OCEAN CIRCULATION DURING THE CENOZOIC

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Introduction

Today the surface circulation in the oceans is dominated by tropical-subtropical anticyclonic gyres in the northern and southern hemispheres, separated from cyclonic gyres in the polar regions by subtropical and polar fronts. The deep circulation acts as a conveyor, with surface water sinking to the depths in the Arctic and Norwegian-Greenland Sea, flowing southward in the interior of the Atlantic, then eastward through the Southern Ocean and turning northward through the depths of the Pacific. The loss of surface water from the Norwegian-Greenland Sea and Arctic is compensated by flow from the Pacific to the Indian Ocean, around Africa to the South Atlantic, across the equator to the North Atlantic and then across the Greenland-Scotland Ridge into the polar seas.

The distribution of Paleogene calcareous plankton indicates that the circulation then was very different and that there were no subtropical or polar fronts. The modern circulation developed in response to the opening of passages between Antarctica and Australia-Tasmania and South America, formation and subsidence of the Greenland-Scotland Ridge, and closure of the Tethys and Panamanian Isthmus. Each of these events changed ocean circulation, initially by redirecting the flows of currents as passages opened, and later by creating salinity differences between the oceans as connections closed. These changes in ocean circulation also had a profound effect on the evolution of the global climate during the Cenozoic.

The Distribution of Calcareous Plankton during the Paleogene

The classic zonations with calcareous plankton were established in the tropics. The Paleogene planktonic foraminiferal zonations were based on observations in the Caucasus, the southern and eastern United States, and most importantly, Trinidad in the West Indies. The calcareous nannoplankton zonations were based on sections in the Alps, southern California, and the U.S. Gulf Coast. When these zonations were established it was not considered likely that they could also be used at high latitudes. Both the planktonic foraminifers and the calcareous nannoplankton were assumed to have their greatest diversity in the tropics as they do today.

Figs 1-8 show the distribution of six species of calcareous nannoplankton and two species of planktonic foraminifer important for Paleocene, Eocene and Oligocene stratigraphic zonations. The calcareous nannoplankton have a better paleobiogeographic record in that they are found at more sites, than the planktonic foraminifera because they are more resistant to solution. It is evident that none of the Paleocene, Eocene or Early Oligocene species is restricted to the tropics. All of these species appear to be cosmopolitan, extending to high latitudes in the southern Atlantic and Indian Oceans. There is unfortunately little data from deep-sea sections in the North Atlantic that would enable us to determine their full northern latitudinal extent, but is known that many of these species occur in land sections in northern Europe.

About 30 million years ago a major change took place. The ranges of the Late Oligocene species of both calcareous nannoplankton and planktonic foraminifera became more restricted and no longer extended into the circumantarctic region.

What does this changing distribution of calcareous plankton imply? Today the calcareous plankton are essentially restricted to the region between the polar fronts, with most species being restricted to the somewhat narrower band between the subtropical fronts. It was probably during the Middle Oligocene that the subtropical and polar frontal systems developed in the Atlantic and Indian Oceans.

The record of DSDP and ODP sites in the far southern Pacific is not adequate to determine whether an Antarctic Polar Front and Subtropical Front existed in that sector in the Early Paleogene, but studies of the planktonic foraminifera and calcareous nannoplankton of New Zealand suggest that the frontal systems came into existence during the Oligocene (Nelson and Cooke, 1999).

Discussion

As discussed by Hay (1995), the modern ocean can be thought of as comprised of four units, three of which are mirrored in each hemisphere. There is an equatorial belt characterized by divergence and shared by the two hemispheres. Poleward of the equatorial belt, to about 45-50° N or S latitude the ocean surface is occupied by the great, stratified tropical-subtropical anticyclonic gyres. Narrow bands of temperate water characterized by convergence and steep meridional temperature gradients bound the poleward margins of the tropical-subtropical gyres at the mid-latitudes. Beyond these lie the deeply convecting polar oceans characterized by cyclonic gyres. The convergences and divergences of the ocean waters are forced by the winds.

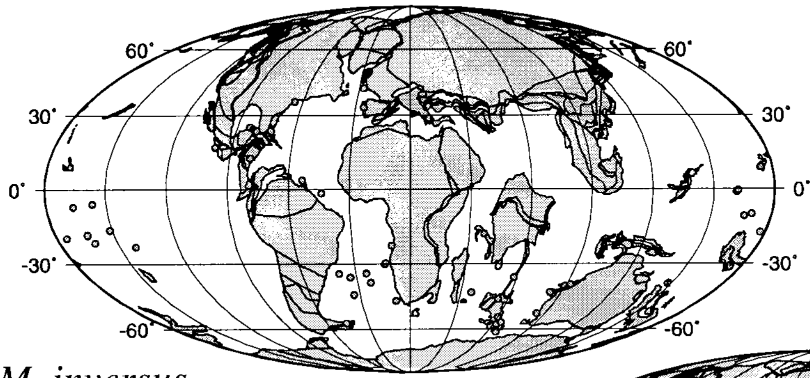


Fig. 1. Paleobiogeographic distribution of theEarly Paleocene calcareous nannoplankton species *Markalius inversus.*

M. inversus

64.0 Ma Reconstruction

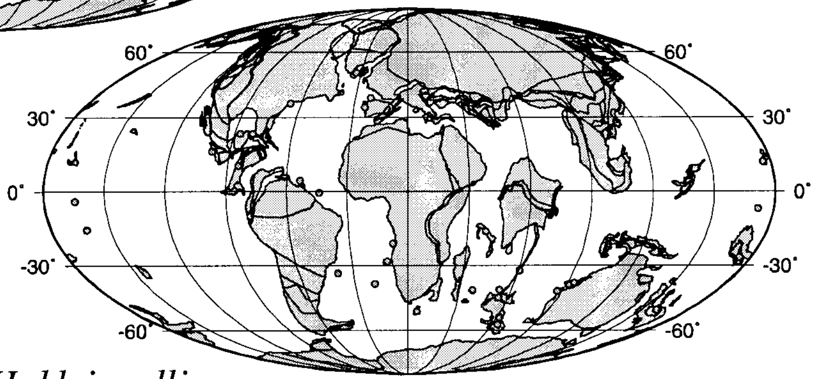


Fig. 2. Paleobiogeographic distribution of the Middle Paleocene calcareous nannoplankton species *Heliolithus kleinpelli.*

H. kleinpelli

58.0 Ma Reconstruction

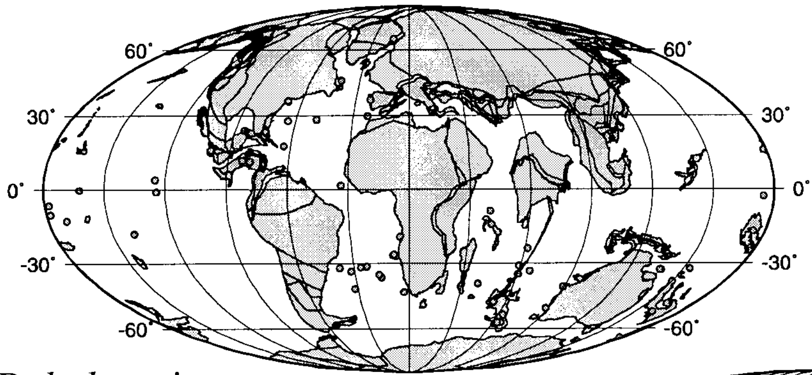


Fig. 3. Paleobiogeographic distribution of the Late Paleocene calcareous nannoplankton species *Discoaster lodoensis.*

D. lodoensis

50.0 Ma Reconstruction

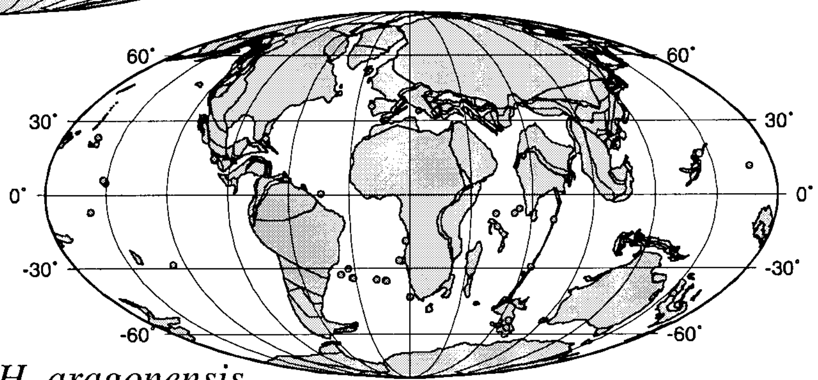
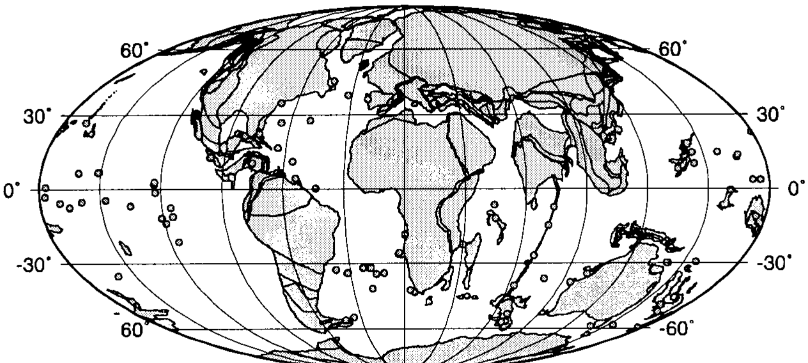


Fig. 4. Paleobiogeographic distribution o the Middle Eocene planktonic foraminiferal species *Hantkenina aragonensis.*

H. aragonensis

43.6 Ma Reconstruction

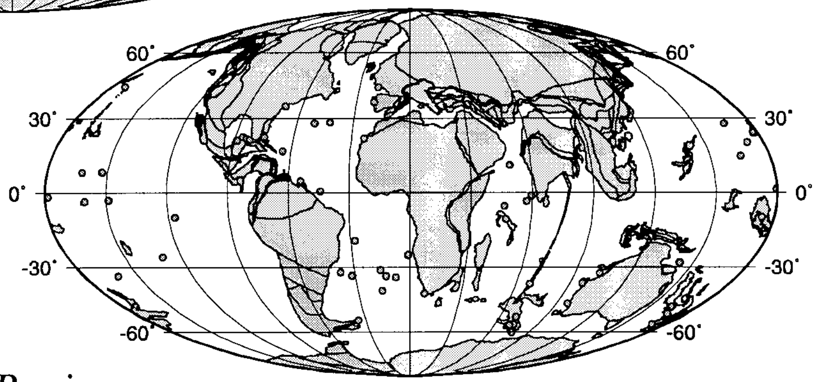
The separation into anticyclonic and cyclonic gyres is of fundamental importance to the way the ocean operates. The motion of water in the middle of an anticyclonic gyre is downward, forcing lower density surface waters down and forming a strong stratification with the underlying dense deep waters. The motion in the center of a cyclonic gyre is upward, promoting open ocean upwelling. However, this



D. saipanensis

38.6 Ma Reconstruction

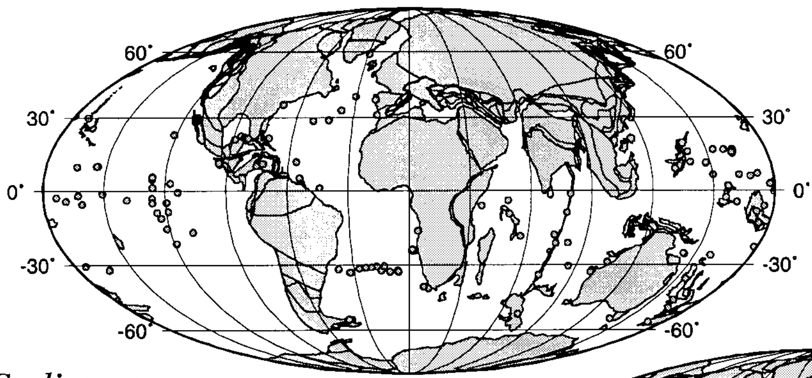
Fig. 5. Paleobiogeographic distribution o the Late Eocene calcareous nannoplankton species *Discoaster saipanensis*.



P. micra

33.2 Ma Reconstruction

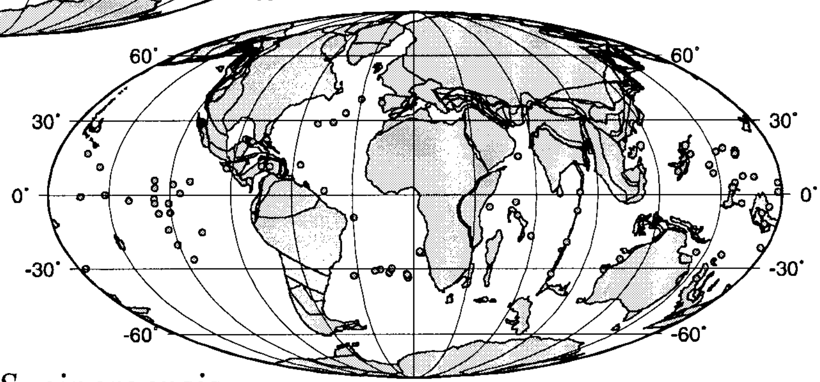
Fig. 6. Paleobiogeographic distribution of the Early Oligocene planktonic foraminiferal species *Pseudohastigerina micra*.



S. distentus

27.5 Ma Reconstruction

Fig. 7. Paleobiogeographic distribution of the Late Oligocene calcareous nannoplankton species *Sphenolithus distentu*.



S. ciperoensis

23.3 Ma Reconstruction

Fig. 8. Paleobiogeographic distribution of the Late Oligocene calcareous nannoplankton species *Sphenolithus ciperoensis*.

upward motion also has the effect of destroying the density stratification and making it possible for dense waters formed at the surface to sink into the deep sea (for a discussion, see Hay, 1993).

The subtropical and polar frontal systems are generated by the maximum of the zonal component of the westerly winds. This occurs at about 45° N and S, but because of the instability of the westerlies the maximum zonal velocity varies over about 10-15E of latitude. In this temperate region, which occupies about 11% of the ocean surface, the ocean waters reach their greatest meridional velocity, flowing equatorward and tending to override waters at the adjacent lower latitudes. This forces the waters to sink along a series of convergences. The subtropical fronts form an effective barrier to poleward ocean heat transport in the Pacific Ocean. However, the ocean currents transport heat northward throughout the Atlantic. This is a consequence of deep-water formation in the Norwegian-Greenland Sea. The loss of water from the surface there induces resupply across the subtropical fronts. The polar fronts lie along the poleward boundary of the region of sinking and form the boundary of the polar oceans.

The present configuration of the ocean makes it possible to maintain a sharp separation between the anticyclonic circulation of the tropical-subtropical gyres and the cyclonic circulation of the polar gyres. It also helps to make the polar gyres the preferred sites for deep-water formation.

What would the ocean circulation be like if there were no subtropical and polar fronts? Deep-water formation would be forced to sites along the arid margins of the tropical-subtropical gyres or into low latitude cyclonic gyres.

Formation of warm saline waters in shallow shelf seas and restricted marginal seas along the ocean margin in latitudes where evaporation greatly exceeds precipitation may have been a source of deep water, as suggested by Brass et al. (1982). The configuration of the closing Tethys is not well known and it may have been a site of formation of warm saline deep waters. There are relatively few areas where shelf seas could have served as sources of warm saline deep water.

The possibility of cyclonic gyres in the tropics and subtropics during the Paleogene has not been explored. The first major subtropical cyclonic gyre in the modern ocean was not discovered until the last decade. Until recently it was thought that the circulation in the South Atlantic had the form of a single large subquadrate anticyclonic gyre (Schott, 1942). More recent analysis has shown that the anticyclonic gyre of the South Atlantic has a triangular form. There is a small cyclonic gyre in the northeast South Atlantic that includes the Angola Dome (Peterson and Stramma, 1991). The eastern side of this cyclonic gyre is the southward-flowing Angola Coastal Current. Similar low latitude cyclonic gyres may have existed in the Paleogene.

There is some evidence for cyclonic circulation during the Eocene in the distribution of deposits rich in siliceous microfossils such as diatoms and radiolarians. These siliceous deposits occur over large areas of the Central Atlantic, and suggest that there was open ocean upwelling in this region. Open ocean upwelling implies cyclonic circulation.

Conclusions

The evidence from calcareous plankton suggests that ocean circulation in the Paleocene, Eocene and Early Oligocene may have been very different from that of today. The apparent lack of subtropical and polar frontal systems in the Atlantic, Indian and southern Pacific sectors suggests that deep-water formation mechanisms may have been different. Most likely deep waters were produced from warm saline waters that formed in restricted marginal seas or in cyclonic gyres and sank into the deep sea.

References

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