# Quaternary climatic changes indicated by planktonic foraminifera of Northern Indian Ocean

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**The relative abundances of planktonic foraminifera, the changes in their coiling and the isotopic record from deep sea cores of some crucial sites in Northern Indian Ocean indicate climatic fluctuations for the past 3.0 million years (Late Pliocene to Pleistocene). The abundance of temperate forms like *Globigerina* spp. together with sporadic occurrence of a polar species *Neogloboquadrina pachyderma* during specific time intervals suggest cooling episodes. Warmer intervals are marked by the dominance of tropical assemblages including *Globigerinoides* spp., *Globorotalia* s.l., *Pulleniatina* and *Globoquadrina*. On the basis of the planktonic foraminiferal frequency changes, four intervals of major climatic cooling have been recognized — one in the Late Pliocene (2–3 m.y.), three in the Pleistocene immediately above the Pliocene/Pleistocene boundary (1.6 m.y.), at 0.6 m.y., and during the late Pleistocene. Marked shift in coiling directions within *Pulleniatina* populations and *Globorotalia* s.l. is observed to coincide with the frequency changes.**

**There was marked increase of $\delta^{18}O$ values in oxygen isotopic record of foraminiferal tests around 2–3 m.y. (Late Pliocene) and within the Pleistocene. Major faunal turnover accompanied by changes in coiling synchronous with the isotopic shifts, suggest these faunal changes to be climatically induced.**

## Introduction

A number of fluctuations in the earth's climatic history during the Quaternary have been identified. Our present knowledge of the Quaternary climatic record of the continents has been exclusively derived from the investigations made on terrestrial sediments. In recent years with the advent of the Deep Sea Drilling Project (DSDP) and Ocean Drilling Programmes (ODP) much new data have been gathered about the climatic changes during the Quaternary.

In the Indian subcontinent the Quaternary sequences are represented by continental facies (sub-Himalaya), marine transgressional facies (Kachchh-Saurashtra, Kerala and Coromandal Coast) and deep water marine facies (Andaman-Nicobar Islands). The continental facies dominates. Extensive studies reveal that coastal and deep water marine facies are patchy and scanty exhibiting only incomplete record of the Quaternary, although almost a complete record is represented by the continental facies of the Siwaliks in the sub-Himalaya. Since the terrestrial Quaternary sequences are disturbed and discontinuous due to neotectonic events and attendant erosion, the palaeoclimatic imprints are not well preserved in these sequences. On the other hand, the deep sea sequences provide an undisturbed and complete record of the Quaternary.

The investigations carried out so far on the Quaternary sediments in India were mainly confined to the problem of demarcating the Neogene/Quaternary (N/Q) boundary. On the other hand, detailed investigations have been carried out on the Quaternary deep sea cores of the Atlantic and Pacific Oceans employing modern approaches to palaeoceanography and palaeoclimatology. Such studies on the Indian Ocear deep sea cores have not been seriously undertaken so far. However, in recent years there has been a growing realization of the importance of the Quaternary deep sea sequences in the Indian Ocean from the palaeoceanographic and palaeoclimatic points of view. This led to quite a few significant contributions on the foraminiferal studies of top cores and to understanding the pattern of climatic fluctuations during the Late Quaternary in the Arabian Sea, Southwest Indian Ocean and Northern Indian Ocean[1-8].

During the last few years a comprehensive study on both planktonic and benthic foraminifera and stable isotope records (oxygen and carbon) of foraminiferal tests from the Indo-Pacific deep sea cores was initiated by Srinivasan and his coworkers[9-20] at the Banaras Hindu University as a part of the international project on the Cenozoic Palaeoceanography Programme (CENOP).

In this paper an attempt is made to decipher the climatic changes in the oceanic materials of the Northern Indian Ocean during the Quaternary, on the basis of qualitative and quantitative planktonic foraminiferal data and the stable isotope record.

## DSDP sites in Northern Indian Ocean

In the early 1970s the Indian Ocean was the centre of drilling activities by JOIDES Deep Sea Drilling Project, and several sites were drilled during DSDP Legs 22 through 29. The four sites (214, 219, 237 and 238) selected for present investigation (Figure 1), are ideal for planktonic foraminiferal biostratigraphic and palaeoceanographic studies because of their continuous coring and good faunal preservation.

DSDP site 214 was drilled along the crest of Ninetyeast Ridge at water depth of 1665 m, whereas site 219 is situated on the crest of Chagos-Laccadive Ridge, a north-south trending structure extending southward from the eastern margin of the Arabian Sea (water depth—1764 m). Site 237 was drilled on the Mascarene Plateau in the saddle joining the granitic Seychelles Bank to the volcanic Saya de Malha Bank (water depth—1640 m). On the other hand, site 238 is located east of the Central Indian Ridge near the southern end of the Chagos-Laccadive at the extreme northeast end of Argo Fracture Zone (water depth—2832 m). The details of samples and location of examined DSDP sites are presented in Table 1.

Eightynine samples of approximately 10 $cm^3$ volume from the DSDP sites 214, 219, 237 and 238 were examined at regular stratigraphic intervals of one sample per section spanning the time range from Late Pliocene to Quaternary.

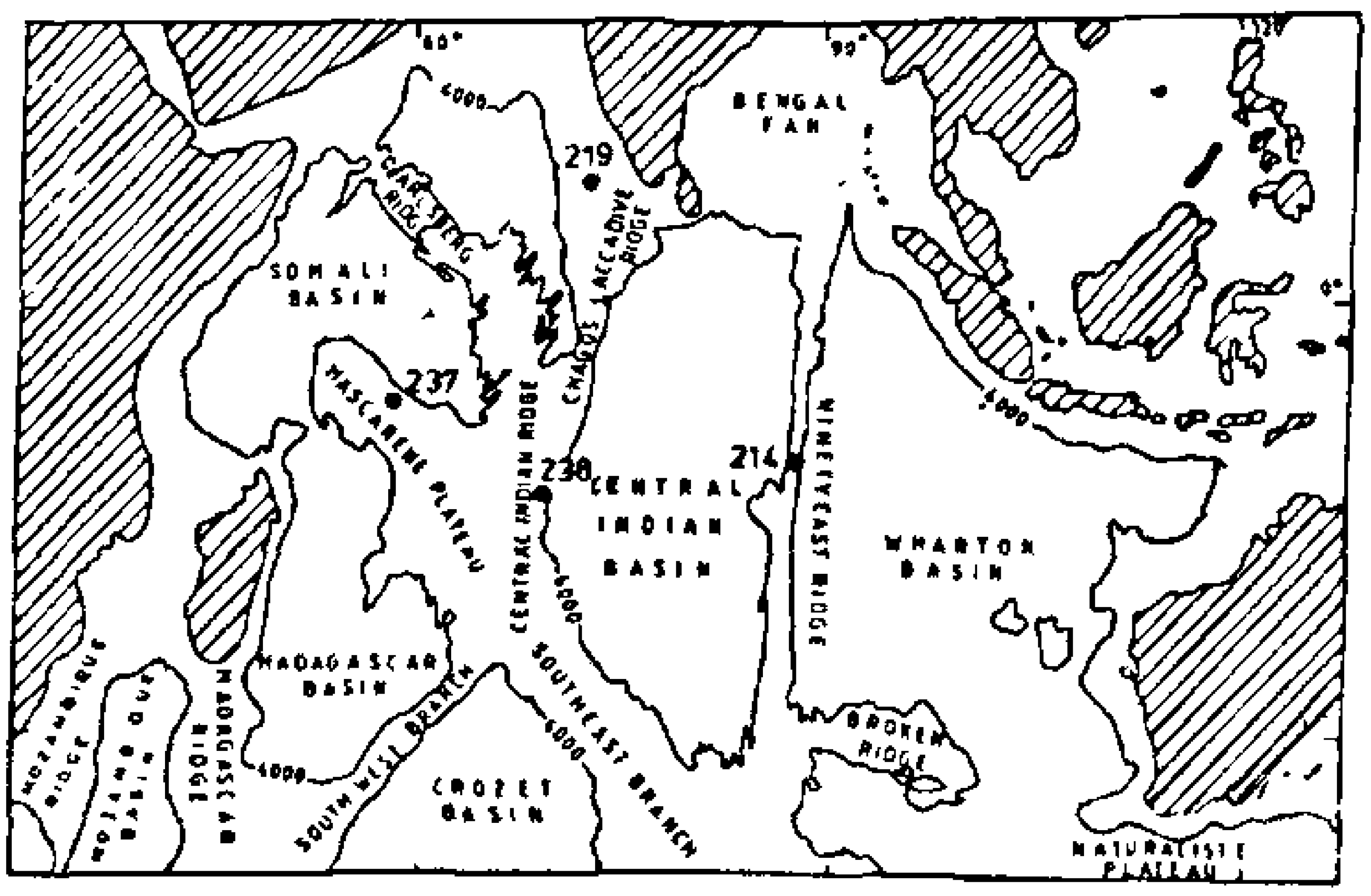


Figure 1. Physiography of the Indian Ocean (after Davies et al.[35]) and the location of the DSDP sites examined

## Quaternary biochronology

The Neogene planktonic foraminiferal events [First Appearance (F.A.) and Last Appearance (L.A.)] in deep sea sections calibrated with palaeomagnetic time scale provide an excellent chronological framework. Many of these events have been demonstrated as isochronous global events by employing Graphic Correlation Technique[21,22]. At the examined sites nine such events have been identified during the Late Pliocene–Pleistocene (Table 2). Of these *Globigerinoides fistulosus* F. A. (3.2 m.y.), *Globorotalia tosaensis* F. A. (3.1 m.y.), *Globorotalia truncatulinoides* F. A. (1.9 m.y.) and *Globarotalia tosaensis* L. A. (0.6 m.y.) mark the zonal boundaries (Figure 2). Figure 3 shows the Late Pliocene–Pleistocene planktonic foraminiferal zones with their thickness at the examined DSDP sites.

## The Pliocene/Pleistocene boundary

The demarcation of the Pliocene/Pleistocene (Neogene/Quaternary) boundary has been a subject of major controversy for several decades. This controversy has now been solved to a great extent by integrated approach using multiple microfossil biostratigraphy, magnetochronology, radiochronology and isotope records. On the basis of integrated biomagnetoradiochronologic studies, the Pliocene/Pleistocene boundary has now been placed at the top of the Olduvai Normal Event dated[23] at 1.6 m.y. Critical examination of the tropical to subtropical Late Neogene planktonic foraminiferal datums from the Indo-Pacific deep sea cores reveal that the *Globigerinoides fistulosus* LAD (Last Appearance Datum) is virtually coincident with the top of the Olduvai Normal Event[23,24]. Therefore, *Globigerinoides fistulosus* LAD marks the Pliocene/Pleistocene boundary (Figure 2).

## Climatic changes

Planktonic foraminifera as compared to other microfossil groups have been used widely to understand

Table 1. Details of core samples and location of examined DSDP sites in Northern Indian Ocean

| DSDP site | Physiographic province | Latitude | Longitude | Water depth (m) | Number of studied samples | Core length (m) |
|---|---|---|---|---|---|---|
| 214 | Ninetyeast Ridge | 11° 20.21′ S | 88° 43.08′ E | 1165 | 27 | 47.5 |
| 219 | Chagos-Laccadive Ridge | 9° 01.75′ N | 72° 52.67′ E | 1764 | 22 | 42.0 |
| 237 | Mascarene Plateau | 7° 04.99′ S | 58° 07.48′ E | 1640 | 12 | 35.0 |
| 238 | Central Indian Ridge | 11° 09.21′ S | 70° 31.56′ E | 2832 | 28 | 49.0 |

**Table 2.** Late Pliocene-Pleistocene planktonic foraminiferal datums recognised and their estimated ages[23,34]

| | |
|---|---|
| *Globorotalia tosaensis* LAD | 0.6 m.y. |
| *Globigerinoides obliquus* LAD | |
| *Globigerinoides fistulosus* LAD | 1.6 m.y. |
| *Globorotalia truncatulinoides* FAD | 1.9 m.y. |
| *Globorotalia multicamerata* LAD | 2.9 m.y. |
| *Dentoglobigerina altispira altispira* LAD | 2.9 m.y. |
| *Sphaeroidinellopsis* LAD | 3.0 m.y. |
| *Globorotalia tosaensis* FAD | 3.1 m.y. |
| *Globigerinoides fistulosus* FAD | 3.2 m.y. |

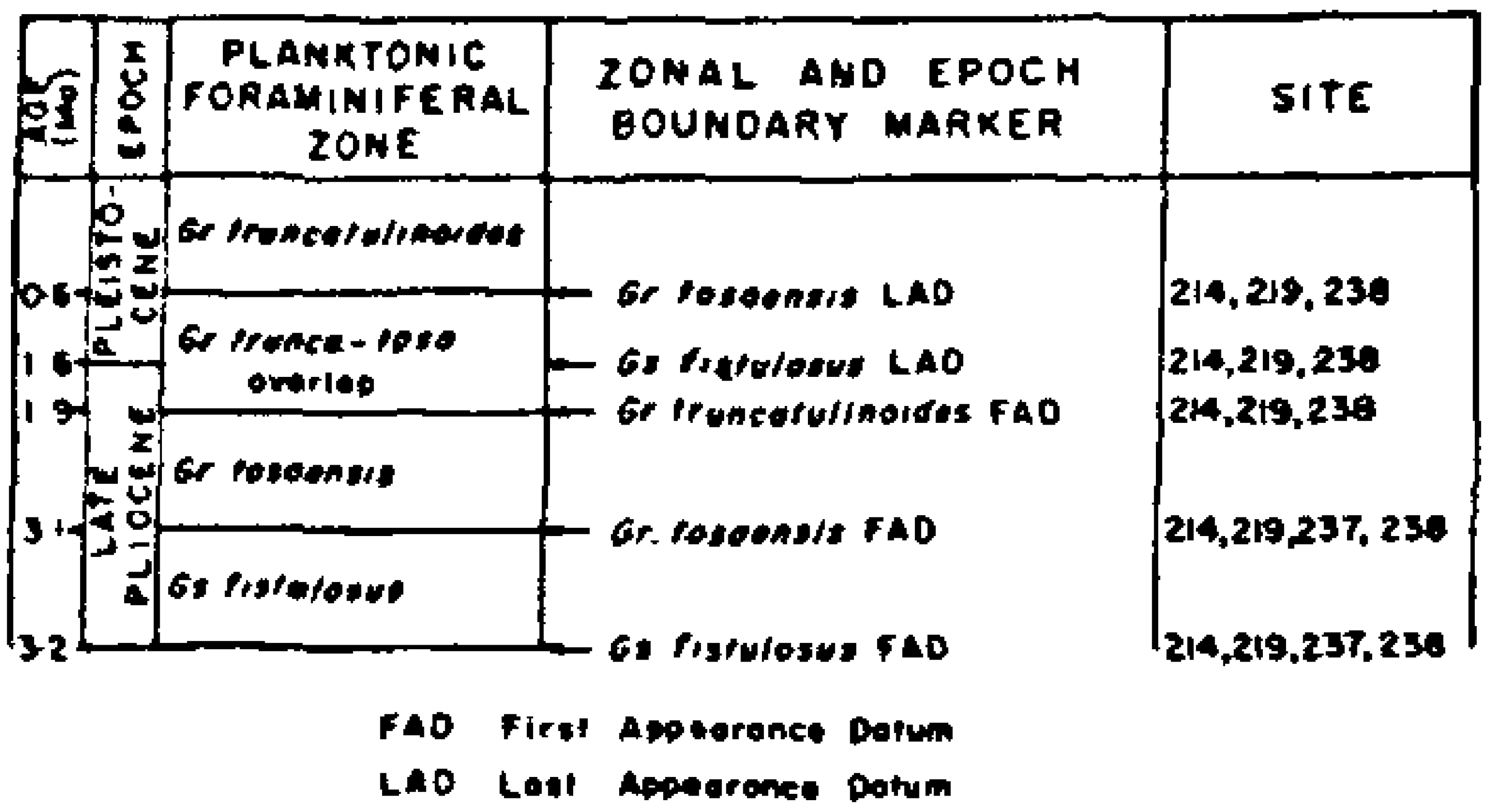


**Figure 2.** Epoch- and zonal boundaries and markers used in the present study.

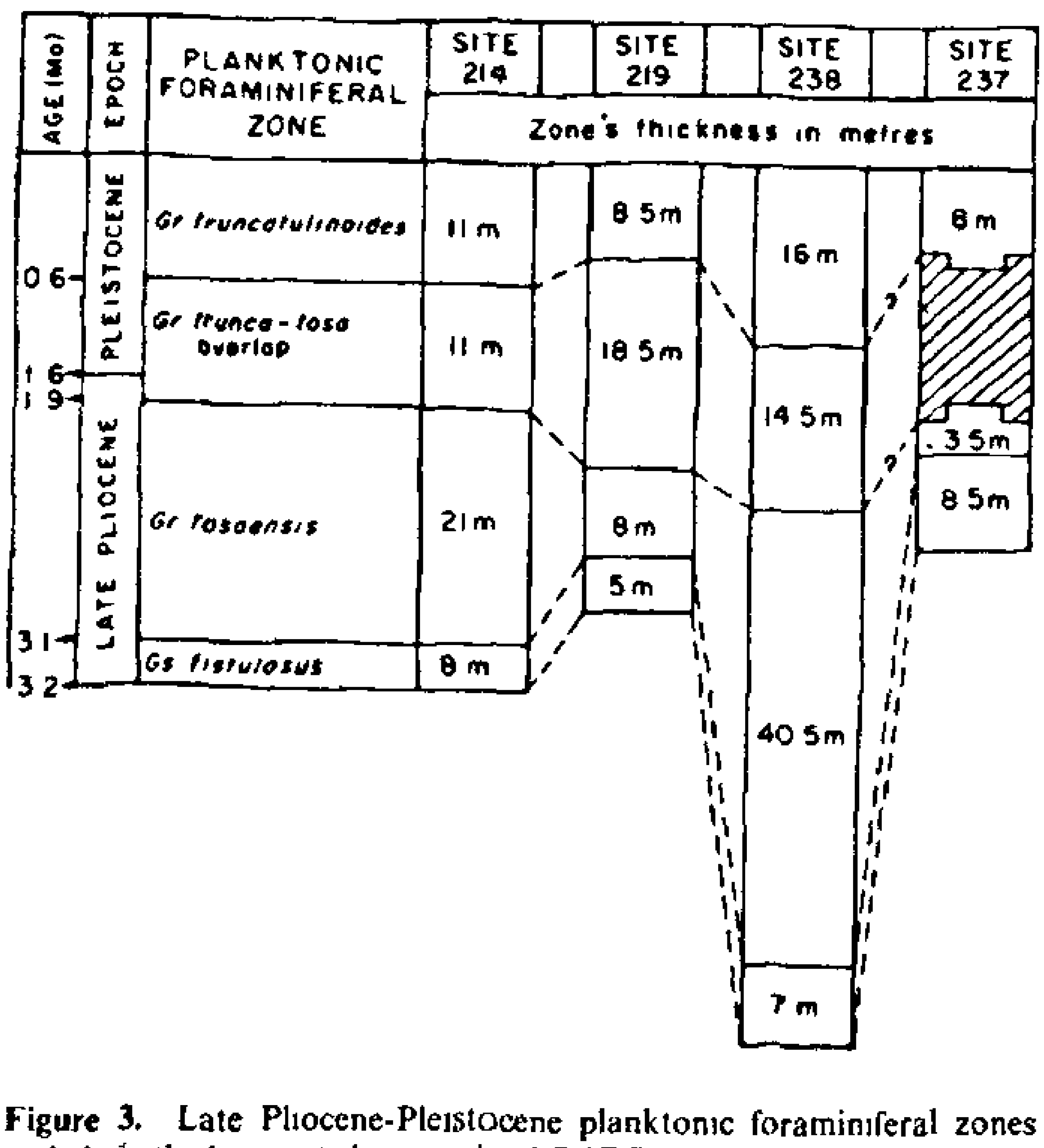


**Figure 3.** Late Pliocene-Pleistocene planktonic foraminiferal zones and their thickness at the examined DSDP sites.

palaeoclimatic and palaeoceanographic changes, because of their high abundance in deep sea sediments, high rate of faunal turnover and having significant response to climatic fluctuations. Investigations carried out on modern planktonic foraminifera have indicated that their distribution is primarily controlled by watermass conditions reflecting surface and near surface sea temperatures[20,25-28]. Keeping this in view the Neogene planktonic foraminiferal species were grouped into four major assemblages representing tropical, subtropical, transitional-temperate and subantarctic bioprovinces[20,27,28]. The planktonic foraminiferal assemblages in the present study have been grouped into—(i) tropical water species, (ii) temperate water species, and (iii) polar species (cold water species) (Table 3). Since the examined sites are optimal for tropical assemblages, the relative increase in the abundance of temperate forms during specific time intervals reflects palaeoclimatic/palaeoceanographic changes attributable to the increase in the volume of polar ice. The presence of the polar species, *Neogloboquadrina pachyderma* in a few core samples further testifies to the upwelling and influence of cold polar waters (Figures 4 to 7).

An attempt has also been made to study the pattern of coiling changes in some important planktonic foraminifera (*Pulleniatina* and *Globorotalia* s.l.) in order to observe whether the changes in coiling pattern have any link with major faunal turnovers and changing watermass conditions.

## Results and discussion

The per cent abundances of important tropical to temperate planktonic foraminiferal assemblages from the DSDP sites 214, 219, 237 and 238 in Northern Indian Ocean plotted against time reveal a number of distinct oscillations during the Late Pliocene and Pleistocene (Figures 4 to 7). These fluctuations in the planktonic foraminiferal assemblages appear to be closely linked with major palaeoceanographic changes triggered by global climatic changes. Four intervals of such major faunal changes have been observed one in the Late Pliocene and three in the Pleistocene.

**Table 3.** Important planktonic foraminiferal species used for palaeoclimatic and palaeoceanographic interpretations

| |
|---|
| Tropical water species: |
| *Globigerinoides* spp. |
| *Globigerinoides conglobatus*, |
| *Globigerinoides triloba*, |
| *Globigerinoides quadrilobatus*, |
| *Globigerinoides sacculifer*, |
| *Globigerinoides ruber*. |
| *Globorotalia* s.l. |
| *Globorotalia menardii*, *Globorotalia tumida tumida*. |
| *Pulleniatina obliquiloculata* |
| *Globoquadrina venezuelana* |
| Temperate-water species: |
| *Globigerina* spp. |
| *Globigerina bulloides*, *Globigerina falconensis*, |
| *Globigerina quinqueloba* |
| Polar species: |
| *Neogloboquadrina pachyderma* |

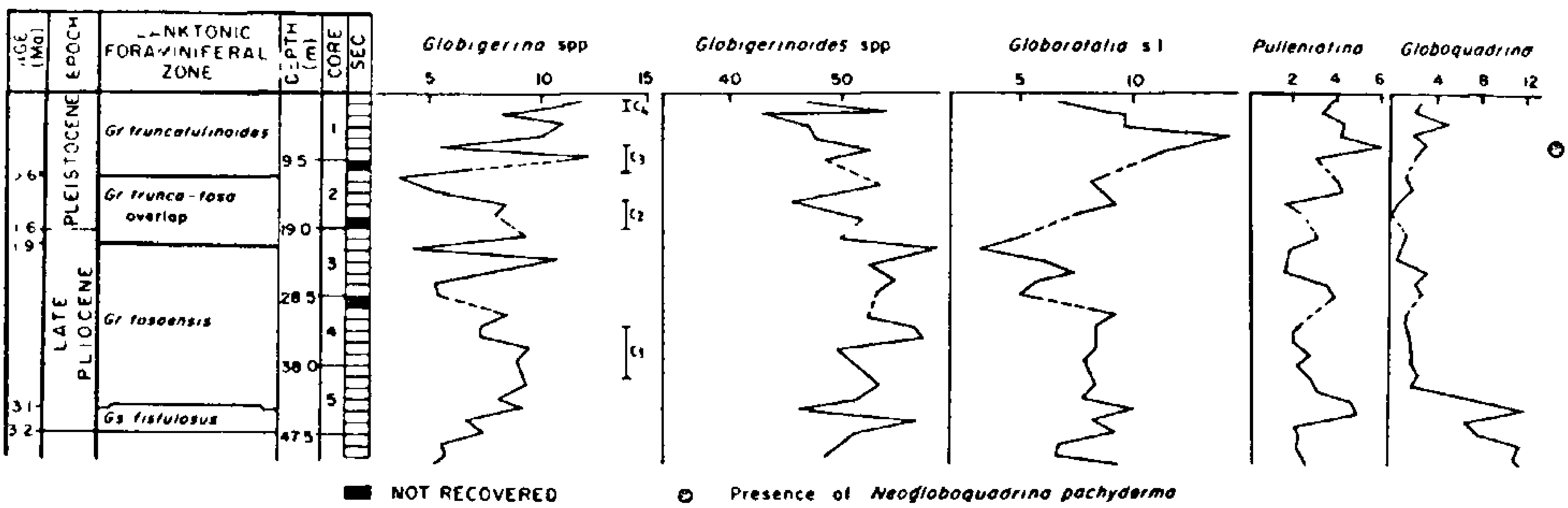


Figure 4. Per cent distribution of *Globigerina* spp, *Globigerinoides* spp., *Globorotalia* s.l., *Pulleniatina* and *Globoquadrina* at DSDP site 214 ($C_1$, $C_2$, $C_3$ and $C_4$ indicate Cool Events).

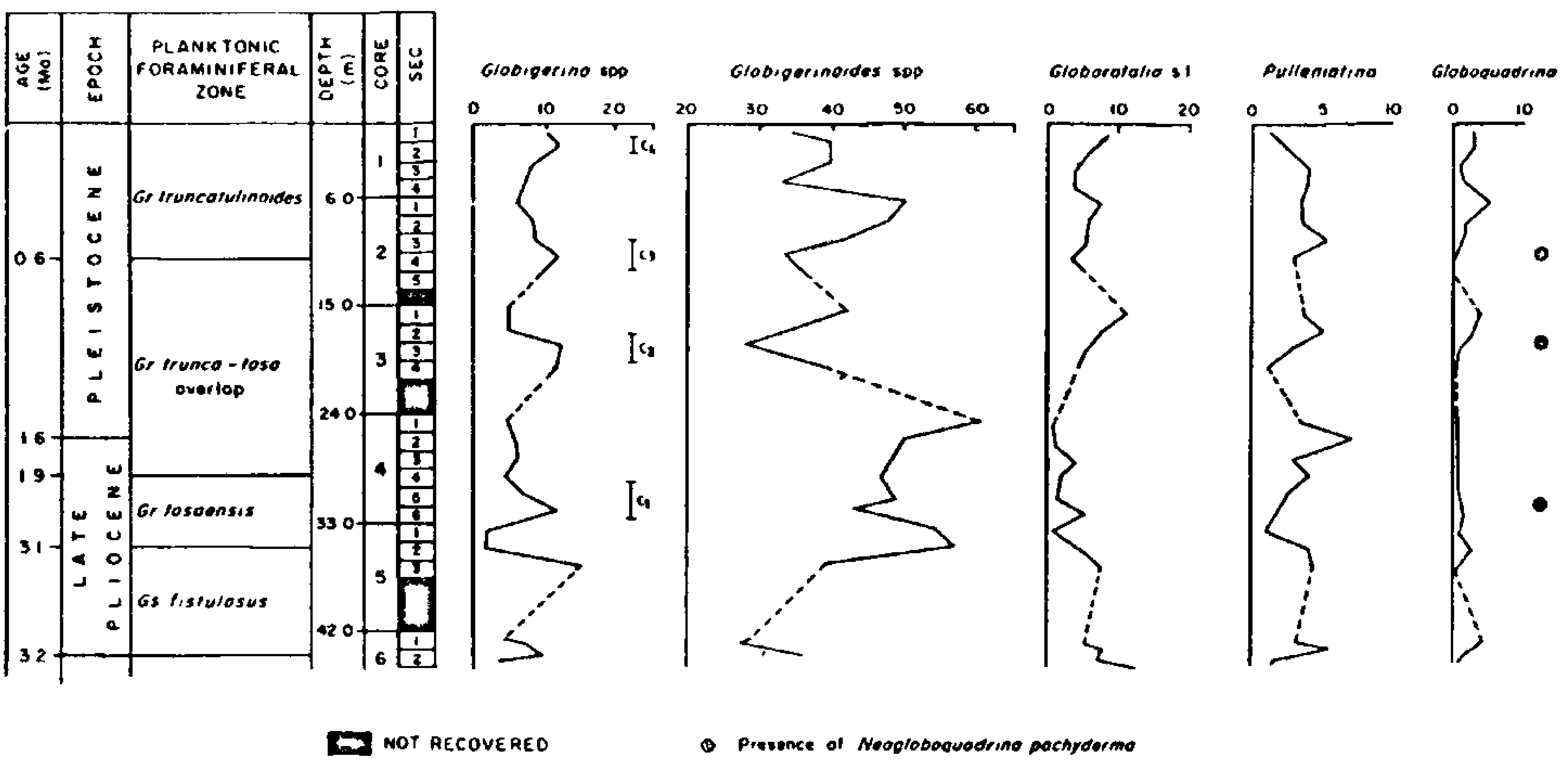


Figure 5. Per cent distribution of *Globigerina* spp., *Globigerinoides* spp., *Globorotalia* s.l., *Pulleniatina* and *Globoquadrina* at DSDP site 219 ($C_1$, $C_2$, $C_3$, and $C_4$ indicate Cool Events).

During the Late Pliocene (2–3 m.y.), a general increase in the abundance of the temperate form *Globigerina* spp. and corresponding decrease in the tropical assemblages (*Globigerinoides* spp., *Globorotalia* s.l., *Pulleniatina* and *Globoquadrina*) reflects cooling of surface waters in the Northern Indian Ocean (Figures 4 to 7). The presence of *Neogloboquadrina pachyderma* (a polar species) in core 4, sec. 6 at site 219 suggests upwelling and flow of cold polar waters to the Arabian Sea during this time. A shift in coiling pattern within the *Pulleniatina* population (dextral to sinistral) and *Globorotalia* s.l. (sinistral to dextral) is observed to coincide with the major faunal change during Late Pliocene (2–3 m.y.) This fact supports the conclusion that coiling changes in some planktonic foraminiferal groups are linked with the palaeoceanographic changes (Figures 8, 9). It may be emphasized that the nature of coiling changes differs in different planktonic foraminiferal groups.

During Late Pliocene times oxygen isotope record of foraminiferal tests shows a noticeable increase in $\delta^{18}O$ values, which has been commonly interpreted to reflect the cooling of waters in high latitudes and the expansion of polar ice sheets[17,29]. The deep sea benthic foraminifera also indicate bottom-water cooling during the Late Pliocene in the Northern Indian Ocean[18], similar to the surface-water cooling indicated by the planktonic foraminifera.

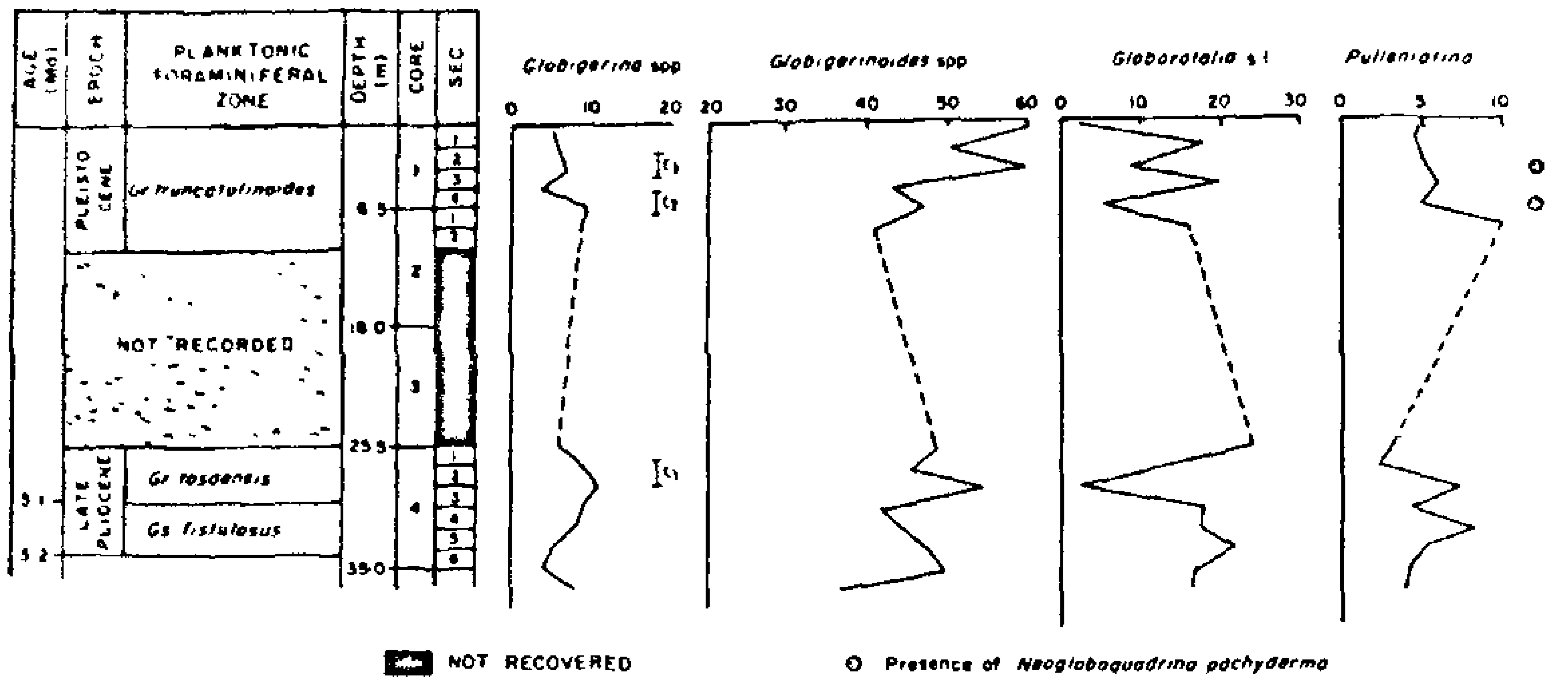

Figure 6. Per cent distribution of *Globigerina* spp., *Globigerinoides* spp., *Globorotalia* s.l., and *Pulleniatina* at DSDP site 237 ($C_1$, $C_2$, and $C_3$ indicate Cool Events).

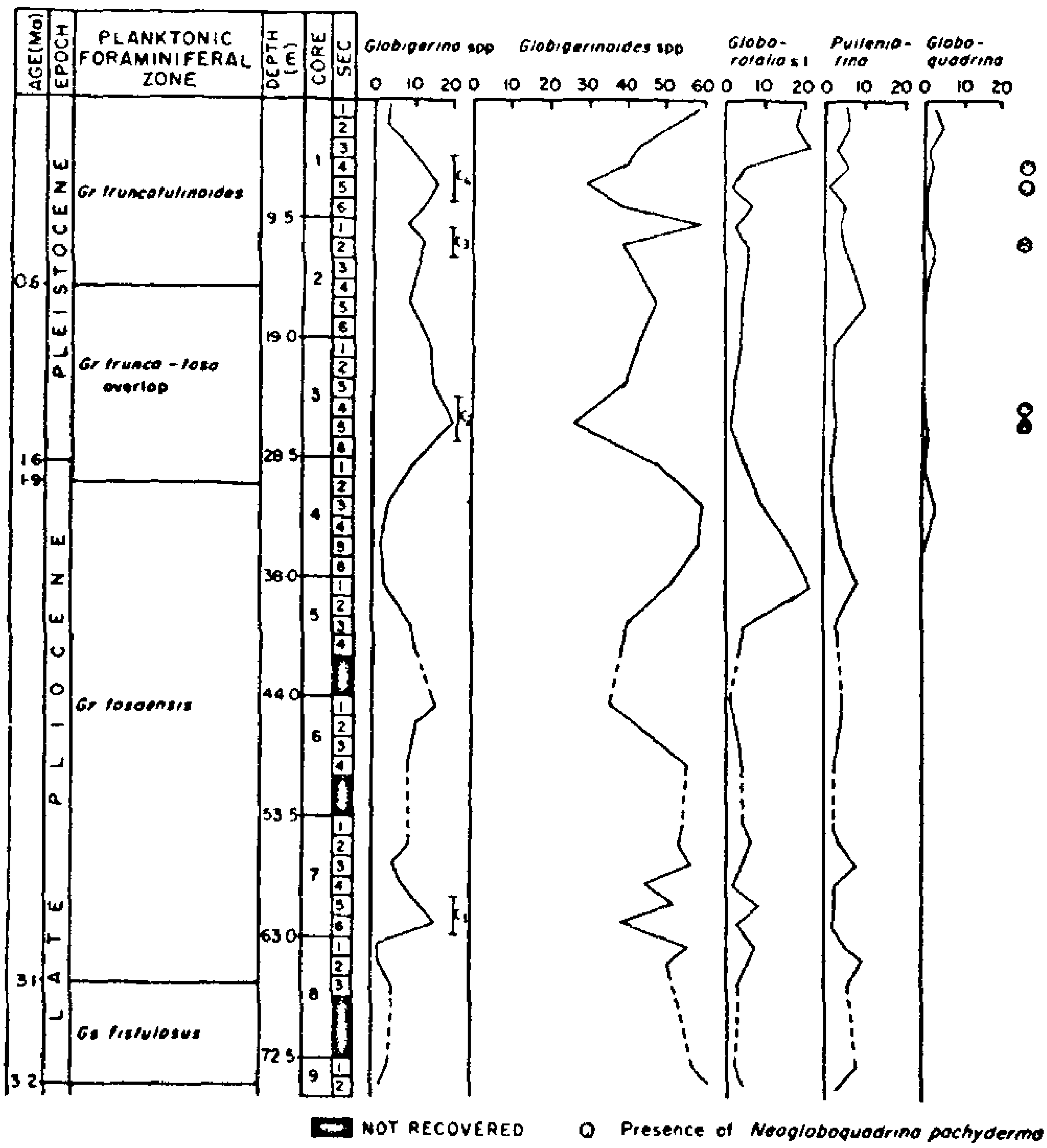

Figure 7. Per cent distribution of *Globigerina* spp., *Globigerinoides* spp., *Globorotalia* s.l., *Pulleniatina* and *Globoquadrina* at DSDP site 238 ($C_1$, $C_2$, $C_3$ and $C_4$ indicate Cool Events).

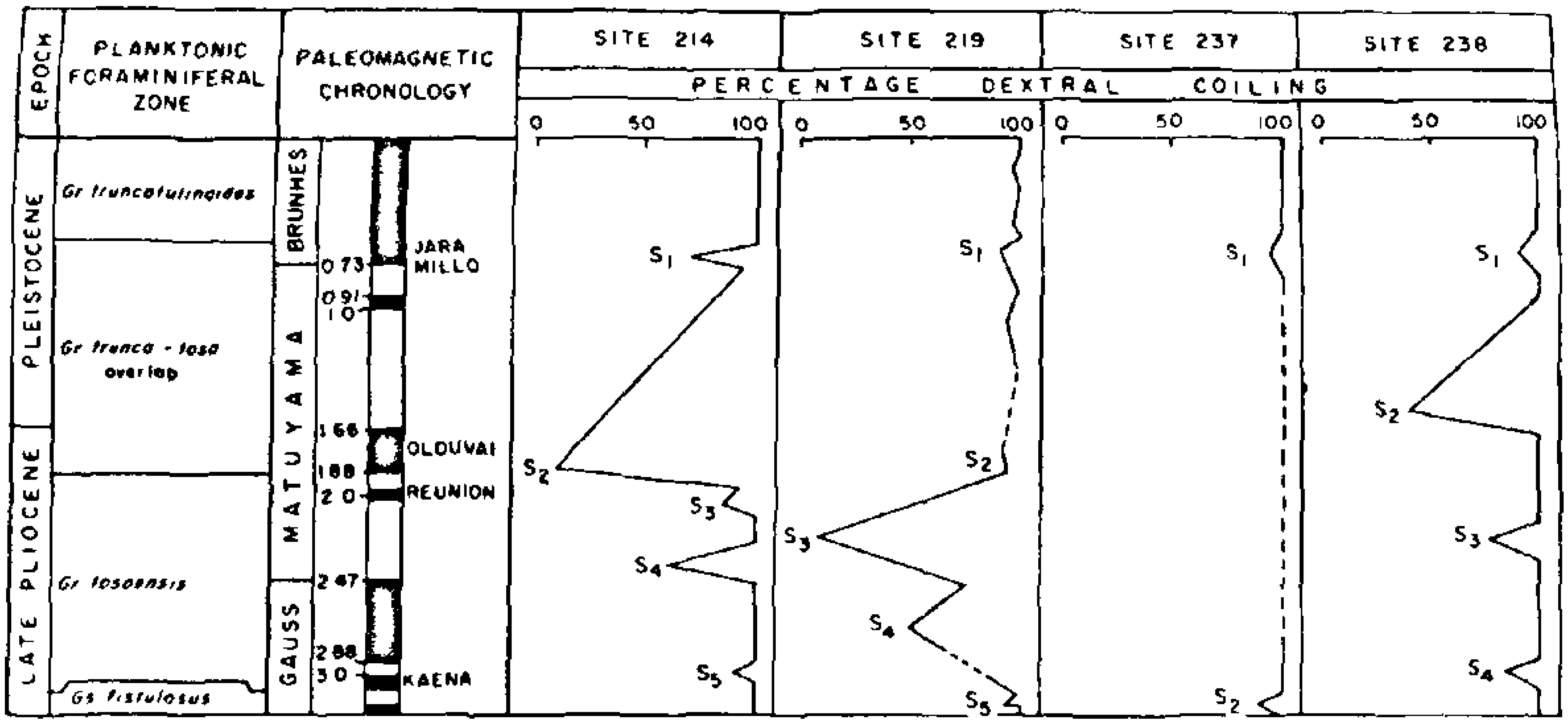

**Figure 8.** Coiling direction of *Pulleniatina* since 3 m.y. in the Northern Indian Ocean.

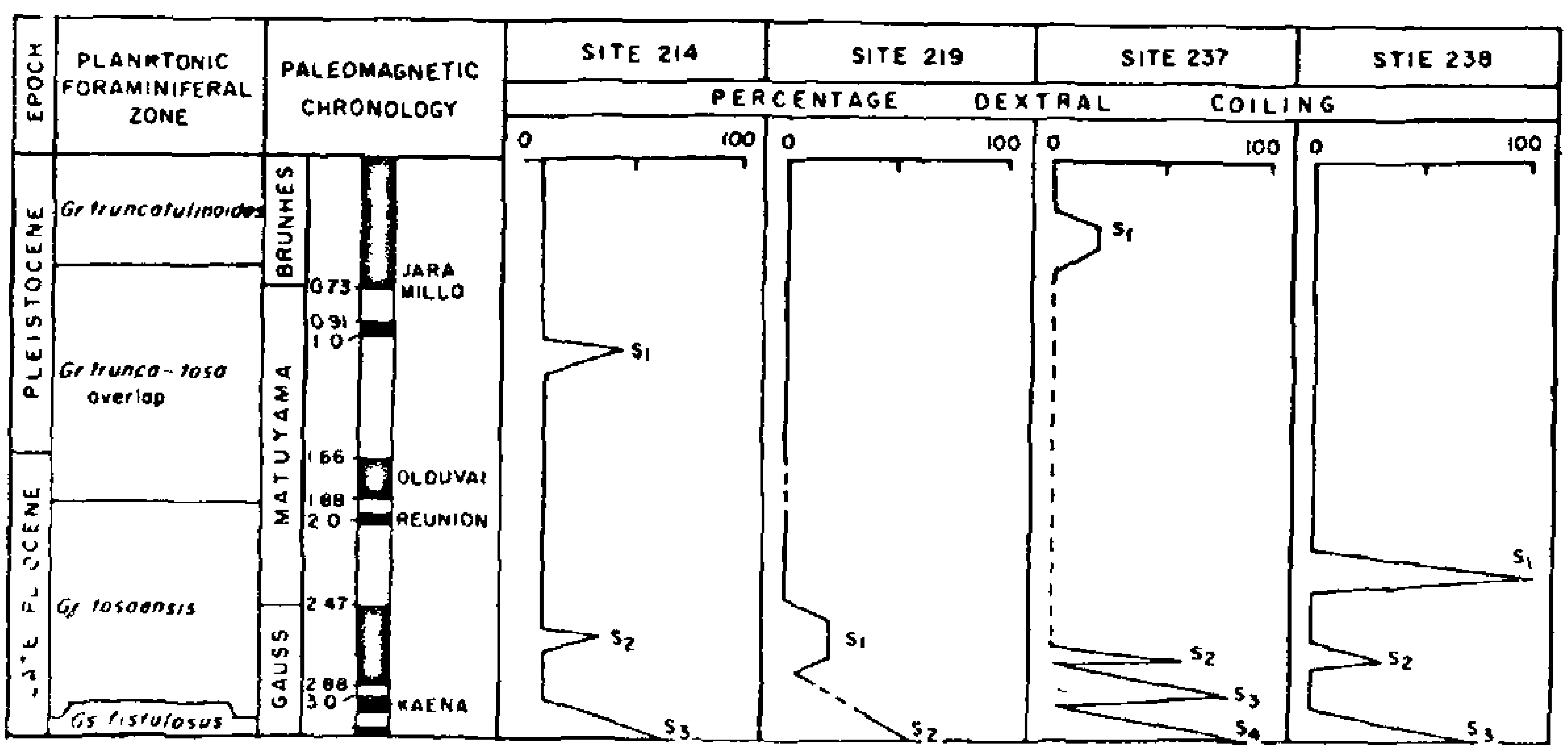

**Figure 9.** Coiling of *Globorotalia* s.l. since 3 m.y. in the Northern Indian Ocean.

Recent studies[30,31] on stable isotope records (oxygen and carbon) and relative abundance of the planktonic and benthic foraminifera also reveal the initiation of glaciation in the Northern Hemisphere during 3.1 to 3.2 m.y. period with marked continental glaciation beginning at about 2.4 m.y. The Northern Hemisphere glaciation has led to the emergence of Panama Isthmus and resulted in mammalian extinction on a large scale during the Late Pliocene. Thus, the marked change in the mammalian fauna observed at the base of Pinjor (Upper Siwalik) of sub-Himalaya, reflects the Late Pliocene climatic cooling as a result of the cryospheric evolution in the Northern Hemisphere. The demarcation of the Pliocene/Pleistocene boundary at the base of Pinjor (where there is a major mammalian faunal turnover in the continental Siwalik Group) as suggested by Rao[32] is not acceptable. As a matter of fact the mammalian faunal change at the base of Pinjor reflects the major global climatic cooling that occurred at 2.4 m.y. (Late Pliocene), and is thus at least 0.8 m.y. older than the top of the Olduvai Normal Event.

The planktonic foraminiferal data reveal a relatively short warmer interval prior to the beginning of the Pleistocene. This is inferred from the dominance of tropical assemblages and the corresponding decrease in abundance of temperate forms (Figures 4, 5, 7). During this interval, a major switch in coiling direction of *Pulleniatina* (sinistral to dextral) is also observed at sites 214 and 219 (Figure 8).

The beginning of the Pleistocene (1.6 m.y.) is marked by a general increase in the abundance of temperate forms and simultaneous decrease in the per cent frequency of tropical assemblages at sites 214, 219 and

Table 4. Major biotic, isotopic, palaeoceanographic and global palaeoclimatic events in the Northern Indian Ocean (Modified after Gupta and Srinivasan[17])

| Age (m.y.) | Epoch | Biotic events: Planktonic foraminiferal events | Biotic events: Benthic foraminiferal events | Isotopic events | Palaeoceanographic events | Global palaeoclimatic events |
|---|---|---|---|---|---|---|
| 0.6 | Pleistocene | Dominance of temperate assemblages, sporadic occurrence of *Neogloboquadrina pachyderma* major shift in coiling mode of *Pulleniatina* | Cooler fauna are dominated | $\delta^{18}O$ increase | Surface and bottom water cooling, increased upwelling | Major glacial/interglacial episodes, increase in polar ice volume, expansion of Southern Hemisphere ice sheets |
| | | Dominance of temperate assemblages, sporadic occurrence of *Neogloboquadrina pachyderma* | Dominance of *Uvigerina* | | Surface and bottom water cooling, increased upwelling | |
| 1.6 | Late Pliocene | Dominance of temperate assemblages, major shift in coiling mode of *Globorotalia* s.l. and *Pulleniatina* | Dominance of *Uvigerina* and *Globocassidulina* | Major shift in isotopic signal towards higher value in $\delta^{18}O$ | Surface and bottom water cooling | Global climatic cooling northward expansion of Antarctic waters, major Northern Hemisphere ice accumulation. |
| 3.1<br>3.2 | | | Significant increase in *Uvigerina* | | | |

238, reflecting climatic deterioration (Figures 4, 5, 7).

The Pleistocene epoch shows a number of intervals of faunal fluctuations which appear to be in response to glacial and interglacial episodes. As the authors have not examined the Pleistocene sequences at very close stratigraphic intervals, all climatic vicissitudes could not be detected. However, recent studies[33] on temporal variation in the distribution of planktonic foraminifera of the top 9 meters core of site 219 at very close stratigraphic interval lead to identification of five pulses of climatic fluctuations.

The present quantitative data reveal three major peaks of abundance in the temperate form of *Globigerina* spp. during the Pleistocene, which are virtually coincident with the decrease in abundance of tropical assemblages thus reflecting three cooling episodes, viz. first immediately after the Pliocene/Pleistocene boundary (1.6 m.y.), second at 0.6 m.y and third in the late Pleistocene. The increase in polar-ice volume during these intervals appears to be plausible explanation for these major faunal changes. The sporadic occurrence of *Neogloboquadrina pachyderma* at sites 214 (core 1, sec. 6), 219 (core 2, sec 4 and core 3, sec. 3), 237 (core 1, sec. 3 and core 2, sec. 1) and 238 (core 1, secs. 4, 5; core 2, sec. 2 and core 3, secs. 4, 5) bears further testimony to the increased influence of upwelling and flow of cold of polar waters towards the Northern Indian Ocean (Figures 4–7).

A shift from dextral to sinistral coiling in *Pulleniatina* population at all the examined sites coincident with the Middle Pleistocene cooling event at 0.6 m.y. has also been observed (Figure 8), suggesting coiling change to be induced by climatic change.

The Pleistocene cooling events are well reflected in the oxygen isotopic record with enriched $\delta^{18}O$ values. On the basis of deep sea benthic faunal record at site 214, Gupta and Srinivasan[17] suggested bottom-water cooling during the early Pleistocene (1.6 to 0.6 m.y.) and late Pleistocene (0.6 m.y. to Recent).


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