizontal axis, and time is displayed on the vertical axis. The mean monthly surface isotherms (*11*) are mapped at intervals of 2.5°C, starting with the annual minimum in March. Using the average drift velocities of the surface water as obtained from ship drift data (*12*), drift trajectories on the time-space diagram are indicated by light dashed lines for four drifts starting in March, June, September, and December from location 1. The latitudinal change along the drift is also indicated (heavy dashed line).

A rapid decrease in *Globigerinoides ruber* occurs between cores 2 and 3 at a latitude of approximately 30°N. This change coincides with the southern limit of winter mixing (*13*). The surface water to the south is permanently stratified, whereas winter cooling north of 30°N mixes the water column to below the photic zone and so brings nutrients into the surface layer, which results in a spring bloom of phytoplankton. Apparently, *G. ruber* is adapted to tropical areas of low primary productivity. The seasonally high productivity of waters north of 30°N may permit other species such as *Globorotalia inflata*, *Globigerina bulloides*, and *G. falconensis* to compete more successfully.

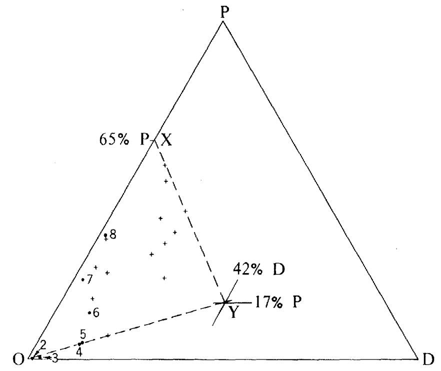
The assemblage of foraminifera in the surface sediments represents the average yearly accumulation that is transferred to and preserved in the sediment. To understand this mixture, however, one must consider the seasonal variations. Water that leaves location 1 in March at a temperature of 22.5°C and moves with the average drift velocity will move beyond location 6 before it is cooled below that temperature. It reaches location 6 in early October and experiences rapid cooling, because, as the season progresses into winter, the water is also moving toward higher latitudes. Since this water mass has reached latitude 30°N only by May, it will not experience a phytoplankton bloom and therefore it should contain primarily the tropical assemblage dominated by *Globigerinoides ruber*. Thus, the persistence of that species at over 10 percent to location 6 could be attributed to such a seasonal drift. In contrast, water that leaves location 1 at other times of the year will experience temperatures below 20°C well south of location 6.

This interpretation is confirmed by the seasonal distribution of planktonic foraminifera at Ocean Station Delta observed by Tolderlund and Bé (*14*) (for location, see Fig. 1). They found a strong seasonal peak of *G. ruber* in September, when it dominates the plankton. This species is absent between December and June. There is a significant variation in the duration and intensity of this annual peak during the 4 years of measurements, which can be ascribed to year-to-year variations in the drift. However, even during the lowest peak, *G. ruber* comprises 70 percent of the planktonic foraminifera. In contrast, at Bermuda, *G. ruber* is present all year round with a reduced abundance in winter.

The colder water species *Globigerina pachyderma* (right-coiling) and *Globoquadrina dutertrei* begin to appear in significant quantities at location 4, although the average monthly surface temperature here does not fall below about 19°C. The percentage of *G. pachyderma* does not increase until location 6, where the monthly average minimum is about 16°C. From there on in the drift trajectory, *G. pachyderma* rapidly increases in dominance.

To explore this matter, I use a triangular composition diagram. A sample that consists of three components which sum to 100 percent can be represented as a point on an equilateral composition diagram. The appropriate components are *Globigerina pachyderma* (*P*), *Globoquadrina dutertrei* (*D*), and all other species (*O*) (Fig. 4). Points representing the compositions for cores 2 through 8 are shown as well as data from all core tops to the west of the track. All the points fall within the triangle *XYO*. We can therefore express the composition of the core tops in terms of the factors *X* (65 percent *P* and 35 percent *O*), *Y* (42 percent *D*, 17 percent *P*, and 41 percent *O*), and *O* (100 percent *O*).

Figure 5 shows the distribution for factors *X* and *Y* along the track and to the west. Except for one location (*15*), we obtain a regular pattern. It appears that factor *X*, the cold-water fauna, is advected southward by the slope current



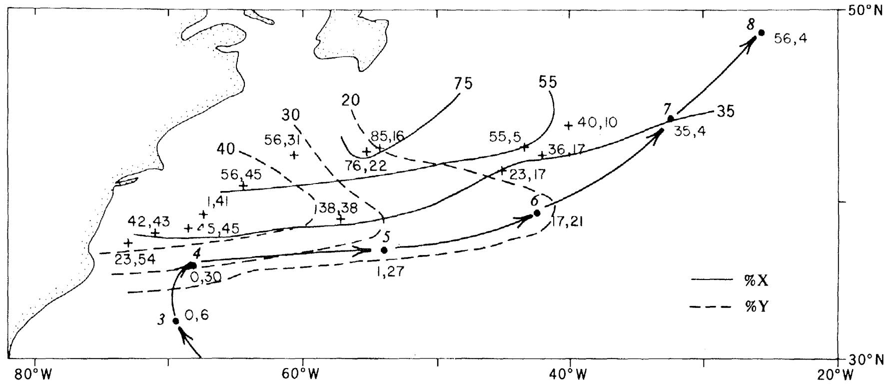
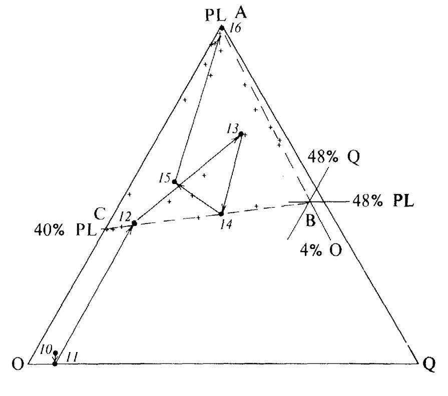


Fig. 4 (left). Triangular percentage composition diagram for cores 2 through 8 and for cores to the west of the track. Vertices of the large triangle: *P*, 100 percent *Globigerina pachyderma*; *D*, 100 percent *Globoquadrina dutertrei*; and *O*, 100 percent all other species; *X* (65 percent *P* and 35 percent *O*) and *Y* (42 percent *D*, 17 percent *P*, and 41 percent *O*). Fig. 5 (right). The distribution of factors *X* (65 percent *P* and 35 percent *O*) and *Y* (42 percent *D*, 17 percent *P*, and 41 percent *O*) in the west-central North Atlantic. The numbers at each core location give the percentages of *X* and *Y*. Core locations are in italic type.



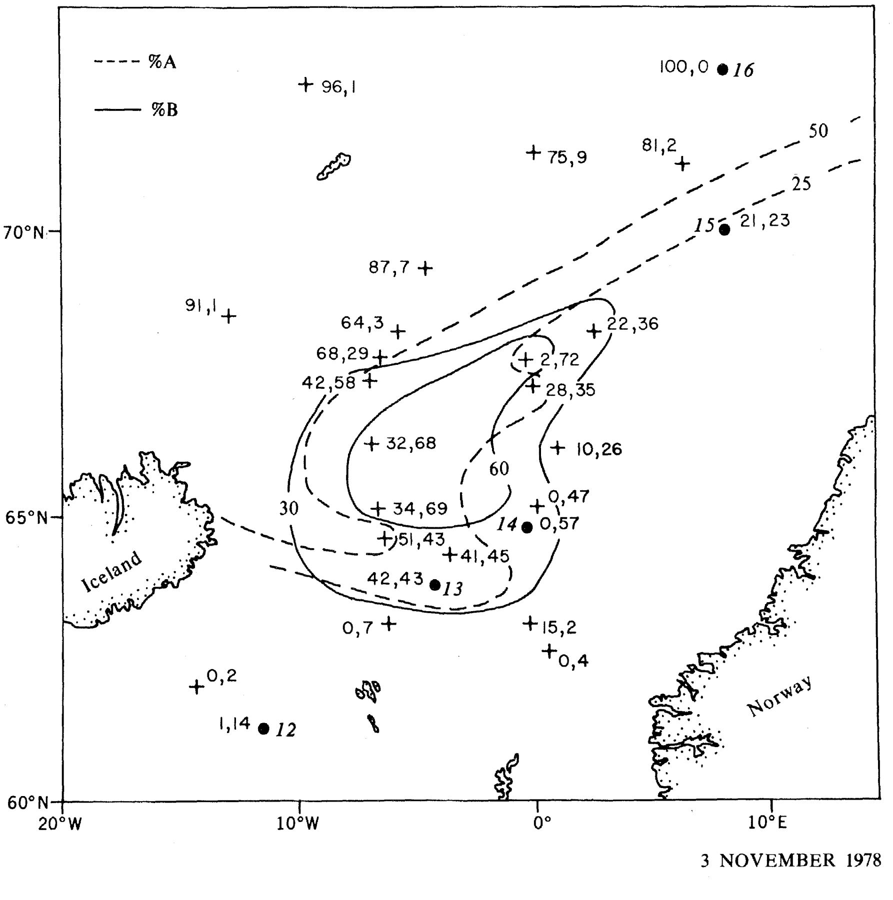
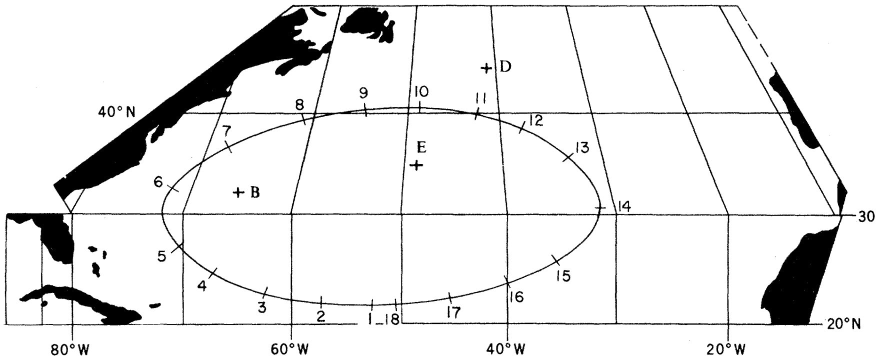


Fig. 6 (left). Triangular percentage composition diagram for cores 10 through 16 and for cores northeast of Iceland: *PL*, 100 percent *Globigerina pachyderma* (left-coiling); *Q*, 100 percent *G. quinqueloba*; *O*, 100 percent all other species; *A* (100 percent *PL*); *B* (48 percent *PL*, 48 percent *Q*, and 4 percent *O*); *C* (40 percent *PL* and 60 percent *O*). Fig. 7 (right). Distribution of factors *A* (100 percent *PL*) and *B* (48 percent *PL*, 48 percent *Q*, and 4 percent *O*) northeast of Iceland. The numbers at each core location give the percentages of *A* and *B*.



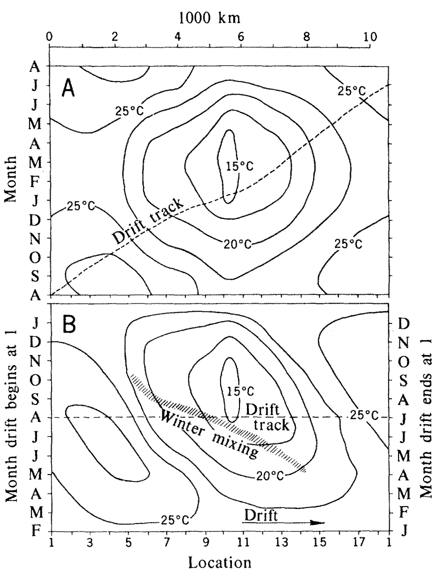


Fig. 8 (left). The drift track around the Sargasso Gyre [Bradley equal area projection (*20*)]: *B*, Bermuda; *E*, Ocean Station Echo; and *D*, Ocean Station Delta. Fig. 9 (right). (A) Mean monthly surface temperature around the Sargasso Gyre. An average drift track leaving location 1 in August is indicated by the dashed line. (B) Temperature along the drift track as a function of the month when the drift departs from location 1. The occurrence of winter mixing north of 30°N is indicated.

which flows west of the Gulf Stream. In contrast, factor *Y*, characterized by a relatively high concentration of *Globoquadrina dutertrei*, is transferred southeastward across the Gulf Stream, probably by cold core rings generated by Gulf Stream meanders (*16*).

The species distribution along the drift track (Fig. 2) shows an anomalous behavior for cores 13 and 14. Here the trend toward the dominance of *Globigerina pachyderma* (left-coiling) is interrupted by a dramatic increase in *G. quinqueloba*. This shows up on a triangular composition diagram giving the percentage of *G. pachyderma* (left-coiling) (*PL*), *G. quinqueloba* (*Q*), and all other species (*O*) (Fig. 6). Also indicated is the composition of the tops of other cores in the region northeast of Iceland. The cores showing the anomaly fall in a composition triangle having vertices *A* = 100 percent *G. pachyderma* (left-coiling); *B* = 48 percent *G. pachyderma* (left-coiling), 48 percent *G. quinqueloba*, and 4 percent others; and *C* = 40 percent *G. pachyderma* (left-coiling) and 60 percent others.

The distribution of *A* and *B* is mapped in Fig. 7 for the region between Iceland and Norway. The *B* factor consisting mainly of equal concentrations of *G. quinqueloba* and *G. pachyderma* (left-coiling) is contained in a gyre, whereas the additional input of *G. pachyderma* (left-coiling), the *A* factor, moves southeast in the East Icelandic Current to be advected into the counterclockwise gyre. A plot of the core depth versus the percentage of *G. quinqueloba* indicates that the relative concentration of *G. quinqueloba* is not an artifact of the preferential dissolution of *G. quinqueloba*, relative to the more resistant species *G. pachyderma* (left-coiling) (*10*).

The *Atlas of Pilot Charts* for the northern North Atlantic (*17*) shows a large gyre centered at about 68°N, 2°W in March and near 68°N, 0° in August. The gyre in Fig. 7 is centered at about 66.5°N, 4°W. One would expect the position of this gyre to be sensitive to climatic change. The core tops will indicate its location averaged over a number of millennia, whereas the pilot atlas data represent a much more recent time average (*18*).

The Sargasso Gyre

The drift from the Sargasso Sea to the Norwegian Sea is unique to the interglacial North Atlantic. More typical are circulations about the subtropical and subarctic gyres. A drift track around the Sargasso Sea is shown in Fig. 8. The arbitrary numbers are spaced at intervals of 300 nautical miles (555 kilometers). The mean monthly surface temperatures around the drift are shown in Fig. 9A (*11*). On the basis of the average drift velocity as determined from ship drifts (*12*), a drift trajectory that starts at location 1 in August is indicated. The complete drift around the gyre takes approximately 11 months, at an average velocity of about 31 km/day (0.7 knot). The temperature ranges from about 14° to 28°C.

The surface temperature experienced by the plankton as it is carried around the drift is shown in Fig. 9B as a function of location, for different starting times from location 1. An average parcel of water that starts at location 1 in February completes the drift in the following January without having experienced a significant temperature change. In contrast, a drift starting at location 1 in August will experience the full temperature range. North of 30°N, the water column mixes in winter to below the photic zone, bringing nutrients to the surface layer and resulting in a subsequent bloom of phytoplankton. Assuming that deep convection occurs in January, I have indicated the location of this event for the different tracks. For tracks that start at location 1 between August and October, mixing is followed by further cooling as the water drifts to the north. In contrast, drifts that start between May and August will experience warming after the winter convection. One would expect the water column to become stratified more rapidly in the latter than in the former case.

The variations in the temperatures experienced by the plankton should give rise to seasonal variations in the absolute abundance of living planktonic foraminifera. These have been observed by Tolderlund and Bé (*14*) at Bermuda and at Ocean Station Echo (see Fig. 8 for locations relative to the drift track). They found that the following species are abundant only during a short time interval (1 to 2 months): *Globorotalia truncatulinoides*, *Globigerina bulloides*, and *Globorotalia inflata*. The species are listed in the order in which the peaks occur at Bermuda in January, February, and March, respectively. A similar sequence occurs at Ocean Station Echo. In contrast, *Globigerinoides ruber* and *Globigerinoides sacculifer* show much less seasonal variation. Their absolute abundances are reduced in winter.

Core locations near the drift track are shown in Fig. 10. The coverage is limited, and the detailed species distribution tends to be somewhat irregular. As many of the cores are relatively deep, this irregularity is partially due to the effect of differential solution (*19*). Figure 10 in-

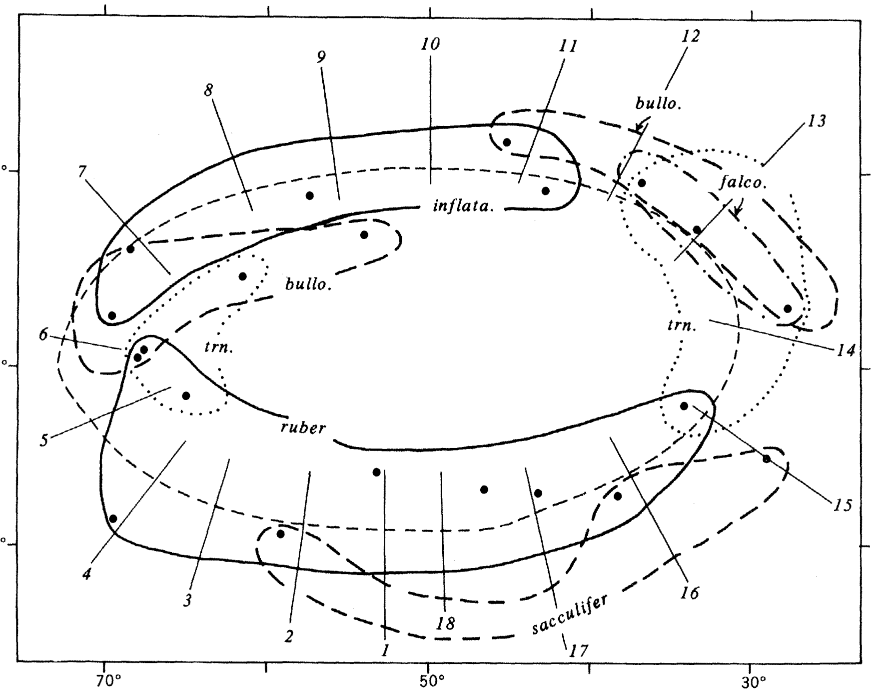


Fig. 10. Relative species distribution around the drift track from core-top data. The areas over which each species has over 50 percent of its maximum relative concentration in the region is indicated. *trn.*, *Globorotalia truncatulinoides; bullo.*, *Globigerina bulloides; falco.*, *Globigerina falconensis*.

dicates the areas for which the relative abundance of each species is at least one half of its maximum abundance for these cores. The maximum abundances (in percent) are as follows: *Globigerinoides ruber*, 82; *Globorotalia inflata*, 35; *Globigerina bulloides*, 18; *Globigerina falconensis*, 16; *Globigerinoides sacculifer*, 15; and *Globorotalia truncatulinoides*, 13. The southern part of the gyre is dominated by *Globigerinoides ruber* with contributions of *Globigerinoides sacculifer*. Moving clockwise around the drift, *Globorotalia truncatulinoides, Globigerina bulloides*, and *Globorotalia inflata* appear and drop out, in turn, at over 50 percent of their maximum relative concentrations. Continuing around the gyre, *Globigerina bulloides* and *Globorotalia truncatulinoides* appear once more at over 50 percent of their maximum abundances. *Globigerina falconensis* makes a major contribution only in this quadrant. This species is not distinguished from *Globigerina bulloides* in this particular study of living plankton. The order of first appearance in the western part of the gyre is the same as the seasonal sequence of the living plankton at Bermuda (*14*).

Using the information on the distribution of living planktonic foraminifera and on the surface temperature, I have attempted to explain the species distribution in the core tops around the gyre (Fig. 11); the approximate species distribution at the surface of the sediment is indicated in the lower part of the figure, and the upper part is a drift diagram similar to Fig. 9B. The drift around the gyre proceeds horizontally for different starting times. Lines of constant time are indicated by the sloping dashed lines. The shading indicates the species that is dominant in the plankton assemblage at a particular time and location.

The abundance in the plankton depends on the concentration of individuals in the sea at a particular time. In contrast, the relative species abundance in the sediment tops depends on the relative rate at which foram tests are transferred to the sediment per unit area, averaged over a number of years. This rate depends on the vertical concentration of the living forams, the variation of their concentration with season, the average time they persist in the plankton, and the fraction of forams removed from the plankton that are sedimented as recognizable individuals.

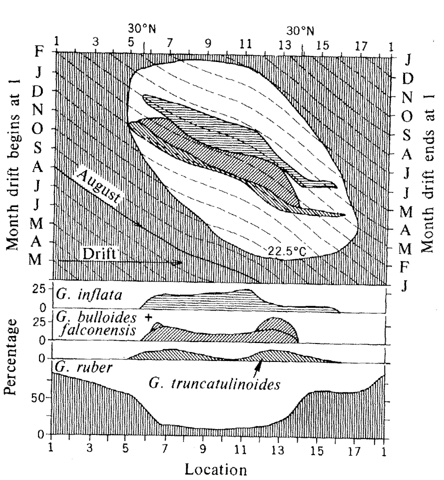


Fig. 11. Inferred species distribution of planktonic foraminifera around the Sargasso Gyre. (Bottom) Distribution of species in sediment tops. (Top) Space-time distribution of dominant species along the drift (compare with Fig. 9B).

In the absence of data on the various factors, the hypothetical distribution depicted in Fig. 11 is only a first-order approximation. Using the lower temperature limit of *Globigerinoides ruber* for Bermuda and Station E [(*12*), figure 17], I assume that particular species to be dominant as long as the surface temperature is greater than 22.5°C. The other species become dominant with appropriate delay, after winter mixing north of approximately 30°N. Averaging over the year at a given location gives a measure of the relative species abundance in the sediment, provided that appropriate factors for the residence time in the plankton, the vertical distribution, and the efficiency of transfer to the sediment are used. The horizontal trends show how the species dominance changes as a parcel of water drifts around the gyre.

The first species to appear after winter mixing is *Globorotalia truncatulinoides*. Its abundance is reduced for stations 8 through 12 as a result of the lower temperatures. The long tail in the sediment distribution from location 13 on implies that this species persists in the drift through March, following the phytoplankton bloom near location 13. *Globigerina bulloides* (including *Globigerina falconensis*) starts somewhat later; its abundance is also reduced by lower temperatures and terminates sharply when the surface temperature exceeds 19°C. The initial appearance of *Globorotalia inflata* occurs even later after the phytoplankton bloom; its abundance is not reduced by the lowering in temperature, and this species persists at reduced levels through April after passing south of 30°N.

The above interpretation is a tentative working hypothesis which should be verified and modified on the basis of further observations. My purpose here is not to present an ultimate interpretation but rather to illustrate methods that can be used to advance toward that goal. They require detailed considerations of the time-space changes in the plankton, as different water parcels drift around the gyre.

Climatic Change and Paleoceanography

All the examples I have used here have been derived from core-top data, and in my interpretation I have used the present ocean surface climate and observations of living planktonic foraminifera. In the case of the gyre northeast of Iceland, the core-top data have suggested a slightly more southerly average position for the time interval represented by the core tops.

To examine earlier climatic change, one must consider the changes in species composition downcore. No direct observations of surface drift and surface temperature are available for these times. One must instead proceed by assuming a changed surface climatology for the ocean and work out how this would alter the species composition of the plankton. Through an iterative process, one then compares the predicted micropaleontological composition with that observed in the cores. The assumptions are then modified until reasonable agreement is reached. A number of possible surface climatologies should be used in order to explore how sensitively the inferred distribution depends on the assumptions.

As long as one is still dealing with present-day species, their ecological characteristics can be determined from the living plankton. If one goes further back and observes now extinct species, assumptions about their ecological characteristics must also be made. At some stage, one will reach a point where the lack of data no longer justifies a sophisticated analysis and one must then rely on simpler interpretations based on classifications of the fossils into rough climatic zones. The examples I have explored, however, suggest that the analysis of drift trajectories can lead to improvements in our knowledge of the ocean surface climate of the Quaternary.

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Economics of Wind Energy Use for Irrigation in India

Wind energy could be economically competitive for irrigation from open wells on small farms.

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Although the technology of wind energy conversion is basically simple and is thus likely to be acceptable in rural areas of India, little attention has been paid to improving windmill design or reducing the costs of manufacturing them. Since there are inherent advantages in utilizing wind energy there should be no difficulty, at least in principle, in considering it along the same lines as rural electrification. The viability of rural electrification projects is determined in terms of cost-effectiveness over an extended period of time and not by the initial costs alone. Moreover, provisions exist for differential interest rates with regard to loans for selected areas of socioeconomic development. The availability of such loans would cushion the influence of the high initial costs of installing windmills.

I propose here that the development of groundwater-dependent irrigational facilities (*1*) for small and marginal farmers, with landholdings of less than 1 or 2 hectares, is a priority task. There are probably more than 50 million such farmers in India (*2*). Most of these farmers are unwilling to use diesel and electrical water pumps because of the high costs of purchasing them and the nonavailability of maintenance services and spare parts in villages. Furthermore, electricity is available in only 32 percent of the approximately one-half million villages in India. Since many farmers could not af-

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