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ABSTRACT

In modern oceans, the tropical isotherm of 20 degrees C. ranges between 20 and 40 degrees N. latitude, depending upon the particular oceanographic conditions at any one locality. Studies of planktonic Foraminifera indicate that there have been two, possibly three, cycles of warming in which the limits of the tropical zone have extended well north of the 40 degree parallel within the Upper Cretaceous-Cenozoic interval. A prominent cycle of warming occurred in the Upper Cretaceous, a second in the later Paleocene and lower Eocene, and a third minor one in the later Eocene. These cycles of warming and cooling are in contradiction to other types of data. The disparity is possibly due to the lack of sampling density for other types of fossil evidence or the greater temperature sensitivity of planktonic Foraminifera.

INTRODUCTION

Climatic trends, since the beginning of the Upper Cretaceous, have been usually represented by a continuous cooling, with a progressive shifting of isotherms toward the equatorial region interrupted by only minor fluctuations until the Pleistocene. Supporting evidence comes from studies of megafossils (Smith, 1919 ; Durham, 1950) and from isotopic analyses of the tests of benthonic Foraminifera (Emiliani, 1957) to cite a few. Minor expressions of a contradictory nature have been noted in recent years. This study is designed to demonstrate the general patterns of planktonic foraminiferal trends and their implications regarding climatic zonation.

PLANKTONIC DEFINITION OF TEMPERATURE ZONATION

In modern oceans, the tropical or warm water planktonic species are found in a broad band within about 30 degrees of the equator, or the 20 degree Centigrade isotherm. Actually, this isotherm varies about 10 degrees in latitude on either side of the 30 degree parallel, depending upon the oceanographic setting. Transitional types of Foraminifera occur between about 30 and 60 degrees, and polar faunas occur between about 60 and 90 degrees of latitude. This highly generalized picture is, of course, modified by the movement of cold and warm currents within the ocean basins ; however, there are basic principles involved in these modern patterns that may be applied to an understanding of climatic shifts of the geologic past.

Climatic zonation is well demonstrated in the researches of Bradshaw (1959), Waller and Polski (1959), and in many other works. More than 30 species of planktonic Foraminifera are known in the tropical waters whereas less than five are known in the Arctic and Antarctic and only one or two of the latter are dominant.

General groupings of planktonic Foraminifera in modern oceans are as follows, according to latitude.

Tropical 0–30° ± 10° Latitude

Candeina nitida d'Orbigny
Globigerina spp*.
Globigerinoides spp.
Globorotalia menardii (d'Orbigny) sinistral
Globorotalia truncatulinoides (d'Orbigny) dextral
Globorotalia tumida (Brady) sinistral
Globorotalia spp.
Hastigerina spp.
Hastigerinella spp.
Orbulina universa d'Orbigny
Pulleniatina obliquiloculata (Parker and Jones) dextral
Sphaeroidinella dehiscens (Parker and Jones)

Temperate 30–60° Latitude

Globigerina bulloides d'Orbigny
Globigerina eggeri Rhumbler dextral
Globigerina quinqueloba Natland
Globigerina pachyderma (Ehrenberg) dextral
Globigerina spp.
Globigerinoides glutinata (Egger)
Globigerinoides minuta Natland
Globorotalia puncticulata (d'Orbigny)
Globorotalia truncatulinoides (d'Orbigny) sinistral

Arctic and Antarctic 60–90° Latitude

Globigerina pachyderma (Ehrenberg) sinistral
Globigerina spp.

(*spp- several species)

The species *Globigerinita glutinata* (Egger) is recognized as belonging to *Globigerinoides* in this study. Fistulose and secondary apertural structures are not consistently present and they are mostly the simple expression of a reproductive phase or and ecologic manifestation ; thus, they should not be used to establish a different generic category (*Globigerinita*) in planktonic Foraminifera. This concept agrees with that expressed by Hofker (1959). Similar stuctures of purely secondary importance are recognized in many polymorphinid genera.

Globigerinella is a junior synonym of *Hastigerina* and is therefore excluded also from the foregoing list. It should be noted that right-coiling (dextral) and left-coiling (sinistral) groups of the same species may define different temperature zones (Bandy, in press). *Globigerina pachyderma* is dominantly sinistral in polar waters whereas it is dextral in temperate and tropical waters. *Globorotalia truncatulinoides* is similarly mostly dextral in tropical waters whereas it is the reverse (sinistral) in temperate regions with the exception of complications due to warm currents invading the temperate regions.

Significant trends in planktonic Foraminifera from the tropical zone toward the polar regions consist of a pronounced decrease in species and genera, with only one dominant genus in the polar areas. Several tropical genera, such as *Candeina* (Miocene to Recent) and *Pulleniatina* (Pliocene to Recent), extend back only into the later Cenozoic. The longest ranging tropical forms are the keeled globorotaloids which are common to abundant in the marine strata of tropical regions throughout the Tertiary.

PALEOCLIMATIC TRENDS

In the geologic past, it is suggested that the most characteristic definition of the tropical planktonic faunas is the presence of the keeled genera *Globorotalia* and *Globotruncana* together with diverse globigerinids. *Globotruncana* is a characteristic planktonic genus of the Upper Cretaceous and the globorotaloids are mostly Cenozoic. Both generic types have great similarity to the restricted tropical forms of modern seas.

European Area. – In Europe Wicher (1953) and Bettenstaedt and Wicher (1955) evaluated the boreal and tethys subdivisions of the Upper Cretaceous. They placed more or less equal emphasis upon the planktonic and benthonic groups, assigning them to boreal and tethys facies. Some species of *Globotruncana* were placed in one facies, other species in the second facies. *Globigerina*, of the *G. bulloides* type, was assigned to the southern or

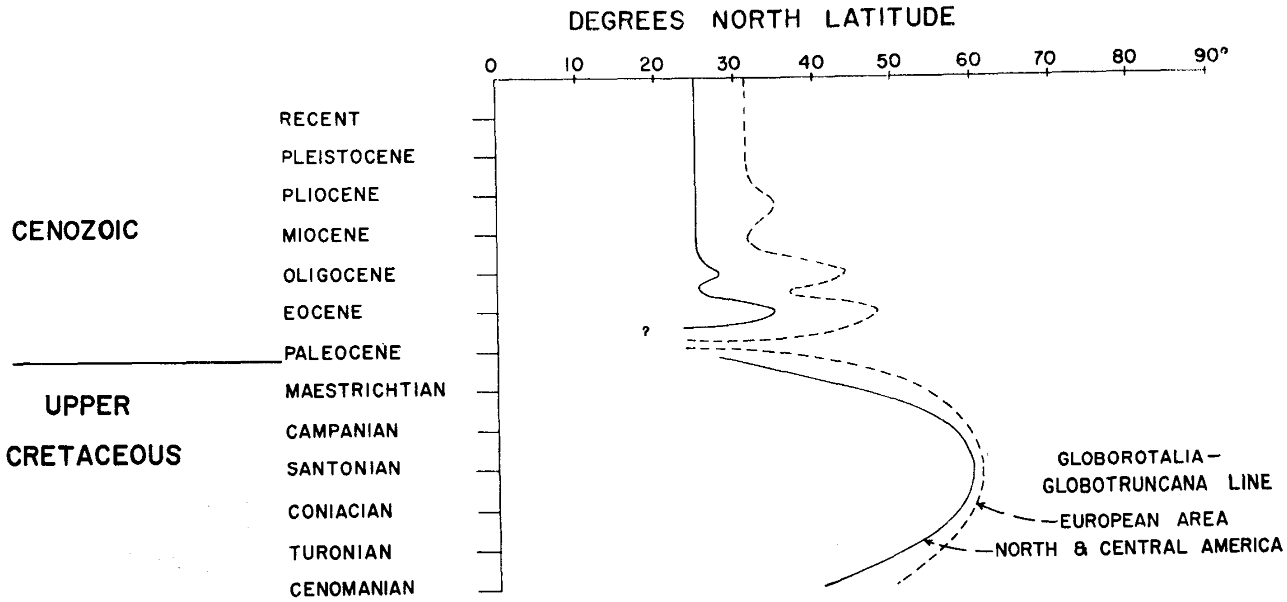

Fig. 1. General Northern Limit of the *Globotruncana-Globorotalia* Faunas for the Upper Cretaceous and Cenozoic.

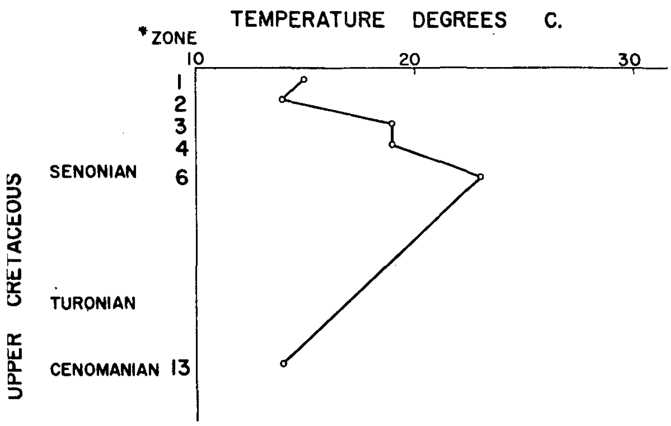

Fig. 2. Paleotemperatures of the Upper Cretaceous of England based upon O^{18} Isotope Analyses of Belemnites. *Data from Urey, Lowenstam, Mckinney, 1950, Table 7.

tethys facies. In modern oceans the globigerinids are less dependable than the globorotaloids, and *G. bulloides* is most characteristic of the temperate and colder regions of modern oceans. Evaluation of data in terms of the northernmost reported limits of *Globotruncana* in the European area shows at least one major expansion of this fauna northward from less than 50 degrees N. latitude in the Cenomanian to nearly 60 degrees (southern Sweden) in the Turonian to Santonian interval (Fig. 1). This trend reversed itself then and there followed the gradual retreat of the *Globotruncana* line to less than 50 degrees (Austria) in the later Maestrichtian. Thus, there was a cycle of warming followed by cooling during the Later Cretaceous. Corroborative evidence is seen in the isotopic studies of Urey and his associates (1951, p. 410) wherein belemnites reflect a similar cycle of warming and cooling in the Cenomanian to Maestrichtian interval of England (Fig. 2). Beginning with temperatures of about 14 degrees C., there was an increase to about 23 degrees in the Senonian and then a decrease to about 15 degrees in the later Maestrichtian. Thus, the *Globotruncana* fauna occurs progressively farther below the top of the Cretaceous toward the polar regions.

The Cretaceous-Cenozoic transition is marked by an almost complete absence of globorotaloids (keeled) with possible exceptions in local areas of the tropical regions. Data from many authors such as Colom (1954), Marks (1951), Subbotina (1953), ten Dam and Reinhold (1942), and ten Dam (1944), indicate that during the later Paleocene and lower Eocene, the globorotaloids expanded northward into the Aquitaine Basin, about 45 degrees N. latitude, and then retreated again during the middle Eocene. A second slight expansion northward is noted in Spain for the later Eocene but thereafter, the planktonic tropical limit was generally within 10 degrees of 30 degrees N. latitude, the general range of the northern limit of tropical assemblages today.

North America. – The general migration of the northern limit of the tropical *Globotruncana-Globorotalia* line (20 degree C. isotherm) in North America parallels that of the European area (Fig. 1). This line was at least as far north as northern California (40 degrees) in the Cenomanian and it advanced into southern Alaska (60 degrees) by about late Turonian time. The tropical isotherm then shifted south from southern Alaska about late Campanian time, reaching northern California by middle Maestrichtian time. By the end of the Maestrichtian this isotherm was generally south of 30 degrees N. latitude. Below this line *Globotruncana* is known to range upward to the end of the Cretaceous (Castanares, 1954), The Danian is considered to be early Paleocene in this study.

Keeled globorotaloids and *Globotruncana* are absent in the earliest Paleocene (Danian) in North America. In the later Paleocene (Landenian), globorotaloids appeared in the tropical regions and expanded rapidly northward to about 35 degrees (central California), retreating then in the middle Eocene to a position mostly south of 30 degrees for the remainder of the Cenozoic. Rare specimens may be noted subsequent to the middle Eocene in some localities to the north of this line. In California, specimens of *Globorotalia aragonensis*, a keeled tropical form, are known to reoccur in the basal upper Eocene of the San Joaquin Valley. These are considered to be reworked from lower Eocene beds because of their preservation and lithologic associations.

Recent studies indicate that colder polar waters affected the coastal region of southern California during the middle Pliocene and the Pleistocene. Sinistrally coiled populations of *Globigerina pachyderma* (Ehrenberg) are characteristic of the polar waters of the modern oceans. These sinistral populations were introduced southward as far as southern California in the middle Pliocene and during much of the Pleistocene (Bandy, in press). The 20 degree Centigrade isotherm must have been shifted much farther southward than the present position, reflecting a compression of the tropical regions during these intervals.

Asiatic Region. – The general migration pattern of the northern limit of the *Globotruncana*-globorotaloid faunas of the Asiatic area appears to conform generally with that in North America and Europe, as inferred from the many works in that area, such as those of Asano (1950, 1953a, b), Hanzawa (1950), and Takayanagi (1950). The modern northern limit of the tropical planktonic globorotaloids in this area is about 30 degrees N. latitude (Waller and Polski, 1959), varying about 10 degrees north and south of this parallel according to oceanographic conditions. In the work of Hanzawa, mentioned above, it is interesting to note that a cooler fauna existed in Japan during the Oligocene than exists there today and that it was followed by warmer water faunas in the lower and middle Miocene. It would appear that the Japanese region was just north of the tropical line for most of the Cenozoic, being affected by one or more shifts of this line northward for temporary periods.

GENERAL DISCUSSION

Generally, in the Upper Cretaceous, the *Globotruncana* line expanded from about 45 degrees to about 60 degrees N. latitude by Turonian time. A southward shifting of the line began in the Santonian and continued into the Maestrichtian, following which occurred the most profound change that has affected planktonic populations. Tropical keeled planktonic Foraminifera were almost completely missing for a time with the possible exception of a few reported occurrences in the equatorial regions of the world. This interval, the Danian, represents the early Paleocene as determined by the first appearance of widespread globigerinids of Cenozoic types (Loeblich and Tappan, 1957). Widespread cooler conditions are indicated by the planktonic trends of the later Cretaceous. Ample corroboration is seen in the work of Campbell and Clark (1944, p. 4) wherein they cite the occurrence, within the Campanian of California, of the ciliate genus *Parafavella* that is restricted to freezing temperatures in modern seas. This is significant in suggesting the upwelling of deeper colder waters, a phenomenon that is common in the coastal waters of southern California and in the Gulf of California. A pronounced reduction in temperatures of the later Cretaceous is also indicated in the paleotemperature studies of Urey, Lowenstam, Epstein, and McKinney (1951, p. 415) in their work on oxygen isotopes in belemenites of England.

Keeled globorotaloids and diversified globigerinids of the Cenozoic appeared in abundance in tropical regions in the middle of the Paleocene, expanding rapidly into latitudes as far north as 45 or 50 degrees and continuing there until middle Eocene time. During the middle Eocene (Lutetian) there was progressive restriction of the tropical diversified planktonic faunas to within less than 40 degrees N. latitude. Following this retreat there was one more expansion northward in the late Eocene into the Aquitaine Basin of southern Europe, otherwise the tropical diversified planktonic faunas were quite restricted to the general zonation observed in modern oceans.

It is important to note that planktonic tropical Foraminifera are restricted to a zone within 30 degrees of the equator plus or minus 10 degrees. The 20 degree variation in the northern limit of tropical faunas results from the clockwise gyrals of the currents in the northern hemisphere in which warm currents extend northward on the western sides of ocean basins and cold currents extend southward on the eastern sides. Analogous variations occur in the southern hemisphere as a result of the counterclockwise gyrals there.

The contrast between the temperature trends indicated by planktonic Foraminifera on the one hand and the molluscs, plants, and vertebrates on the other hand is plainly contradictory. One explanation is that the data are not as complete for the larger fossils as for the planktonic Foraminifera. For example, Durham's curve for the North American region is supported by molluscan evidence at scattered points with none for the lower Paleocene and uppermost Cretaceous (1950, Fig. 3). He does show warmer conditions (20 degree C. isotherm) in the later Eocene as far north as about 48 degrees N. latitude with supporting evidence. Perhaps the Foraminifera are much more sensitive to temperature changes than the larger fossils. It is important to note that larger fossils in Japan show that conditions in the Oligocene were cooler than they are now and that there was a warming of marine temperatures during the early Miocene (Hanzawa, 1950, p. 76).

Emiliani (1957) reported a gradual cooling of abyssal waters of the Pacific Ocean from Oligocene to the present based upon isotopic analyses of benthonic Foraminifera of the eastern equatorial Pacific Ocean. His fossil data indicate assemblages that are mixed in both age and ecology (Bandy, 1956, p. 459; Emiliani, 1956, p. 460). It is highly questionable that his assemblages lived in abyssal waters, and that they are all indigenous. For example, in his lower middle Miocene sample he reports *Pulleniatina obliquiloculata* which is a Pliocene to Recent species.

CONCLUSIONS

Commencing with the Late Cretaceous, planktonic Foraminifera indicate that there have been two major expansions of tropical marine faunas beyond the general limits of modern tropical faunas. The first expansion occurred in the Upper Cretaceous and the second in the later Paleocene and lower Eocene. A relatively minor third expansion occurred in the later Eocene. Otherwise, compressions and expansions of tropical marine faunas have affected the regions bounded by about 40 degrees N. and S. latitude.

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