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THE BIOSTRATIGRAPHY AND PALAEOECOLOGY OF MIDDLE TO LATE MIOCENE PLANKTONIC FORAMINIFERA AND RADIOLARIA FROM THE EQUATORIAL PACIFIC OCEAN (DSDP SITES 289 AND 71)

by

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ABSTRACT

Planktonic foraminifera and Radiolaria from the Middle to Late Miocene of DSDP Sites 289 and 71 in the western and central equatorial Pacific have been investigated with the aim of explaining certain changes in the biota in terms of pre-mortal (palaeoenvironmental and palaeoecological) and post-mortal (dissolution) factors.

The oceanography, planktonic ecology, pelagic (biogenic) sedimentology and Cenozoic history of the Pacific Ocean are reviewed.

A taxonomic review is presented for all forms encountered at both sites, including fifty seven planktonic foraminifera and one hundred and sixty three radiolaria, of which four new species are described and named.

A biostratigraphical analysis identifies the standard planktonic foraminiferal and radiolarian zones.

The extent of dissolution of planktonic foraminifera and radiolaria is discussed.

An interpretation of changing palaeotemperature in the epipelagic zone of the Middle to Late Miocene water column at Site 289 is attempted by reference to distributional trends in Orbulina universa, and keeled globorotaliids, including G. fohsi s.l. and G. cultrata gp.

The palaeotemperature curve suggests variation between 24°C and 29°C, fluctuations being possibly due to periodic development of upwelling in the surface waters of the western equatorial Pacific, caused by variation in the size of the Antarctic ice sheet.

Faunal trends, which are expressed by the percentage abundance of individual taxa, diversity and similarity indices of entire assemblages, and evolutionary events, were compared with palaeotemperature trends to seek correlation and thereby explain distribution. A biometric analysis of the radiolaria Stichocorys delmontensis is described to highlight an apparent relationship between abundance, morphology and palaeotemperature.

Finally, the palaeotemperature trends at Site 289 were considered in relation to previous interpretations. An overall agreement of results validates the palaeotemperature conclusions of the present study, allowing the results to be used for precise stratigraphical dating of important palaeoceanographic events, particularly in the latest Miocene (Messinian).

(See pp.214-226 for more detailed summary).

NOTE

The main text of this thesis is accompanied by an Appendix volume containing a taxonomic review of all planktonic foraminifera and radiolaria encountered in the study. It is recommended that this review be consulted in conjunction with the main text.

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CHAPTER I

AIMS, MATERIALS, BACKGROUND AND METHODS

1. INTRODUCTION

Leg 30 of the Deep Sea Drilling Project (DSDP) involved a geological investigation of the southwest Pacific arc and marginal sea complex (ANDREWS, PACKHAM *et al.*, 1975). As part of this programme, two sites were chosen on the Ontong Java Plateau situated north of the Solomon Islands in the western equatorial Pacific: DSDP Sites 288 and 289.

DSDP Site 289 was drilled to a depth of 1271m below the sea floor where oceanic basalt was penetrated. A cored sedimentary sequence consisting entirely of pelagic (biogenic) carbonates ranging in age from Pleistocene to Early Cretaceous (Aptian) was recovered during this operation.

Following preliminary biostratigraphic studies outlined in ANDREWS, PACKHAM *et al.*, (1975), the present project was initiated in October 1977 to investigate in detail the planktonic foraminifera and radiolaria of the Middle to Late Miocene interval at Site 289, with particular emphasis on palaeoenvironmental and palaeoecological aspects.

2. AIMS OF THE STUDY

HOLDSWORTH (1975) was primarily concerned with applying a radiolarian biostratigraphic zonation to the Cenozoic sequence at Site 289. In the course of this investigation he became aware of some major undescribed changes in the radiolarian assemblages, particularly during the Miocene interval. These changes involved the numerical distribution and intraspecific variation of particular radiolarian taxa which were not obviously related to simple evolutionary trends. A study of the quantitative nature and cause of all the phenomena was considered beyond the scope of a preliminary biostratigraphic report, although HOLDSWORTH and HARKER (1975) tried to demonstrate that some variation in taxonomic distribution was due to dissolution effects.

As well as reflecting post-mortal dissolution, HOLDSWORTH (pers. comm.). believed that some of the variation in the radiolarian assemblages was due to palaeoenvironmental and palaeoecological factors reflecting changes in the nature of palaeo-water masses.

The present study was initiated in the hope of explaining some major changes apparent in microfossil assemblages (planktonic foraminifera and radiolaria) of Middle to Late Miocene age at Site 289 in terms of pre-mortal (environmental and ecological) and post-mortal (dissolution) processes.

This aim was pursued through the following steps:

1) From the qualitative distribution of index taxa, a high resolution biostratigraphic framework was erected which refined the radiolarian zonation applied by HOLDSWORTH (1975) and incorporated the planktonic foraminiferal zonation of BLOW (1969).

2) The quantitative distribution of all planktonic foraminifera and radiolaria (below the generic level where possible) was established for the Middle to Late Miocene sequence at Site 289. As well as a basic description of the relative distribution of individual species, changes in the nature of entire microfossil assemblages was assessed from diversity and similarity measurements.

3) Stratigraphical intervals of increased dissolution were identified from the distribution of those planktonic foraminifera and radiolarian taxa thought to be particularly sensitive to dissolution

processes.

4) A palaeotemperature interpretation for the Middle to Late Miocene epipelagic zone in the western equatorial Pacific Ocean was derived from the distribution of those planktonic foraminifera at Site 289 which are thought to be particularly sensitive to palaeotemperature variation. The specific distributional trends used were:

a) mean size in Orbulina universa

b) relative abundance of the keeled globototaliids Globorotalia fohsi s.l. and Globorotalia cultrata gp.

c) coiling direction in G. cultrata gp.

5) The relative distribution of individual taxa and the changes in the nature of entire assemblages were compared with the palaeotemperature curve. Correlation of micropalaeontological events with palaeoceanographical events was then sought to explain changes in the quantitative distribution of particular taxa.

To test the regional significance of some of the micropalaeontological and palaeoceanographical events recognised at Site 289, a short stratigraphical interval within the Middle Miocene from a further locality, DSDP Site 71 in the central equatorial Pacific, was selected for comparative purposes (fig.1). In addition, the palaeoceanographical events postulated for the western equatorial Pacific during the Middle to Late Miocene was compared to the palaeoceanographic record throughout the Pacific Ocean as elucidated by previous research.

The present study is considered to be particularly topical in view of the CENOP[1] project. CENOP is an on-going co-operative study by

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[1] CENOP is an acronym of "Cenozoic Paleoceanography"

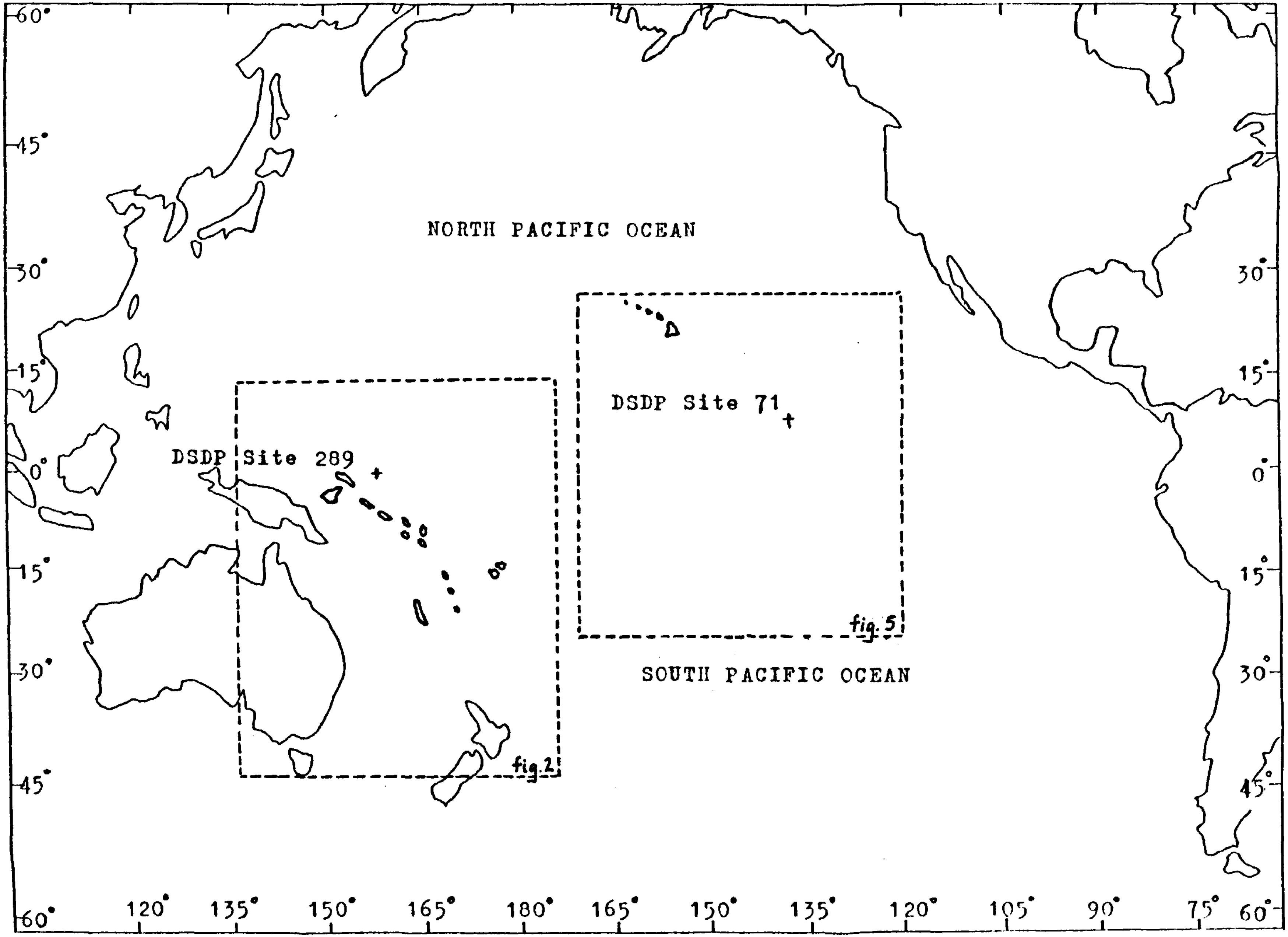

Fig.1 Location of DSDP Sites 289 and 71

institutions based mainly in the U.S.A. which is seeking to reconstuct the palaeoenvironment of the Miocene world ocean, prior to and after the ice build-up on Antarctica, by means of stable isotope and quantitative micropalaeontological data from deep sea cores (HAQ et al., 1980).

The present study involves thick, undisturbed sequences of pelagic, biogenic sediments derived from the fertile equatorial current system. Such material forms an excellent source for monitoring palaeoceanographical events during the Neogene (Van ANDEL et al., 1975).

3. DSDP SITE 289 : PROVINCIAL GEOLOGY, STRATIGRAPHICAL SEQUENCE, PREVIOUS WORK, MATERIAL AND METHODS

i) Provincial Geology

DSDP Site 289 is located on the Ontong Java Plateau,north of the Solomon Islands in the western equatorial Pacific (lat. 00° 29.92'S; long. 158° 30.69'E) (fig.2).

The western equatorial and south west Pacific is dominated geologically by a convergent plate boundary between the Pacific and Indian plates. The boundary is expressed as a series of trenches and island arcs from New Guinea to New Zealand i.e. the Solomon, New Hebrides and Tonga-Kermadec Trenchs and the Solomon and New Hebrides island arcs (ANDREWS, PACKHAM, et al., 1975). Within the Indian plate east of Australia is a complex of ridges and basins (fig. 2).

The Ontong Java Plateau is a dominant structural feature in the western equatorial Pacific. The plateau is a N.W. - S.E. striking platform, 800km wide and 1600km long with an average water depth of 1.7km (VALENCIA, 1977).

According to RESIG et al. (1976), the plateau is an anomalous oceanic area defined by the following characteristics:

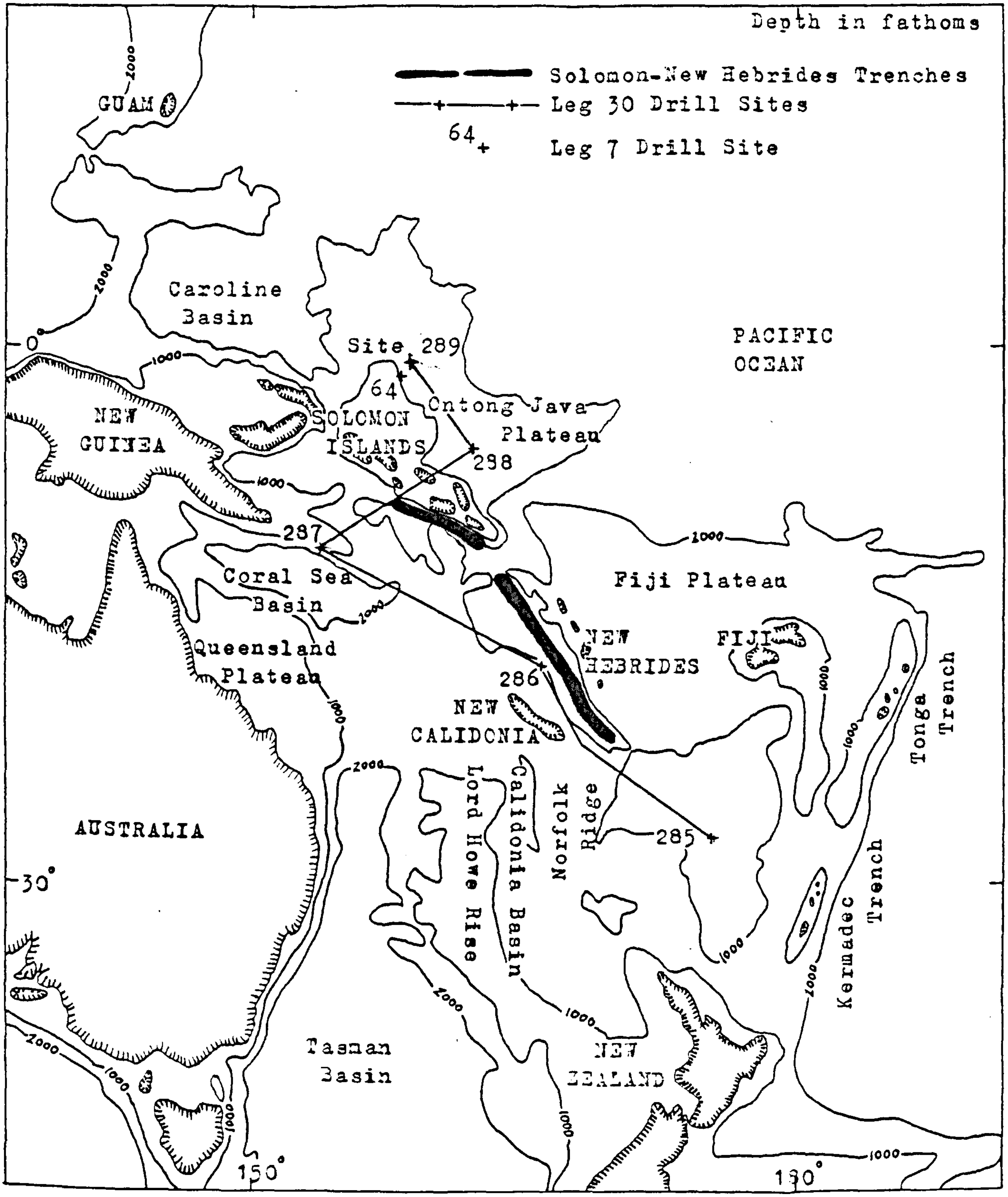

Fig.2 Location of Drill Sites, Leg 30; Site 64, Leg 7 and Structural Features in the Region.

- it is unusually large and forms an extensive structural high.
- the oceanic crustal thickness is of continental magnitude as defined by seismic refraction (25-40 kms thick).
- it has accumulated a thick column of stratified biogenic sediments of extensive areal continuity.

Seismic refraction studies show that layering of the crust within the plateau is similar to typical oceanic sections but with each layer thicker than normal (FURUMOTO et al., 1971). KROENKE (1972) has discussed the formation of the plateau and concluded that is originated through the accumulation of flood basalts along an east-west aligned spreading ridge during Mesozoic times.

A thick sequence of flat lying, highly stratified, pelagic, biogenic limestones, chalks and oozes covers oceanic basalt (ANDREWS, PACKHAM et al., 1975). Undisturbed sequences exist on the stable plateau centre whereas sediments are disturbed by faulting, slumping, erosion and volcanism around the margins (KROENKE, 1972;BERGER and JOHNSON, 1976; BERGER et al., 1977). Sedimentation has remained above the level of the C.C.D. since Mesozoic times while the mean depth of the lysocline is believed to have remained near the present depth of 3500m since the Oligocene (JOHNSON et al., 1977).

Palaeomagnetic investigations suggest that the plateau has moved northward by about 32° since its formation and had reached its present latitude by about 30m.y. B.P.-during the Oligocene-with only westerly movement along latitude since then (HAMMOND et al., 1975). To the south west of the Ontong Java Plateau, on the edge of the Pacific plate, lay the Solomon Island arc system. The Solomon Sea to the south is an area where oceanic crust is at present being subducted beneath the Pacific plate to the north (ANDREWS, PACKHAM et al., 1975). The plate boundary is believed to have been positioned to the north of the island arc but has since been relocated to its present position (PACKHAM, 1973).

In the eastern Solomon Islands, the basement rocks are tholeiitic basalts of probable Mesozoic age (HACKMAN, 1973). The southern islands have Late Oligocene to Early Miocene volcanics with younger shallow water clastics and limestones overlying basement (ANDREWS, PACKHAM _et al._, 1975). On the northern island of Malaita, the basement rocks are overlain by deep water biogenic limestones and chalk ranging in age from Early Cretaceous (Albian) to Pliocene (Van DEVENTER and POSTUMA, 1973), a succession similar to that of the Ontong Java Plateau (ANDREWS, PACKHAM _et al._, 1975). The island arc is seperated from the plateau by a fault along which ultramafic bodies are found (COLEMAN, 1970).

ii) Stratigraphical Sequence

DSDP Site 289 was drilled in a water depth of 2206 metres and cored continuously to 1271 metres below the sea floor. One hundred and thirty-three cores were obtained although incomplete recovery yielded only 712.6 metres of sediments and igneous rock (fig.3).

The cored sequence can be divided into three lithostratigraphic units (ANDREWS, PACKHAM, _et al._, 1975):

- Unit 1 (0-969.0m): Nanno-foram. ooze, interbedded nanno-foram. ooze and nanno-foram. chalk. Pleistocene to Late Eocene.
- Unit 2 (969.0-1262.0): nanno-foram. chalk, nanno-foram. limestone, siliceous limestone, nodular chert, tuff. Late Eocene to Early Cretaceous.
- Unit 3 (1262.0-1271.0m): Basalt. Early Cretaceous, early Aptian.

At least six substantial stratigraphic breaks are present in the section. These occur between the Early Oligocene (Rupelian) and the Late Eocene (Bartonian), the Middle Eocene (Lutetian) and Early Eocene

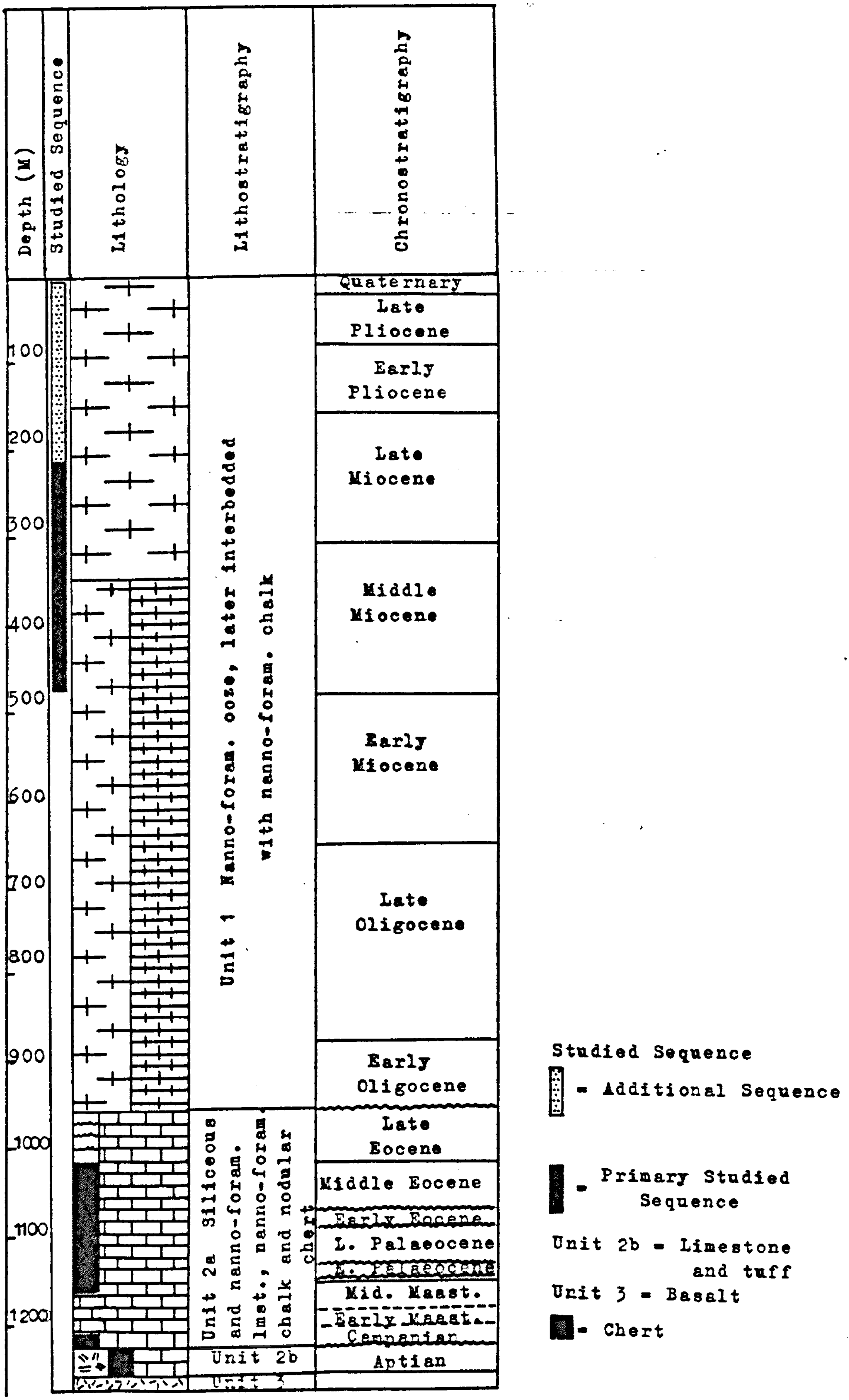

Fig.3 Stratigraphic Succession, Site 289
(after Andrews, Packham *et al.*, 1975)

(Ypresian), the Early Eocene (Ypresian) and Late Palaeocene (Thanetian), the Late Palaeocene (Thanetian) and Early Palaeocene (Danian), the Early Palaeocene (Danian) and Late Cretaceous (Maastrichtian) and the Late Cretaceous (Campanian) and Early Cretaceous (late Aptian) (ANDREWS, PACKHAM, et al., 1975).

ANDREWS, PACKHAM, et al., (1975) have discussed the sequence of geological events responsible for the succession. Sedimentary processes at Site 289 have been almost exclusively pelagic with the accumulation of biogenic carbonates dominated by nannofossils and planktonic foraminifera with subordinate radiolaria.

Tholeiitic plateau basalt lavas were extruded during or prior to early Aptian time. Following the extrusive phase, volcanic ash and biogenic sediments of Aptian age were deposited. A period of non-deposition or erosion followed from late Aptian to Campanian times.

Biogenic sedimentation during Campanian to Maastrichtian time was interrupted by a second period of non-accumulation during latest Maastrichtian and earliest Palaeocene time. Biogenic sedimentation continued during the Late Palaeocene followed by a third period of non-deposition during latest Palaeocene to Early Eocene.

A short period of continued biogenic sedimentation occurred during the Early Eocene followed by a fourth hiatus. Biogenic sediments accumulated during the Middle and Late Eocene followed by a fifth period of non-deposition at the end of Eocene time which persisted into the earliest Oligocene.

From the Early Oligocene until the Holocene, continuous biogenic sedimentation of foraminifera, nannofossils and radiolaria above the C.C.D. has occurred at Site 289.

iii) Previous Geological and Micropalaeontological

Investigations of the Ontong Java Plateau

The Ontong Java Plateau has been the subject of much geological investigation in recent years.

Geophysical surveys and interpretations have been undertaken by FURUMOTO et al. (1971), KROENKE (1972), BERGER and MEYER (1978) and JOHNSON et al. (1978). Stratigraphic and sedimentological studies have been conducted by BERGER and JOHNSON (1976) and BERGER et al., (1977). Micropalaeontological investigation of Cenozoic sediments have been carried out by VALENCIA (1972, 1977), REISG et al. (1976), SHACKLETON and OPDYKE (1973) and THOMPSON and SCIARRILLO (1978).

Three sites were drilled by the DSDP programme: Site 64 of Leg 7 (WINTERER, RIEDEL et al., 1971) and Sites 288 and 289 of Leg 30 (ANDREWS, PACKHAM et al., 1975).

At Site 64, biogenic sediments of Pleistocene to Eocene age were discontinuously cored. Micropalaeontological studies for biostratigraphical purposes included those by BRÖNNIMANN and RESIG (1971) (planktonic foraminifera) and RIEDEL and SANFILIPPO (1971) (radiolaria).

The Initial Reports volume for Leg 30 includes details of a comprehensive geological analysis of sediments recovered from Site 289 (ANDREWS, PACKHAM, et al., 1975). Aspects of lithology, mineralogy, palaeontology, geochemistry, diagenesis and physical properties have been investigated in detail and integrated into a regional synthesis involving biostratigraphy, tectonic history, facies development and palaeoceanography of the western and south west Pacific region.

Since the publication of the DSDP Leg 30 Initial Reports volume, subsequent investigations have been carried out involving material from Site 289. WESTBERG and RIEDEL (1978) integrated the radiolarian biostratigraphical zonation at Site 289 into a regional study which assessed the correlation of Miocene sediments by means of radiolarian events. WOODRUFF (1979) investigated the distribution of benthonic foraminifera and the O_2 isotope record in the Middle Miocene sequence while SHACKLETON (in press) has illustrated the O_2 isotope record over the Early/Middle Miocene boundary (see Chapter III, p.66). A provisional account of several aspects of the present work has recently been published in abstract form (DYER, 1981).

iv) Studied Sequence: Site 289

The studied sequence at Site 289 is indicated briefly in fig.3 and in further detail in fig.4a-c. The sequence can be divided into two broad intervals:

1) a primary studied sequence from the Middle to within the Late Miocene (cores 50 to 24). Investigations in this interval involve the qualitative and quantitative distribution of all planktonic foraminifera and radiolaria encountered.

2) an additional sequence covering the remainder of the Late Miocene (cores 23 to 18) and the Pliocene to Quaternary (cores 17 to 1). Brief investigation of certain planktonic foraminifera from this interval, namely Orbulina universa and Globorotalia cultrata group, furnished additional biostratigraphical and palaeoenvironmental information which proved useful for the purpose of comparison with the primary studied sequence.

The position of all samples taken at Site 289 is indicated on fig.4a-c. To appreciate sample labelling, it will be necessary to briefly explain routine DSDP coring and labelling procedure (ANDREWS, PACKHAM, *et al.*, 1975).

A core is usually taken by droping a core barrel down the drill string and coring for 9.5 metres. Sediment is retained in a plastic liner

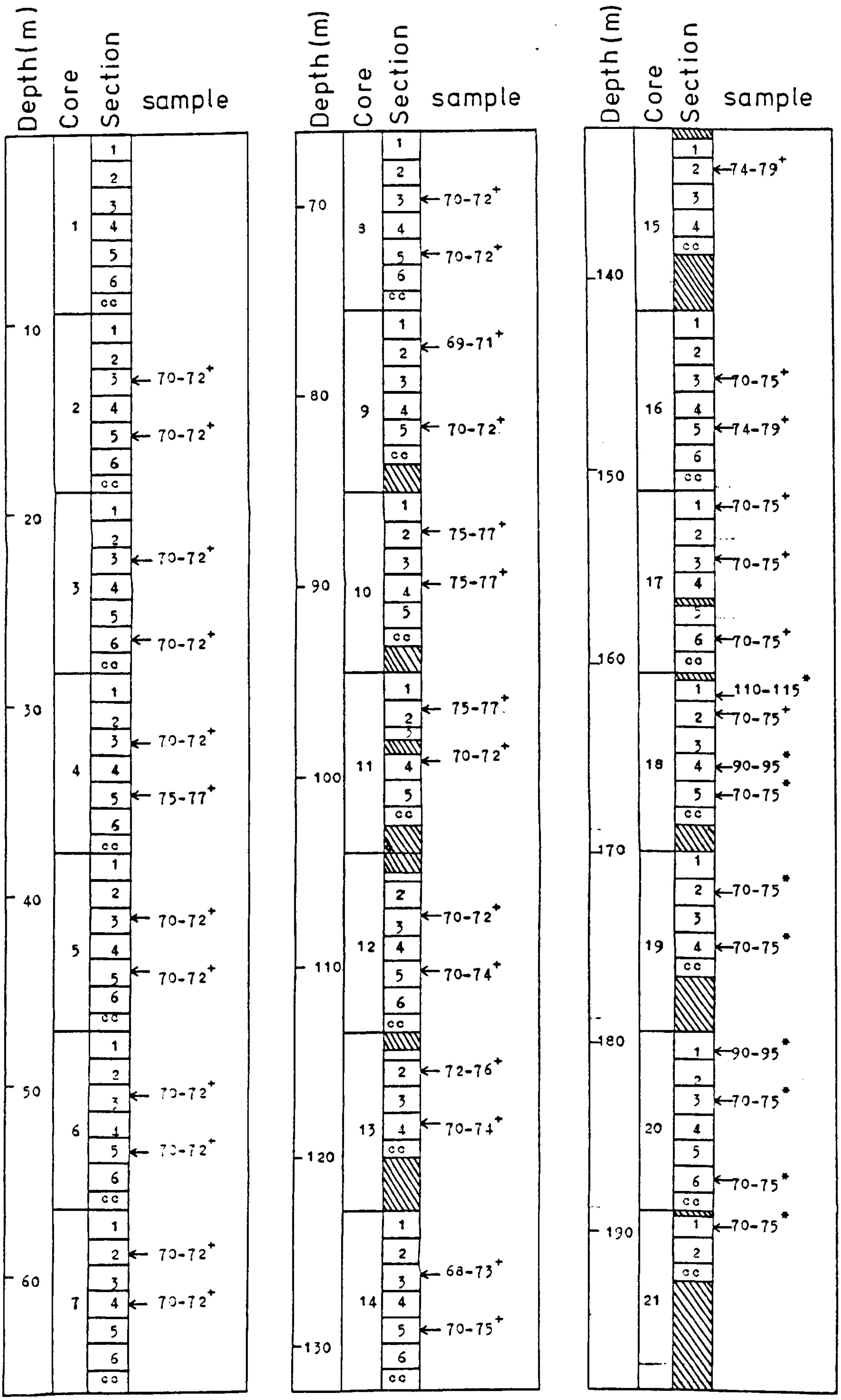

Fig.4a Sample Location, Site 289

(←- = analysed for planktonic foraminifera; ←—— = analysed for radiolaria;

* = G. cultrata group and O. universa analysis only

\+ = G. cultrata group analysis only (coiling trends))

▨ unrecovered interval

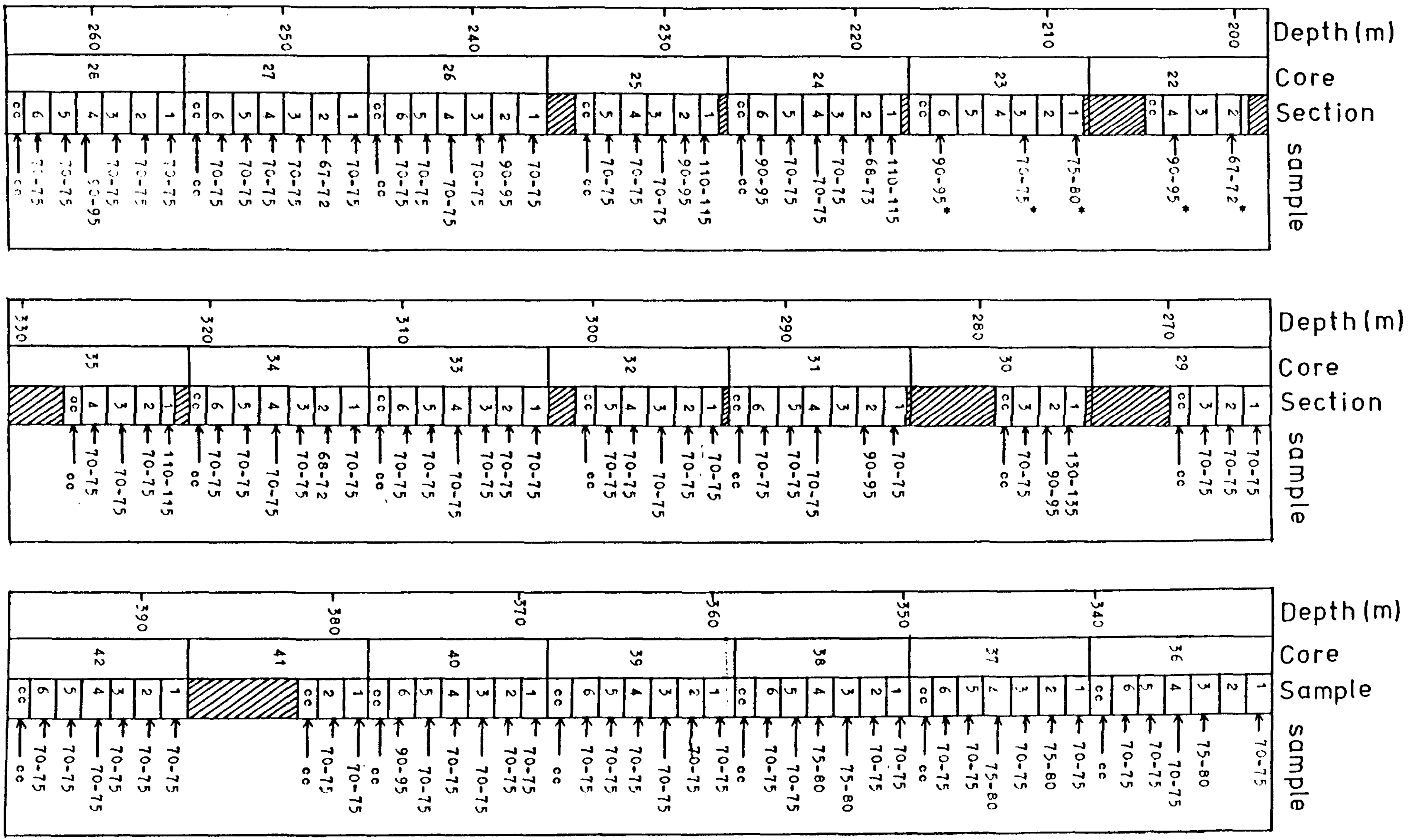

Fig 4b Sample Location, Site 289 (← = analysed for planktonic foraminifera; ←— = analysed for radiolaria; * = G. cultrata group and C. universa analysis only)

▨ unrecovered interval

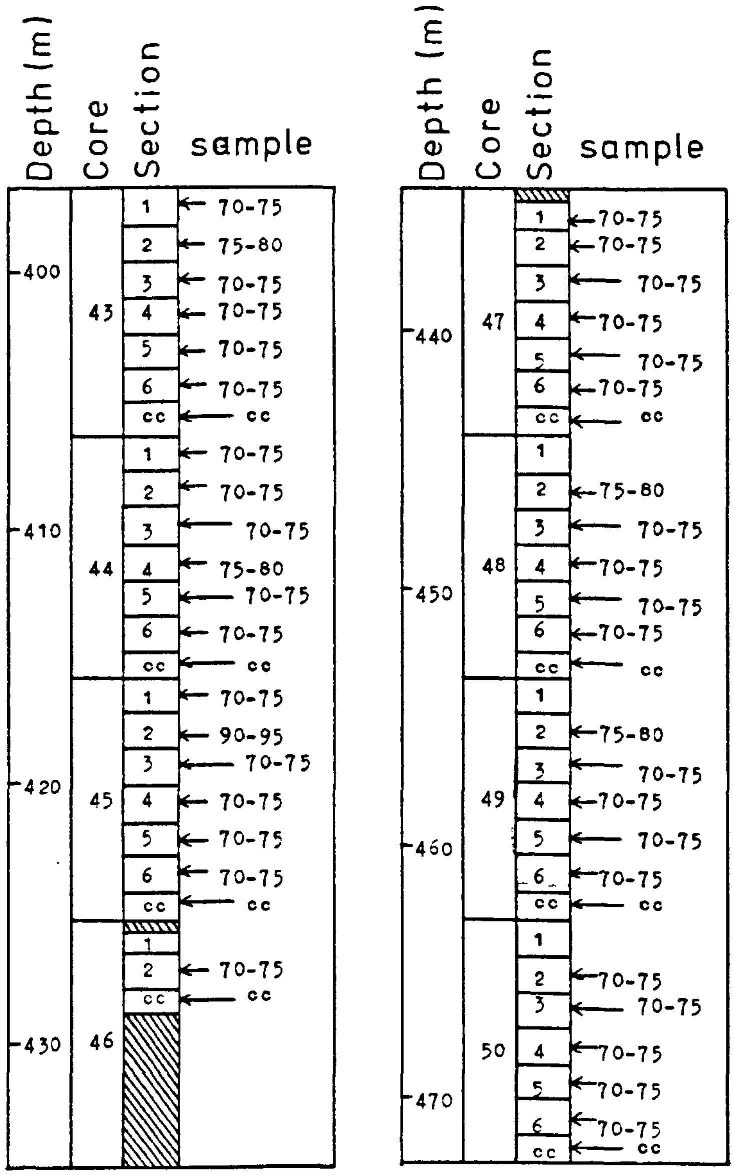

Fig. 4c Sample Location, Site 289

(← = analysed for planktonic foraminifera;
⟵ = analysed for radiolaria)

▨ unrecovered interval

9.28m long inside the core barrel and in a 0.20m long core-catcher assembly below the liner.

On recovery, the liner is cut into sections of 1.5m measured from the lowest point of sediment within the liner. The sections are labelled from 1 for the top section to a figure as high as 6 for the bottom section, depending on the total length of core recovered. The core-catcher samples are always considered to be continuous with the lowest recovered section although in interpretation they are often assumed to represent the base of the total interval cored.

All samples taken from cores were numbered according to the system described in the Shipboard Handbook for Leg 30. The label "30-289-27-4, 70-75"cm thus refers to Leg 30, Site 289, Core 27, Section 4, sampled between 70 and 75cm from the top of that section. The label "30-289-27cc" refers to the core-catcher sample at the base of Core 27.

The labelling of samples is rigorously tied to the position of the samples within a section as the position appears when the section is first cut open. When recovery is severely reduced, it may be impossible to assess where exactly in the hole the sample came from.

In refering to cores, sections, and samples in the text of this thesis, the leg, site and cm designations are usually omitted as this information is obvious from fig.4a-c (see also fig.7).

In the primary studied sequence, comprising 256.5m of sediment from cores 50 to 24 (475m-218.5m), 109 samples were analysed for their planktonic foraminiferal content while 56 intercalated samples were analysed for their radiolarian content (fig.4a-c). Where possible, every core section and core catcher interval was sampled for one of the two types of analyses, so that the sample interval was approximately 1.5m.

In the additional studied sequence, comprising 218.5m of sediment from cores 23 to 1, 47 samples were analysed for particular information concerning the planktonic foraminifera Orbulina universa and Globorotalia cultrata group (see fig.4a-c for details). In this sequence, the sampling interval was generally greater, at approximately 4m, with only alternate or one in every three core sections being sampled.

v) Core Description and Interpretation

The studied sequences at Site 289 occur within lithology Unit 1 of ANDREWS, PACKHAM et al., (1975). In the present study, the cored sediments were not made available and the following account is taken from ANDREWS, PACKHAM, et al. (1975).

Unit 1 was recovered from cores 1 to 102 and consists of a 969m succession of nanno-foram. ooze and interbedded nannoforam chalk. Disturbed soft ooze occurs from the top to 350m whereas interbedded semi-lithified chalk and both disturbed soft and undisturbed stiff ooze occur from 350 to 969m (fig.3).

The ooze and chalk are characterised by the same colours and mineral and fossil components. The change in hardness reflects increased diagenesis with increased depth of burial.

White is the dominant colour while light grey is subordinate. Accessary colours include black laminae, greenish white and various shades of grey.

Planktonic foraminifera and nannofossils are dominant and together comprise 99% of the total components present. Accessary components include benthonic foraminifera, radiolaria, micro-carbonate (micarb), traces of feldspar, pyrite, volcanic glass, opaque and heavy minerals, sponge spicules and silicoflagellates. Texturally the oozes are silty clays and clayey silts generally containing in excess of 90% $CaCo_3$.

Sedimentary structures are apparent in the lower and better indurated oozes and chalks below the studied sequences. They include parallel laminae, colour bands, flaser bedding, lenticular bedding and wavy bedding. Biogenic structures include small horizontal and vertical burrows. The environment of deposition is oceanic, middle bathyal, above the C.C.D. under conditions of high equatorial productivity. Bottom current velocities were sufficiently high to generate current ripples with flaser drapes indicating an alternation of bedload and suspension deposition. Oceanic bottom currents with a tidal velocity or periodic storms were perhaps responsible (ANDREWS, PACKHAM, et al., 1975). In the studied sequences only parallel laminae are noticeable.

The Initial Reports volume for Leg 30 contains a detailed diagramatic and written lithological description of all cored sediments from Site 289 at a scale of approximately 1 in 75. In addition, photographic plates of all cores are given at a scale of approximately 1 in 6.6.

vi) Processing Methods

Samples were taken from each core section by inserting and retracting a hollow plastic tube of 20cc volume. The tube was not always full of sediment upon retreval from the core.

a) Planktonic Foraminifera

1. The samples were dried in an oven for approximately 48 hrs at 200°C.

2. Boiled in a solution of water and sodium hexametaphosphate (Calgon) for up to 10 hrs.

3. Vibrated for up to 2 minutes.

4. Sieved into >63μ and >250μ fractions.

5. Dried, bottled and stored.

The drying, boiling and vibrating treatment was sufficient to dissaggregate all samples although the time taken varied according to original induration.

b) Radiolaria

Samples designated for radiolaria analysis were treated for lithological breakdown in the same manner as planktonic foraminifera under steps 1 and 2.

3. Sieved into >63µ fraction.

4. Residue treated with 10% HCL to dissolve calcareous components.

5. Resieved and washed into >63µ fraction.

6. Concentrated siliceous residue aggitated and strewn evenly onto slide via a pipette.

7. Strewn residue permanently mounted with Canada Balsam and cover slip.

In most samples, the size of the siliceous residue was such that more than one strewn slide could be prepared. Extra residue was also split into two size fractions - from 63µ to 150µ and >150µ - to enable quick identification of rare large forms.

vii) Description of Prepared Residues

The methods of sample preparation described above yielded calcareous and siliceous residues over 63µ in size.

a) Calcareous Residues

The calcareous residues are consistently dominated by planktonic foraminifera. Accessary components include benthonic foraminifera while radiolaria, sponge spicules, diatoms and mineral grains of quartz, feldspar, pyrite and volcanic glass are extremely rare.

Nannoplankton and some of the smaller, juvenile planktonic foraminifera were lost during the sieving process.

The preservation of the planktonic foraminifera is generally good to excellent and consistent with deposition above the depth of the lysocline. Nevertheless, the quality of the assemblages does vary. In most samples nearly all individuals are entire and show no evidence of test corrosion so that fragile structures such as teeth in globoquadrinids remain intact. Although evidence of dissolution is discussed within the Biostratigraphy Chapter (Chapter IV), a full appraisal of the phenomenon at Site 289 will be considered following a detailed description of the quantitative taxonomic distributions (Chapter V).

b) Siliceous Residues

The siliceous residues consist mainly of polycystine radiolaria with very rare and sporadic occurrences of diatoms and sponge spicule fragments. Variation in the preservation of radiolarian assemblages at Site 289 appears to be greater than of the planktonic foraminifera, although this is probably due largely to the greater morphological variation and hence greater sensitivity to destructive influences in the radiolaria. Well preserved samples contain fragile species and tests with fine, delicate structures such as abdominal and post-abdominal segments in nassellarians, latticed panels in plagoniids and a patagium in three rayed spongodiscids.

According to JOHNSON (1974), diatoms are highly susceptible to dissolution. At Site 289, the occasional presence of diatom frustules coincides with the presence of well preserved tests as outlined above. Poorly preserved samples contain limited abundance of fragile species and structures.

Preservational variations in siliceous residues can be ascribed to two main factors: artifical and natural.

Artificial factors are believed to have been introduced into the residues because of differential treatment during washing and sieving processes. All core catcher samples were treated on board the Glomar Challenger for routine shipboard biostratigraphic studies during drilling operations. The intervening section samples however were processed at the Geology Department, Keele University at a later date to supplement the core catcher samples and provide greater biostratigraphic control for the sequence for the purpose of the Initial Reports V.30 publication (ANDREWS, PACKHAM *et. al.*, 1975). The core catcher samples appear to have suffered less mechanical destruction than the section samples; complete tests are more common and the overall diversity of assemblages in terms of species numbers is higher (see Chapter V). The following taxa are only found in core catcher samples:

Artopilium undulatum

Botryopyle dictyocephalus gp.

Botryostrobus sp. aff. B. bramlettei

Corocalyptra cervus

Eucyrtidium sp. 2

Litharachnium tenthorium

Lithopera bauerii

Stichopilium rhinoceros

S. sp. cf. S. rhinoceros

S. sp. cf. S. bicorne

Spirocyrtis gyroscalaris

Theocorythium sp. cf. T. trachelium

Verticillata hexacantha

In addition, the following taxa appear in core catcher samples in more than 80% of total occurrences:

Acrobotrys spp.

Centrobotrys thermophilia

Corocalyptra kilmari

Lipmanella dictyoceras

Lithostrobus sp. cf. L. hexagonalis

Lithopera thornburgi

Siphocampe spp.

Spirocyrtis spp.

"Cyrtid spp. gp. 1"

These twenty two taxa are all fragile nassellarians. Their almost exclusive restriction to core catcher samples is sufficient to explain diversity differences with section samples. Other differences between the two sample types involve the relative abundance of certain taxa, e.g. spyrid spp. are almost always 5 to 10% less abundant in section samples than in core catcher samples (see fig.30b). It is suggested that over vigorous washing of Site 289 section samples has created these differences with core catcher samples.

Natural preservational differences in the radiolarian assemblages at Site 289 are caused by variations in dissolution intensity and are discussed further in Chapter V.

viii) Study Methods

a) Foraminifera (cores 50 to 24)

Planktonic foraminifera were analysed only from the calcareous residue size fractions greater than 250µ. Each residue contained many thousands of individuals and complete analysis was considered impractical. Instead a representative subsample of 500 individuals was selected from each sample.

The entire residue (>250µ) was brushed evenly over a grid picking tray and 500 individuals were selected at random by undertaking diagonal and criss-cross traverses and picking all individuals within each grid square along the course.

The 500 individuals were then sorted into different species or subspecies, glued down in a grid slide and counted. The percentage abundance of each taxon was then calculated.

Finally, the remaining residue was meticulously searched for any taxa not encountered in the initial survey.

Two aspects of these methods are not entirely consistent with those of previous workers - the size grade of the residue used and the method of subsample selection.

The use of particular size fractions in studies of planktonic foraminifera seems to vary from worker to worker e.g. JENKINS and ORR (1971) use the size fraction >63µ; BÉ and HUTSON (1977) use the size fraction >125µ; while HECHT (1973a) use the size fraction >250µ. A quantitative comparison of the basic data from these studies would seem to be meaningless in these circumstances because different species have different mean sizes (BÉ, 1977).

BÉ and HUTSON (1977) have indicated the large quantitative variation in species composition of different size fractions taken from the same sample. The advantage of the very small size fractions (>63µ) is that small species are not lost or under-represented in the study. The advantage of using large size fractions (>250µ) is that juveniles - which often occur in vast numbers, are difficult or impossible to identify at the species level and generally constitute 'noise' in ecological studies - are eliminated from the investigation. It is thus important to arrive at a balance between excluding the majority of juveniles and including the majority of adults of all species. However, because of the large difference in the mean sizes of different species, such a compromise is probably impossible to achieve to perfection.

In the present study, only the size fraction >250µ has been studied for the following reasons:

a) tropical taxa are generally larger than average (HECHT, 1976) so that even the smallest species may be included.

b) the difficulty of identifying juveniles and the problem of their status in a palaeoecological study is by-passed.

c) HECHT (1973a, 1973b) has demonstrated the use of planktonic foraminiferal size fractions >250µ for successful palaeotemperature analyses. In addition, a further study (HECHT, 1976), indicated that similar environmental trends were observed by the same species from different size fractions (125-250µ and >250µ).

By restricting the study to those planktonic foraminifera >250µ, it is acknowledged that much information is undoubtedly ignored and that numerical bias towards the larger taxa is introduced. However, it is believed that the advantages gained in terms of juvenile elimination tend to compensate for those disadvantages outlined above.

The method of subsample selection may produce unrepresentative data because of the large bias which can occur when spreading planktonic foraminiferal tests over a picking tray. Because of the large variation in shape, density and aerodynamic property apparent is the tests, an element of sorting may ensue during the spreading process.

To restrict this phenomenon, previous workers have used a microsplitter to provide a representative subsample, although HERMAN and BOGYO (1980) have recently highlighted the fallibility of such methods.

To overcome sorting bias, subsample selection was carefully regimented about a diagonal and cross-cross pattern. In addition, 500 individuals were selected - against 300 which is usually recognised for statistical validity (see BOLTOVSKOY and WRIGHT, 1976).

To test the results derived by this method one sample was selected for reproduceability of data. Sample 26-5 was used to produce three additional subsamples. A taxonomic similarity index test of each of these subsamples against the original yielded similarities of 88.8%, 90.4%, and 93.6% respectively (see Chapter V, p.106 for the nature of the index).

Apart from normal abundance analysis, specialist investigations for palaeotemperature interpretation were carried out on Orbulina universa (mean size) and Globorotalia cultrata gp. (coiling direction).

For the O. universa biometric study, individuals were picked at random from the strewn residues until a 'representative subsample' was obtained. The number of individuals per subsample ranged from 10 to 74 with an average of 26. Care was taken to pick individuals from across the whole area of the picking tray to help avoid inherant bias caused by size sorting during the spread of the residue. Several diagonal traverses were made in which all individuals from each grid square covered were picked. Samples which contained less than ten O. universa individuals were discarded from the biometric study. Diameter measurements were made using a X10 graduated eye piece at X60 magnification.

Coiling directions in G. cultrata group have been calculated in seventy four samples from the Middle to Late Miocene interval. This data is based on those individuals included in each subsample of 500 planktonic foraminifera. Numbers per subsample varied from one to 285 with a mean of 94.

b) Planktonic Foraminifera (cores 23 to 1)

The investigation of samples from cores 23 to 1 only involves distribution in O. universa and G. cultrata gp. (fig.4a-c).

In the interval covering the late Late Miocene, from cores 23 to 18, mean size in O. universa, and abundance and coiling direction in G.

cultrata gp. were calculated to interpret the palaeoclimatic history and thereby allow a palaeotemperature reconstruction of the entire Middle and Late Miocene sequence. O. universa individuals were selected for biometric analysis in the same manner as those picked from cores 50 to 24. The quantitative abundance of G. cultrata gp. was investigated in thirteen samples from cores 23 to 18 by selecting a subsample of 500 individuals and calculating the proportion of G. cultrata gp. tests.

In the interval covering the late Late Miocene, coiling directions in G. cultrata gp. were investigated to contribute towards the palaeotemperature interpretation. In the interval covering the Pliocene and Pleistocene, from cores 17 to 2, coiling directions were investigated so as to completely cover the coiling direction history of the taxon since it's evolutionary inception at Site 289, and to enable a comparison with results of previous research. Fourtysix samples were selected from cores 23 to 2, from which individuals were selected at random from strewn residues until a "representative subsample" was established. The number of individuals per subsample varied from eight to thirtynine with a mean of 26.

c) Radiolaria

Each radiolarian residue contained many thousands of individuals and complete analysis was considered impractical. Instead a representative subsample was selected from each sample.

At X60 magnification, using a standard transmitted light microscope, three fields of view were selected from the centre and two peripheries of the slide. All the radiolarian individuals were identified and counted within each field. The counts from all three fields were grouped and percentage abundances for each taxonomic catagory were calculated.

Finally the remaining residue was meticulously searched for any taxa not encountered in the initial survey.

The central position of fields of view and the position of additional taxa encountered elsewhere were indicated by means of an England Finder. The study of a field of view was enhanced by the use of cross wires which divided the view into four segments.

As in the case of planktonic foraminifera, some bias may be introduced to the strewn slides via the use of a pipette during the transfer of radiolarian tests from a beaker onto a slide. The influence of such bias was minimised by the use of three fields of view from various positions on the slide. In addition, many individuals were counted in each subsample. The average number examined per sample was 712.

To test the results derived by the method used, one sample was selected for reproduceability of data. Sample 43cc was used to produce two additional subsamples. A taxonomic similarity index test of each of these subsamples against the original yielded similarities of 85.2% and 87.7% respectively (see Chapter V, p.106 for an explanation of the index).

Apart from normal abundance analyses, a biometric analysis of Stichocorys delmontensis was undertaken to investigate a possible relationship between intraspecific variation in this taxon and palaeoenvironmental events (see Chapter VII).

4. DSDP SITE 71: PROVINCIAL GEOLOGY, STRATIGRAPHICAL SEQUENCE, MATERIALS AND METHODS

i) Provincial Geology

DSDP Site 71 is located in the central equatorial Pacific (lat. 04° 28.28'N; long. 140° 18.19'W) (fig.5). The site was drilled during DSDP Leg 8 which investigated the Cenzoic geology of the eastern and

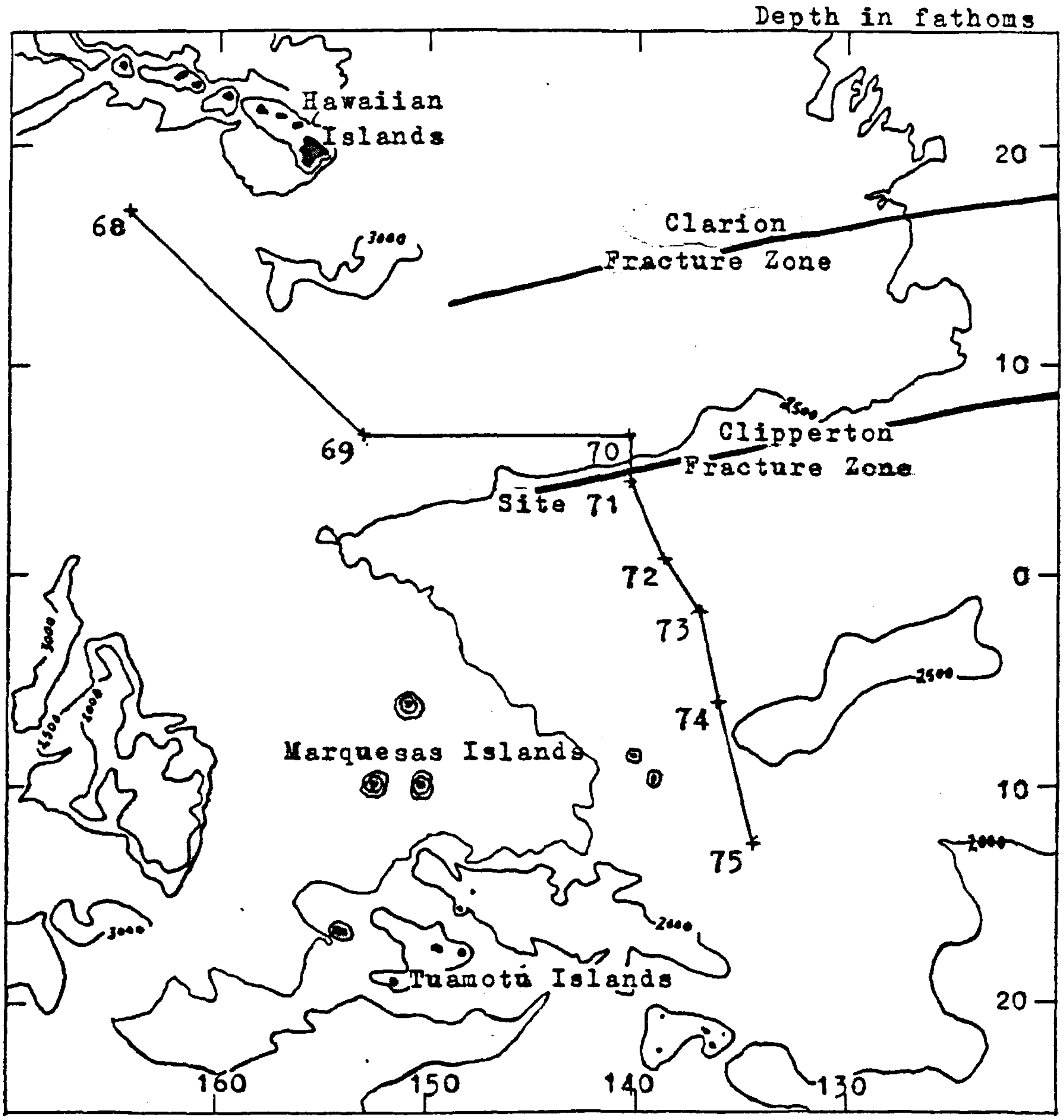

Fig.5 Location of Drill Sites, Leg 8 - including Site 71 - and Structural Features in the Region.

central equatorial Pacific Ocean with particular emphasis on the history of the equatorial current system (TRACEY et al., 1971).

Site 71 is situated on the Pacific plate west of the East Pacific Rise (fig.5). To the immediate north lies the Clipperton Fracture Zone, a structural and topographic feature aligned approximately E.S.E. - W.N.W. which is believed to be a transform fault related to the mid-oceanic ridge situated to the east.

The floor of the central equatorial Pacific is characterised by a thick lens of undisturbed Cenozoic biogenic sediments which is aligned E-W with maximum development directly below the equator. The sedimentary body thins gradually to the east and west and more rapidly to the north and south. Site 71 is situated near the depocentre (TRACEY et al., 1971). Oceanic basalt was reached at Sites 74 and 75 of Leg 8 and was overlain by sediments of Middle Eocene and Early Oligocene age respectively (TRACEY et al. 1971). Oceanic crust in the area is thus younger than that at Site 289.

ii) Stratigraphical Sequence, Site 71

DSDP Site 71 was drilled in a water depth of 4419m and cored continuously to 436m and discontinuously to 475m below the sea floor. Fourty-nine cores were obtained although incomplete recovery yielded only 369.1m of sediment (fig.6).

The cored sequence can be divided into two main lithostratigraphic units (TRACEY et al., 1971):

- Clipperton Oceanic Formation (0-188m): alternating calcareous and siliceous oozes and varicoloured calcareous oozes. Quaternary to Early Miocene.
- Marquesas Oceanic Formation (188-475m): calcareous ooze with chert at the base. Early Miocene to Late Oligocene.

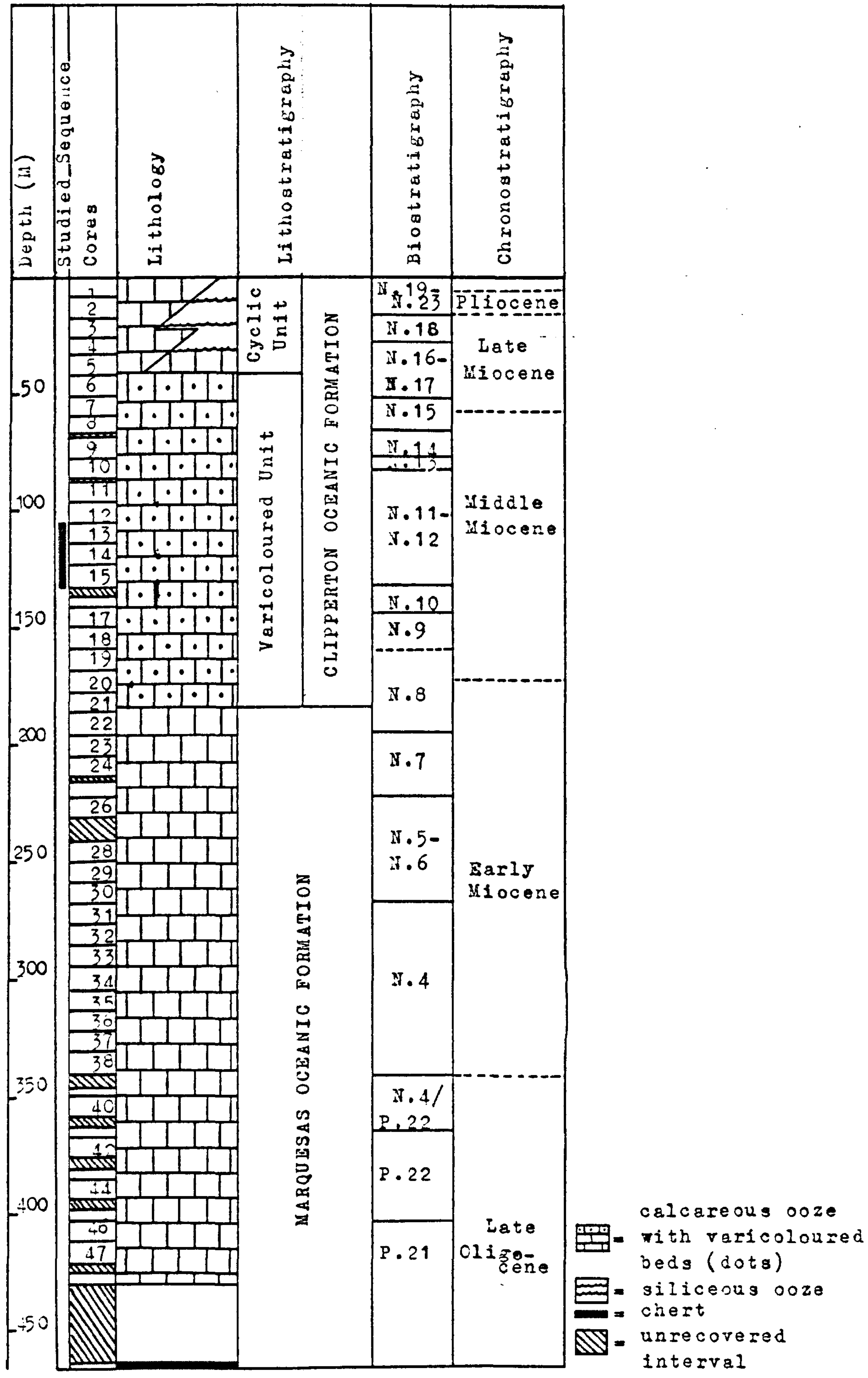

Fig.6 Stratigraphic Succession, Site 71 (after Tracey *et al.*, 1971)

Preliminary biostratigraphical studies by BECKMANN (1971) using planktonic foraminifera, HAQ and LIPPS (1971) using nannofossils and MOORE (1971) using radiolaria indicate a complete stratigraphical sequence (fig.6).

TRACEY et al. (1971) have discussed the accumulation of the sequence. Sedimentary processes at Site 71, as in those of Site 289, have been almost exclusively pelagic with the accumulation of biogenic carbonates and siliceous sediments dominated by nannofossils, planktonic foraminifera and radiolaria.

iii) Studied Sequence: Site 71

The studied sequence at Site 71 is indicated birefly in fig.6 and in further detail in fig.7.

A short interval was selected within the Middle Miocene (within Zones N.11-12) (cores 15 to 13). Investigations in this interval involve the qualitative and quantitative distribution of all planktonic foraminifera and radiolaria encountered.

The position of all samples taken is indicated on fig.7. Sample labelling follows the same procedure discussed previously for those from Site 289.

Coring recovery was complete in cores 15 to 13 and yielded 27m of sediment representing the interval 107m to 134m below the sea floor.

Seventeen samples were analysed for their planktonic foraminiferal content, nine of which were also analysed for their radiolarian content (fig.7). Where possible, every core section was sampled so that the sampling interval was approximately 1.5m.

iv) Core Description and Interpretation

The studied sequence occurs within the varicoloured unit of the Clipperton Oceanic Formation. In the present study, the cored sediments

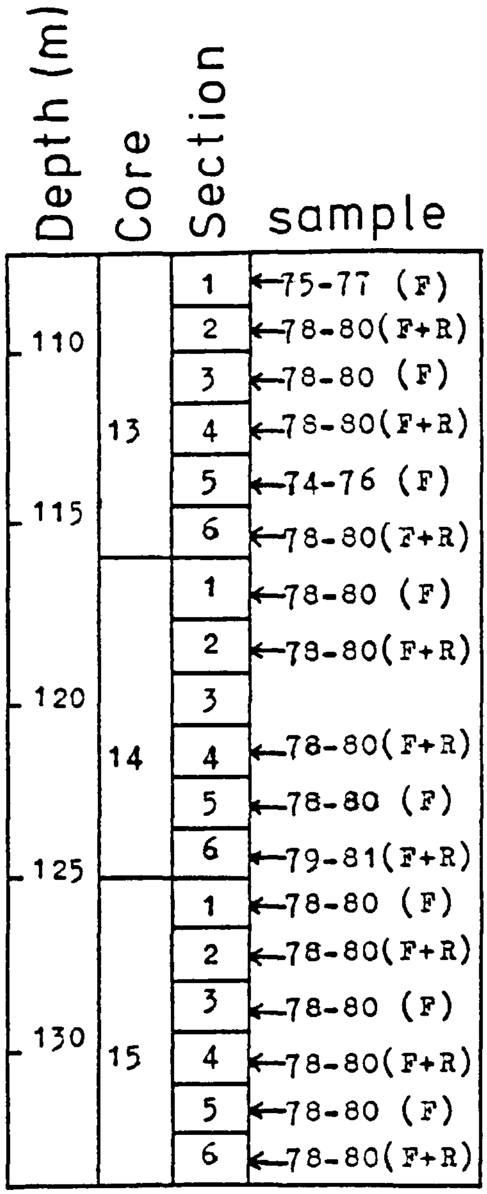

Fig. 7 Sample Location, Site 71
(F+R) = analysed for planktonic foraminifera and radiolaria
(F) = analysed for planktonic foraminifera

were not made available and the following account is taken from TRACEY *et al.*, (1971).

The varicoloured unit extends from a depth of 43 to 188m and consists of a radiolarian-nannofossil ooze (fig.6). Calcareous nannofossils and foraminifera predominate (approximately 75%) with subordinate radiolaria (approximately 25%). Sediment colour varied from bluish white to greenish white.

Most cores are disturbed by drilling and contain deformation swirls. Original sedimentary structures consist of occasional fine laminae.

The Initial Reports volume for Leg 8 contains a detailed diagramatic and written lithological description of all cored sediments from Site 71 at a scale of approximately 1 in 50. In addition, photographic plates of all cores are given at a scale of approximately 1 in 6.6.

v) Processing Methods

The samples were processed in a similar manner as indicated for those from Site 289. However, processing the siliceous fraction was only carried out after the calcareous planktonic foraminifera had been examined. The calcareous fraction, apart from the 500 picked tests, of these samples analysed for their radiolarian content has thus been destroyed by HCL treatment.

vi) Description of Prepared Residues

The calcareous and siliceous residues at Site 71 are generally similar in content to those at Site 289. The preservation of the planktonic foraminifera is however, most similar to the poorest preserved samples at Site 289 and appears to be related to deposition in water depths near the level of the lysocline. The present day water depth at

Site 71 is 4419m compared to a depth of 2206m at Site 289. On the contrary, the radiolarian assemblages tend to be in a very good state of preservation and are accompanied by numerous, large diatom frustules.

vii) Study Methods

Methods of study are as outlined for planktonic foraminifera and radiolaria from Site 289. However the lack of sufficient numbers of *Orbulina universa* individuals prevented a meaningful investigation of mean size in this species at Site 71.

A taxonomic treatment of the planktonic foraminifera and radiolaria encountered in this study is given in Appendix I, with full taxonomic names, including author and date of description. It is recommended that this review be consulted in conjunction with the main text.

The material and basic data on which this thesis is based are stored in the Micropalaeontology Laboratory, Dept. of Geology, Keele University.

CHAPTER II

OCEANOGRAPHY, PLANKTONIC ECOLOGY AND PELAGIC (BIOGENIC) SEDIMENTOLOGY OF THE PACIFIC OCEAN

1. PACIFIC OCEANOGRAPHY

i) Introduction

The present day oceanography, ecology, biogeography and sedimentology of the Pacific Ocean forms a frame of reference for Cenozoic palaeoceanographic evolution and reconstruction (Van ANDEL *et al*., 1975).

In the following oceanographic account, only the general features of circulation and water mass distribution in the Pacific Ocean are outlined. The reader is referred to SVERDRUP *et al*. (1942) and DEFANT (1961) for a more definitive treatment of the subject. Most information offered here has been taken from the recent concise accounts by PICKARD (1975) and TCHERNIA (1980). In addition to the equatorial Pacific, particular attention is paid to the South Pacific. The circulation pattern of the ocean is asymmetrical about the geographical equator with the result that the study areas lie within, and are influenced by, the South Pacific circulation system.

ii) The Circulation System

The circulation systems of all the world's oceans are driven and controlled by several related factors of which solar energy, atmospheric circulation and continental configuration are most important. Uneven heating of the earth's surface by the sun is the principal driving force behind both atmospheric and oceanic circulation. Oceanic circulation can be broadly divided into two catagories: vertical motion, a direct response to the uneven heating; and horizontal motion, an indirect response to uneven heating via the wind system.

Vertical motion is initiated in high latitudes where surface waters generally undergo density increase due to increased salinity (from ice formation) and decreased temperature. The subsequent sinking effect creates the so called thermo-haline circulation of cold, salty, dense bottom waters flowing from high to low latitudes.

Horizontal circulation of the surface waters involves the upper few hundred metres of the water column and is a response to the wind patterns, the earth's rotation (Coriolis Force) and continental configuration. Horizontal circulation systems are therefore important to the study of living and fossil planktonic oganisms such as radiolaria and planktonic foraminifera which mainly inhabit the epipelagic zone (upper 300 metres).

The surface circulation of the Pacific can be considered under two regions, the North and the South Pacific Oceans. These oceans are dominated by clockwise and anticlockwise gyres respectively which meet to form a well developed Equatorial Current system (fig. 8). The South Pacific Gyre forms the South Equatorial Current following west between 10°S and 3°N and the North Pacific Gyre forms the North Equatorial Current flowing west from about 8°N. These two currents help contribute to an Equatorial Counter Current in the extreme western Pacific which flows eastwards across the entire equatorial region and separates the North and South Equatorial Currents. DSDP Sites 289 and 71 lie directly under the South Equatorial Current (fig. 8). The system is driven by the trade winds. In the tropical North Pacific, the Northeast Trades blow west or south west while in the tropical South Pacific the Southeast Trades blow west. The Pacific Trade winds converge north of the equator (5° to 8° N) and the

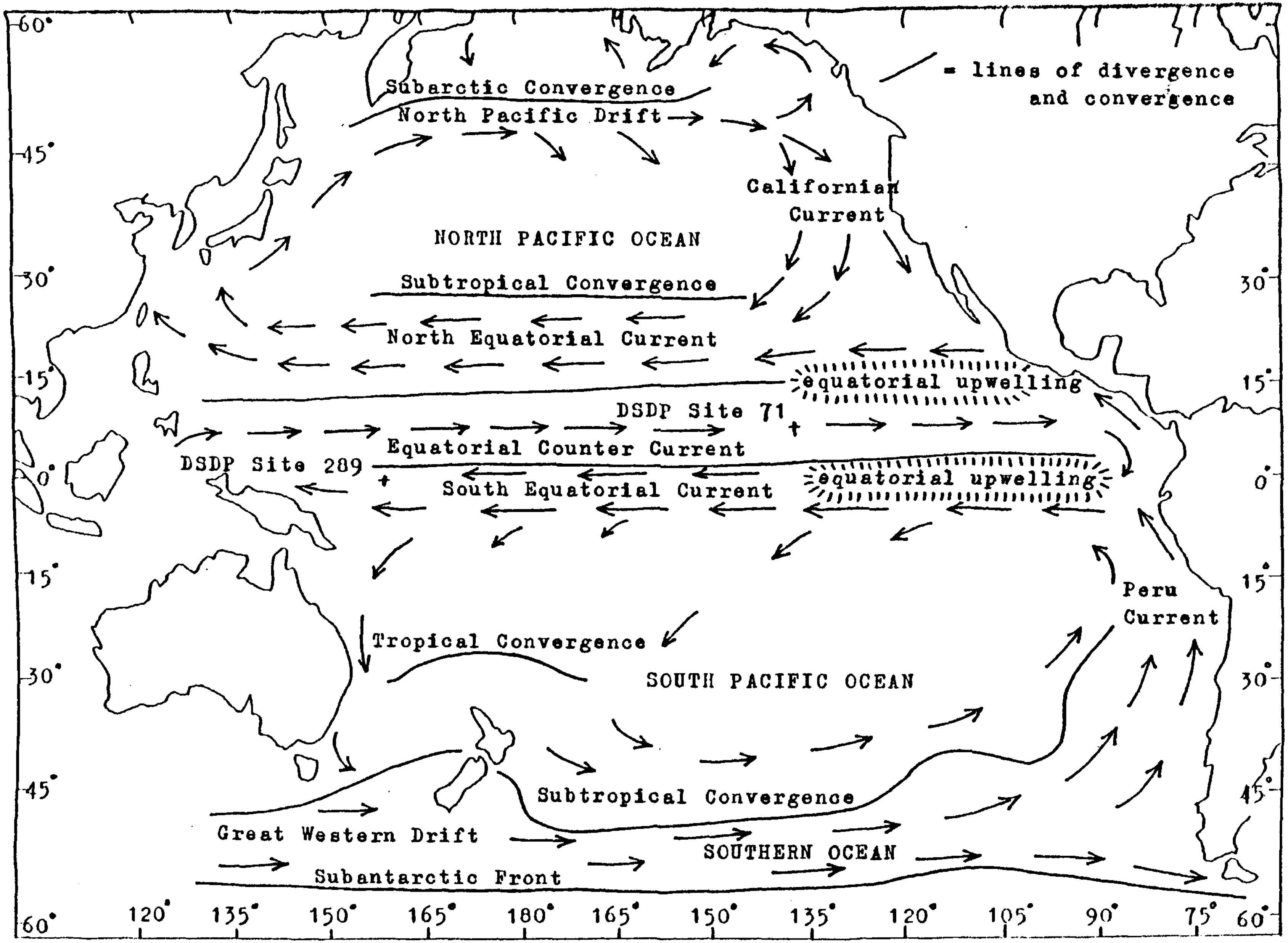

Fig.8 Surface water circulation of the Pacific Ocean (Northern Hemisphere winter; after DEFANT, 1961; Van ANDEL, *et al.*, 1975 and TCHERNIA, 1980)

Equatorial Current system is likewise asymmetrical with respect to latitude. The situation is complicated by the presence of an eastward flowing Equatorial Undercurrent (Cromwell Current) lying at a depth of 100 metres or less beneath the South Equatorial Current. In the western Pacific, the Equatorial Counter Current and Undercurrent are usually connected beneath the surface. A weak and narrow counter-current is also present south of the South Equatorial Current.

Although well defined, the Equatorial Current system can be complex and variable, particularly in the western Pacific where seasonal monsoons exist.

The South Pacific Gyre continues from the South Equatorial Current into the Coral Sea off the eastern coast of Australia towards high latitudes where it is driven eastwards by the West Wind Drift of the Antarctic Circumpolar Current. The Gyre is completed by the Peru Current which flows north along the west coast of South America and turns west near the equator to form the South Equatorial Current (fig. 8).

The North Pacific Gyre flows north from the North Equatorial Current in the western Pacific, following some loss of water to the Equatorial Counter Current. Passing Japan, the Gyre is deflected eastwards as the North Pacific Drift. As the Current approaches the North American continent, it divides north to form the smaller Alaskan Gyre and south to form the Californian Current which eventually feeds into the westward flowing North Equatorial Pacific Current to complete the cycle (fig. 8).

iii) <u>Temperature</u>

The Pacific Ocean is characterised by a steep surface water temperature gradient ranging from 29°C to - 1.9°C between low and high latitudes respectively (REID, 1969). The isotherms generally follow latitude, except where they are disturbed by particular currents as in the south east and eastern equatorial Pacific (fig. 9). Temperature gradients are strongest in mid-latitude temperate regions where sharp variations, known as lines of convergence, separate regions of diverse hydrological character (fig. 8).

Variation of temperature with depth depends on surface water values. The equatorial Pacific, with high surface temperatures, is characterised by a steep temperature/depth gradient and the water column can be divided into three distinct units. An upper layer, which can extend down to 200 metres, is well mixed by wind induced turbulence and is characterised by fairly uniform temperatures throughout. An intermediate layer, in which temperature decrease is rapid, overlies the third and most extensive layer where temperatures are cold and fairly uniform and decrease slowly to the ocean floor. The intermediate layer is known as the thermocline and is an important hydrographic feature. In addition to a temperature change, this discontinuity is characterised by salinity and density anomalies and its' presence ensures stability to the overlying mixed zone by inhibiting the vertical transfer of water properties. The thermocline is permanent in equatorial and tropical waters, seasonal in temperate waters and is absent in subpolar and polar waters, where the temperature difference between surface and bottom waters is small. The upper limit of the thermocline in equatorial regions varies from 150 to 200 metres depth in the western Pacific to 50 metres or less in the eastern Pacific.

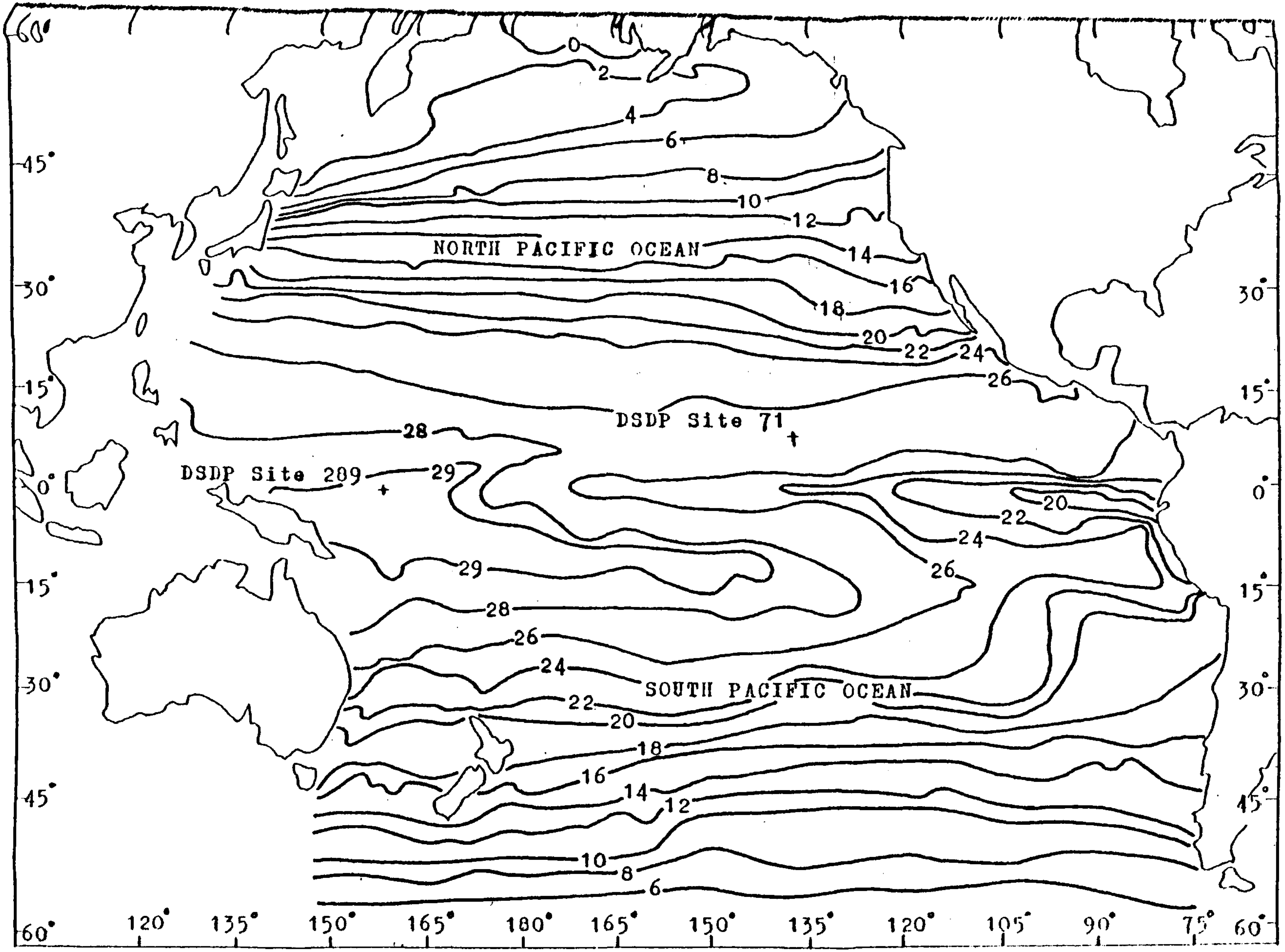

Fig.9 Pacific Ocean sea-surface temperature in northern winter (°C) (after RIED, 1969)

iv) Salinity

The salinity range in open Pacific Ocean surface waters varies from 33 to 36°/oo. Maximum values typically occur in tropical waters due to excess evaporation while minimum values tend to occur along the equatorial belt because of increased precipitation. In equatorial regions, there is a salinity maximum at about the level of the upper limit of the thermocline.

Fig. 10 illustrates temperature and salinity profiles against depth for two stations lying approximately over Sites 289 and 71 in the western and central equatorial Pacific respectively. The data, which was upplied by the U.S. Hydrographic Station data file via the Institute of Oceanographic Sciences, reveals the position of the thermocline and salinity maximum with depth. At station A in the western Pacific, surface water temperatures are around 29.5°C; the thermocline extends from 150 to approximately 300 metres and the salinity maximum is situated around 125 metres. At station B in the central equatorial Pacific,the surface water temperatures are somewhat lower, around 25.5°C; the thermocline extends from 150 to approximately 250 metres and the salinity maximum is situated around 125 metres.

Seasonal temperature variations of surface waters range around 1°C or less in these areas (REID, 1969).

v) Nutrients

Phosphate, or dissolved inorganic phosphorous, generally increases with depth from very low values in the photic zone to maximum values at some intermediate depth. In the Pacific Ocean, surface values vary from 0.2 ug-atom/l in the oligotrophic central gyre to over 1 ug-atom/l in eutrophic waters of high latitudes, the south east Pacific and the eastern equatorial Pacific (REID, 1962).

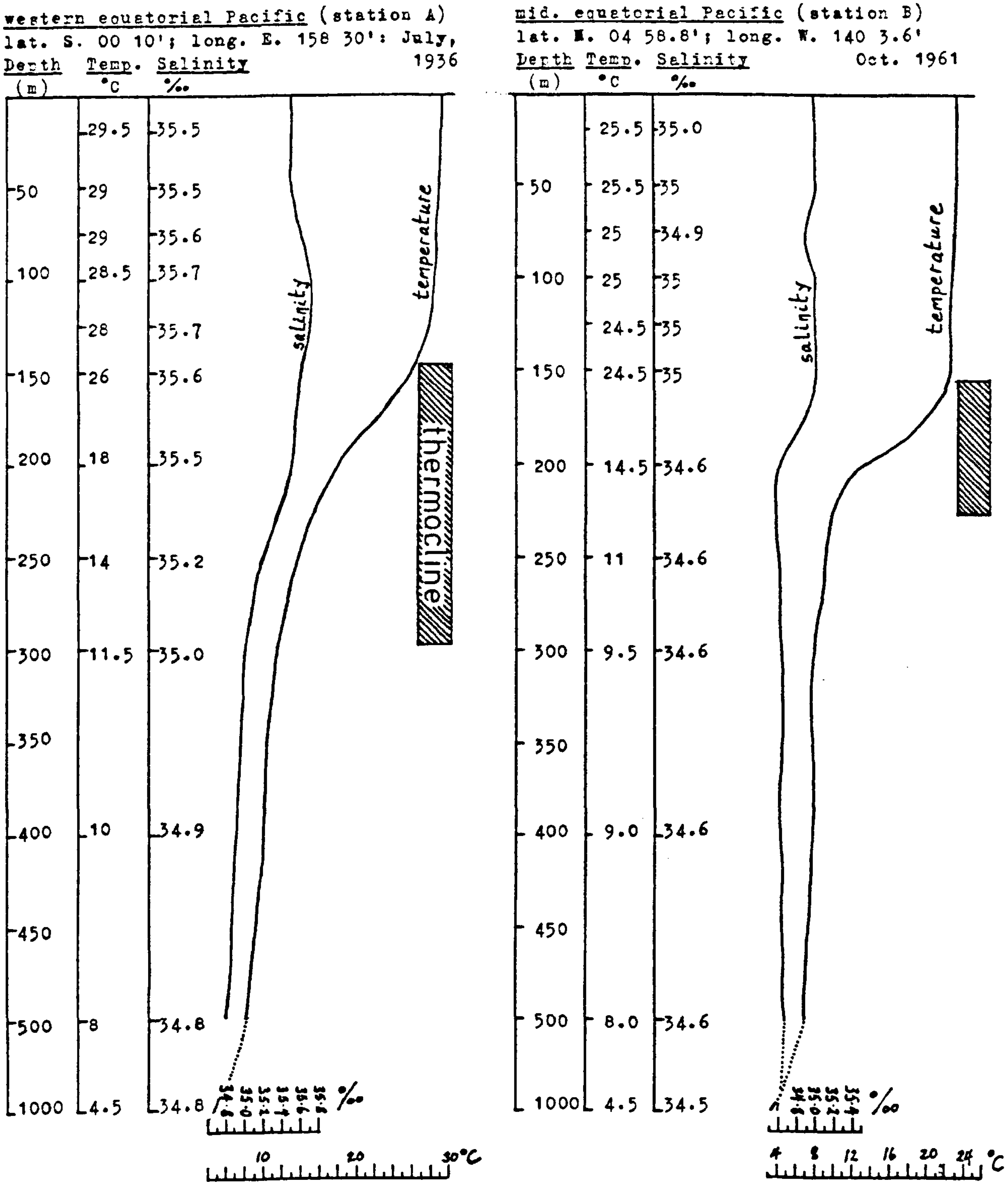

Fig.10 Temperature and Salinity profiles vs. depth; western and mid. equatorial Pacific (from U.S. Hydrographic Station Data File)

A review of surface temperature and nutrient values along the equatorial Pacific reveals anomalous values in the eastern region. Isotherms are relatively low and are bordered to the north and south by higher values (fig. 9). Nutrient values, as outlined above, are relatively high. The anomalies are due to two main factors:

a) The advection of cold water from the Peru current arriving from high latitudes.

b) Coastal and equatorial upwelling.

vi) Upwelling

Upwelling involves the ascending motion of some minimum duration and extent in which water from subsurface layers is brought to the surface layer and removed from the area of upwelling by horizontal flow (WYRTKI, 1963). The phenomenon is a result of wind induced horizontal divergence on the surface layer, with replacing water originating from a depth of about a few hundred metres. Upwelling is particularly common around the Antarctic continent, along the west coasts of continents (coastal upwelling) and along equatorial regions (equatorial upwelling) where prevailing winds are strong. The introduction of subsurface waters to the surface creates the horizontal anomalies in the distribution of physical and chemical properties by disrupting the stable, well mixed surface waters. The phenomenon is of great importance to oceanic biological productivity.

The dynamics of upwelling is extremely complex and only a rather basic outline is offered herein. The reader is referred to the review work of SMITH (1968) who warns against any oversimplified approach to the problem.

EKMAN (1905) provided a basis for understanding the relationship between wind stress and oceanic circulation responsible for oceanic upwelling. Due to the effect of the earths rotation (Coriolis Force), and frictional forces, the net transport of water due to wind stress is directed 90° to the right of the wind in the Northern Hemisphere and 90° to the left of the wind in the Southern Hemisphere.

Coastal upwelling in the South Pacific occurs most prolifically off the coast of Peru, where one sided divergence is induced by wind stress parallel to the coast.

Equatorial upwelling is more pertinent to the present study and occurs in the eastern equatorial Pacific, where zones of divergences lie on the equator and on the northwest edge of the Equatorial Counter Current (fig. 8) (SVERDRUP et al., 1942). Equatorial upwelling at these divergences is related to the Equatorial Undercurrent. In the pronouced shear and mixing associated with the Undercurrent, the mixed layer ascends into the surface layer and the 'upwelling' effects are intensified by trade wind convergence (SMITH, 1968). The phenomenon is believed to extend to a depth of 50 metres in the eastern Pacific and to 100 to 150 metres in the central or mid-Pacific. The maximum downward extension of upwelling in these regions coinsides with the upper limit of thermocline (WOOSTER and JENNINGS, 1955). AUSTIN (1958) reports a western extention of equatorial upwelling to about 180°; the process is presently absent in the western Pacific (TSUCHIYA, 1961).

The effects of upwelling influences the distribution of the physical, chemical and biological properties of surface waters. In general, increasing water depths within the epipelagic zone of non-upwelling areas is characterised by decreasing values of temperature, salinity and oxygen content and increasing values of density and nutrient content. In areas of upwelling, surface waters are characterised by decreased values of temperature oxygen content and salinity, and increased values of density and nutrient content. Consequently, vertical profiles of these parameters in the epipelagic zone during upwelling are less steep due to homogenisation of the environment.

The ascending subsurface waters of the eastern equatorial Pacific are up to 9°C cooler than waters in higher latitudes to the immediate north and to waters of corresponding latitude in the western equatorial Pacific (fig. 9).

An increase in nutrient values in regions of upwelling is one of the more significant consequences, particularly to the commercial fishing industry. Phosphate, one of the principle nutrients of plankton and very important to marine productivity, is generally low in surface waters of the Pacific Ocean. The higher values normally found below the photic zone are continually supplied to the surface waters in upwelling regions to create a ten fold increase of available nutrients compared to less fertile areas (REID, 1962). Primary producers of the photic zone thrive under such conditions and the increased productivity is reflected in higher trophic levels via food chains (SMITH, 1968). A five fold increase in the productivity of phytoplankton compared to the world ocean average has been measured in upwelling areas using C^{14} techniques (HOLMES _et al._, 1957). Standing crops of zooplankton are similarly high (WOOSTER and REID, 1963). The effect of upwelling with respect to planktonic foraminifera and radiolaria in particular will be discussed later in this chapter.

vii) Pacific Ocean Water Masses

The Pacific Ocean - as in the case of other oceans of the world - can be subdivided into a series of water masses which are characterised by particular temperature and salinity values. The water masses are depth zoned into upper, intermediate and bottom waters.

Upper water masses exist between approximately 100 and 800 metres depth in the Pacific Ocean. They consist of an Equatorial Water Mass separating the Central Water Masses of the North and South Pacific Oceans respectively.

The Equatorial Water Mass extends from 20°N to 10°S in the eastern Pacific and diminishes in north-south extent towards the west. The water mass is separated from the well mixed surface waters by the upper limit of a strong thermocline which reaches the surface in some parts of the eastern Pacific.

The North Pacific Central Water Mass extends from the northern limit of the Equatorial Water Mass to about 40°N.

South of the Equatorial Water Mass are the western and eastern South Pacific Central Water Masses extending to the subtropical convergence at 40°S. The Subantarctic and Antarctic Water Masses are considered to lie within the Southern Ocean.

Intermediate Water Masses are present below the Central Water Mass of the Pacific Ocean to a depth in excess of 1000 metres. In the South Pacific, Antarctic Intermediate Water, formed by subsurface mixing at the Antarctic Convergence, extends north to be limited by the Equatorial Water Mass. An Equatorial Intermediate Water Mass is present below the North Pacific Central Water Mass.

The deep and bottom water of the Pacific Ocean, from 2500 metres, is characterised by very uniform temperature and salinity values. The water does not originate in the Pacific but enters from the south between New Zealand and Antarctica to flow slowly north over the equator into the North Pacific basin.

2. THE ECOLOGY OF LIVING PLANKTONIC FORAMINIFERA

The ecology of living planktonic foraminifera has been the subject of many oceanographic surveys since the early work of OWEN (1867), BRADY (1884) and MURRAY (1897). However, the past two decades in particular has witnessed an upsurge in interest in biological aspects of the group as a response to increased applications of the fossil counterparts in biostratigraphic and palaeoecological studies. In a major ecological, zoogeographic and taxonomic review, BÉ (1977), has been able to refer to the extensive survey results of SCHOTT (1935), BRADSHAW (1959), BÉ (1960), PARKER (1960), BELYAEVA (1964), JONES (1964, 1967), BERGER (1969, 1971), BÉ and TOLDERLUND (1971) and WILLIAMS (1971).

The following account incorporates many of the views expressed by BÉ (1977), together with those conveyed by LIPPS (1979) in a more recent review paper, to which the reader is referred for additional and specific information.

Calcareous planktonic foraminifera are common and widespread in the open ocean. Most of the thirtythree species and subspecies live in the epipelagic zone (upper 300 metres) where they tend to concentrate between 10 and 50 metres depth within the well lit (euphotic) zone. Mesopelagic (between 300 and 1000 metres) and bathypelagic (between 1000 and 3000 metres) species are few. A preliminary survey by BEERS and STEWART (1971) indicate that planktonic foraminifera constitute a very small proportion of the total hetergenous marine microzooplankton.

Environmental factors controlling species distribution and abundance are very complex and it is unlikely that specific factors are singularly responsible. Distribution is influenced by both biological and physical-chemical considerations, including predation, light, temperature, salinity, water density, currents, CO_2, O_2, pH, symbiosis, nutrient supply, food supply and productivity. BÉ (1977) has demonstrated the particular importance of temperature, salinity, O_2 content and phosphate values.

The distribution of absolute abundance corresponds to the general pattern of oceanic fertility with maximum concentrations occuring in areas with high concentrations of nutrients, phytoplankton and microzooplankton. These areas occur in eutrophic current systems, boundary currents, divergences and upwelling zones. A seasonal fluctuation in abundance of planktonic foraminifera follows the phytoplankton productivity cycle. Very sparse populations are encountered over continental shelves.

Spinose *Globigerinoides spp., Orbulina spp., and Hastigerina spp.* tend to harbour symbiotic zooanthellae and concentrate in the euphotic zone. Symbionts are absent in the non-spinose globorotaliids.

The vertical range of depth habitats for individual species is wide and subject to regional, seasonal and diurnal variation. Consequently, tropical and subtropical species can only be divided into three broad catagories with respect to depth habitats. "Shallow water" species are spinose forms predominating in the upper 50 metres and include all *Globigerinoides spp.* and some *Globigerina spp.* "Intermediate water" species include both spinose and non-spinose forms inhabiting the upper 100 metres but predominating within 50 to 100 metres. The genera *Globigerina, Hastigerina, Pulleniatina, Globoquadrina, Orbulina, Candeina* and *Globigerinita* are represented. "Deep water" species are non-spinose forms living in the upper few hundred metres but whose adults predominate below 100 metres. They include all *Globorotalia spp, some Globoquadrina spp.* and *Sphaeroidinella dehiscens.*

All living species have a restricted horizontal distribution within the epipelagic zone. MURRAY (1897) first recognised the biogeographic pattern and divided planktonic foraminifera into several faunal assemblages. BÉ and TOLDERLUND (1971) have recently distinguished five worldwide faunal provinces by delimiting areas where each species occurs most abundantly. Each latitudinal province occurs in each hemisphere and includes the arctic and antarctic, subarctic and subantarctic, transitional, subtropical and tropical realms. Fig. 11 illustrates those delineated in the Pacific Ocean. The zones are latitudinal except where they are displaced by particularly strong currents such as those of the North Pacific Gyre. They generally correspond to the major hydrographic regions or water masses of the worlds oceans of SVERDRUP et al., (1942). These circumglobal distribution patterns seem to be strongly linked to the surface water temperature gradient between low and high latitudes (BÉ, 1977), although BRADSHAW (1959) suggests that no one temperature can be shown to form a common boundary for any of the faunal groups in the Pacific Ocean.

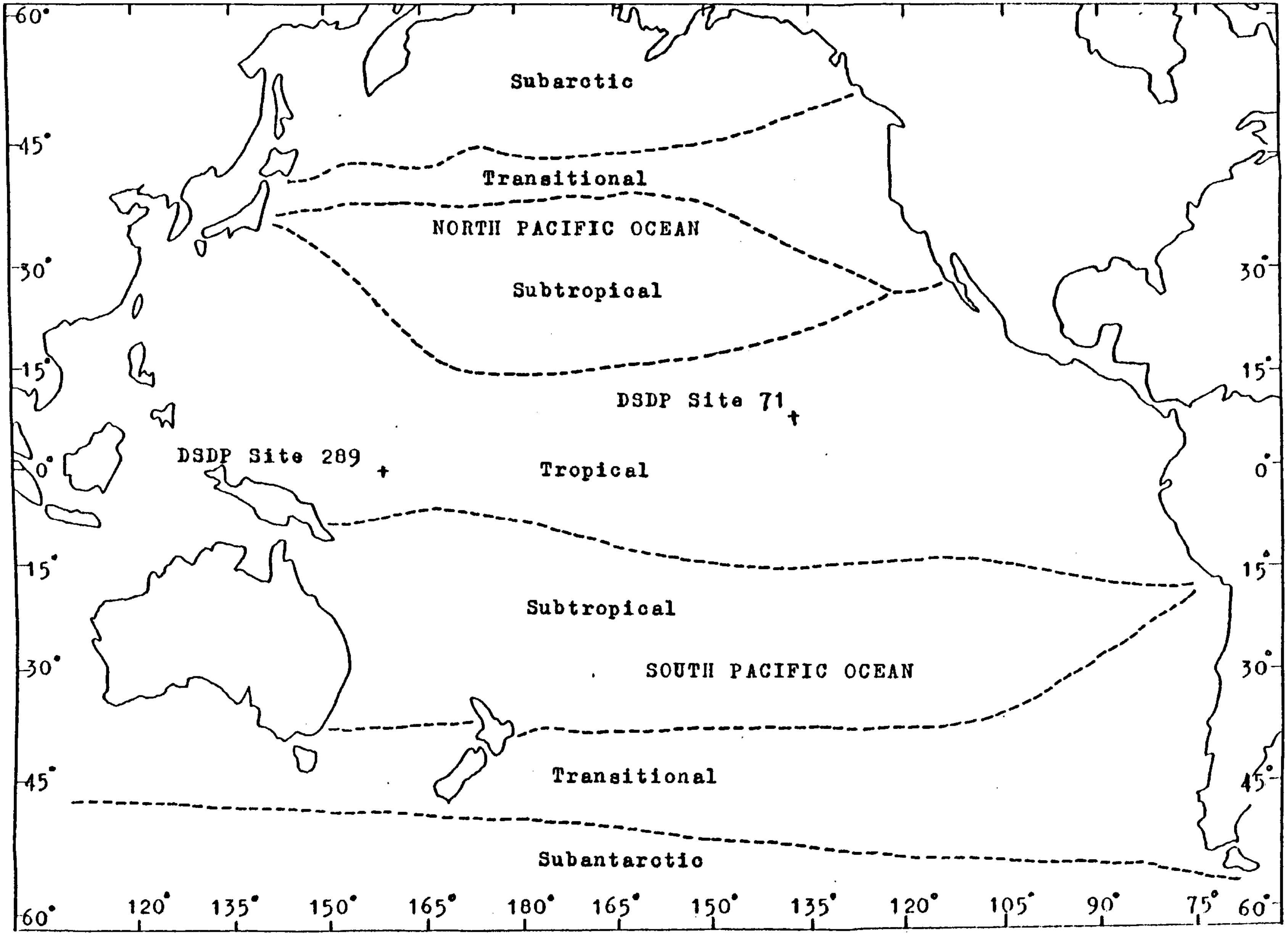

Fig.11 Planktonic foraminiferal provinces of the Pacific Ocean
(after BÉ and TOLDERLUND, 1971)

BÉ and TOLDERLUND (1971) recognised that many species are indigenous to individual zones while others transgress zones. In general, species diversity decreases from low to high latitudes, with twenty species in the tropical zone to five species in the arctic and antarctic zone. Morphology varies from simple (trochoform) types in high latitudinal provinces to more complex (flattened, spherical and keeled) types in low latitudinal provinces (LIPPS, 1979).

A close relationship has been reported between the distribution of many unrelated groups of plankton communites (euphasisiids, chaetognaths, pteropods, copepods, squid, salmon, diatoms and foraminifera) and the major hydrographic regions of the world (McGOWAN, 1971, 1974). Further, McGOWAN (1974) theorized that the Pacific Ocean biotic provinces possess "cores" which can be regarded as discrete ecosystems, each containing a characteristic group of interacting organisms historically adapted to their environment (fig. 12). Each core ecosystem is bounded by mixed regions or ecotones. The ecosystems may have several significant properties (McGOWAN, 1974). They are believed to be semi-closed systems, few in number, within which conditions are monotonous and predictable. The cores are thought to have been developed in the early Neogene and are thus old in terms of Recent evolutionary ecology. Each core ecosystem can be distinguished by qualitative and quantitative differences in basic processes related to climate and broad circulation patterns.

LIPPS (1979) concluded that the ecosystem - ecotone model of McGOWAN (1974) cannot be disproved as yet and may provide a useful working hypothesis for palaeoecological and palaeoceanographical work.

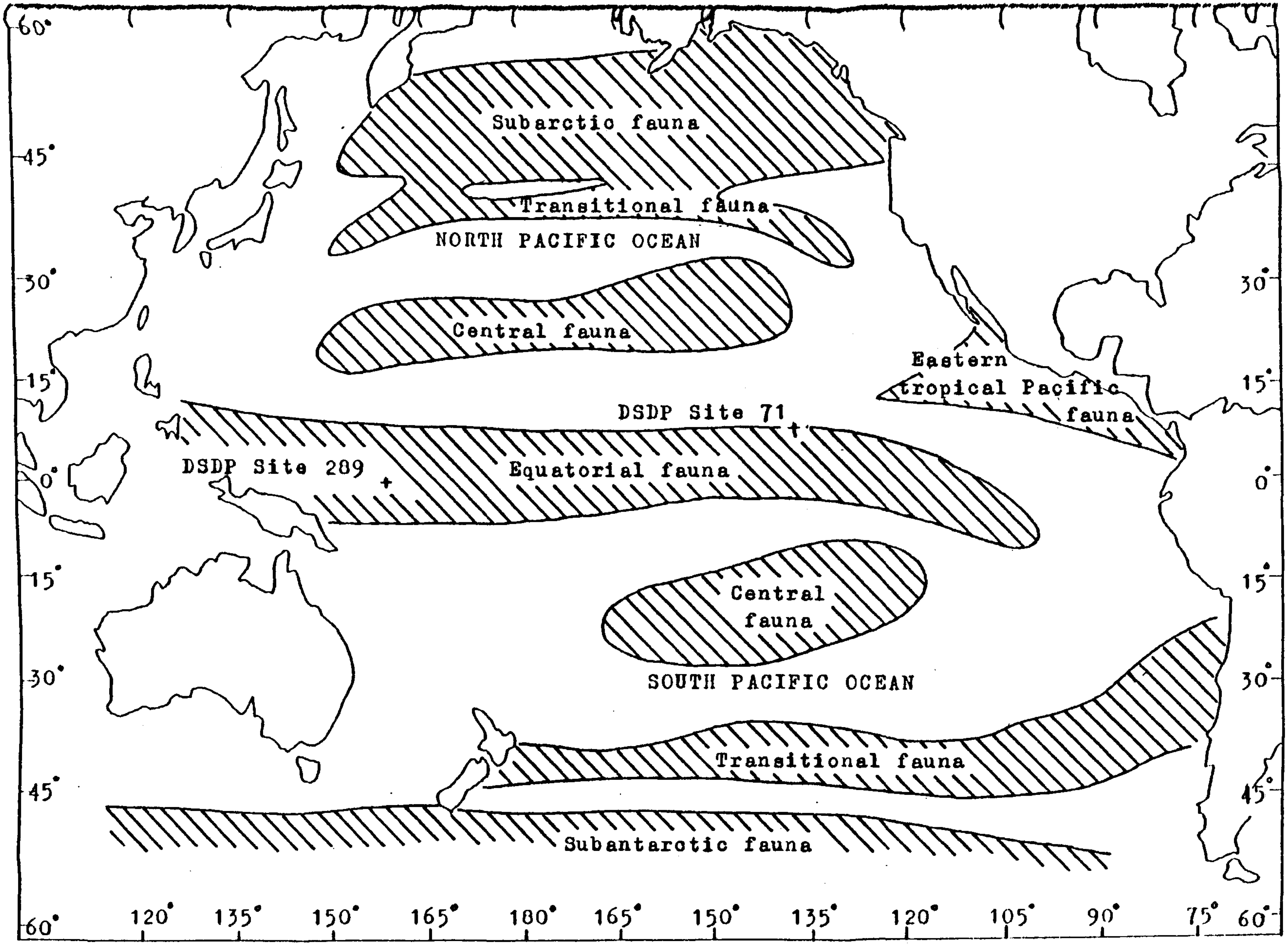

Fig.12 The "core" ecosystems (shaded) and ecqtones (unshaded) of the Pacific Ocean (according to McGOWAN, 1974)

DSDP Sites 289 and 71 lie within the "tropical planktonic foraminiferal province of BÉ and TOLDERLUND (1971) and within the "equatorial" biotic province of McGOWAN (1974).

3. THE ECOLOGY OF LIVING RADIOLARIA

Our knowledge of the ecology of living radiolaria is limited compared to that of planktonic foraminifera. In spite of early pioneering work by HAECKEL (1887), studies of living radiolaria have, until the last decade, been sporadic. The recent successful application of fossil radiolaria in palaeoceanographical and palaeoecological reconstructions (CLIMAP, 1976; MOORE, 1978; SANCETTA, 1978) has however, dispelled the large held belief that the group has negligable application in geological studies involving Cenozoic marine sediments. As in the case with planktonic foraminifera, ecological studies of living forms have been stimulated by the potential of fossil counterparts in biostratigraphic and palaeoenvironmental work. Studies by CASEY (1966, 1971a, 1971b), PETRUSHEVSKAYA (1971a, 1971b), RENZ (1976) and KLING (1966) involving radiolaria from Pacific Ocean plankton have vastly increased our understanding of their ecology, although further work is necessary. A useful comprehensive review of previous studies is offered by CASEY (1977).

Polycystine radiolaria are marine planktonic protozoans that secrete skeletons of almost pure opaline silica. The group are common in oceanic waters and rare in coastal regions (CASEY, 1971a). BEERS and STEWART (1971) report up to 30% abundance in particular size grades of microzooplankton from waters of the eastern tropical Pacific. Radiolaria are herbivores or organic suspension feeders with some forms harbouring symbiotic zooanthellae (CASEY and SLOAN, 1971), prompting CASEY (1977) to consider the group an important part of the planktonic ecosystem. RIEDEL and SANFILIPPO (1977) estimate some 100 to 300 living species in tropical and equatorial regions of the world's oceans.

A basic similarity in the distributional pattern of radiolarian and planktonic foraminiferal latitudinal provinces in waters of the Pacific Ocean suggest that similar limiting factors control both groups (CASEY 1977; see also herein).

The vertical and horizontal distribution of radiolaria is subject to daily and seasonal fluctuations which can be related to cyclic variations in oceanographic conditions (CASEY, 1977).

Greatest densities of radiolarins occur in eutrophic equatorial, high latitude and upwelling regions while lowest densities occur in oligotrophic regions within major ocean gyres (PETRUSHEVSKAYA, 1971a; BEERS and STEWART, 1971; RENZ, 1976).

Studies by HAECKEL (1887), PETRUSHEVSKAYA (1966, 1971a) RENZ (1976), CASEY (1966, 1971a, 1971b) and KLING (1979) indicate that radiolaria are zoned with respect to depth. Vertical faunal breaks occur at depths of approximately 50, 200, 400 and 1000 metres in temperate and tropical waters. The faunal boundaries appear to be related to discontinuities in the physical/chemical environment such as changes in temperature (thermocline), salinity, density (water mass changes), light penetration and food supply (CASEY, 1977). PETRUSHEVSKAYA (1966, 1971a) and KLING (1979) found radiolaria at all levels within the Central North Pacific Ocean. Maximum concentrations and diversity were found between the surface and 300 metres depth, followed by a general faunal impoverishment at greater levels. Species distribution is limited so that assemblages from the shallow layers differ markedly from those of the deeper layers. KLING (1979) concluded the depth zonations exhibited by radiolaria to be similar to those seen in other planktonic organisms.

The horizontal distribution of radiolaria in the Pacific Ocean has been mapped by CASEY (1966, 1971a, 1971b). Using the distributional limits of particular species, several radiolarian biogeographic faunal zones, incorporating both vertical and horizontal distribution patterns can be recognised in plankton and sediment samples. The zones, indicated in fig. 13 , show a good correlation with the major water masses described by SVERDRUP et al., (1942) (CASEY, 1977), eg. there appears to be an easily recognisable faunal break near the Subtropical and Polar Convergences. Several species which appear to be endemic to polar waters dive at the Polar Convergence and submerge under low latitude tropical waters.

The results of PETRUSHEVSKAYA (1971b), RENZ (1976) and CASEY (1977) indicate that greatest radiolarian diversities are found in equatorial regions of the world's oceans. Using a simple index, CASEY (1977) demonstrated, for Recent Pacific Ocean sediments, greatest radiolarian diversities in equatorial regions, lowest diversities in central gyres and intermediate diversities in subpolar regions.

Although not considered by McGOWAN (1974), the Pacific Ocean distribution patterns of surface dwelling radiolaria, by resembling those of planktonic foraminifera, may well conform to the "core ecosystem" model.

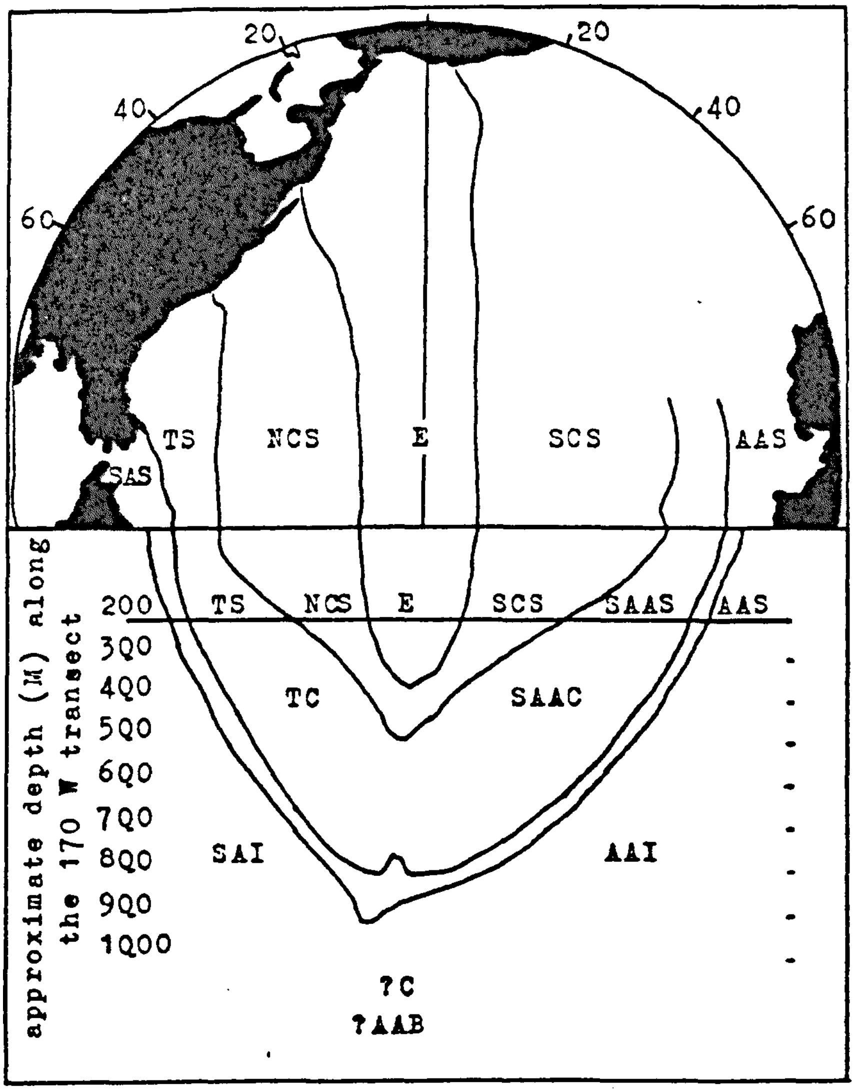

Fig. 13 Biogeographic zones for polycystine radiolarians in the Pacific Ocean (from CASEY, 1971a,b)

AAS = Antarctic Shallow Faunal Zone
AAI = Antarctic-Intermediate Faunal Zone (tropical submergent)
SAAS = Subantarctic Shallow Faunal Zone
SAAC = Subantarctic Central Faunal Zone
SCS = South Central Shallow Faunal Zone
E = Equatorial Faunal Zone
NCS = North Central Shallow Faunal Zone
TC = Transition-Central Faunal Zone
TS = Transition Shallow Faunal Zone
SAI = Subarctic Intermediate Faunal Zone (tropical submergent)
SAS = Subarctic Shallow Faunal Zone
?C = ?Common Faunal Zone
?AAB = ?Antarctic Bottom Faunal Zone

4. FACTORS INFLUENCING THE NATURE AND DISTRIBUTION OF SEDIMENTARY ASSEMBLAGES OF PLANKTONIC FORAMINIFERA AND RADIOLARIA

i) Introduction

The successful use of the ecological principles exhibited by planktonic foraminifera and radiolaria for palaeoecological and palaeoenvironmental reconstruction largely depends on understanding and appreciating the differences between a fossil assemblage and its' original living counterpart.

Organic assemblages can be divided into three different phases. Life assemblages (biocoenoses) sampled directly from the living habitat, death assemblages (thanatocoenoses) sampled from a site of recent accumulation and fossil assemblages (taphocoenoses) sampled from a sedimentary sequence. Life, death and fossil assemblages from adjacent localities differ because they are each subject to different modifying factors.

Foraminiferal and radiolarian tests become available for sedimentation due to predation, natural mortality or reproduction. During the conversion of a life assemblage into a fossil assemblage,the following factors can be of importance: time, productivity, predation, settling velocity and current transport, scouring and redeposition, bioturbation and dissolution.

Death and fossil assemblages are time and space averaged equivalents of a series of life assemblages. Short term seasonal variations and species depth zonations apparent in life assemblages are usually homogenised in death and fossil assemblages.

Long term productivity differences and turnover rates between species may inflict a bias with a higher incidence of highly productive forms in a death assemblage compared to the original life assemblage. At present however, quantitative estimates of productivity rates remain rather speculative (BÉ, 1977).

Selective predation of planktonic foraminifera and radiolarian species by pelagic organisms may play a vital role in the modification of a life to a death assemblage. Unfortunately, the extent of this process remains unresolved (BÉ, 1977).

Foraminiferal and radiolarian tests display a wide range of inter- and intraspecific morphological variation, with each form possessing an unique settling velocity. Forms with very high settling velocities will be represented to a greater extent in the death assemblage compared to the life assemblage. BERGER and PIPER (1972) have shown that thick, non-spinose planktonic foraminifera have a greater settling velocity than thin shelled, spinose forms.

Oceanic currents acting at virtually all depths can remove a test from its original habitat and transport it large distances before it eventually settles on the sea floor.

On the sea floor itself, a death assemblage may be disrupted by the winnowing and sorting processes associated with natural bottom water and turbidity current activity. PRELL (1977) and CONOLLY and EWING (1969) have demonstrated the effect of winnowing and turbidity current action respectively on microfossil assemblages in deep sea pelagic deposits. SEIBOLD (1978) has recently reviewed erosion, transportation and redeposition in deep sea sediments.

Vertical faunal fluctuations imprinted in sedimentary sequences can be penecontemperaneously homogenised, and faunal anomalies may be introduced, by the process of bioturbation (THOMPSON and SCIARRILLO, 1978).

The extent of bioturbation in deep sea sediments depends on the sedimentation rate, surface productivity, and the activity of the burrowing benthos.

ii) Dissolution

The selective dissolution of calcareous and siliceous tests is probably one of the more significant factors involved during the post-mortal history of planktonic assemblages in deep sea sediments. The voluminous literature recently published on the subject testifies to its importance (BERGER, 1967, 1968, 1971, 1973, 1978, 1979; HAY, 1974; HEATH, 1974; SLITER et al., 1975; Van ANDEL et al., 1975).

The dissolution of calcareous and siliceous tests occurs at depths of below a few hundred metres in the Pacific Ocean because of the effects of increased pressure and undersaturation of water with respect to calcium carbonate (BÉ, 1977). BERGER (1968, 1970, 1971), in considering the dissolution of planktonic foraminifera, regards the following factors as important: depth, latitude, bottom water flow, organic productivity, sedimentation rate, rate of supply of calcareous and non-calcareous particles and test morphology.

The degree of undersaturation of ocean water with respect to $CaCo_3$ increases with increasing depth and latitude (BERGER, 1971). BERGER (1968) has defined the "lysocline" as the depth range where the dissolution rate of planktonic foraminiferal tests increase rapidly. The calcite compensation depth (C.C.D.) is defined as the depth below which the amount of $CaCo_3$ in sediments has been reduced to less than 10% (LISITZIN, 1972). The depth of the lysocline and C.C.D. varies locally and regionally (BÉ, 1977). PARKER and BERGER (1971) suggest a depth of about 4000 metres for the lysocline over much of the South Pacific, including the present study area. The depth of the C.C.D. varies from approximately 5000 metres in the equatorial Pacific to less than 3500 metres in higher latitudes (BERGER and WINTERER, 1974).

The rate of bottom water flow controls the rate of replenishment by fresh, corrosive, undersaturated waters from high latitudes (BÉ, 1977).

In well oxygenated bottom waters, the rate of organic input determines the amount of CO_2 production from oxidation of the organic material. High CO_2 production may lower the pH and thus increases the corrosive ability of the environment with respect to $CaCO_3$ (PARKER and BERGER, 1971).

The sedimentation rate determines the length of time that tests are exposed to corrosive bottom waters. The productivity and biogenic output of the epipelagic zone partly controls the sedimentation rate of deep sea pelagic carbonates and may influence the degree of dissolution by affecting the corrosive potential of bottom waters and by governing the period of time tests are exposed on the sea floor (BERGER, 1979).

Studies of dissolution effects on planktonic foaminiferal assemblages by BERGER (1967, 1968, 1970) and PARKER and BERGER (1971) show that the dissolution process is selective with regard to species and their test size, microstructure, wall thickness and porosity. BERGER (1970) has ranked Recent species according to their relative susceptibility to dissolution; highly susceptible species are relatively small in size and have large pores, thin walls and are spinose (eg. *Globigernoides spp.)* while more resistant forms have relatively large tests with small pores, thick walls and are non-spinose (eg. *Globorotalia spp., Pulleniatina* *obliquiloculata, Sphaeroidinella dehiscens).*

A comparison of planktonic foraminiferal assemblages settling through the water column with those on the sea floor suggests that dissolution of $CaCo_3$ occurs mostly on the sediment - water interface (ADELSECK and BERGER, 1975; KU and OBA, 1978). Selective dissolution changes the species composition of life to death assemblages with increasing depth. Thus, as a common rule, the shallower the sediment sample, the greater the similarity in species composition between life and death assemblages (BÉ, 1977)

Dissolution processes may have large repercussions with regard to palaeoclimatic interpretations. The susceptible and resistant species of BERGER (1970) tend to generally inhabit relatively shallow (warm) and deep (cold) levels respectively. Thus poorly preserved assemblages may convey a spurious "cold water" aspect (BERGER, 1979).

Because the depth of the C.C.D. depends on oceanic fertility and current mixing, it is believed to have fluctuated in the geological past as a response to oceanographic changes (BERGER, 1979).

The dissolution of siliceous tests, including radiolaria, diatoms and silicoflagellates, does not generally follow the same laws as those for calcareous tests. BERGER (1979) has shown that the maximum dissolution of radiolaria occurs in the upper 1000 metres of the water column where waters are relatively warm, under low pressure and generally undersaturated with respect to silica. Other sites of dissolution occur within the sediment (BERGER, 1976).

RIEDEL and SANFILIPPO (1977) suggest the preservation of radiolaria in deep sea sediments is dependant on the rate of production in the overlying water column and the rate of sedimentation on the sea floor. The selective dissolution of particular radiolarian species has been considered by JOHNSON (1974).

The process of dissolution in altering life assemblages to death assemblages appears to be significant. HEATH (1974) and BERGER (1976) suggest that almost all silica organically precipitated in the upper layers of the water column is eventually dissolved and retained within the system.

The role of dissolution in altering both planktonic foraminifera and radiolaria assemblages in the present study is discussed in Chapter V.

5. THE RELATIONSHIP BETWEEN LIFE AND DEATH ASSEMBLAGES IN SURFACE SEDIMENTS OF THE PACIFIC OCEAN

The nature of planktonic death assemblages on the Pacific Ocean floor is a function of several factors discussed in the previous section. Since such assemblages constitue the dominant element in pelagic sediments over large areas of the Pacific, it will be useful to outline some general features of sedimentation in this ocean before considering particular case studies.

It is evident from the previous sections that biogenic pelagic sedimentation in the deep sea environment is mainly a function of original biological productivity and water depth. Deep sea biogenic sedimentation in the Pacific Ocean has been considered by Van ANDEL *et al*., (1975), DAVIES and GORSLINE (1976), WORSLEY and DAVIES (1979) and LEINEN (1979).

The productivity variation in the surface waters of the Pacific Ocean produces a high output of calcareous and siliceous tests (planktonic foraminifera,nannoplankton, radiolaria, diatoms and silicoflagellates) in the fertile waters of the equatorial belt and ocean margins where current activity is intense. Upwelling regions such as the eastern equatorial Pacific are particulatly high with respect to planktonic productivity. The sterile waters of the central water mass gyres produce, by comparison, low output of planktonic tests to the underlying sea floor (Van ANDEL et al., 1975; WORSLEY and DAVIES, 1979).

The influence of dissolution creates a close relationship between the abundance of planktonic tests and ocean floor topography or depth. This relationship has greater clarity for planktonic foraminfera than for radiolaria because of the relative independance of solution to depth in the latter group (LEINEN, 1979). The Pacific Ocean can be divided into a series of basins separated by mid-oceanic ridges and bounded by continental slopes or oceanic rises and plateaus (BÉ, 1977). Detrital sediments form only a small portion of the total sediment mass and are largely restricted to continental shelves and slopes and ocean margin trenches (DAVIES and GORSLINE, 1976). Elsewhere, pelagic sediment type depends mainly on water depth. Above the level of the C.C.D., along the East Pacific Rise, the equatorial belt and the western Pacific (New Zealand Plateau, Lord Howe Rise, Fiji Plateau and Ontong Java Plateau), calcareous and siliceous biogenic sediments accumulate in thick sequences (Van ANDEL et al., 1975; WORSLEY and DAVIES, 1979). Below the C.C.D., under the central water mass gyres within the North and South Pacific basins, a large but thin expanse of deep sea red clay accumulates (fig. 8).

Van ANDEL et al., (1975) offer an extensive description of sediment accumulation in the central equatorial Pacific Ocean. The deposits grade from highly calcareous near the equator, to dominantly siliceous to the north and south as water depth increases. Because calcareous material constitutes a large part of the total biogenic supply, a large body of sediment, lens shaped in north-south section, exists within the area (Van ANDEL et al., 1975).

It is thus evident that studies of planktonic assemblages in sediments of the Pacific Ocean for palaeobiogeographical purposes will be most fruitful in regions where test accumulation rates are at an optimum.

The distribution of planktonic foraminifera and radiolarian species and species assemblages in Pacific Ocean surface sediments have been carried out by PARKER and BERGER (1971), CASEY (1971b), PETRUSHEVSKAYA (1971a), RENZ (1976), BÉ (1977) and MOORE (1978).

In general, large scale species distributions in the surface sediments are similar to those in the overlying waters. However, inevitable anomalies do occur (BÉ, 1977) and there is a general information loss during the transformation of life into death assemblages. In the Central North Pacific, RENZ (1976) found the number of radiolarian species in the plankton exceeded that in the underlying sediment, presumably due to dissolution loss. PETRUSHEVSKAYA (1971a) claims to match the number of radiolarian species in adjacent plankton and surface samples although the relative abundance of each taxon is modified.

In spite of information loss and modification, several authors have identified faunal zones in surface sediments which can be related to original biogeographic zones of the plankton and are therefore useful in the recognition of overlying ocean water masses.

The distribution of planktonic foraminifera in the surface sediments of the South Pacific is related to major oceanic features such as circulation and water mass distribution, and to depth related dissolution trends, although the role of both factors can be separately distinguished (PARKER and BERGER, 1971).

CASEY (1971b) recognised four radiolarian zones in surface sediments of the South Pacific and Southern Ocean, compared to six biogeographic zones in the plankton of the same region (CASEY, 1971a). Natural breaks in the surface sediment assemblages correspond well with large scale hydrographic boundaries such as the subtropical and polar convergences. CASEY (1971b) concluded that polycystine radiolaria may be used as indicators of both past and present water masses.

Using a Q-mode factor analysis, MOORE (1978) demonstrated seven major radiolarian factors or assemblages in surface sediments throughout the Pacific Ocean. An additional four minor factors were recognisable within the temperate to tropical western Pacific Ocean. MOORE (1978) suggested the distribution of these factors tended to follow those of the surface water masses and currents.

An essential difference between biogeographic zones of the plankton and those transferred into the surface sediments is that the number of zones and hence oceanographic resolving power is usually reduced in the latter (BÉ and HUDSON, 1977).

By relating surface sediment microfossil assemblages to overlying water mass distribution, it follows that down core changes in assemblage distribution can be related to palaeoceanographical and palaeoecological fluctuations. Such studies have been carried out with a reasonable degree of success for the last Pleistocene glacial stage by the CLIMAP project members (CLIMAP, 1976; MOORE, 1978) and for the whole of the Neogene by SANCETTA (1978) in the Pacific Ocean.

Palaeoceanographical and palaeoecological reconstructions for the Pacific Ocean during the Cenozoic are discussed in the following Chapter. This is intended to create a framework within which the aims and significance of the present study may be viewed.

CHAPTER III

PALAEOCEANOGRAPHICAL RECONSTRUCTION OF THE CENOZOIC PACIFIC OCEAN

1. INTRODUCTION

Palaeoceanographical studies of the Cenozoic Pacific have proliferated over the last ten years due to an unprecedented supply of deep sea sequences recovered by the Deep Sea Drilling Project. Multidisciplined approaches using the geophysical, geochemical, sedimentological and palaeontological records available from these sections have allowed general palaeoceanographical reconstructions for most of the major ocean basins, including the Pacific.

The large supply of published information has been synthesised and reviewed by the following authors to which the reader is referred.

BERGGREN and Van COUVERING (1974) integrated the Cenozoic planktonic zonations within a geochronological framework to provide a means of dating palaeoenvironmental events. A palaeoclimatological review of the Pacific Ocean has been undertaken by KENNETT (1977; 1978), SAVIN (1977) and FRAKES (1979). Van ANDEL et al. (1975) have synthesised DSDP data to provide an account of the Cenozoic history and palaeoceanography of the central equatorial Pacific Ocean while BERGER and ROTH (1975) and ARTHUR (1979) offer more general reviews of palaeoceanographic studies.

The environment of the world's oceans is determined by a wide range of factors, including climate, ecology, sedimentation, tectonics, topography and depth. Palaeoceanographical studies have paid particular attention to changes in oceanic climate. However, this variable is generated by a complex interaction of factors, evidence for which, such as rainfall, evaporation and salinity are rarely reflected in the stratigraphical record. Therefore, the palaeoclimatic record of the worlds oceans known to date depends heavily on the reconstruction of palaeotemperature (SAVIN, 1977). In this respect, the application of new concepts in the field of micropalaeontology and stable isotope geochemistry have been particularly useful (CLIMAP, 1976; SAVIN et al., 1975 respectively).

In the following accounts of Pacific Ocean Cenozoic palaeoceanography, a continuous emphasis is placed on palaeoclimate. Palaeoclimatic factors are important in palaeoceanographic processes in that they influenced circulation and past water mass distribution, which in part determined the present distribution of planktonic microfossils such as foraminifera and radiolaria. An appreciation of the overall palaeoecology and palaeobiogeographic distribution of these groups thesefore depends on an understanding of the palaeoclimatic/paleotemperature regime of the time.

The palaeoceanography of the Pacific Ocean with respect to palaeogeography and palaeoclimate is believed to have been fundamentally different at the beginning of the Cenozoic compared to that of today (Van ANDEL et al., 1975). The history of Cenozoic climate in particular is complex and over the period several factors were apparently important in the evolution of the present climate, with each playing a role at different times. These factors basically involve variations in the capture of solar energy or variations in the flow and distribution of this energy (FRAKES, 1979). The influence of tectonics is believed to have been particularly important with respect to this latter process and the disruption and evolution of circulation patterns appears to be related to the displacement of land masses (FRAKES, 1979).

Generally, the Cenozoic history of the earth can be viewed within a special framework of a gradual climatic deterioration which began with global cooling at the Mesozoic/Cenozoic boundary, creating glacial conditions in the Eocene and culminating in the large climatic extremes of the Pleistocene (BERGGREN and Van COUVERING, 1974; FRAKES, 1979). The glacial evolution of Antarctica is of fundamental importance in this respect and it is believed to have exerted a strong influence on palaeoceanographical developments elsewhere in the Pacific. Van ANDEL et al. (1975).believe that events in the equatorial Pacific to be so closely related to the climatic and oceanographic history of the Antarctic continent that the latter can be considered "the motor that drove and drives the equatorial Pacific depositional and palaeoceanographic evolution".

The importance of the Antarctic glacial regime to present day Pacific oceanography and climatology can be explained in the following manner. The continent harbours major East and West Antarctic ice caps which feed and maintain extensive sea ice deveopment. Antarctic Bottom Water originating from cold, dense surface water initiates a thermo-haline circulation which forms an integral part of Pacific Ocean circulation processes. The polar caps of Antarctica thus contribute towards the distribtuion of water masses in the Pacific Ocean and also contribute to the steep latitudinal temperature gradients characteristic of the present time. The glacial mode of the continent also influences sedimentation in the Pacific Ocean by controlling planktonic productivity and dissolution factors (Van ANDEL et al., 1975; KENNETT, 1977).

Cenozoic palaeoceanographic reconstructions of the Pacific have been formulated using the geophysical magnetic anomaly record, the O_2 isotope record, sea level variations, changes in sedimentary facies with emphasis on calcareous, siliceous and ice rafted sediments, the stratigraphical and geographical distribution of unconformities and biogeographical and ecological aspects of planktonic palaeontology. This information from the deep sea record is supplemented by continental evidence such as the stratigraphical distribution of tillites.

The O_2 isotope record of Cenozoic marine sediments offers the most useful technique for understanding the thermal evolution of the Pacific Ocean by providing quantitative isotopic palaeotemperatures of past water masses. SAVIN et al. (1975) have analysed the O_2 isotopic composition of planktonic and benthonic foraminiferal tests from several DSDP sites to provide a general picture of low and high latitude marine palaeotemperatures throughout the Cenozoic. Despite difficulties associated with the technique, the model compares favourably with evidence from other disciplines and can be used as a general framework for Cenozoic palaeoceanographic studies (fig. 14). SHACKLETON and KENNETT (1975a, 1975b) offer a more detailed O_2 isotopic record for the Neogene of the South Pacific and Southern Ocean.

In spite of these recent advances, much of the following discussion remains tentative and subject to problems of correlation and interpretation. Particularly detailed attention is paid to the palaeoceanographical reconstruction of the south west and equatorial Pacific.

Although the continental configuration around the Pacific Ocean margin has continually evolved during the Cenozoic era, the oceanic expanse has remained fairly constant (WINTERER, 1973).

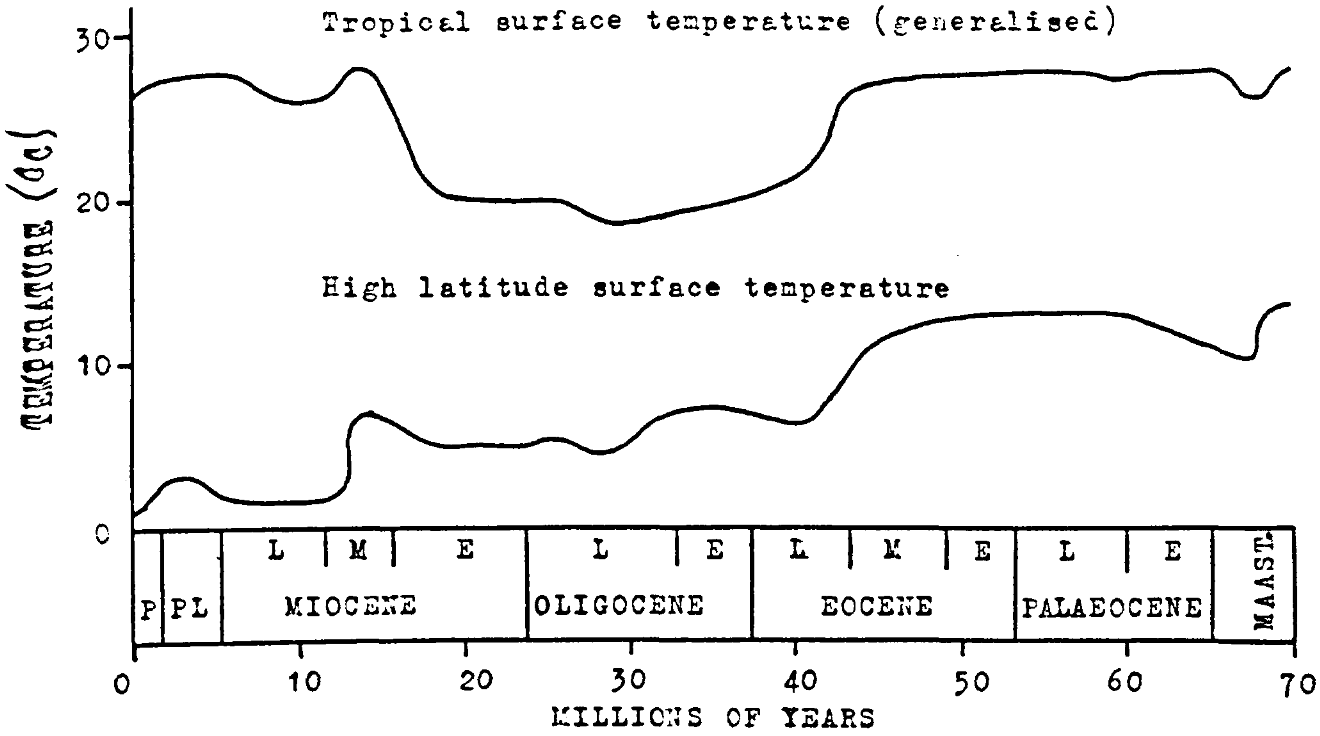

Fig. 14 O_2 isotope palaeotemperature reconstructions of the oceans through the Cenozoic (from SAVIN et al., 1975)

2. LATE CRETACEOUS - PALAEOCENE

Towards the end of the Cretaceous period (~70 m.y.), Australia, New Zealand and Antarctica constituted a single continent that had survived the Mesozoic breakup of Gondwanaland (FIRSTBROOK et al., 1979). Along the equator, a vast circumglobal current flowed through the Pacific from the Atlantic into the Tethys Ocean. Although the destruction of the Tethyan seaway began during the Mesozoic (BERGGREN and HOLLISTER, 1974), by the end of the era, a broad deep marine passage between Australia and Indonesia ensured an Indo-Pacific flow in the early Cenozoic.

Surface waters of the Pacific Ocean were characterised by warm temperatures in both low (~27°C) and high (~12°C) latitudes and the Antarctic continent was believed to be unglaciated. The shallow horizontal and vertical temperature gradients produced a wide tropical belt with no apparent thermocline (SAVIN et al., 1975).

New Zealand began to separate from Australia near the Mesozoic/Cenozoic boundary (EDWARDS, 1975), a time which was characterised by a palaeotemperature drop along all latitudes (SAVIN et al., 1975).

During the mid-Palaeocene, Australia moved north from Antarctica producing a marine passage between the two continents. To the north of Australia, the Indo-Pacific link constricted as the land mass encroached Indonesia (EDWARDS, 1975).

3. EOCENE

The tectonic pattern of the south west Pacific changed by the Eocene with the development of several basins, including the Fiji, Coral Sea and New Hebridean Basins to the east of Australia. Subsequent events involved very complex disruption of northern and eastern rims of the southwest Pacific marginal seas (EDWARDS, 1975). Van ANDEL et al. (1975) report a rapid cooling of marine palaeotemperatures in the Late Eocene and at the Eocene/Oligocene boundary. Low latitude surface waters fell to around 20°C while high latitude waters fell to about 7°C. Evidence that the Eocene witnessed the initiation of Cenozoic glaciation is offered by FRAKES (1979), who suggests the development of high latitude glaciers on the West Antarctic continent at this time. Up to the end of the Eocene, the circulation pattern of the South Pacific Ocean was thought to be similar to that of the North Pacific today with more than one major gyre creating a semi-closed system (EDWARDS, 1975). This situation was eventually disrupted by the development of the circum-Antarctic Current (C.A.C). Van ANDEL et al. (1975) suggest that the present day zone of maximum biogenic deposition along the equatorial Pacific has been in existence since at least the Middle Eocene although it has since witnessed large changes in deposition caused by fluctuations in biological productivity and dissolution. This evidence testifies to the continued potency of the Pacific equatorial current system with respect to biological productivity, despite undergoing major reorganisations.during the Cenozoic involving the progressive breakdown of unrestricted equatorial circum-global flow.

4. OLIGOCENE

The general cooling event at the end of the Eocene continued into the Oligocene. The exact cause of this event is unknown although continued tectonic evolution may have played an important role by altering the oceanic circulation patterns. The progressive restriction of the circum-global Tethys seaway during the Oligocene culminated with the closure of the Mediterranean / Indo-Pacific passage (VEEVERS, 1969; DEWEY et al., 1973). Continued rifting between Australia and Antarctica opened a shallow passage across the South Tasman Rise in the Early Oligocene (Van ANDEL et al., 1975), allowing restricted C.A.C. flow (KENNETT, 1977). KENNETT et al. (1975) and BARKER and BURRELL (1977) suggest the full development of the C.A.C. was initiated in the Late Oligocene by a gradual size increase in the Australian/Antarctic and South American/Antarctic (Drake Passage) rifts respectively, which allowed the uninterrupted flow of surface and bottom water within the system.

The present day Circum-Antarctic Current mixes water of three major oceans and is believed to transport the greatest volumes compared to all other current systems (KENNETT et al., 1975). The development of the current in the Cenozoic created a reorganisation of the Pacific Ocean circulation system and is thought to have played a major role in the subsequent climatic evolution of the world oceans by creating the thermal isolation of the Southern Ocean (EDWARDS, 1975).

The Oligocene witnessed prolonged Antarctic glaciation, with the development of ice masses originating in Western Antarctica occupying sea level positions in the Ross Sea region (FRAKES, 1979). The O_2 isotope palaeotemperatures for high latitudes given by SAVIN et al. (1975) are probably too high (4°C) to allow the development of sea ice although KENNETT (1977) reports on an increase in ice rafted sediments in the Southern Ocean at the time. Van ANDEL et al.(1975) suggest that extensive Oligocene deep sea unconformities resulted from the initiation of cold dense Antarctic Bottom Water flow comparable with the thermo-haline circulation process evident in todays oceans.

The reduced surface water temperatures at low and high latitudes during the Oligocene has prompted CIFELLI (1969) to suggest the associated homogenisation of water masses and breakdown of thermal barriers to be responsible for the drop in diversity and reduction of provincialism evident in Oligocene planktonic foraminifera. KENNETT (1978) indicates that most calcareous and siliceous planktonic microfossil groups (foraminifera, coccoliths, radiolaria and diatoms) were of low diversity, with most species displaying cosmopolitan distributions.

5. MIOCENE

i) Early Miocene

During the Early Miocene, surface water palaeotemperatures began to rise by about 3°C in high and low latitudes (SAVIN, et al., 1975; KENNETT, 1977). The circulation pattern of the Pacific Ocean is thought to have developed a close resemblance with that of the present time (KENNETT, 1977), although a substantial interchange of water between the equatorial Pacific and the Indian Ocean was likely until the end of the Early Miocene, since the collision of Australia with

Indonesia is believed to occurred in the Middle Miocene (EDWARDS, 1975).

ii) Middle Miocene

The beginning of the Middle Miocene (~15 m.y) witnessed the full development of the modern circulation systems and water mass distribution in the Pacific Ocean (SAVIN et al., 1975; KENNETT et al., 1975; Van ANDEL et al., 1975). The introduction of steep vertical temperature gradients and a tropical thermocline is believed to be related to the increased glacial development of the Antarctic continent. SAVIN et al. (1975) and SHACKLETON and KENNETT (1975a, 1975b) indicate a dramatic cooling of high latitude surface waters in the early Middle Miocene with palaeotemperatures falling by 3°C in two to three million years. KENNETT (1977) has suggested that the disruption of a single oceanic gyre in the South Pacific during the Oligocene by the development of the C.A.C. may have led to the eventual formation of the major East Antarctic ice cap and associated sea ice formation in the Southern Ocean at the beginning of the Middle Miocene. The direct cause of the Middle Miocene Antarctic glacial event is unknown however. It is difficult to reconcile the well documented Early Miocene warming event with a model of increased thermal isolation of the Southern Ocean by the development of the C.A.C. (KENNETT, 1977). Nevertheless, O_2 isotope evidence from SAVIN et al. (1975) suggests an intimate relationship between the Middle Miocene glaciation and the development of the C.A.C. At the time of lowered high latitude palaeotemperatures, the low latitude isotopic record indicates a palaeotemperature rise to about 28°C. SAVIN et al. (1975) tentatively suggest that the apparent anomaly indicates that low latitude surface waters were no longer cooled by vast quantities of high latitude waters because the latter became isolated within the semi-closed C.A.C. system. Consequently, low latitude surface waters would increase in temperature while high latitude surface waters would cool. SAVIN et al. (1975) cite the results of PITMAN et al.(1974), who identified the oldest oceanic crust in the Drake Passage as Miocene in age, to indicate a Middle Miocene age for the full development of the C.A.C.

Regardless of the cause, the earth has been in a permanent glacial mode since the Middle Miocene. The East Antarctic ice cap has remained as a constant feature although it has since exhibited changes in volume (KENNETT, 1977).

The Middle Miocene collision of Australia with Indonesia may have created the eastward flowing Cromwell Current and initiated equatorial upwelling in the Pacific Ocean (Van ANDEL et al, 1975).

The Middle Miocene onwards is thus characterised by a steep latitudinal surface water temperature gradient and a steep surface to bottom temperature gradient in low latitudes. As the temperature gradients increased, wind and surface water current velocities increased, the thermocline strengthened and coastal and equatorial upwelling intensified (BERGER, 1979). Van ANDEL et al. (1975) report a large erosion event during the Middle Miocene (∿12 m.y.) in the equatorial Pacific resulting from enhanced bottom water flow as a consequence of Antarctic glaciation.

The development of a modern oceanic system in the Middle Miocene is believed to have exerted a profound effect on planktonic microfossil ecology, biogeography and evolution. The Oligocene pattern of low diversity and cosmopolitan distribution was transformed during the Early and Middle Miocene to a condition of increased diversity, ecological radiation and latitudinal provincialism in several unrelated groups including planktonic foraminifera, radiolaria and nannoplankton (KENNETT, 1978). CIFELLI (1969) has described the radiation of planktonic foraminifera during the early Neogene which he ascribes to the formation of new niches resulting from the increased latitudinal palaeotemperature gradient. By the Middle Miocene, planktonic foraminiferal faunas were essentially modern at the generic level, although most species either extend into the Recent or have traceable phylogenies to extant forms (CIFELLI, 1969). Similarly, CASEY (1977) suggests that many of the modern radiolarian species used as oceanographic indicators first evolve around the Early or Middle Miocene at a time when the modern water masses were believed to have first developed. The development of provincialism in planktonic microfossil groups during the Neogene of the Pacific Ocean has been considered by SANCETTA (1978) who concluded that the distribution of the major modern faunal provinces had been established by the Middle Miocene.

iii) Late Miocene

The study by SAVIN et al. (1975) involves a relatively wide stratigraphic sampling interval and reveals little change in the O_2 isotope record during the Late Miocene.

However, detailed studies in the South Pacific by SHACKLETON and KENNETT (1975a) indicate a large drop in isotopic palaeotemperatures towards the end of the Late Miocene which they interpret as indicating a large glacial buildup on Antarctica which developed an ice volume 50% greater than the present day dimension and which created a 40 metre glacial-eustatic sea level drop. FRAKES (1979) indicates an enormous size increase in the Ross Ice shelf spreading sea ice at least 150 kms. beyond its present position. KENNETT (1978) suggests the major global cooling is characterised by increased ice rafting and further, is recognisable in the paleobiogeographical and palaeoecological studies of planktonic microfossils by INGLE (1967), BANDY et al. (1971), CASEY (1972), KENNETT and VELLA (1975) and SHACKLETON and KENNETT (1975b). Worldwide regressive sequences of Late Miocene age associated with glacio-eustatic sea level drop have been reviewed by ADAMS et al. (1977).

6. PLIOCENE

Global cooling continued into the Pliocene and resulted in the formation of the northern hemisphere ice cap (KENNETT, 1977). The closure of the Isthmus of Panama, the final element of inter-oceanic equatorial circum-global flow, occurred during this period (KANEPS, 1970). SAVIN et al. (1975) record a large drop in palaeotemperatures in the Late Pilocene which they relate to the expansion of ice sheets and the widespread formation of sea ice. According to SHACKLETON and OPDYKE (1977), extreme glacial and interglacial fluctuations have characterised the earths climate for the past 3.2 million years since the Late Pliocene. These authors suggest the formation of major ice masses in northern Europe and North America around 3 to 2.5 m.y., although these glaciations were believed to be less intense than those of the Late Pleistocene. The Quaternary is therefore clearly different from the Tertiary, not because of the presence of glacial events, but by their relative intensity.

7. PLEISTOCENE

The Pleistocene witnessed a series of glacial/interglacial cycles in which the oscillation of northern hemisphere ice sheets were extreme. The deep sea sedimentary record has successfully recorded these events in both high and low latitude sequences in the Pacific Ocean. Studies by ARRHENIUS (1952) EMILIANI (1966; 1971), HAYS et al. (1969), ERICSON and WOLLIN (1970), KEANY and KENNETT (1972) BERGER (1973), SHACKLETON and KENNETT (1975a,b), EMILIANI and SHACKLETON (1974) and the CLIMAP project members (1976) involving carbonate and dissolution cycles, the O_2 isotope record and faunal variations indicate between 20 and 22 glaciations over the past million years having an average periodicity of between 80,000 to 90,000 years (EMILIANI and SHACKLETON, 1974).

8. NEOGENE GLACIAL EVENTS - A DISCUSSION

The Cenozoic palaeoceanographical history of the Pacific Ocean has been greatly influenced by the gradual development of glacial conditions. Major changes in the global circulation of surface and deep waters resulting from shifts in the configuration of the marginal continents probably initiated this glacial evolution in the Eocene although present day conditions have their origins in the Early to Middle Miocene. Climatic deterioation has been gradual over most of this period although the process appears to have greatly accelerated in intensity over the past two million years. Although the causes seem to be principally tectonic in origin, EMILIANI (1978) has recently reiterated the relationship between astronomical parameters such as obliquity and glacial and interglacial events of the Quaternary.

A primary aim of the present study involves the recognition of palaeotemperature trends in the equatorial Pacific Ocean during the Middle and Late Miocene. As stated in the previous section, the basic circulation pattern and water mass distribution of the time were thought to have been similar to that of today, although two influential factors, the development of the northern hemisphere ice sheet and the restriction of flow between the equatorial Pacific and Atlantic Oceans, had yet to be established.

Recent evidence by SAVIN et al. (1975) and SHACKLETON (in press) from the O_2 isotope record of closely spaced Miocene deep sea samples indicate relatively small scale cyclic fluctuations in isotopic palaeotemperatures showing similar periodicities to Pleistocene climatic cycles (80,000 to 90,000 years).

SAVIN et al. (1975) demonstrated the cycles in Early (N.7) and Middle (N.9-10) Miocene samples from the South Atlantic and tropical North West Pacific respectively. A close similarity of periodicities between these and Pleistocene cycles suggests that the factors which caused Pleistocene climatic fluctuations, be they astronomical or terrestrial in origin, may have also operated in the Miocene. However, because the Miocene amplitudes are much smaller, SAVIN et al. (1975) suggest either that these factors did not operate as strongly in Miocene time or that different conditions in the Pleistocene rendered the earth's climate relatively unstable so that small changes in one or more variables could have a much larger effect on the world's temperature regime.

SHACKLETON (in press) has undertaken O_2 isotope analyses of closely spaced samples from the Early/Middle Miocene boundary of the DSDP Site 289 sequence (cores 60 to 49). Surface palaeotemperatures ranged from 15^o to 20^o and the vertical temperature gradient was shallow ($\sim 12^oC$), with relatively warm bottom waters. The sampled section predates the strong Middle Miocene Antarctic glacial buildup which induced steep vertical temperature gradients and associated thermocline formation in low latitudes (SAVIN et al., 1975). SHACKLETON (in press) concluded that the periodicity and amplitude (2^o-3^oC) of the palaeotemperature variations seem to be similar to those of the Pleistocene in the western equatorial Pacific Ocean (CLIMAP, 1976).

The results of SAVIN et al. (1975) and SHACKLETON (in press) concerning Pleistocene-like climatic cycles in the Miocene are very important to the aims of the present study. They illustrate that palaeotemperature oscillations have characterised the earths climatic regime prior to the Pleistocene extremes and that these cyles can be detected in equatorial deep sea sediments in the Pacific Ocean by geochemical methods. To understand how equatorial palaeotemperature cycles may effect planktonic microfossil groups during the Miocene,it would be first useful to consider the influence of well documented Pleistocene extremes on equatorial Pacific palaeometerology, palaeoceanography and planktonic palaeoecology.

ARRHENIUS (1952) suggested that the eastern Pacific zone of equatorial divergence and upwelling was in existence throughout the Quaternary with an increased rate of upwelling and concomitant biological surface productivity during glacial stages. Intensified vertical circulation is believed to have been caused by increased tropical atmostpheric circulation (Trade Winds) (ARRHENIUS, 1959). Further evidence by HUTCHINSON (1950, 1952) and VALENCIA (1977) favours the extension of a persistant, well devloped zone of equatorial upwelling across the entire Pacific Ocean. QUINN (1971) has considered the role of meterological factors in the process. Modern fluctuations in the intensity of the intertropical general atmostpheric and oceanic circulation over the Indo-Pacific region is related to atmostpheric pressure shifts and is termed the southern oscillation (QUINN, 1971). If atmostpheric pressure is abnormally low in the western Pacific (dry conditions), it is unusually high in the subtropical south east Pacific and the large pressure gradient between the subtropical high and Indonesian low strengthens atmostpheric and oceanic circulation to create an extensive well developed equatorial dry zone and induce intensified upwelling.

Cold waters arriving in the western equatorial Pacific would create a rise in atmostpheric pressure, reversing the east-west pressure gradient, decelerating oceanic and atmostpheric circulation and inhibiting upwelling along the equator and South

American Coast (El Nino). The cycle is completed because waters arriving in the western equatorial Pacific are warmer than usual and cause a decrease in atmospheric pressure (BERLAGE, 1961). QUINN (1971) suggests that persistent equatorial upwelling during glacial stages and the associated dry zone which extended across the Pacific seem to have been caused by the lowering of sea level. As the shallow seas in the Malay-Indonesia area and between New Guinea and Australia emerged during the sea level drop, cooler waters associated with stronger south-east trades and equatorial upwelling were prevented from entering the area. The mechanism which controls atmospheric and oceanic fluctuations along the tropical Pacific was thus eliminated, the well developed Indonesian equatorial low and South Pacific subtropical high therefore persisted and strong trade winds and intensified upwelling evolved. The situation persisted until sea level rises at the end of the glacial stage allowed the process to reverse.

The intensification of upwelling in the eastern equatorial Pacific and the extension of the process to the western equatorial Pacific during Pleistocene glacials should have a significant effect on the planktonic assemblages by lowering surface water temperatures and destroying the thermal statification of the epipelagic zone.

The CLIMAP* project of the last decade (CLIMAP, 1976; CLINE and HAYS, 1976) has been involved with the reconstruction of the earth's surface conditions (land and sea) at the height of the last glacial stage, ~18,000 years. B.P. The study used quantitative evidence from continental geography, surface albedo (reflectivity), the extent and elevation of permanent ice and the sea surface temperature pattern of the world oceans.

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*FOOTNOTE: CLIMAP is an acronym of "Climate: Longrange Investigations, Mapping And Prediction."

The sea surface palaeotemperature pattern was mainly derived from a comparison of the planktonic microfossil assemblages (planktonic foraminifera, radiolaria and coccoliths) at the 18,000 year B.P. datum with those at the present sediment surface.

The results of the project, in terms of the temperature differences in surface waters of the Pacific Ocean between the present day and the height of the last glacial, can be used in the present study as a model for palaeotemperature cycles and palaeoceanographic changes during the Middle and Late Miocene, although it must be appreciated that the Pleistocene example represents more extreme conditions than most of the Miocene counterparts (SAVIN et al., 1975). By indicating the extent of palaeotemperature changes in the equatorial Pacific Ocean at 18,000 yrs. B.P., the CLIMAP project also allows us to estimate the degree to which the planktonic microfossil assemblages of equatorial regions were effected by high altitude glaciation.

The palaeontological palaeotemperature reconstructions are performed using advanced statistical proceedures known as "biological transfer functions" (IMBRIE and KIPP, 1971; SACHS et al., 1977). The transfer function method provides a method of converting quantitative descriptions of fossil assemblages into estimates of past seasonal sea surface temperatures.

The modern assemblages from a suite of piston cores are subjected to a form of factor analysis using the relative abundance of each taxonomic unit (species) as the basic data. If the assemblages, defined as a number of empirical orthogonal functions, reflect the distribution of surface water masses, they can then be related to the seasonal surface temperatures by multivariate regression equations. The regression step thus expresses sea surface temperatures as a function of the various assemblages. The samples from the 18,000 yrs. B.P. datum are then described in terms of the assemblages defined by factor analysis in the surface sediments and, from this numerical description and the regression equations relating modern assemblages to temperature, it is possible to arrive at a temperature estimate for the time interval in question (CLIMAP, 1976).

The results of this technique have been plotted and contoured to give the surface isotherm pattern for 18,000 yrs. B.P. (CLIMAP, 1976). The temperature anomaly pattern between the Recent and the last glacial stage in the Pacific Ocean is given in fig. 15. The map shows that during glacial conditions in the Pacific Ocean, greatest temperature changes occurred in high and low latitudes. It is believed that sea ice in both hemispheres had far greater latitudinal extent compared to the present time. The Southern Ocean is thought to have been characterised by an increase in the thermal gradient and northward displacement of the polar front by about 4^{o} latitude.

By contrast, the central ocean gyres are believed to have undergone little change. In the South Pacific, the steepened temperature gradient in the subantarctic region probably gave rise to increased transport of cooler waters extending into the Chile Current. A large temperature decrease in the eastern north Pacific is thought to have resulted from a southward shift of the frontal region associated with the Californian Current.

The equatorial region of the Pacific Ocean appears to have suffered marked cooling during the last glacial. Increased upwelling along the Pacific equatorial divergence produced temperatures up to 6^{o} cooler as the thermoclime broke down or reached the surface (CLIMAP, 1976). The westward limit of this is unknown due to poor sampling in the west and southwest Pacific region although the cool waters do not appear to reach the western equatorial Pacific; there, glacial temperatures appear to be quite similar to those of today.

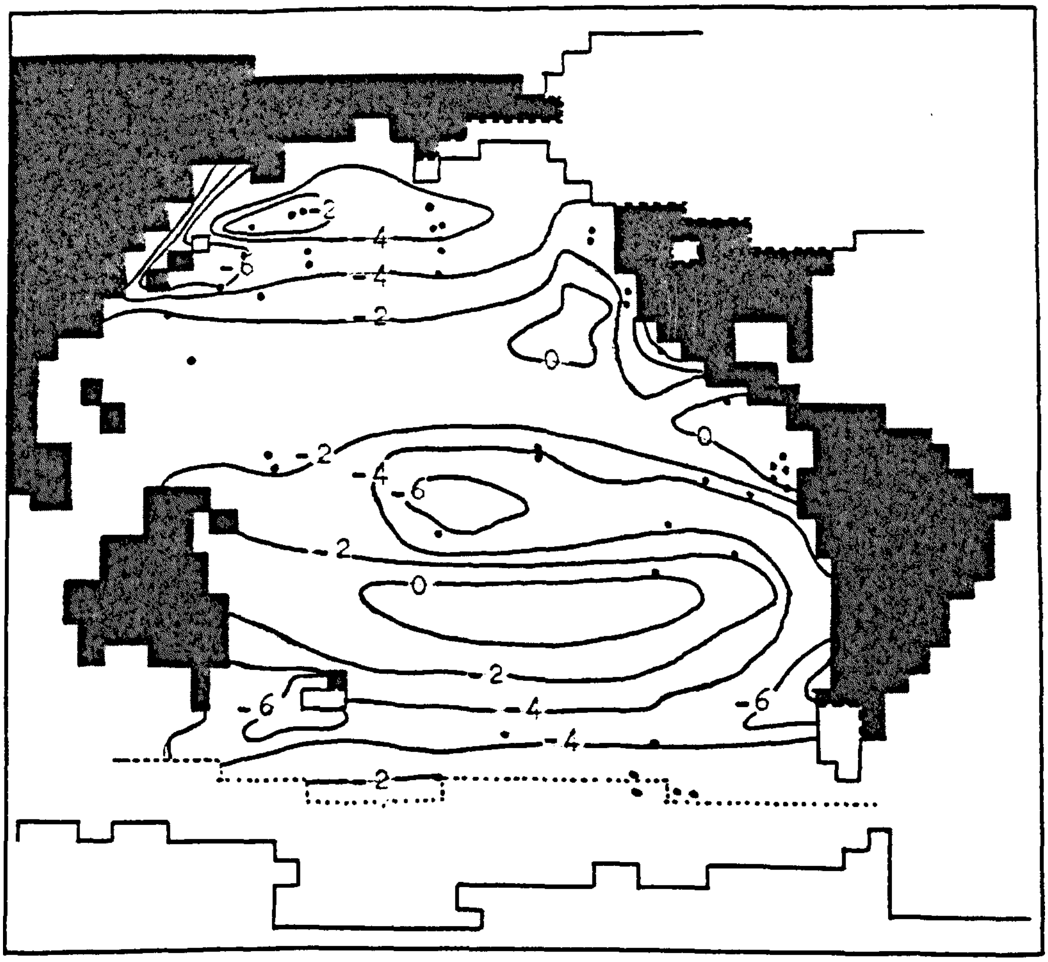

Fig. 15 Difference between August sea-surface temperatures 18000 years ago and modern values in the Pacific Ocean.

■ = ice free land
▣ = extent of land ice
····· = sea ice margins
• = location of cores used in reconstructing sea-surface temperatures 18000 years ago

Contour interval is 2°C (from CLIMAP Project Members, 1976)

In general, the results of the CLIMAP project indicate that overall sea surface temperature changes were not very large with an average difference of only 2-3°C. However, the Pacific Ocean, where an increase in divergence and the compression of thermal gradients suggest a more energetic circulation system, apparently suffered the greatest change during times of high latitude glaciation.

A comparison of the present day surface water temperatures above the two DSDP sites involved in the present study with the surface water palaeotemperatures in the same region as indicated by the CLIMAP results suggests little change in both cases.

At Site 289 in the western equatorial Pacific, present day surface water temperatures are approximately 29.5°C (REID, 1969; U.S. Hydrographic Data File). According to the CLIMAP study, the surface temperatures at the height of the last glacial were 1.5°C cooler at 28°C.

At Site 71 in the central equatorial Pacific, present day surface temperatures, at 25.5°C (REID, 1969; U.S. Hydrographic Data File), are 3.5°C warmer than the 22°C estimate by the CLIMAP project.

The results of the CLIMAP project for the western equatorial Pacific region may be regarded with some caution however because the area was poorly sampled (CLIMAP, 1976; see Fig. 15). In regions of poor control, it was assumed that changes in oceanic gyre geometry between 18,000 B.P. and today were similar to those that occurred in regions where the control is good. In this respect, the meteorological considerations of QUINN (1971), concerning the extension of equatorial upwelling throughout Pacific low latitudes seem to have been neglected. Moreover, the results around the area of DSDP Site 289 show a smaller temperature amplitude between 18,000 yrs. B.P. and today than those deduced by SHACKLETON (in press) from isotopic palaeotemperature reconstructions over the Early/Middle Miocene boundary, a time when temperature fluctuations were generally less intense than those of the Pleistocene (SAVIN et al., 1975).

Although temperature fluctuations over the past 18,000 years in the surface waters of the western equatorial Pacific are small in absolute terms, present seasonal temperature variations are almost non-existent (less than 1°C, REID, 1969) and the region is characterised by stable surface water temperatures.

Small temperature variations may be ecologically significant however. JONES (1967), in a study of living planktonic foraminifera from the Atlantic Ocean Equatorial Current system, found that relatively small variations in measured environmental parameters appear to exert major control in the population dynamics of this group. In particular, temperature variations of as little as 2°C and salinity variations of as little as 0.2-0.5 ppm. appear to exert primary control of absolute and relative abundances of a number of species.

A major synthesis of radiolaria distribution in both surface sediments and at the 18,000 years B.P. datum throughout the Pacific Ocean by MOORE (1978) reveal that factors (assemblages) recognised in the western equatorial Pacific for the present climatic regime were shifted or reduced at the height of the last glacial stage.

It can be demonstrated therefore that long term (glacial/interglacial) temperature variations of around 1.5° to 3°C in a region such as the western equatorial Pacific, where short term (seasonal) changes are less than 1°C, are likely to be reflected in faunal variations in the underlying sedimentary sequence.

The work of the CLIMAP project (CLIMAP, 1976; MOORE, 1978) and the upwelling theory of QUINN (1971), provide models for palaeoceanographical reconstruction through the Pleistocene. In view of the conclusions by SAVIN *et al*. (1975) and SHACKLETON (in press) with regard to existence of Miocene climatic variation of similar wavelength to those of the Pleistocene, the model may be extended back for use in Miocene equatorial sequences in the Pacific Ocean. However, it is important to recognise that though the wavelength of such cycles may have remained constant, recognition must be made of the gradual increase in the temperature amplitude during the Neogene, particularly in the past two million years.

CHAPTER IV

THE BIOSTRATIGRAPHY OF THE MIDDLE TO LATE MIOCENE AT DSDP SITES 289 and 71

1. INTRODUCTION

The following account involves a description of the vertical ranges of individual species in the studied sequences and forms the basis of the biostratigraphical and chronostratigraphical synthesis.

Planktonic groups, including planktonic foraminifera, radiolaria, nannoplankton, diatoms and silicoflagellates are characterised by rapid evolution, widespread distribution and great abundance in deep sea sediments. Consequently, their fossil remains have been extensively used for biostratigraphic zonation and worldwide correlation of Mesozoic and especially Cenozoic open marine sediments. The zonations of the Cenozoic provide a subdivision of the interval into units of about one to two million years duration. The correlation of these planktonic zonations with the palaeomagnetic and radiometric time scales has enabled absolute ages to be assigned to evolutionary events with a view to convert biostratigraphic zones into chronostratigraphic units (BERGGREN and Van COUVERING, 1974; THEYER and HAMMOND, 1974; THEYER, MATO and HAMMOND, 1978). The development of such a system is however frought with difficulties and the prepared schemes have not gained universal acceptance. Nevertheless, the advances have had a significant effect on Cenozoic stratigraphy.

Modern investigations show that the classic European stages form an unsatisfactory basis for accurate correlation and age determination because of the overlap and diachronous nature of stage boundaries (STAINFORTH _et al_., 1975). The general paucity of planktonic foraminifera and radiolaria in inner continental shelf waters and sediments, their latitudinal provincialism and susceptibility to destruction generally precludes the application of planktonic zonations in the shallow water marine facies originally chosen for European stage designations. Nevertheless, where possible, such schemes have been used to amend and refine previous ideas regarding age dating and correlation via European stages (BLOW, 1969; BERGGREN and Van COUVERING, 1974; RYAN *et al*., 1974; SAITO *et al*., 1975; BERGGREN and HAQ, 1976). Consequently, STAINFORTH *et al*. (1975) suggest an informal utilization of planktonic zonations as a basic Cenozoic time scale to which other stratigraphic units and marine events be referred. BLOW (1970) however, warns that the possibility of diachronous marker horizons and subjective taxonomic concepts may inhibit the realisation of such a goal.

2. PLANKTONIC FORAMINIFERAL ZONATIONS

The development and application of Cenozoic biostratigraphic zonations by means of planktonic foraminifera has been directly related to the demands of petroleum exploration in tropical and subtropical regions of the world (BOLLI, 1957a, 1957b, 1966; BANNER and BLOW, 1965a; BLOW, 1969; POSTUMA, 1971; STAINFORTH *et al*., 1975). BOLLI (1957a, 1957b, 1959, 1966), in erecting schemes for the Caribbean area, realised their potential for worldwide correlation in low latitude regions and his zonation forms the basis of many subsequent models STAINFORTH *et al*., 1975).

BANNER and BLOW (1965a) and BLOW (1969) introduced an alternative scheme which asserted the importance of phylogenetic lineages, discontinued the use of temperature sensitive species and paid particular attention to taxonomic detail. The zonation, which emphasised both boundary markers and associated assemblages, is informally abbreviated for ease of communication and has since been accepted by many as the more versatile scheme on which to build a Cenozoic chronostratigraphic framework (BERGGREN and Van COUVERING, 1974; VINCENT, 1975). Additional schemes erected for Pacific sequences by BANDY (1964) and McTAVISH (1966) have not gained widespread acceptance.

The disadvantage of BLOW's zonation includes its restriction for regional correlation to within low and mid-latitude regions only, difficulty of application in sediments deposited below the depth of the lysocline and in local facies controlled sequences. The development of latitudinal provincialism by planktonic foraminifera, particularly during the Neogene, inhibits the application of a single biostratigraphic zonation on a global scale. In middle and high latitude regions, the zonal taxa of BLOW (1969) are invariably absent or the stratigraphic ranges are modified. JENKINS (1973) recommended the recognition of three different zonal schemes based on climatic belts to overcome correlation difficulties in the Neogene. In the Pacific Ocean, middle and high latitude Cenozoic zonations have been erected by JENKINS (1971) and KENNETT (1973). Nevertheless, correlation across climatic boundaries remains a problem although the zonation of STAINFORTH et al. (1975) intended to resolve the complication. JENKINS and ORR (1972) encountered great difficulty in applying BLOW's (1969) zonation to deep water sediments of the eastern Pacific Ocean and their alternative scheme emphasised the use of solution resistant forms. BRÖNNIMANN and RESIG (1971) expressed the need to modify the zonation of BLOW (1969) for local use in the western equatorial Pacific,where they discovered anomalous ranges in certain index species.

In recent years,palaeontologists have moved away from using assemblage zones and have applied the concept of datum levels (appearances, extinctions, changes in abundance, changes in coiling direction) in an attempt to increase biostratigraphic resolution of Cenozoic sequences (JENKINS, 1966; BERGGREN and Van COUVERING, 1974; STAINFORTH et al., 1975). Datum planes cut the stratigraphic column into discrete intervals of restricted age-range and form a useful basis for biochronology. However, BLOW (1970) has expressed doubt as to the isochroneity of extinction datums in light of local palaeoecological conditions and upward biological reworking in sediments. Datum planes are biochronologically valuable so long as they mark points in time and reflect real evolutionary instantaneous palaeontological events (BRÖNNIMANN and RESIG, 1971) and consequently should complement, rather than replace formally defined zones (BLOW, 1970).

In the present study of equatorial Pacific sequences, the zonation scheme of BLOW (1969) for the Middle to Late Miocene was found to be readily applicable, although certain difficulties - explained in the following account - were experienced.

3. PLANKTONIC FORAMINIFERA: SITE 289

The Initial Reports volume for DSDP Leg 30 (ANDREWS, PACKHAM et al., 1975) contains biostratigraphic reports on Cenozoic sequences encountered at all sites using planktonic foraminifera (see below), radiolaria (HOLDSWORTH, 1975), phytoplankton (BURKY, 1975) and nannofossils (SHAFIK, 1975). Unlike those of the other microfossil groups, the account of the planktonic foraminiferal distributions is extremely sparse and limited to an indication of the position of important datum planes at each site (SAITO, in ANDREWS, PACKHAM et al., 1975). For Site 289, these events were related to the biostratigraphic zonation of BLOW (1969) (ANDREWS,PACKHAM et al., 1975, p. 252, fig. 21). A comparison of these results with those obtained in the present study is given below (p. 87).

The stratigraphical distribution of all planktonic foraminifera encountered at Site 289, together with an indication of the index species and position of the zonal boundaries of BLOW (1969) is given in fig. 16 (see also fig. 22).

The sequence from cores 50 to 24, encompassing approximately 256.5 metres of sediment, includes a continuous sequence of zones from N.9 near the base of the Middle Miocene to within N.17 in the Late Miocene. The main quantitative biostratigraphic and palaeoecological analysis of planktonic foraminiferal and radiolarian assemblages was carried out in this interval. In addition, a less detailed investigation of the remainder of the Late Miocene sequence, from cores 23 to 18, was undertaken for mainly palaeoenvironmental purposes. The biostratigraphic information offered by ANDREWS, PACKHAM et al. (1975) was used for planktonic foraminiferal biostratigraphic control in this interval and is discussed later.

Quantitative data regarding foraminiferal and radiolarian distributions obtained in this study, when taken together with biostratigraphic synthesis in ANDREWS, PACKHAM et al. (1975), suggest that no stratigraphic discontinuities exist in the Middle to Late Miocene section (core 50 to core 18). "Continuous sedimentation" is therefore assumed.

The zonation of Middle to Late Miocene deep sea tropical sequences has been accomplished by the use of several independent, well documented,phylogenetic lineages involving the

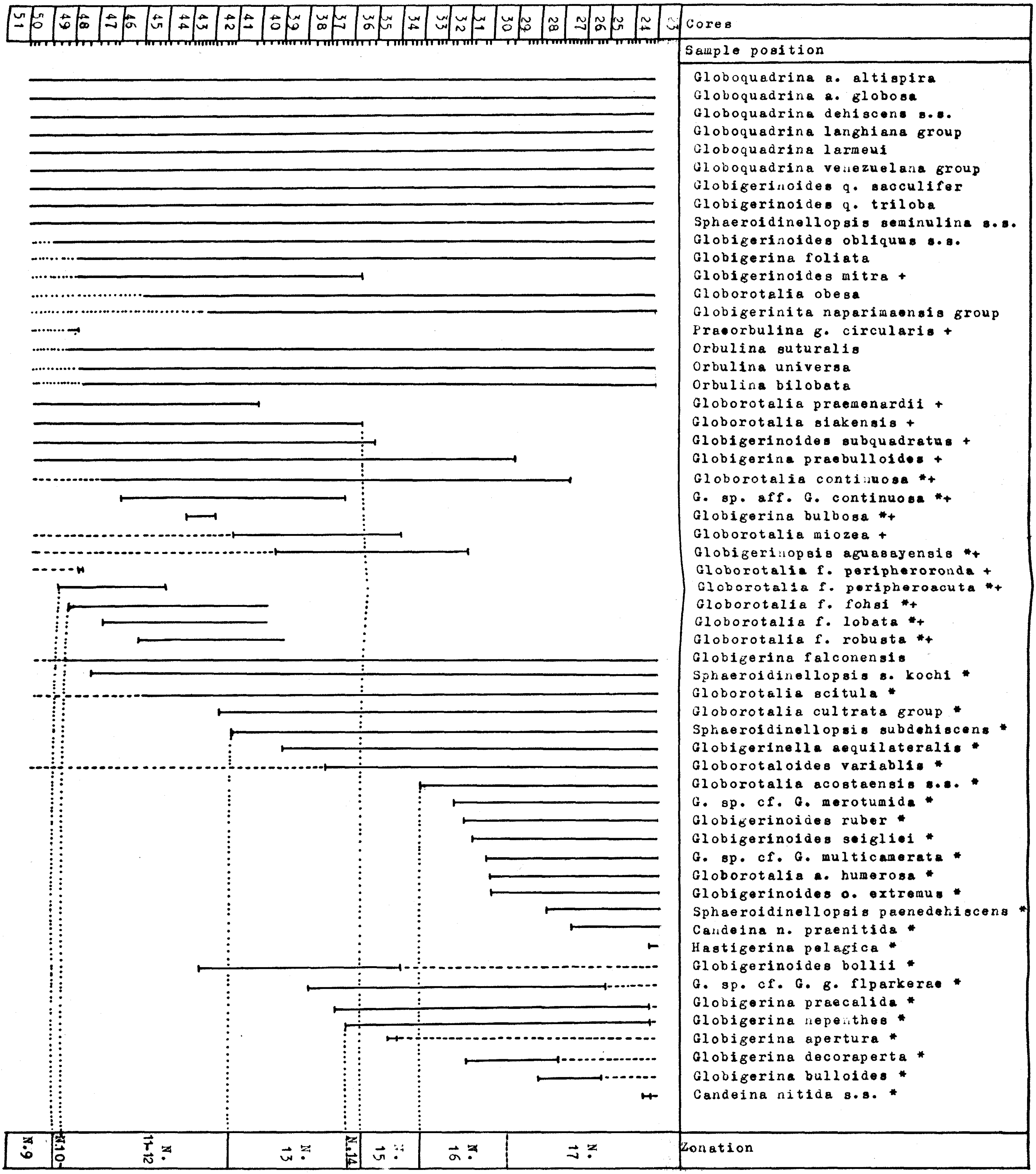

Fig.16 Planktonic foraminiferal ranges and biostratigraphical zonation (after Blow, 1969) at DSDP Site 289

datum used for definition of zonal boundary

range known to extend higher or lower elsewhere

absence believed to be due to dissolution

* + appearance and extinction events used for the consideration of evolutionary trends at Site 289 (see Chapter VII)

following taxa: *Orbulina, Sphaeroidinellopsis* and *Globorotalia (Fohsella, Globorotalia* and *Turborotalia),* most of which are well represented at DSDP Site 289. Taxonomic and stratigraphic information concerning individual taxa mentioned in the following account is presented in Appendix I.

The studied sequence commences at core 50, within Zone N.9 and just above the Early/Middle Miocene boundary. ANDREWS, PACKHAM et al. (1975), indicate the base of Zone N.9 by the initial appearance of the genus *Orbulina* in sample 51 cc. BLOW (1969) and BERGGREN and Van COUVERING (1974) regard the *Orbulina* datum (first appearance of *O. suturalis* from *Praeorbulina glomerosa circularis)* as consistent with the Early/Middle Miocene boundary. According to BLOW (1969), Zone N. 9 *(Orbulina suturalis-Globorotalia peripheroronda* Partial-range zone) is characterised by the appearance of *O. suturalis* and *G. peripheroronda*, prior to the evolutionary development of *G. peripheroacuta.* At Site 289, the two important zonal indicators are absent from the oldest part of the studied sequence, as are other important zonal species, including *Globigerinatella insueta, Globigerinoides sicanus* and *P. glomerosa circularis.* The zone has been therefore delineated on indirect evidence at Site 289, ie. the first appearance of *Orbulina spp.* in 51 cc as indicated by ANDREWS, PACKHAM et al. (1975) and the recognition herein of the base of Zone N.10. As such, the zone extends from 51 cc to 50-2 (fig. 16).

BLOW (1969) and JENKINS and ORR (1972) have commented on the difficulty of recognising the zone in deep sea sediments because of the susceptibility of *Orbulina spp.*

to dissolve at depth. At Site 289, the absence of the genus from 50-6 to 49-4 is considered to be related to dissolution processes.

BLOW (1969) defined the base of Zone N. 10 *(Globorotalia peripheroacuta* Consecutive-range zone) by the first evolutionary appearance of *G. peripheroacuta* from *G. peripheroronda*. The zone forms one of a series of consecutive partial-range zones, each of which is defined by the successive evolutionary development of taxa within the *Fohsella* lineage. At Site 289, the first appearance of *G. peripheroacuta* constitutes a well defined datum and the zone extends from 49-6 to 49-4.

Zones N. 11 *(Globorotalia praefohsi* Consecutive-range zone) and N. 12 *(Globorotalia fohsi* Partial-range zone) of BLOW (1969) have been amalgamated in the present study because of difficulties encountered in applying the taxonomic concepts of BLOW (1969) concerning members of the *Fohsella* lineage (see Appendix I). BLOW (1969) defines the base of Zone N.11 by the initial evolutionary appearance of *G. praefohsi* from *G. peripheroacuta* and the base of Zone N. 12 by the development of *G. fohsi* from *G. praefohsi*. In the present study, *G. praefohsi* and *G. fohsi* s.s. of BLOW (1969) have been synonymised as *G. fohsi fohsi* (Taxonomy, Appendix I), making the distinction of Zone N. 12 from Zone N. 11 impossible. At Site 289, the appearance of *G. fohsi fohsi* is used to define the base of Zone N. 11-12. The zone extends from 49-2 to 42-3 and is characterised by the appearance of several important associated taxa such as *G. lobata* (47-6), *G. robusta* (46-2), *G. cultrata* (42-6) and *Globigerinoides bollii* (43-5) (BLOW, 1969). The zone is therefore readily identifiable at Site 289. In addition to the afore-mentioned taxa, the important zonal forms *G. peripheroronda* and *P. glomerosa circularis* are briefly encountered at 48-2 and 49-2 + 48-6 respectively, although the latter occurrence within Zone N.11 is anomalously high according to the range given by BLOW (1969).

The base of Zone N.11-12 also heralds the appearance and subsequent consistent presence of *O. suturalis, O. universa* and *O. bilobata* in the studied sequence. BANDY (1963, 1966) has suggested that the first appearance of the genus *Orbulina* is diachronous and the evidence from the present study may superficially tend to support this view, although a detailed examination of the assemblages suggests that the delayed appearance of *Orbulina spp.* in the present study be due to a decrease in dissolution intensity over the N.10/N. 11 zonal boundary (see p. 85).

BLOW (1969) defines the base of Zone N. 13 (*Sphaeroidinellopsis subdehiscens-Globigerina druryi* Partial-range zone) at the horizon of the first evolutionary appearance of *S.subdehiscens* from it's immediate ancester, *S. seminulina* s.s., which occurs within the range of *G. druryi*. At Site 289, the first appearance of *S. subdehiscens* is an easily recognisable datum, although *G. druryi* is never encountered in the sequence. The zone extends from 42-2 to 37-2 and is further characterised by the extinction of *G. praemenardii* (41-2) and the subgenus *Fohsella (G.fohsi fohsi* (40-6) *G. fohsi lobata* (40-6) and *G. fohsi robusta* (40-1) (BLOW, 1969).

The base of Zone N.14 (*Globigerina nepenthes/Globorotalia siakensis* Concurrent-range zone) of BLOW (1969) is defined by the first appearance of *Globigerina nepenthes* occuring within the range of *G. siakensis*. At Site 289, *G. nepenthes* appears at 37-1. This proposed horizon for the base of Zone N.14 may, however, be spuriously high. *G. nepenthes* is a rather small species and it's presence in the sequence prior to 37-1 may have gone undetected in the present study because of the exclusive use of residues over 250u in size. *G. siakensis* is well represented within the latter part of it's range at Site 289 and the recognition of Zone N.14 is therefore not difficult.

BLOW (1969) defines the base of Zone N.15(*Globorotalia continuosa* Consecutive-range zone) as the horizon immediately above the level of extinction of *G. siakensis* within the range of *G. continuosa*. At Site 289, the abrupt extinction of *G. siakensis* after the appearance of *G. nepenthes* constitutes one of the most easily recognisable datums in the studied sequence. In the latter part of Zone N.13 and throughout Zone N.14, *G. siakensis* forms a dominant element in the planktonic foraminiferal assemblages and the extinction of the species, at 36-5, is characterised by a gradual though marked decrease in numbers. However, the potential unreliability of extinction datum planes for biostratigraphic dating is demonstrated by the distribution of *G. siakensis* at Site 289 where a 'pseudo-extinction' - characterised by a drop in the numerical abundance of the species of similar magnitute to the probable real extinction - occurs within Zone N. 11-12,where the presence of *G. fohsi s.l.* precludes any misinterpretation as to the age of this event (see Chapter V, p.111). At Site 289, the zone extends from 36-3 to 34-1. Although the base of Zone N.15 and the base of the overlying Zone N.16 is easily recognised, the distribution of *G. continuosa* within Zone N.15 is very sparce so that the correlation of sediments within the zone depends mainly on indirect or negative evidence, such as the presence of *G. nepenthes* and the absence of *G. siakensis* and *Globorotalia acostaensis* s.s., the index form of Zone N.16. According to BLOW (1969), Zone N.15 spans the Middle/Late Miocene boundary.

BLOW (1969) defines the base of Zone N.16 (*Globorotalia acostaensis acostaensis-Globorotalia merotumida* Partial-range zone) at the horizon of the first evolutionary appearance of *G. acostaensis* s.s. from *G. continuosa*. *G. merotumida* first appears at a level just above the base of this zone (BLOW, 1969). At Site 289, the early appearance of *G. acostaensis* s.s. is rather sporadic, although again this may reflect the size grade of the residue. The base of Zone N.16 is taken from 33-6 and the zone is extended with caution to 31-1. Individuals tentatively refered to *G. merotumida* (included herein under *G. cf. merotumida)* appear within the first half of this interval (32-4). Other taxa, which according to BLOW (1969) characteristically appear within this zone, also first appear within the said interval at Site 289 and include *Globigerinoides ruber* (32-2) and *G.acostaensis humerosa* (31-1). The vertical extent of most of the zone at Site 289 is therefore well established.

The approximate position of the N.16/N.17 zonal boundary at Site 289 constitutes the only major problem associated with the application of BLOW's scheme in the present study.

BLOW (1969) defines the base of Zone N.17 (*Globorotalia tumida plesiotumida* Consecutive-range zone) at the horizon of the first evolutionary appearance of *G. tumida plesiotumida*. According to BLOW (1969), the zone is characterised by diversification of planktonic assemblages with the appearance of *Candeina nitida nitida* in the early part of the zone, *G. multicamerata* in the mid-part of the zone and *S. paenedehiscens* in the latter part of Zone N.17. At Site 289, difficulty in discriminating the zonal index form

G. tumida plesiotumda from it's precursor, *G. merotumida,* rendered the exact placement of the N.16/N.17 zonal boundary impossible. In addition, forms tentatively referrable to *G. multicamerata* (herein included under *G. cf. multicamerata)* appear within Zone N.16 prior to the appearance of *G. acostaensis humerosa.* According to BLOW (1969), *G. acostaensis humerosa* appears slightly below the N.16/N.17 zonal boundary. The boundary at Site 289 is tentatively placed between 31-1 and 30-3, just above the first appearance of *G. acostaensis humerosa* and below the appearance of *S. paenedehiscens* (28-5). Zone N.17 thus extends from 30-3 to beyond the upper limit of the studied sequence at Site 289. Important taxa which appear within this zone up to the limit of the present biostratigraphic study include *C. nitida praenitida* (27-4), *C. nitida s.s.* (24-5) and *Hastigerina pelagica* (24-3). *G. continuosa* becomes extinct within Zone N.17 (27-4).

The difficulties encountered placing the N.16/N.17 zonal boundary at Site 289 on the evidence of the planktonic foraminifera reflect the rather subjective nature of the subspecific distinctions made in this group hitherto.

In addition to the forementioned taxa used by BLOW (1969) in the formulation of his biostratigraphic zonation for the Middle to Late Miocene, the distribution of other planktonic foraminifera within the studied sequence at Site 289 deserves attention.

The following forms range throughout the sequence from cores 50 to 24: *Globoquadrina altispira altispira, G. altispira globosa, G. dehiscens, G. langhiana, G. venezuelana, Globigerinoides quadrilobatus sacculifer, G. quadrilobatus triloba* and *Sphaeroidinellopsis seminulina* s.s.

Several taxa, some of which are known to extend down into the Early Miocene (see Appendix I), have disrupted ranges at Site 289 around the base of the studied sequence, particularly in cores

50 and 49: *Globigerinoides obliquus* s.s., *G. mitra, Globigerina foliata, Globorotalia obesa, Globigerinita naparimaensis, Praeorbulina glomerosa circularis, Orbulina suturalis, O. universa* and *O. bilobata.* These forms have surface wall textures that can be described as cancellate, finely pitted or hispid. BERGER (1970) regards modern forms with equivalent textures as highly susceptible to dissolution. Samples in which the above taxa are absent (cores 50 to 49), contain assemblages dominated by heavy, robust, non-spinose globoquadrinids and it is believed the sediments deposited within this interval were subject to an increase in dissolution intensity (see Chapter V).

A number of taxa were found to have restricted ranges within the studied sequence and may have potential for biostratigraphic application: *Globigerinoides subquadratus*, which becomes extinct near the base of Zone N.15 (36-1); *Globigerina bulbosa,* which ranges within Zone N.11-12 (44-2 to 43-1); *S. seminulina kochi,* which appears near the base of Zone N.11-12 (48-2); and *G. obliquus extremus,* which appears within the latter part of Zone N.16 (31-1).

Several taxa display ranges within the studied sequence at Site 289 which are shorter than those recorded by workers elsewhere: *Globigerina praebulloides, G. bulloides, G. decoraperta, G. falconensis, Globigerinoides bollii, Globorotalia continuosa, G. miozea, G. scitula, Globorotaloides variablis, Candeina nitida praenitda, C. nitida nitida* and *Globigerinaspis aquasayensis* (see Appendix I). The taxa have relatively stable taxonomic concepts and their stratigraphic restriction at Site 289 may have some palaeo-ecological significance (see Chapter VII).

Similarly, two taxa, *Praeorbulina glomerosa circularis* and *Globigerinoides subquadratus*, display upper ranges within the studied sequence at Site 289 that are younger than those recorded by workers elsewhere (see Appendix I). This phenomenon may be due to delayed extinction because local conditions remained favourable or because of upward reworking in the sediment by benthonic organisms.

Biostratigraphic analysis of DSDP sequences is occasionally hindered by the problem of downhole or shipboard contamination during drilling operations. If the contaminating microfossils transect a large stratigraphic interval they can be easily identified as such; sample 46-1 for example, contained a rich Pleistocene assemblage including *Pulleniatina obliquoloculata, Globorotalia tumida* and *G. truncula tinoides* as well as indigenous Middle Miocene forms and the sample was subsequently removed from the study. However, if the contaminants arrive from a short stratigraphic interval, they may easily remain undetected as such. The presence of forms referable to *G. cf. multicamerata* in 34-5 and 34-2 within Zone N.15 may well represent such a case.

The analysis of planktonic foraminifera within the sequence from core 23 to core 18 was carried out with a view to ascertain the relative abundance of keeled globorotaliids and mean size distribution in *Orbulina universa*. Since no biostratigraphic control using planktonic foraminifera was carried out for this interval, the writer has relied in part on the information given by ANDREWS, PACKHAM et al. (1975, fig. 20, p. 249-250; fig. 21, p. 252). Accordingly, the sequence from core 23 to core 18 represents the remainder of Zone N.17, the top of which is defined therein by the extinction of *G. tumida plesiotumida,* a level which ANDREWS, PACKHAM et al. (1975) regard as coincidental with the Miocene/Pliocene boundary (fig. 18). This definition of the N.17/N.18 zonal boundary deviates from that erected by BLOW (1969), who nominated the level at the initial evolutionary appearance of *G. tumida tumida,* occurring prior to the extinction of *G. tumida plesiotumida.* BLOW (1969) thus places the N.17/N.18 zonal boundary before the Miocene/Pliocene boundary.

In both cases, however, cores 23 to 18 would appear to extend to the top of the Miocene. The sequence can be divided by the first appearance datum of *Pulleniatina spp.*, which occurs at 22-1, and, according to BLOW (1969) and BERGGREN and Van COUVERING (1974), lies in the upper part of Zone N.17.

A comparison of the planktonic foraminiferal biostratigraphic zonation for the Middle to Late Miocene at Site 289 offered by ANDREWS, PACKHAM et al. (1975), with that presented herein, reveals some inconsistencies which deserve explanation.

The stratigraphic position of datums given by ANDREWS, PACKHAM et al. (1975) generally conform to those presented herein. That displaying the greatest deviation is the position of the first evolutionary appearance of *G. acostaensis*, s.s. which defines the base of Zone N.16. ANDREWS, PACKHAM et al. (1975) place the level between 32-5 and 32cc while the subspecies was first encountered at 33-6 in the present study. However, it is the actual definition of zonal boundaries which has created most of the discrepancies. ANDREWS, PACKHAM et al. (1975, p. 250) state that "most of the zonally diagnostic species recorded by BLOW (1969) are present at this site (289) and occur in successions similar to those established by him, thus enabling rather precise application of BLOW's zonal scheme.". However, their biostratigraphical subdivision of Site 289 is not accompanied by any further written explanation and the zonation (ANDREWS, PACKHAM et al., fig. 21, p. 252) appears to be based on the position of important foraminiferal events. Unfortunately, these events are not always the diagnostic index events erected by BLOW (1969). ANDREWS, PACKHAM et al. (1975) seem to define the N.12/N.13 zonal boundary by the extinctions of *G. fohsi lobata* and *G. fohsi robusta* rather than the first evolutionary appearance of *S. subdehiscens*; while the N.13/N.14 zonal boundary is defined on the extinction of *Cassigerinella chipolensis* instead of the first evolutionary appearance of

G. nepenthes. Consequently, the position of these zonal boundaries at Site 289 differs in ANDREWS and PACKHAM et al. (1975) compared to those offered herein.

4. RADIOLARIAN ZONATIONS

The development and application of Cenozoic biostratigraphical zonations using radiolaria owes a great deal to the advent of the Deep Sea Drilling Project. For almost sixty years after the monographic work of HAECKEL (1887), it was generally believed that the group could not be used in stratigraphic studies of Cenozoic sediments because of the widespread, but largely false belief that most radiolarian genera and species were long ranging (see RIEDEL and SANFILIPPO, 1977).

However, following early stratigraphic work by RIEDEL (1952, 1957), RIEDEL and SANFILIPPO (1970, 1971, 1978) MOORE (1971) and FOREMAN (1973) have erected zonations for low latitude tropical and subtropical sequences from DSDP material which divides the Late Palaeocene to Recent into twenty six zones, five of which span the Middle and Late Miocene.

Nevertheless, in spite of the recent amendments by RIEDEL and SANFILIPPO (1978), the zonation is limited by unsatisfactory taxonomic treatment of radiolaria in general and by the need to use alternative schemes in high latitude sequences, with which correlation is difficult. WESTBERG and RIEDEL (1978) estimate that only about 10% of all available taxa are used in biostratigraphic zonations and note that many of the species used for the tropical zonation do not extend into higher latitude regions. Consequently, alternative schemes have been simultaneously erected for extra-tropical areas (CHEN, 1975; PETRUSHEVSKAYA, 1975; BJØRKLUND, 1976; KEANY, 1979). An additional problem associated with the application of the zonal scheme outlined by RIEDEL and SANFILIPPO (1978) relates to the basic biostratigraphical philosophy employed. The boundaries of all zones are associated with extinction or appearance events. RIEDEL and

SANFILIPPO (1971) and SANFILIPPO and RIEDEL (1973) distinguish three types of appearance: morphological, morphological-evolutionary and evolutionary. The former two are objective and relate to the first appearance of a taxa. However, the "evolutionary appearance" datum involves the numerical relationship between a taxa and it's newly evolved descendant species and is defined as the level at which the latter becomes greater in abundance than the former. Such events may easily exhibit diachroneity over large geographical areas where different evolutionary rates operate according to different environments. In addition, the recognition of such datums may be difficult and may introduce an element of subjectivity in those biostratigraphic studies which utilise only qualitative or semi-quantitive data. Nevertheless, WESTBERG and RIEDEL (1978) have demonstrated a consistent application of the zonal scheme of RIEDEL and SANFILIPPO (1978) in Cenozoic sediments from the Pacific Ocean.

The zonation is also supplemented by a large selection of datum planes which can be used to indicate the presence of particular zones when the nominate taxa are absent or difficult to identify. The combination of zones and datum planes has produced a scheme which has been successfully employed on many DSDP Cenozoic sequences, including those at Sites 289 and 71 (RIEDEL and SANFILIPPO, 1970, 1971, 1973; MOORE, 1971; GOLL, 1972; PETRUSHEVSKAYA and KOZLOVA, 1972; DINKELMAN, 1973; JOHNSON, 1974, 1977; HOLDSWORTH, 1975). WESTBERG and RIEDEL (1978) have outlined and considered the various limiting factors associated with the detailed accuracy of radiolarian correlations in Miocene DSDP sediments of the Pacific Ocean.

5. RADIOLARIA: SITE 289

The radiolarian stratigraphy was well established prior to the present study, by HOLDSWORTH (1975), who considered the biostratigraphic distribution and zonation of Cenozoic species at Site 289 as part of the Initial Reports volume for Leg 30 (ANDREWS, PACKHAM et al. 1975). In general, the zones outlined by RIEDEL and

SANFILIPPO (1971) were recognised for the Oligocene to Recent, although the placement of certain zonal boundaries, involving the "evolutionary appearance" datums of *Stichocorys peregrina* and *Ommatartus penultimus* proved difficult or impossible.

HOLDSWORTH (1975) recognised three "zones" between cores 50 to 24 (Middle to Late Miocene) and an additional "zone" between cores 23 to 18 (Late Miocene). In addition, seventy-two appearance, evolutionary and extinction events were tabulated through this sequence. The comparative ease in recognising the established radiolarian zones and datum planes at Site 289 prompted HOLDSWORTH (1975) to suggest that the sequence be recognised as a reference section for the series of radiolarian biostratigraphic events from the Late Eocene to Late Miocene in the equatorial Pacific. In addition, to compensate the relatively low resolution of each standard zone and problems of diachronous datum planes, HOLDSWORTH (1975) erected thirty five provisional biostratigraphical divisions of the Late Eocene to Pleistocene sequence (Ontong Java segments) which outlined the more confidently recognisable datum planes to provide an informal zonation of greater resolution than the standard scheme. Within the studied sequence of the present work, HOLDSWORTH (1975) erected twelve Ontong Java segments against four formal radiolarian zones.

The stratigraphical distribution of the more important radiolaria encountered at Site 289, together with an indication of the index species and position of the zonal boundaries of RIEDEL and SANFILIPPO (1978) is given in fig. 17 (see also fig. 30a-d).

The zonation of the Middle to Late Miocene has been largely accomplished by use of a well documented phylogenetic lineage involving artiscan radiolaria.

The base of the studied sequence, at core 50, coincides with the base of the *Dorcadospyris alata* Zone, defined by the initial appearance of *D. alata* in 50cc (HOLDSWORTH, 1975). Important events

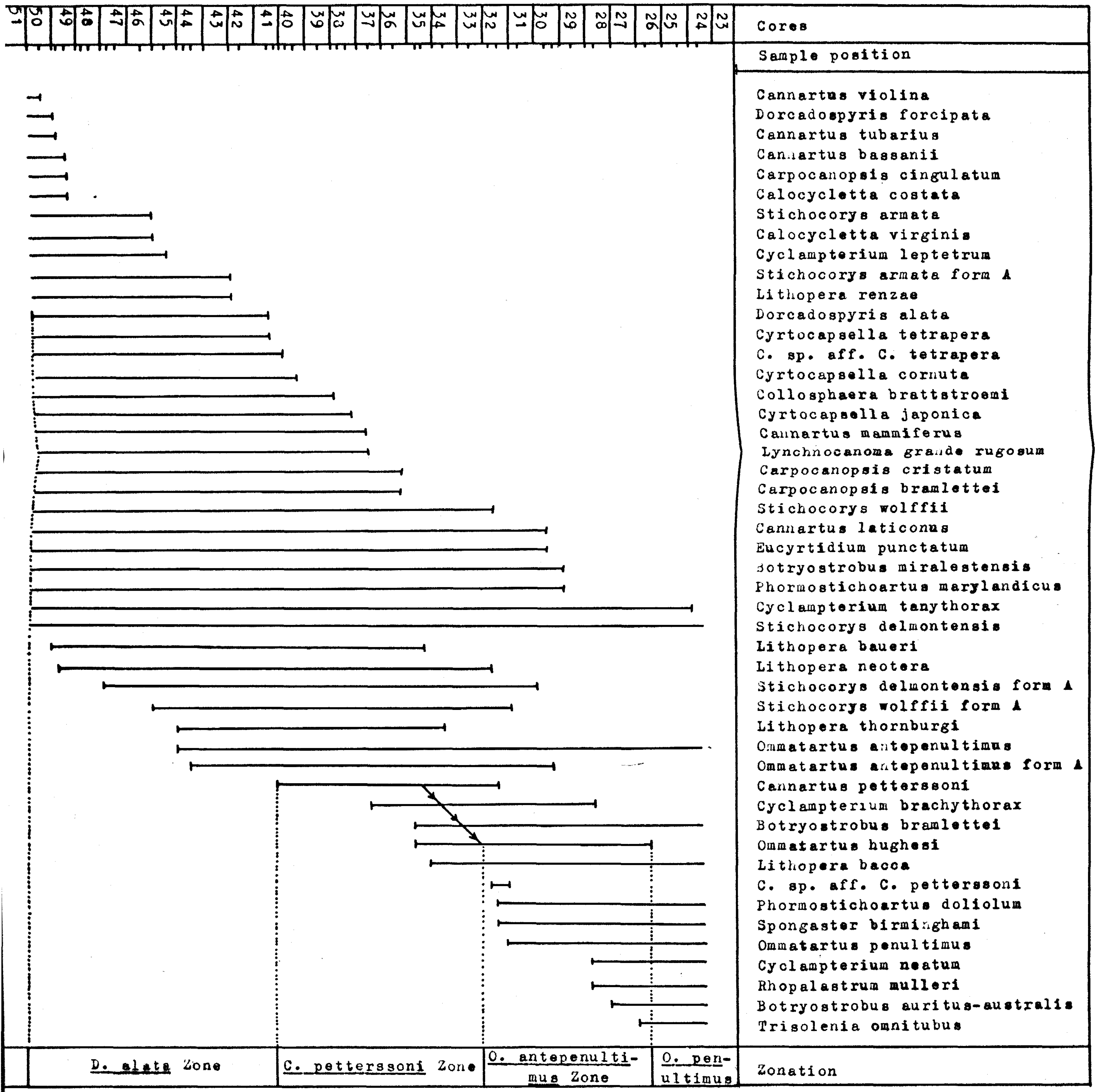

Fig. 17 Ranges of the more important radiolaria and biostratigraphical zonation (after Riedel and Sanfilippo, 1978) at DSDP Site 289

.... datum used for definition of zonal boundary

'evolutionary transition'
]

within the zone, as indicated by RIEDEL and SANFILIPPO (1978), and apparent at Site 289, include the extinction datums of *Calocycletta costata* at 49-3 and *C. virginis* at 45 cc and the appearance of *Lithopera thornburgi* at 44 cc.

RIEDEL and SANFILIPPO (1978) define the base of the *Cannartus?petterssoni* Zone at the level of the first appearance of *C.?petterssoni*. At Site 289, the species appears at 41-1. Important events recognisable within the zone include the extinction datum of *Cyrtocapsella cornuta* at 39 cc and the "evolutionary appearance" of *Ommatartus antepenultimus* from *Cannartus laticonus*, although the exact level is difficult to locate.

According to RIEDEL and SANFILIPPO (1978), the base of the *Ommatartus antepenultimus* Zone is defined by the "evolutionary appearance" of *Ommatartus hughesi* from *Cannartus?petterssoni*. At Site 289, the transition occurs at 32 cc and is reasonably identifiable. An important event recognisable within the zone at Site 289 is the appearance of *Cyclampterium neatum* from *C. brachythorax* at 27 cc.

The base of the *Ommatartus penultimus* Zone is defined by the level of extinction of *Ommatartus hughesi* (RIEDEL and SANFILIPPO, 1978). At Site 289, this event occurs at 26-4. The top of this zone extends beyond core 24 and is marked by the "evolutionary appearance" of *Stichocorys peregrina* from *S. delmontensis* at 22 cc (HOLDSWORTH 1975). An important event within the lower part of the zone and recognisable at Site 289 is the level of first appearance of *Trisolenia omnitubus* at 25 cc.

RIEDEL and SANFILIPPO (1978) consider the base of the *Dorcadospyris alata* and *Ommatartus antepenultimus* Zones to approximate the Early/Middle and Middle/Late Miocene boundaries respectively.

The zonal breakdown of the Middle to Late Miocene at Site 289 presented herein differs in two respects to that offered by HOLDSWORTH (1975). These differences can be directly attributed to modifications and improvements of the zonal scheme used by HOLDSWORTH (1975) (RIEDEL and SANFILIPPO, 1971), which were subsequently presented by RIEDEL and SANFILIPPO (1978).

HOLDSWORTH (1975) defined the base of the *Ommatartus antepenultimus* Zone by the "evolutionary appearance" of *O. antepenultimus* from *Cannartus laticonus* and placed the boundary between 31 cc and 32-3 (cf. RIEDEL and SANFILIPPO, 1978 and herein). Secondly, HOLDSWORTH (1975) was unable to place the base of the *Ommatartus penultimus* Zone in it's true stratigraphical context using the definition of RIEDEL and SANFILIPPO (1971), which involved the "evolutionary appearance" of *O. penultimus* from *O. antepenultimus*. RIEDEL and SANFILIPPO (1978) redefined the base of the zone and as such, is recognisable at Site 289 in the present study.

Consequently, the Middle to Late Miocene sequence under study herein can be subdivided into four radiolarian zones from cores 50 to 24, with an additional zone within the sequence from cores 23 to 18.

In general, the stratigraphic ranges of radiolarian species at Site 289 presented in this study are similar to those offered by HOLDSWORTH (1975). WESTBERG and RIEDEL (1978) have also considered the stratigraphic distribution of taxa in the Miocene section at Site 289 and their results can be used as an independent control.

Certain anomalous stratigraphic ranges, apparent from a comparison of results between the three studies, are considered below and can be attributed to two main factors: the nature of the study methods and subjectivity in taxonomic concepts. The original DSDP Initial Reports study by HOLDSWORTH (1975) treated this data in a qualitative and semi-quantitative manner. In contrast, a fully quantitative approach has been used in the present study, a method which perhaps produces slightly more reliable results, particularly in the end ranges of rare species. Problems and differences in taxonomic concept in relevant species are discussed in Appendix I.

In the present study, the top ranges of *Carpocanopsis bramlettei* and *Stichocorys wolffii* and the bottom range of *Lithopera thornburgi* are higher than those given by HOLDSWORTH (1975) but similar to those given by WESTBERG and RIEDEL (1978). Other differences between the ranges given herein compared to those given by HOLDSWORTH (1975) involve *Calocycletta caepa* and *Cannartus mammiferus*, whose bottom and top range respectively are tabulated lower herein. In the case of *Cannartus laticonus*, both the bottom and top range differs from that given by HOLDSWORTH (1975) and WESTBERG and RIEDEL (1976).

6. GEOCHRONOLOGY: SITE 289

The main subdivisions of the Cenozoic, including the Miocene epoch, were originally defined in Europe and later adopted for use as international time stratigraphic units (BERGGREN, 1971). Nevertheless, the identification of these units and correlation of the European standard stratotype sections with sequences from other parts of the world has proved difficult (STAINFORTH et al., 1975).

However, recent advances involving the separate disciplines of planktonic biostratigraphy, the geomagnetic polarity time scale and the radiometric time scale have provided an increased understanding of the true geochronological position of Cenozoic events (HAYS et al., 1969; THEYER and HAMMOND, 1974; RYAN et al., 1974; SAITO et al., 1975). In a major review, BERGGREN and Van COUVERING (1974) have attempted to calibrate the zonal schemes, geomagnetic time scale and European stages with the radiometric time scale to provide an accurate geochronological framework for the past 15 million years, from the Middle Miocene to Recent. In the present study, the synthesis of BERGGREN and Van COUVERING (1974) has been applied in an attempt to relate the biostratigraphic events at Site 289 to the classic European stages and to an absolute time scale. Palaeoenvironmental and palaeoecological conclusions arising from this study may then be viewed in relation to regional and global geological events of the Middle and Late Miocene.

The time scale of BERGGREN and Van COUVERING (1974) for the Miocene is based on the calibration of biostratigraphic events to K-Ar radiometric dates and to suggested correlation between sea floor magnetic anomalies and palaeomagnetic epochs. Further estimation of the ages of important planktonic zones is based on the extrapolation of sedimentation rates between reliably dated datum levels at several DSDP sites.

The correlation of the planktonic foraminiferal and radiolarian zonations at Site 289 with the European stage boundaries and absolute time scale is offered in fig. 18.

The stratigraphic relationship between the two zonal schemes has been considered by BRÖNNIMANN et al.(1971) and BERGGREN and Van COUVERING (1974). It is difficult to compare the relative position of the zonal boundaries presented herein for Site 289 with those offered in these reviews because the definitions and hence placements of certain radiolarian boundaries have since been changed (RIEDEL and SANFILIPPO, 1978). Nevertheless, the limited comparison possible reveals a general agreement with only slight discrepancies. BERGGREN and Van COUVERING (1974) place the base of the *Dorcadospyris alata* zone within the Early Miocene (within Zone N.8) whereas the boundary falls within the Middle Miocene (within Zone N.9).at Site 289. Similarly, whereas the base of the *Cannartus?petterssoni* Zone falls within Zone N.14 according to BERGGREN and Van COUVERING (1974), at Site 289 the datum is placed with Zone N.13, in agreement with BRÖNNIMANN et al.(1971).

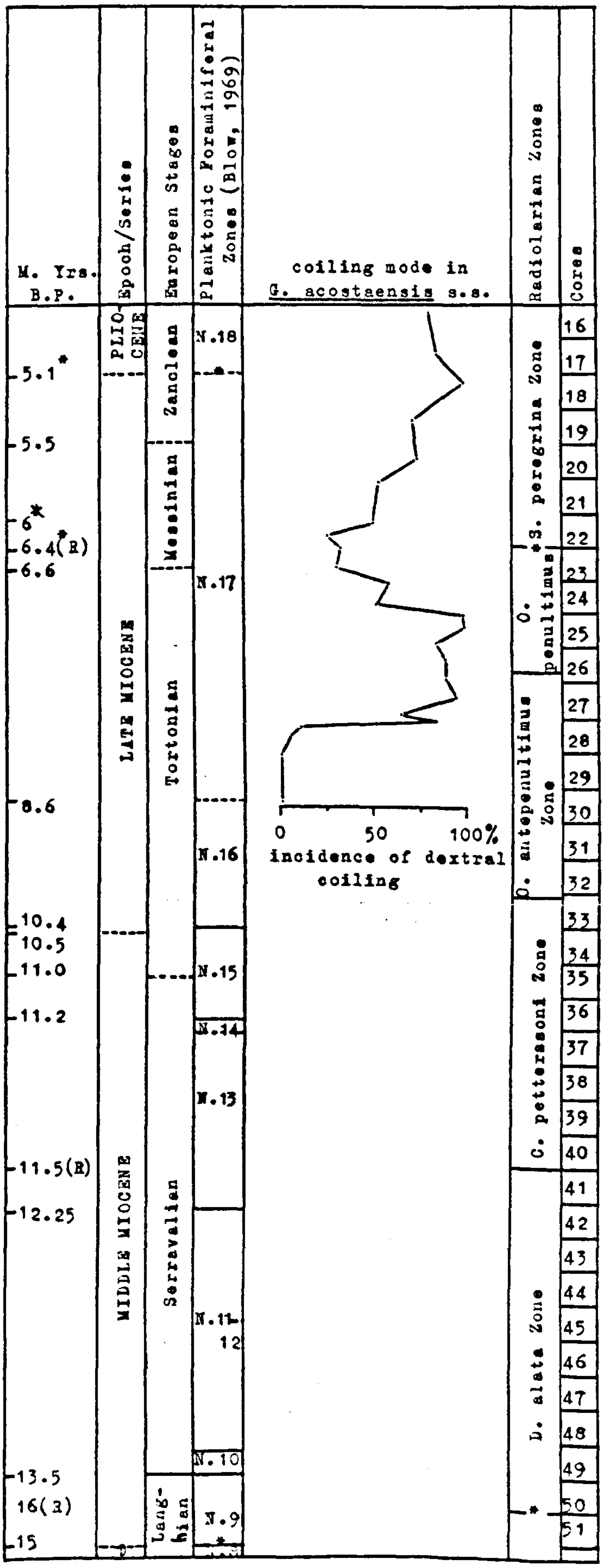

Fig.18 Geochronology : Site 289
* = from Initial Reports, v. 30
(R) = age derived from radiolarian datum
θ = Early Miocene

The ages of the following datums, as assigned by BERGGREN and Van COUVERING (1974) have been applied to those at Site 289 (fig. 18)

1. Appearance of *Orbulina spp.* (base of the Middle Miocene and Zone N. 9: 15 m.y. B.P.
2. Appearance of *G. peripheroacuta* (base of Zone N.10): 13.5 m.y. B.P.
3. Appearance of *S.subdehiscens* (base of Zone N.13): 12.25 m.y. B.P.
4. Extinction of *G. siakensis* (base of Zone N.15): 11.2 m.y. B.P.
5. Appearance of *G. acostaensis* (base of Zone N.16): 10.4 m.y. B.P.
6. Base of Zone N.17: 8.6 m.y. B.P.
7. Appearance of *Pulleniatina spp:* 6 m.y. B.P.
8. Base of Zone N.18: 5.1 m.y. B.P.

BERGGREN and Van COUVERING's (1974) estimate for the appearance of *G. nepenthes* (base of Zone N.14) was not applied because of uncertainity as to the exact placement of this datum at Site 289.

In addition, BERGGREN and Van COUVERING (1974) assign an age of 6.4 m.y. B.P. to the base of the *Stichocorys peregrina* Zone. The estimated ages for the base of the *Dorcadospyris alata* and *Cannartus?petterssoni* Zones at 16 m.y. and 11.5 m.y. respectively appear as anomalous time plots against those outlined above at Site 289 (fig. 18) and reflect differences in the stratigraphical positioning of the boundaries as mentioned above.

Palaeontological and absolute age criteria can be correlated with traditional chronostratigraphic (stage) boundaries.

BERGGREN and Van COUVERING (1974) correlate the base of Zone N.10, at 13.5 m.y. B.P., with the Langhian/Serravalian boundary; within Zone N.15, at 11. m.y. B.P., with the Serravalian/Tortonian boundary; within Zone N. 17, at 6.6 m.y. B.P., with the Tortonian/Messinian boundary and within Zone N.17, at 5.5 m.y. B.P., with the Messinian/Zanclean boundary..

The boundary between the Middle and Late Miocene occurs at 10.5 m.y. B.P. according to BERGGREN and Van COUVERING (1974), within the Tortonian stage and within Zone N.15.

At Site 289, the base of the Serravallian is plotted between core 50 and core 49; the base of the Tortonian is tentatively placed below the base of Zone N.16 within core 35; the base of the Messinian is tentatively placed below the base of the *S. peregrina* Zone within core 23 and the base of the Zanclian is tentatively placed below the base of Zone N.18 within core 20(fig. 18). The Middle/Late Miocene boundary is tentatively placed within core 34.

The placement of the base of the Messinian stage is of particular importance to the present study because the boundary precedes a major geological event, ie., the accumulation of vast evaporite deposits in the Mediterranean basin which is believed to have exerted a major influence on palaeoceanographical processes throughout the world (RYAN et al., 1974). Unfortunately, the Messinian stratotype consists of gypsum-anhydrite beds with fossil occurrences restricted to marine marly intercalations, thus rendering a distinct palaeontological definition of the stage very difficult (BERGGREN and Van COUVERING, 1974).

D'ONOFRIO et al. (1975) have suggested the first appearance of *Globorotalia conomiozea* as coincidental with the base of the Messinian. Unfortunately, the form appears to be restricted mainly to temperate areas (VINCENT, 1974) and it is not encountered within the Late Miocene sequence at Site 289. However, a second biostratigraphic event, which has proved useful for correlation with the Tortonian/Messinian boundary, is a sudden coiling change observed in *G. acostaensis* from sinistral (below) to dextral (above)

(SALVATORINI and CITA, 1979). The datum has been recorded at the base of the Messinian from Crete, Sicily and northern Algeria (ZACHARIASSE, 1975), in the "Tripoli" Formation immediately underlying the first evaporitic beds in Sicily (STAINFORTH et al., 1975), in the uppermost Miocene of southern Spain (MONTENANT et al., 1976) and a few metres beneath the basal evaporites in the Riba dello Zolfo section in Piedmont (BOSSLO et al., 1976). According to STAINFORTH et al. (1975), the datum closely approximates the base of the Messinian and may be recognised on a global scale.

At Site 289, the coiling preference of *G. acostaensis* was recorded in twentysix samples spanning Zone N.17 in the Late Miocene (twenty individuals per sample). The relative distribution of both coiling varients, seen in fig. 18 , reveals two peaks of sinistral forms intercalated with two peaks of dextral forms. The younger switch from sinistral to dextral coilers, occurring around the *S. peregrina* datum (6.4 m.y.) is believed to represent the event discussed above and has been used herein to define the base of the Messinian (6.6 m.y.) within core 23 at Site 289.

Supportive evidence concerning the correct stratigraphical placement of the base of the Messinian stage at Site 289 is offered by HAQ et al. (1980). In an attempt to identify globally synchronous events (both palaeontological and isotopic) in Late Miocene deep sea sequences, the authors have consistently dated, via the palaeomagnetic time scale, a carbon isotope shift bracketed by several phytoplankton datums between 6.25 m.y. B.P. and 5.20 m.y. B.P. Data from several DSDP Sites, including Site 289, throughout the Pacific Ocean reveal striking consistencies in the relative positioning of these datums. At Site 289, a phytoplankton event believed to represent a synchronous marker at 6.25 m.y. B.P. (the first appearance of *Amaurolithus spp.*) occurs above 23-3 (HAQ et al., 1980) - within the same core in which the base of the Messinian stage, at 6.6 m.y. B.P., has been tentatively placed.

Although applied in the present study, the geochronological synthesis of BERGGREN and Van COUVERING (1974) is perhaps not a definitive scheme for the Neogene and further work concerning refinement of the geomagnetic time scale can be expected to revise and improve the existing framework (LABRECQUE et al., 1977). THEYER, MATO and HAMMOND (1977, 1978) have recently attempted a palaeomagnetic and geochronologic calibration of latest Oligocene to Pliocene radiolarian events in the equatorial Pacific Ocean. The application of this work to the present study created several geochronological inconsistencies and anomalies when compared to the synthesis of BERGGREN and Van COUVERING (1974). WESTBERG and RIEDEL (1978) have questioned the work of THEYER et al. (1977) with respect to their stratigraphic sequence of radiolarian events. It was therefore considered premature to adopt the results of THEYER et al. (1977) in the present study while such discrepancies remain unresolved.

7. SEDIMENTATION RATE: SITE 289

The geochronological conclusions for the Middle to Late Miocene sequence at Site 289 has allowed a detailed analysis of fluctuations in the rate of sedimentation through this interval.

Variations in sedimentation rate in a sequence of pelagic biogenic ooze and chalk, where inorganic detrital input is constantly very low, reflect changes in the productivity of the overlying surface waters or fluctuations in the rate of dissolution or a combination of both.

The Initial Reports volume for Leg 30 (ANDREWS, PACKHAM et al., 1975) includes a sediment accumulation curve for the whole of the sequence at Site 289, in which the Cenozoic interval is based on a calibration of the planktonic foraminiferal zonation with the absolute time scale of BERGGREN and Van COUVERING (1974) (via VINCENT, 1974). The curve has been corrected for modification of original thicknesses by pressure compaction and indicates a uniform sedimentation rate throughout the Late Oligoence, Early Miocene and within the Middle to Late Miocene sequence (36 to 42 metres per million years) which brackets an anomalously high rate over the Early/Middle Miocene boundary (72 metres per million years). ANDREWS, PACKHAM et al. (1975) suggest the anomaly is due to an incorrect estimate for the age of the Early/Middle Miocene boundary of 14 m.y. B.P.* by BERGGREN and Van COUVERING (1974) and suggest a revised estimate of 16 m.y. B.P. based on the evidence at Site 289.

The sedimentation rate curve derived from the results of the present study for Site 289 is given in fig. 19.

The curve is offered as an alternative to that given for Site 289 in the Initial Reports for the Middle to Late Miocene sequence because of modifications in the basic methods of construction.

In the present study, the definitions of the planktonic foraminiferal boundaries follow strictly where possible, to that of BLOW (1969) calibrated via BERGGREN and Van COUVERING (1974) with the absolute time scale (cf. ANDREWS, PACKHAM et al., 1975 for Site 289 - see biostratigraphy section above). In addition, greater resolution is offered for the sequence by using nine data points (against four by ANDREWS, PACKHAM et al., 1975). However, no allowance is made herein for compaction effects with the result that fluctuating rates can only be compared on a relative, rather than absolute scale. Nevertheless, the results do prove useful in light of the suggestion made by ANDREWS, PACKHAM et al. (1975) as to the correct age of the Early/Middle Miocene boundary. The sediment accumulation curve (fig. 19), drawn using the scale of BERGGREN and Van COUVERING (1974), reveals a low sedimentation rate at the base

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* revised to 15 m.y. B.P. in the Appendix of BERGGREN and Van COUVERING (1974).

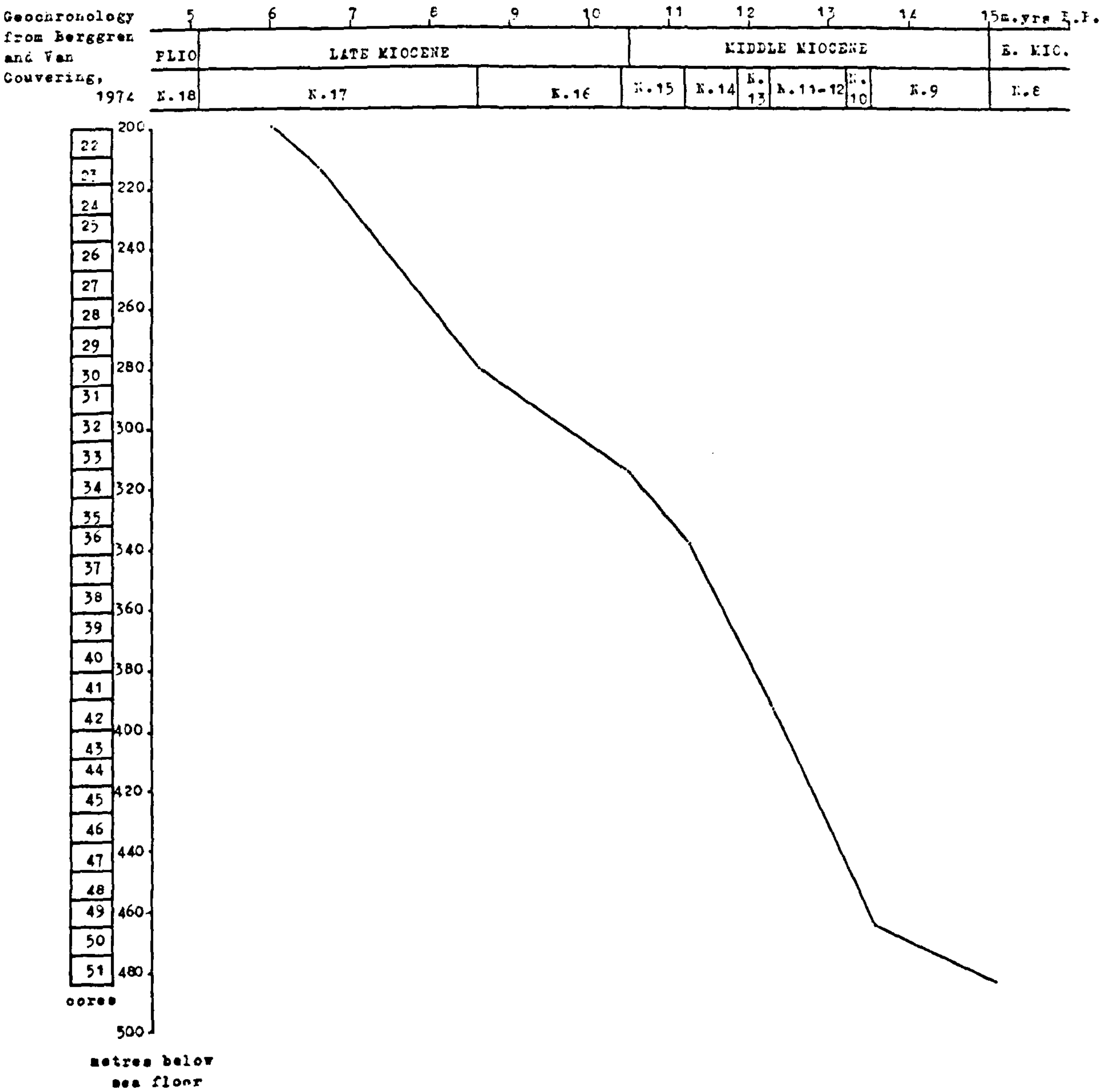


Fig. 19 Sedimentation Rate Curve, Site 289

of the Middle Miocene and over the Middle/Late Miocene boundary intercalated between intervals of higher sedimentation rates within most of the Middle and the remainder of the Late Miocene. The curve shows superficial resemblance to that given in ANDREWS, PACKHAM *et al*. (1975) with sedimentation rates generally higher in the Middle Miocene compared to the Late Miocene. The anomalously low rate at the base of the Middle Miocene (throughout Zone N.9) was not recognised by ANDREWS, PACKHAM *et al*. (1975), probably because their sample intervals were too long. Supportive evidence for such sharp changes in sedimentation rate with particularly low values throughout Zone N. 9 can be taken from variations in dissolution rates. The planktonic foraminiferal and radiolarian assemblages throughout Zone N. 9 are characterised by robust forms consistent with increased rates of dissolution, itself a strong factor controlling sedimentation rates in biogenic planktonic oozes (see Chapter V , p. 115).

The conclusions presented herein suggest that anomalous sedimentation rates at Site 289 may be caused by factors such as variation in dissolution rather than incorrect calibrations to the absolute time scale.

8. PLANKTONIC FORAMINIFERA: SITE 71

The Initial Reports volume for DSDP Leg 8 (TRACEY *et al*., 1971) contains biostratigraphic reports on Cenzoic sequences encountered at all sites, by means of planktonic foraminifera (BECKMANN, 1971), radiolaria (MOORE, 1971), coccoliths (BUKRY, 1971), and nannofossils (HAQ and LIPPS, 1971). For Site 71, BECKMANN (1971) applied the zonal scheme of BOLLI (1957a,b,1966) although communicated these zones via the letter and number symbols of BLOW (1969).

The stratigraphical distribution of all planktonic foraminifera encountered at Site 71, together with an indication of the index species and position of zonal boundaries, is given in fig. 20.

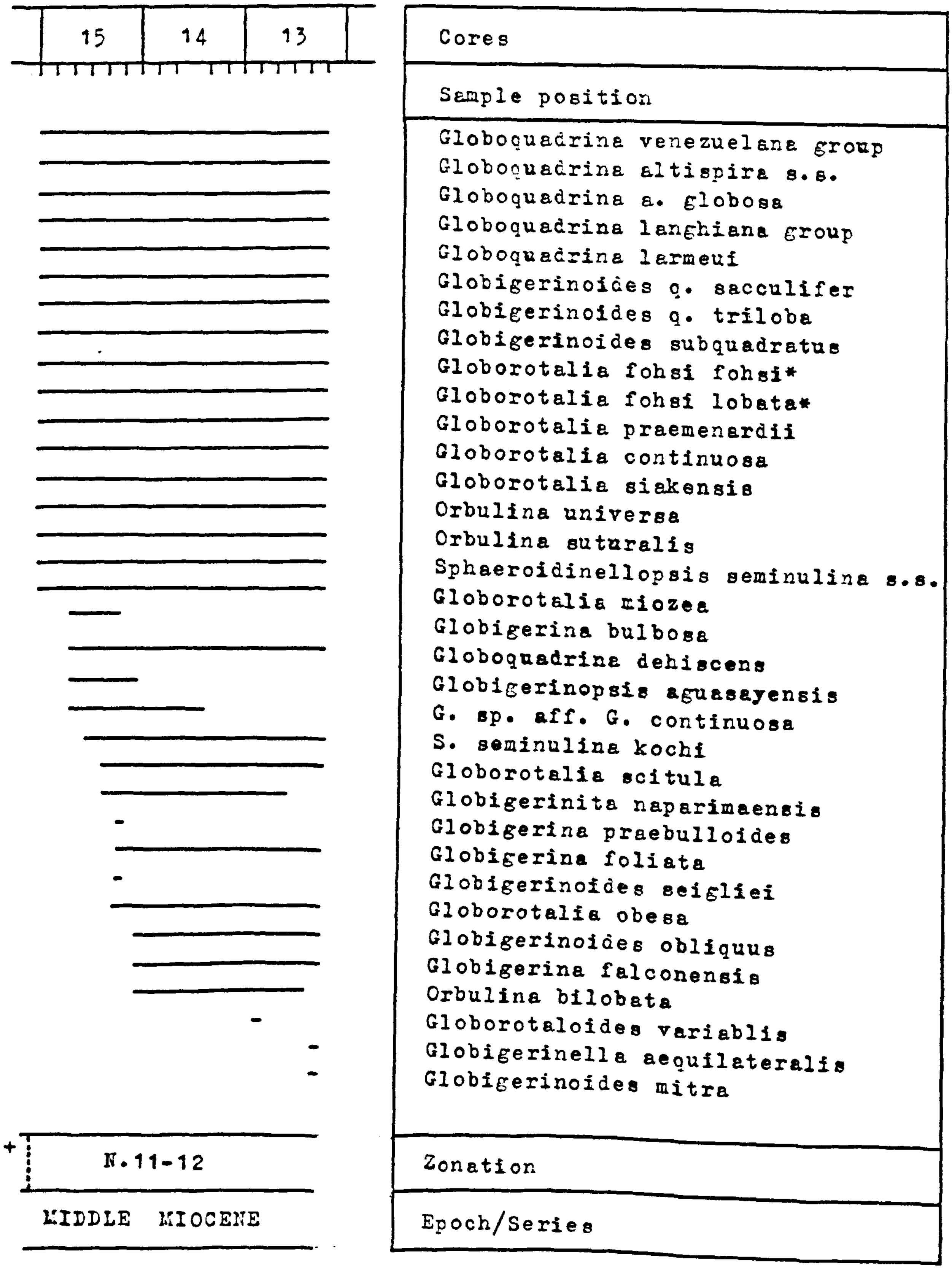


Fig. 20 Stratigraphical ranges of all planktonic foraminiferal taxa within the studied sequence at Site 71 (* = index taxon; + = boundary according to Beckmann,1971)

According to BECKMANN (1971), the sequence from cores 15 to 13, encompassing approximately 27 metres of sediment, includes a continuous sequence from the base of Zone N.11 to within Zone N. 12 of the Middle Miocene.

BECKMANN (1971) defined the base of Zone N.11 (15 cc) as the horizon containing the first appearance of *Globorotalia fohsi praefohsi* (herein included under *G. fohsi fohsi*) and the base of Zone N.12 (13- 5) as the horizon containing the first appearance of *G. fohsi lobata.*

In the present study, the important zonal forms, *G. fohsi fohsi* and *G. fohsi lobata,* are believed to range throughout the studied sequence from cores 15 to 13, thus placing the interval within Zone N.11-12 of BLOW (1969). The discrepancy betwenn the lower range of *G.f. lobata* as given by BECKMANN (1971) and herein probably reflects inconsistencies in the subspecific concept of the taxon, particularly concerning the character of 'distinctly lobate chambers' (see Appendix I).

9. RADIOLARIA: SITE 71

For Site 71, MOORE (1971) applied the radiolarian zonal scheme of RIEDEL and SANFILIPPO (1970) for the Middle Eocene to Recent, although offered a modified scheme for the Oligocene to Early Miocene sequence.

The stratigraphical distribution of important radiolaria encountered at Site 71, together with an indication of the index species and position of zonal boundaries, is given in fig. 21.

According to MOORE (1971), the sequence from cores 15 to 13 includes parts of the *Dorcadospyris alata* and *Cannartus laticonus* Zones. Following RIEDEL and SANFILIPPO (1970), MOORE (1971) defined the base of the *Cannartus laticonus* Zone at the level of extinction of *D. alata.* RIEDEL and SANFILIPPO (1971) since abandoned

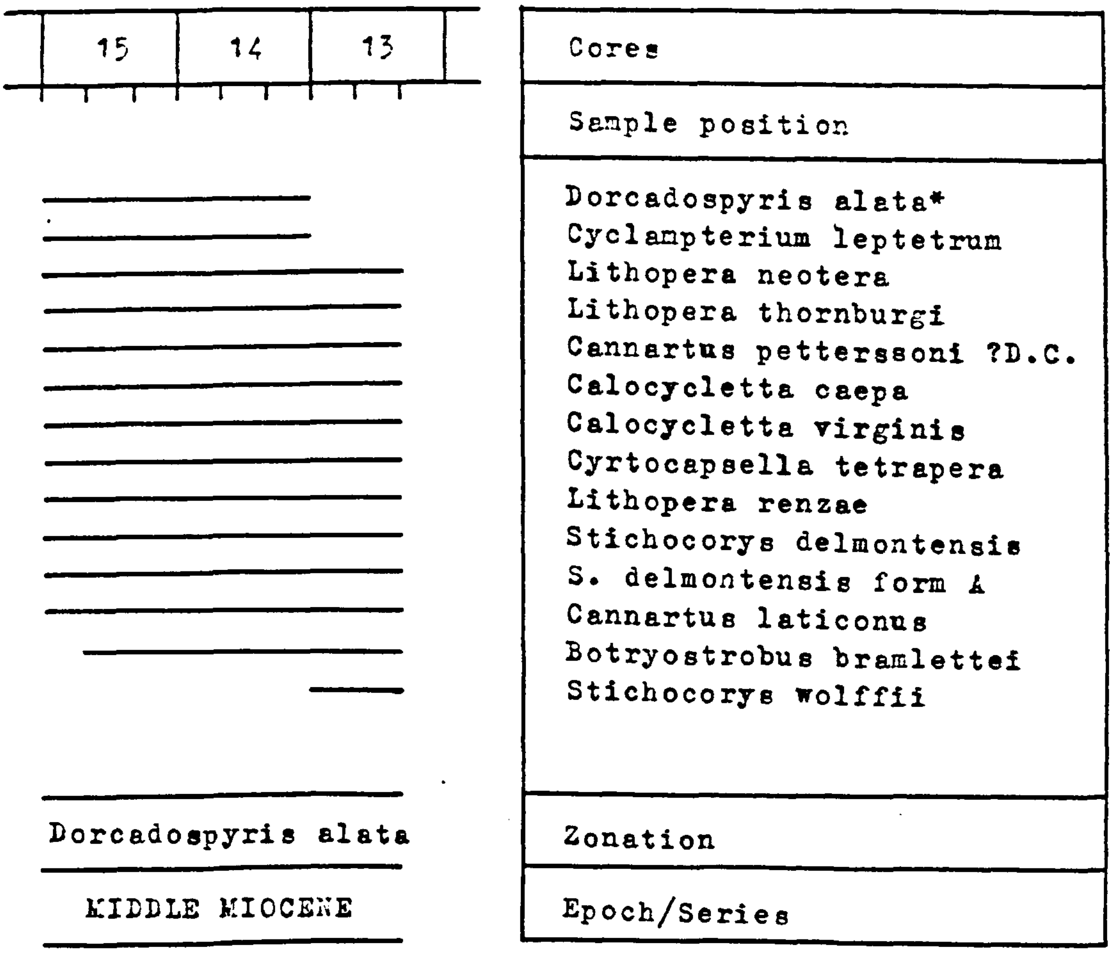


Fig. 21 Stratigraphical ranges of selected radiolarian taxa within the studied sequence at Site 71
(* = index taxon ; ?D.C. = probable downhole contaminant)

the use of the *Cannartus laticonus* Zone and extended the upper limit of the *Dorcadospyris alata* Zone, so that those parts of the studied sequence which MOORE (1971) referred to the former zone, would now be included within the latter sensu RIEDEL and SANFILIPPO (1971, 1978).

In the present study, the presence of *D. alata, Cyclampterium leptetrum* and *Calocycletta virginis* dates the interval as no younger than the *Dorcadospyris alata* Zone. However, individuals referrable to *Cannartus?pettersoni*, the index form of a younger zone, were encountered in five samples and represent a stratigraphic enigma. MOORE (1971) does not tabulate such forms within the studied sequence. However, TRACEY et al. (1971) refer to contamination (downworking) of radiolaria at Site 71, 15-5. The presence of *C.?petterssoni* in samples from cores 15 and 13 is herein believed to reflect this downhole contamination.

A correlation of the studied sequence at Site 71 with that at Site 289 using both planktonic foraminifera and radiolaria is attempted in the following Chapter.

CHAPTER V

QUANTITATIVE ASPECTS OF PLANKTONIC FORAMINIFERA AND RADIOLARIA DISTRIBUTION AT DSDP SITES 289 and 71

1. INTRODUCTION

The following is a description of distributions of taxa in planktonic foraminiferal and radiolarian assemblages at DSDP Sites 289 and 71. The aim is to present the basic data in a manner suitable for two main purposes.

a. to help formulate palaeoenvironmental conclusions regarding the stratigraphical sequences.

b. to help assess the palaeoecological preferences of individual taxa and entire assemblages.

The data is presented in two forms: the relative abundance distribution of individual taxa, and diversity and similarity indices of entire planktonic foraminiferal and radiolarian assemblages.

i) Relative Abundance

Absolute numbers of individuals per sample were not considered in this study because of variation in the original sample size (in some cases by a factor of two). The distribution of all taxa at Sites 289 and 71 is considered briefly in the Taxonomy section of Appendix I and the account in this chapter expands on these summaries for the numerically important forms.

The relative abundance of individual taxa can be regarded as an index of the species success in a particular environment and further, can be used to identify the 'optimum environment' for a species (BÉ, 1977). Thus changes in relative abundance with time may indicate environmental and ecological changes in the original habitat.

Changes in the palaeoenvironment may also be reflected in the nature of entire planktonic foraminiferal and radiolarian assemblages in terms of diversity and similarity indices.

ii) Diversity Indices

The diversity of an assemblage can be expressed by the number of species present (simple diversity or species density) and by the relative abundance of each (compound diversity or species equitability or dominance) (BUZAS, 1979).

Diversity trends in planktonic foraminifera have shown great promise for palaeoenvironmental (palaeotemperature; palaeoceanography) studies following the work of JENKINS (1968) and WILLIAMS and JOHNSON (1975) under the assumption that high species diversity and species equitability reflects high surface temperatures and low diversity and species dominance reflects low surface temperatures (BE, 1977).

However, despite these relationships, CIFELLI (1969) indicates that many aspects of the distribution and relative abundance in planktonic foraminifera probably have no direct relationship with temperature. In a study of diversity in planktonic foraminifera from deep sea sediments in the south Pacific Ocean, BERGER and PARKER (1970) found only limited correspondance between diversity and the temperature of overlying surface waters, although the authors emphasise the strong modifying influence of dissolution in the samples. CASEY (1977) has demonstrated a latitudinal diversity gradient in modern radiolarian assemblages of the Pacific Ocean. This relationship has not been extrapolated in fossil assemblages although it may in theory, be used as a model for palaeoenvironmental studies following the same principles that favour the use of planktonic foraminifera.

Simple diversity values for planktonic foraminiferal assemblages of the present study relate only to those species encountered in each subsample of 500 individuals, inconsistencies due to variable sample sizes being thus eliminated.

In the case of radiolarian assemblages, the simple diversity index is slightly more sophisticated because of variation in absolute numbers of individuals both per sample and per subsample (i.e. in three fields of view at x60 mag.). The Fisher α Index, which considers both the number of individuals and number of taxa (MURRAY 1973), was employed to overcome the problems associated with comparing simple diversity values in subsamples representing differing population sizes. Values of α can be read from a graph which plots the number of taxa on a linear scale against the number of individuals on a logarithmic scale. The index has been used by MURRAY (1973) to discriminate benthonic foraminiferal assemblages from different environments.

As a measure of diversity, the simple diversity index does not take account of differing abundances among the various species present in an assemblage. BUZAS (1979) recommends the use of several indices for a complete comparison of assemblages in terms of the number of species present and the distribution of their proportions. In the present study, a simple diversity and a compound diversity (Shannon-Wiener) Index is used.

The Shannon-Wiener Index incorporates both the components of species number and the percentage abundance of each and is given by the equation:

$$H(s) = -\sum_{i=1}^{s} pi \log pi$$

Where S = number of species and pi = the proportion of the i'th species in the total number of species (SANDERS, 1968). The Shannon-Wiener Index has been increasingly used as a diversity index of fossil and living populations (LYNTS, 1971; GIBSON and BUZAS, 1973; WILLIAMS and JOHNSON, 1975). Using the index, samples with the same number of species may have different diversity values if the relative abundances of the species vary. High diversity values are obtained where the individuals are more evenly distributed among the species (species equitability) and low diversity values are obtained where the individuals are concentrated in a few species (species dominance) (WILLIAMS and JOHNSON, 1975). McMILLEN and CASEY (1978) suggest the index be used to identify niche diversity in planktonic ecosystems.

iii) Similarity Indices

The use of a similarity index to compare a stratigraphical sequence of microfossil assemblages can offer a useful tool for ascertaining the palaeoenvironmental significance of the basic data. By comparing all samples to the oldest sample, the index can be used to indicate the 'rate of change' in assemblages within a particular stratigraphical sequence and thus outline intervals of quantitative taxonomic stability (?stable environment) and change (?changing environment).

In the present study, the degree of similarity between the oldest sample and all others was computed using the method outlined by MURRAY (1973). Using the percentage abundance of each taxon in a sample as the basic data, the similarity index reflects the percentage occurrence of each species common to each pair of samples. A similarity index of 100% results from a pair of samples in which all species occur in both samples in the same relative abundance.

The nature of fossil planktonic foraminiferal and radiolarian assemblages, in terms of individual species abundance and overall diversity, is mainly a reflection of both original environmental conditions and post-mortal dissolution. In order to relate assemblages to original environments it is first necessary to assess the role of dissolution. The factor is addressed in this chapter following the consideration of quantitative distributions in each fossil group at each site.

2. DSDP SITE 289

i) Planktonic Foraminifera

a. General Features

The relative abundance distribution of the fifty seven species and subspecies of planktonic foraminifera encountered at Site 289 is given in fig.22. Several general distributional features are apparent from this composite histogram:

a. Taxa which tend to dominate the assemblages, such as species/subspecies of *Globoquadrina* and *Globigerinoides* also range throughout the studied sequence, although three other numerically important forms, *Globorotalia cultrata* group, *G. siakensis* and *G. (Fohsella) spp.* are stratigraphically restricted to certain intervals.

b. Variations in relative abundance may be gradual (continuous) e.g. *G. cultrata* group; abrupt (discontinuous), e.g. *G. siakensis*; or a combination of both, e.g. *Globoquadrina venezuelana*.

c. Many taxa, while never found in substantial numbers in any sample, nevertheless are constantly encountered in almost every sample within their stratigraphical range e.g. *Orbulina universa*.

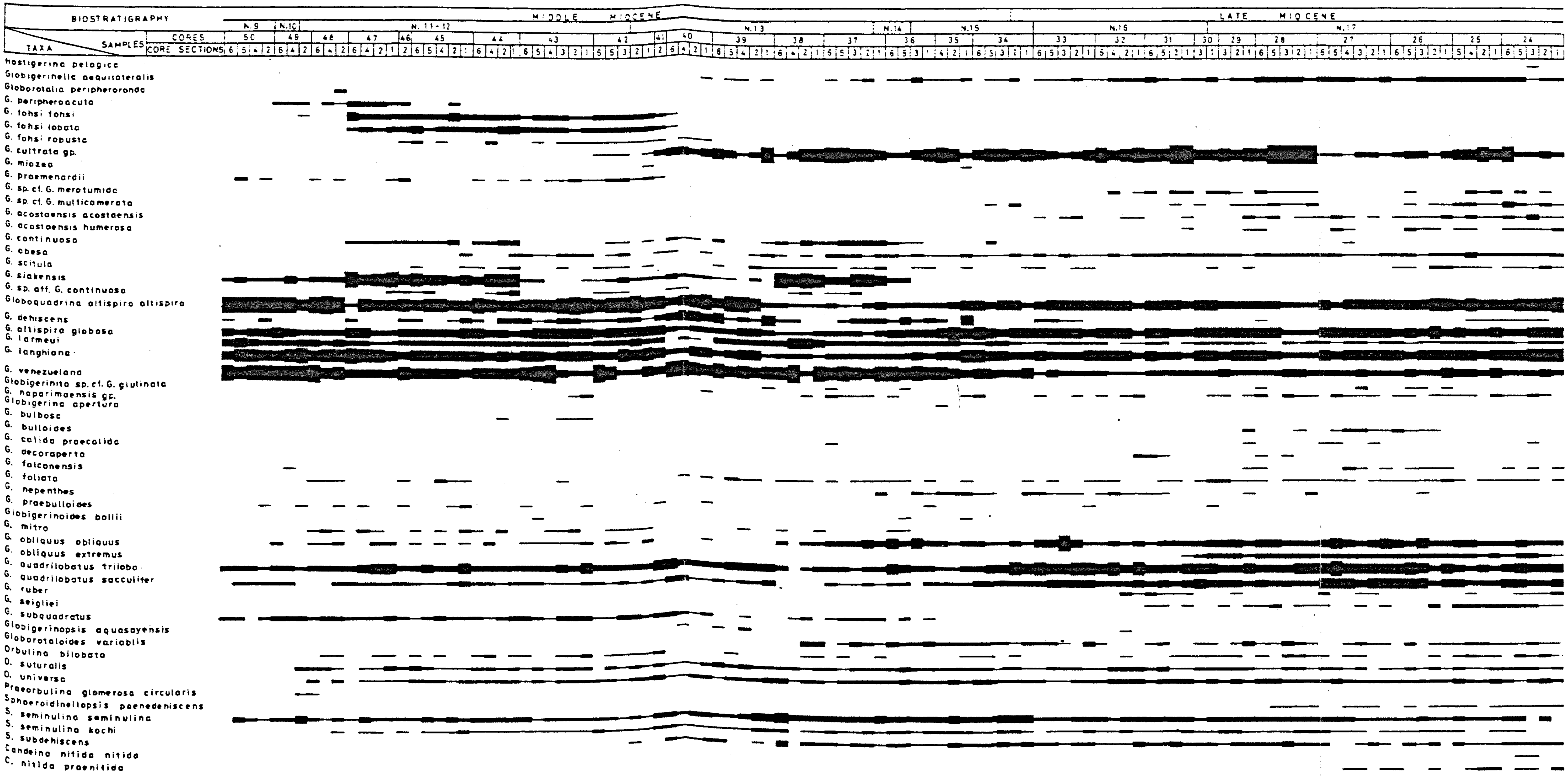


Fig. 22 Percentage distribution of planktonic foraminiferal taxa, DSDP Site 289

Key: present 0·2-1·0 >1-5 >5-10 >10-20 >20-30 >30-40 >40

b) Distribution of Individual Taxa

Outlined below is a general description of the relative distribution of the more numerically important taxa at Site 289. Terms of relative abundance (rare, few, etc.) relate to similar values as used in the taxonomy section (see Introduction, Appendix I).

The distribution of individual taxa has been plotted seperately to give a more detailed account than that offered in fig.22.

Globoquadrina altispira s.s. (fig.23) forms an important element of the foraminiferal assemblages in the Middle Miocene (N.9 to within N.13) where values generally vary from very common to very abundant. A rapid drop in abundance within Zone N.13 (39-1) from abundant below to few above is followed by a gradual increase in abundance through the late Middle and Late Miocene.

G. altispira globosa (fig.23) shows a similar distribution in many respects to that of *G. altispira* s.s. with generally high values of common to very common in the early Middle Miocene, low values within Zone N.13 followed by similarly high values throughout the remainder of the Middle to Late Miocene. Superimposed on this trend is a continual and apparently regular sequence of shorter cycles of abundance.

G. dehiscens is generally very rare, few or absent through most of the sequence. The interval from the base of Zone N.13 to within N.15 of the late Middle Miocene is however, marked by discrete horizons where abundance is very common (fig.24).

The relative distribution of *G. langhiana* is generally quite stable through most of the sequence and tends to vary from common to very common (fig.23). This pattern is disrupted within the late Middle Miocene (within N.13 to within N.15) where numbers fall to few or rare.

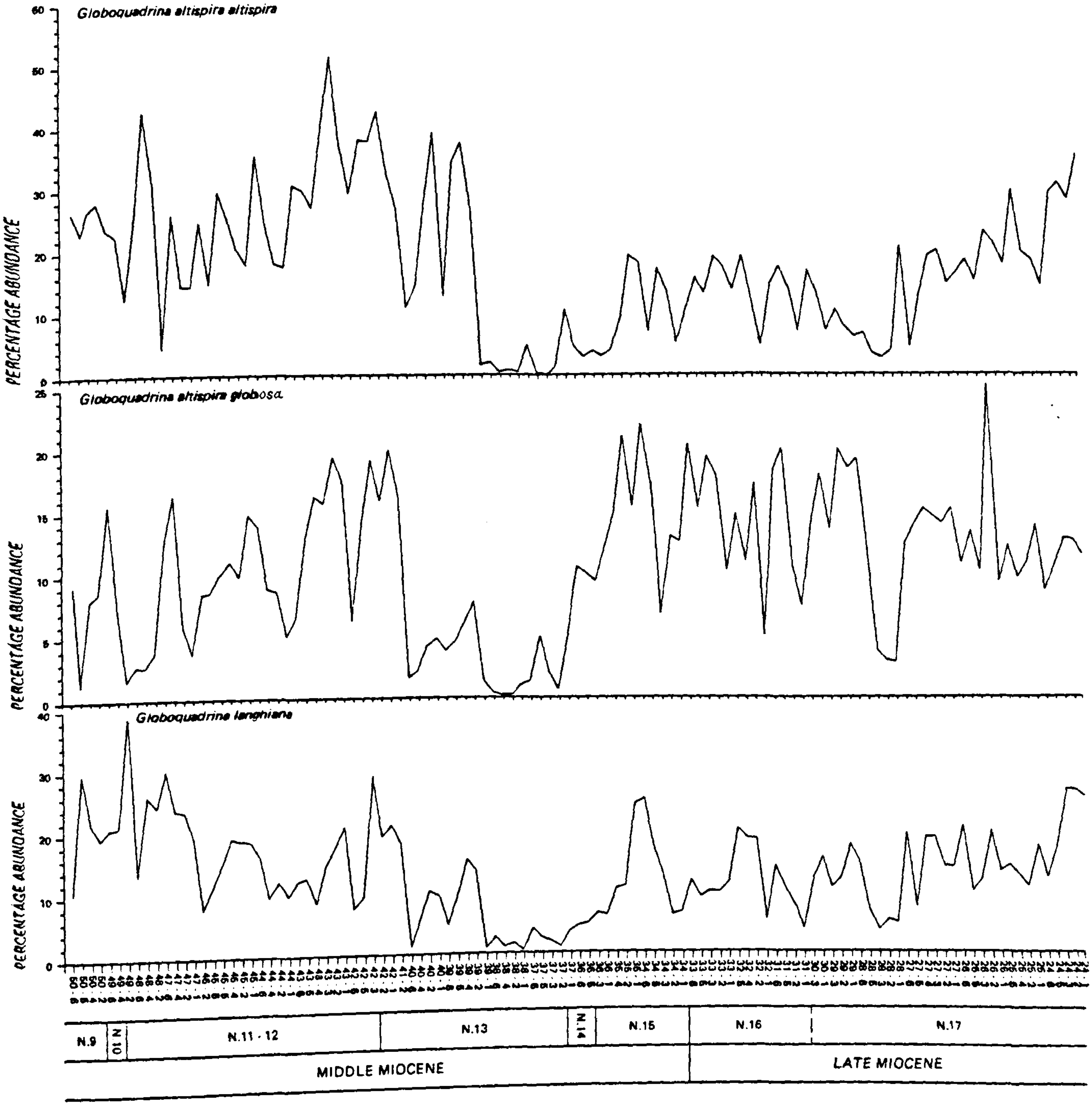


FIGURE 23 RELATIVE DISTRIBUTION OF PLANKTONIC FORAMINIFERAL TAXA, DSDP SITE 289

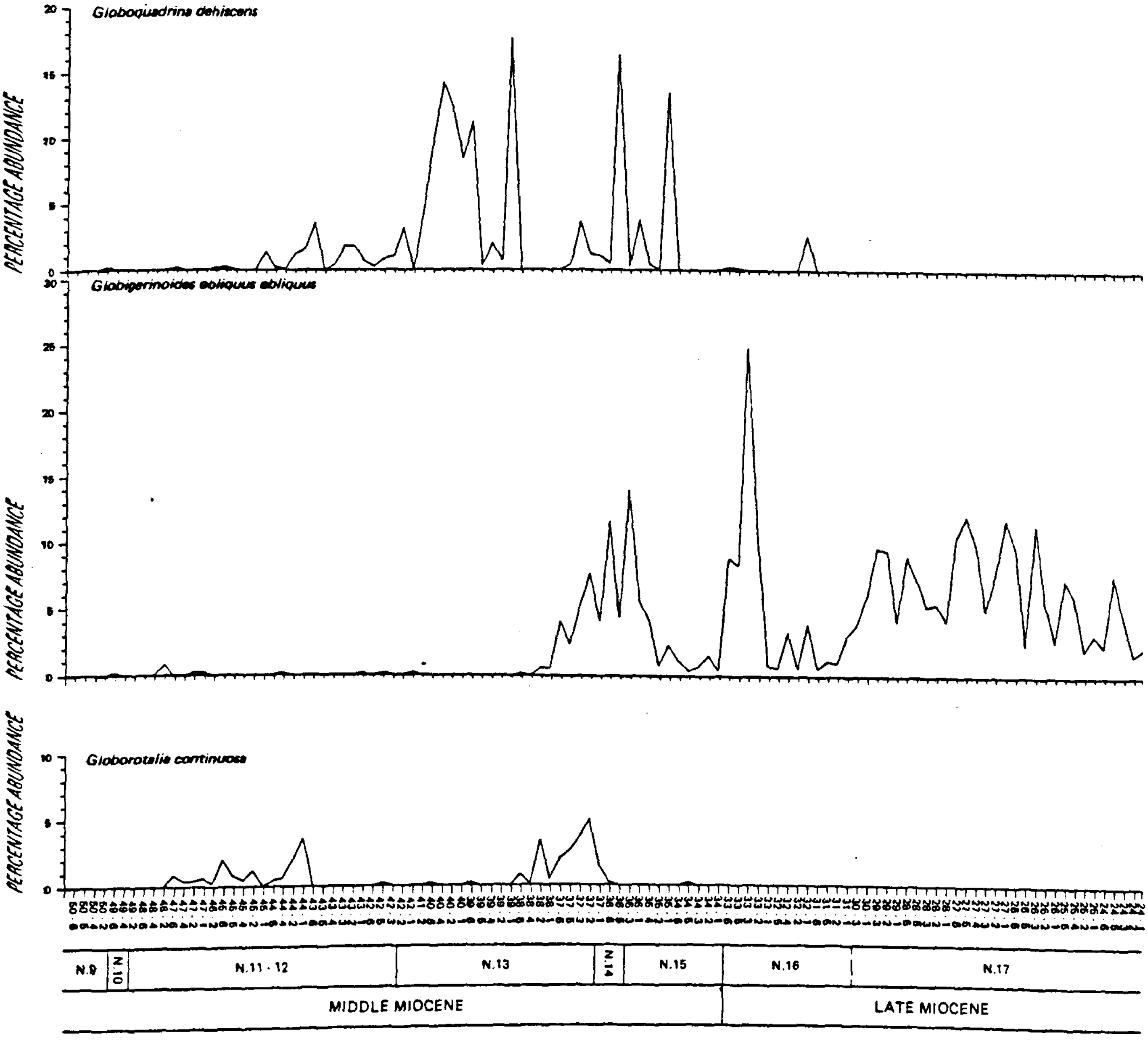


FIGURE 24 RELATIVE DISTRIBUTION OF PLANKTONIC FORAMINIFERAL TAXA, DSDP SITE 289

The distribution pattern of *G. larmeui* (fig.25) can be conveniently divided into two intervals by the Middle/Late Miocene boundary. Throughout the Middle Miocene, abundance varies from rare to common while in the Late Miocene, values are consistently lower at very rare, rare or absent. An anomalous peak of very common abundance occurs in three consecutive samples within Zone N.13 (38-4, 38-2, 38-1).

G. venezuelana displays a similar trend to *G. larmeui* (fig.25)with generally high values, ranging from few to very abundant, throughout the Middle Miocene and low values, generally ranging from rare to common, though occasionally very common, throughout the Late Miocene sequence. A distributional characteristic of this species involves rapid and large variations in abundance over short stratigraphical horizons, especially in the Middle Miocene.

The relative distribution of *Globigerinoides quadrilobatus triloba* (fig.26) indicates low values throughout most of the Middle Miocene, from rare to very common, with higher values in the Late Miocene, from common to abundant. A general trend of increasing abundance up through the sequence is accompanied by continual shorter cycles of high and low values.

G. quadrilobatus sacculifer shows a relative distribution pattern which is very similar to that of *G. quadrilobatus triloba* (fig.26). The Middle Miocene is characterised by constantly low values between very rare and few or absent, while in the Late Miocene abundance increases rapidly to a peak of very common within Zone N.17 (27-5).

The distribution of *G. obliquus* s.s. can be divided into a lower interval of low abundance and an upper interval of high abundance (fig.24). The early Middle Miocene (N.9 to within N.13) is characterised by infrequent occurrences in which abundance is very rare, rare or absent.

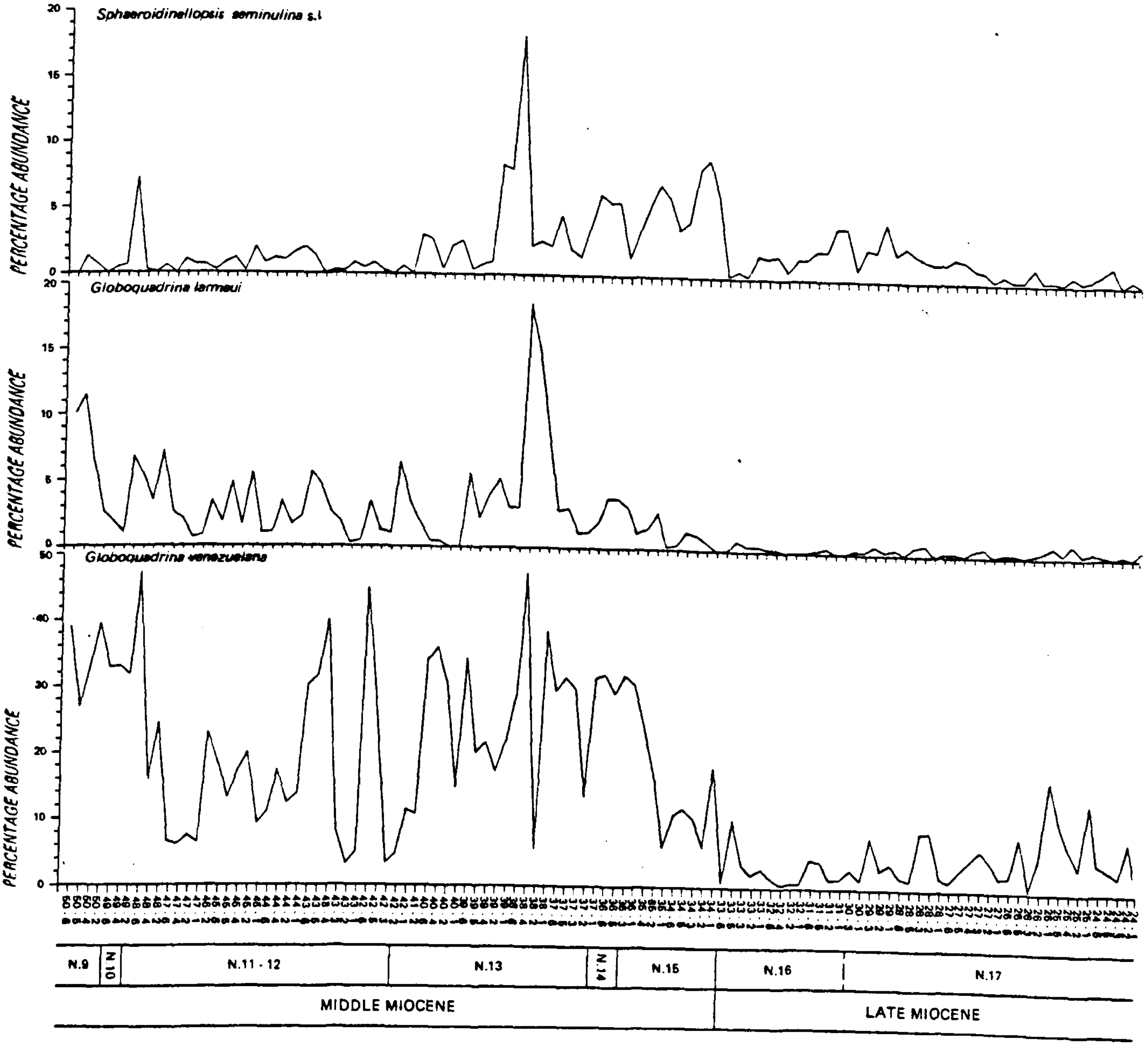


FIGURE 25 RELATIVE DISTRIBUTION OF PLANKTONIC FORAMINIFERAL TAXA, DSDP SITE 289

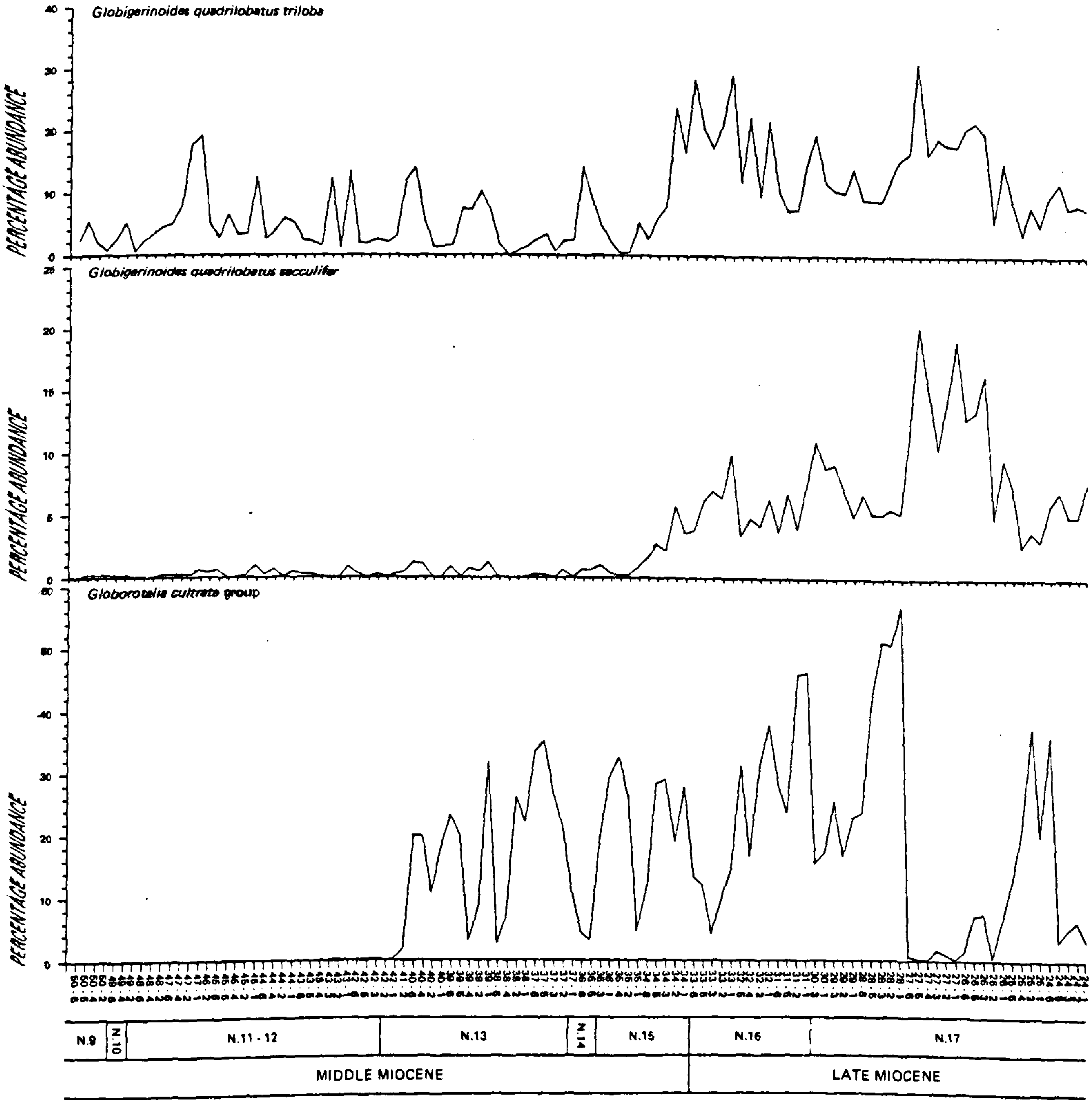


FIGURE 26 RELATIVE DISTRIBUTION OF PLANKTONIC FORAMINIFERAL TAXA, DSDP SITE 289

In contrast, the late Middle through Late Miocene sequence displays a discrete trimodal pattern in which values range from rare to abundant.

In terms of species dominance in particular samples, Globorotalia (G.) cultrata group is the most important taxon at Site 289. The distribution pattern (fig.26) is characterised by a steady increase in abundance from the initial appearance level within the Middle Miocene (late N.11-12) which culminates in peak abundance of over 50% in sample 28-1 in the Late Miocene (N.17). This peak is followed by an immediate abrupt decline to low values of very rare to rare which marks one of the most distinct horizons in the studied sequence. Values gradually increase after this event to produce a discrete peak near the top of the sequence (26-1 to 24-6). Superimposed on this simple pattern are important and discrete cycles of abundance which appear to have near constant wavelength and amptitude, in which relative values vary from rare to very abundant. The G. (G.) cultrata group is unique with respect to the consistent development of this distributional feature.

The distribution of G. (F.) fohsi s.s. (fig.27) is roughly unimodal and generally restricted to Zone N.11-12 of the Middle Miocene. The subspecies is characterised by a comparatively large influx of individuals at sample 47-6, soon after the initial appearance datum, in which abundance is very common. This peak is followed by a gradual overall decline in numbers through the remainder of its stratigraphic range.

G. (F.) fohsi lobata (fig.27) exhibits a more trimodal distribution throughout its range within the Middle Miocene (N.11-12 to within N.13). The modes of G. (F.) fohsi lobata occur stratigraphically higher than the mode of its immediate ancestor, G. (F.) fohsi s.s. (see Appendix 1) and appears to reflect the phylogenetic relationship between

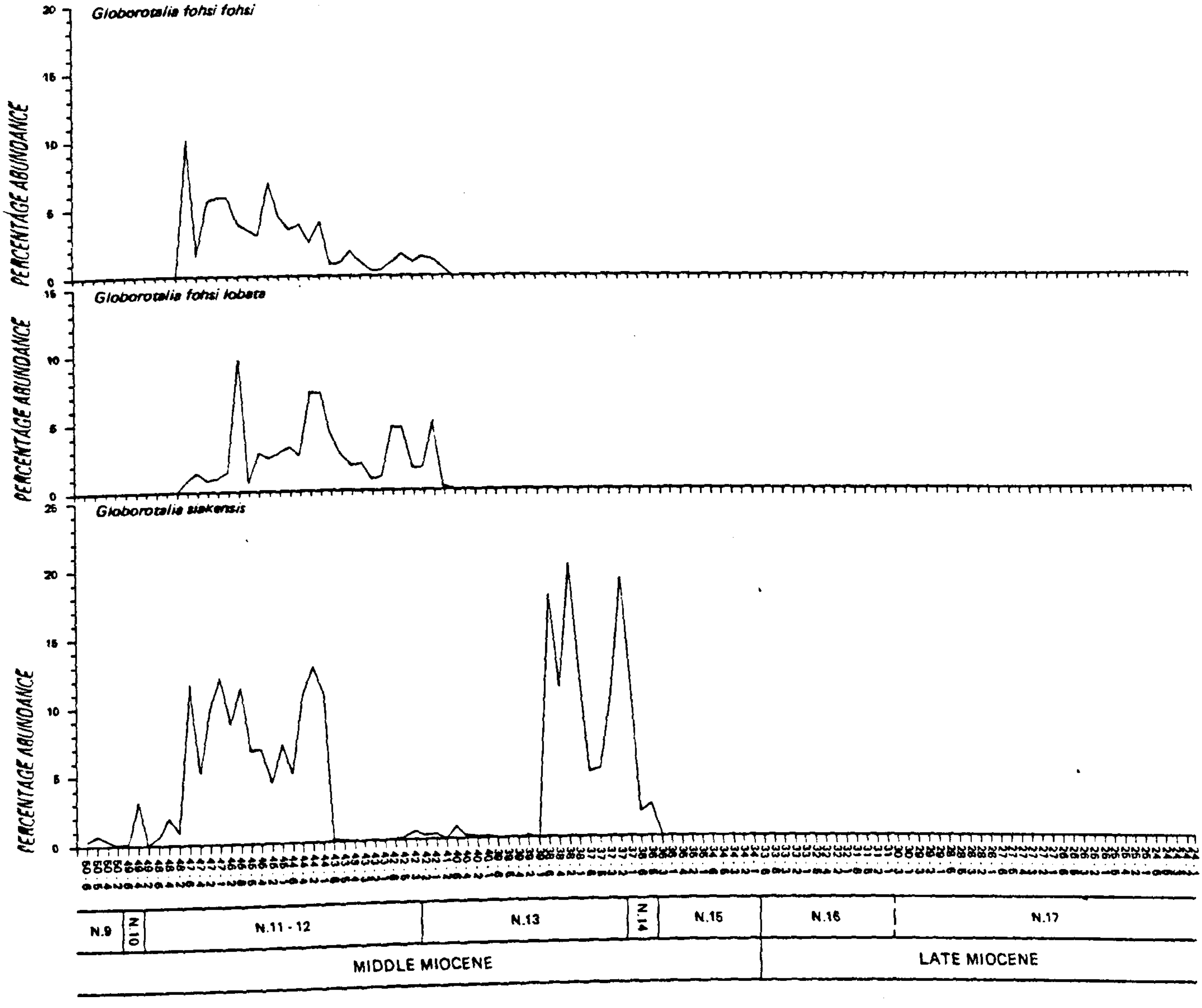


FIGURE 27 RELATIVE DISTRIBUTION OF PLANKTONIC FORAMINIFERAL TAXA, DSDP SITE 289

the two subspecies.

The relative distribution pattern of G. (T.) siakensis (fig.27) is particularly remarkable. The trend consists of two discrete abundance peaks within Zone N.11-12 (47-6 to 44-1) and Zone N.13 to N.14 (38-6 to 36-5) which are separated by an interval, which, by comparison, is virtually barren of the species. At the abundance peaks, which are well defined, values range from very common to abundant. In contrast, the intervening and earlier intervals are characterised by low values of very rare to few or absent. The species becomes extinct following the rapid termination of the latter peak.

G. (T.) continuosa displays a very similar pattern of relative distribution to that of G. (T.) siakensis (fig.24), although abundance is never as high. Two small and well defined peaks, within similar stratigraphic intervals as those of G. (T.) siakensis, in which values vary from very rare to few, are seperated by three intervals in which abundance is very rare or absent.

The distribution of Sphaeroidinellopsis seminulina s.l. (incl. subspecies seminulina and kochi) is given in fig.25. Values are relatively constant through most of the sequence and generally range from very rare to few. However, within the late Middle Miocene, within Zones N.13 to N.15 (39-4 to 34-1) an interval of increased abundance can be recognised, in which values range from few to very common.

A comparison of the various distributional histograms for individual taxa reveals normal correlations between several pairs of taxa, although these relationships have not been quantified by statistical means.

The close similarity in the distributional pattern of G. altispira s.s. and G. altispira globosa, G. quadrilobatus triloba and G.

quadrilobatus sacculifer, *G. venezuelana* and *G. larmeui*, and *G. siakensis* and *G. continuosa* has already been mentioned. Normal correlation in the distribution of these pairs of taxa can be possibly explained by close phylogenetic relationships and/or high morphological similarity which tends to intergrade taxonomic boundaries and create difficulties in objective discrimination (see Appendix I).

The following pairs of taxa also show close similarities in their quantitative distributional patterns: *G. langhiana* and *G. altispira globosa* (fig. 23) and *G. langhiana* and *G. altispira* s.s. (fig. 23). In addition, several pairs of taxa, including *G. siakensis* and *G. fohsi fohsi* (fig. 27), *G. siakensis* and *G. fohsi lobata* (fig. 27), *G. obliquus* s.s. and *G. quadrilobatus sacculifer* (figs. 24, 26) and *G. obliquus* s.s. and *G. quadrilobatus triloba* (figs. 24, 26) show normal correlations in only part of the studied sequence because one of the pair has a restricted stratigraphical range.

Although the distributional patterns do not generally coincide, anomalous peak values in *G. larmeui* and *S. seminulina* s.l. occur at the same stratigraphical horizon (fig. 25).

In these latter examples, the taxonomic pairs do not include phylogenetically related species or forms of close morphological similarity and the relationships are considered to reflect palaeoenvironmental (palaeoecological) processes, which will be considered further in Chapter VII.

Two pairs of taxa, *G. cultrata* group and *G. quadrilobatus triloba* and *G. cultrata* group and *G. quadrilobatus sacculifer* (fig. 26) show a distinct inverse relationship in their distribution patterns which are similarly thought to represent palaeoenvironmental factors (see Chapter VII).

c) Diversity and Similarity Indices

Palaeoenvironmental reconstruction in the present study is primarily based on the distribution features of individual taxa, although this is partly supported by taxonomic variation as expressed in the whole assemblages.

Changes in the quantitative taxonomic nature of the planktonic foraminiferal assemblages are presented by means of diversity and similarity indices.

The number of species, or species density for each sample at Site 289 is given in fig.28. The number of taxa per sample varies from eight to twenty one and although the pattern exhibits rapid, large scale fluctuations, with several one point peaks and troughs, certain consistent trends, to be discussed shortly, are evident.

The Shannon-Wiener diversity Index was computed from the relative abundance data comprising 500 individuals of planktonic foraminifera per sample (fig.28). Values vary from 1.39 to 2.38 and several well defined peaks and troughs are apparent.

A comparison of both diversity indices used at Site 289 for planktonic foraminiferal assemblages reveals general aggreement in the trends (fig.28).

Low diversity values are apparent in core 50 to 48 (within Zone N.9 to N.11-12) where the assemblages are dominated by Globoquadrina spp. with very low percentages of Globigerinoides spp. and Globorotalia spp.(fig.22).

From cores 47 to 44 (within Zone N.11-12), diversity values are generally high and form a well defined peak. The development towards species equitability and higher diversity is partly reflected by increased abundance in G. quadrilobatus triloba, G. (Fohsella) spp. and G.

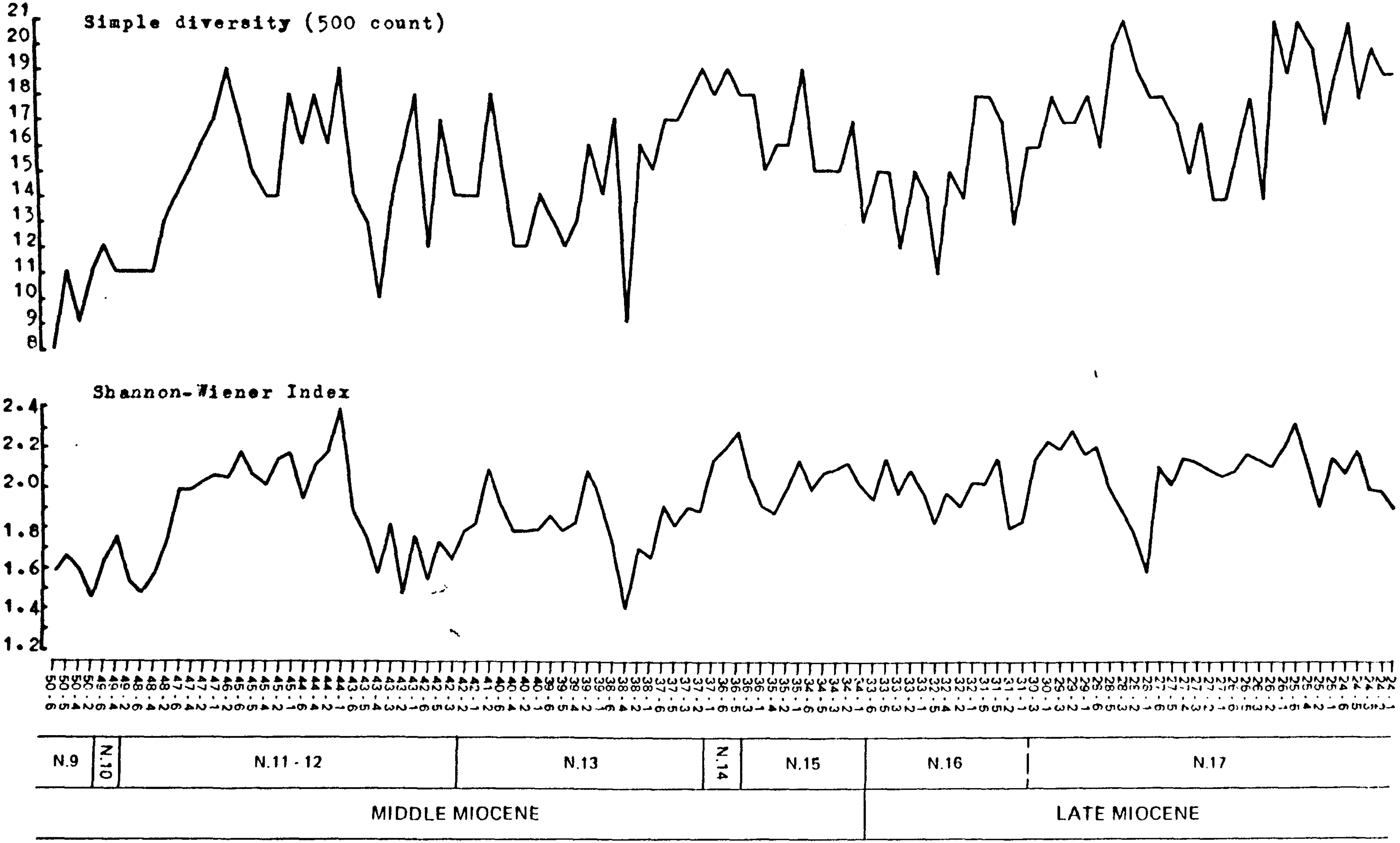


Fig. 28 Diversity indices of planktonic foraminifera at Site 289

siakensis, and speciation in the Fohsella group (fig.22). A decrease in the intensity of dissolution is also believed to have been responsible for higher diversity values however (see Chapter IV, p.85 and this Chapter, p.115).

Diversity values from core 43 to within core 38 (within Zones N.11-12 to N.13) are generally low though they increase in core 41. Globoquadrina spp. dominate the assemblages while G. siakensis undergoes a rapid and large decline in abundance. G. (Fohsella) spp. become extinct in this interval (fig.22).

Within cores 38 and 36 (within Zones N.13 to N.15) diversity values reach a peak. Increased species equitability reflects increased abundance of G. siakensis and G. cultrata (fig.22).

Following a drop in values within core 35, diversity gradually increases to the top of the studied sequence (within Zone N.15 to N.17). This interval is characterised by an overall increase in the relative abundance of Globigerinoides spp. and G. cultrata (fig.22) and increased speciation (see Chapter VII, p.184).

Major departures between the trends displayed by simple and H(S) diversity values occur in core 28 (within Zone N.17) where simple diversity increases while compound diversity falls and in core 27, where simple diversity falls while compound diversity increases. BERGER and PARKER (1970) similarly illustrated only limited correlation between simple and compound diversity in planktonic foraminiferal assemblages.

Fig.29 illustrates the similarity of all samples to the sample at the base of the studied sequence (50-6). The pattern is highly variable although a general trend of decreasing similarity to sample 50-6 through the sequence is evident.

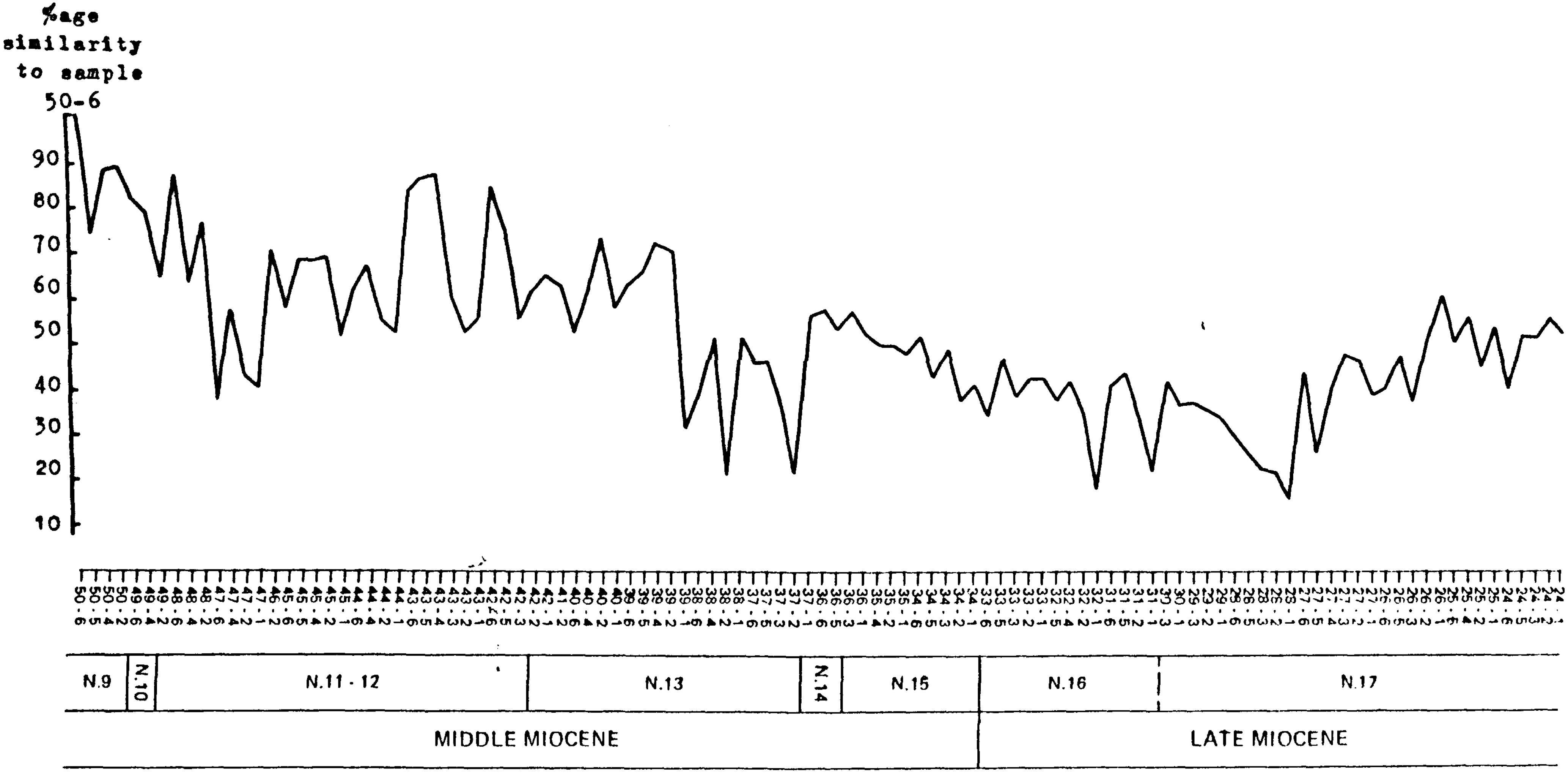


Fig. 29 Similarity Index (Rate of Change) - planktonic foraminifera, Site 289

Intervals characterised by sharp changes, such as those between cores 48 and 47 and within core 39 and 38 indicate changes in the relative abundance of planktonic foraminiferal taxa within the assemblages. Intervals characterised by near horizontal profiles, such as those between cores 47 and 39 indicate taxonomic stability.

The use of the similarity index serves to unambiguously define the stratigraphical horizons where greatest change occurs, although in many instances this is self evident in fig.22. It is of further use however in the recognition of subtle cyclic features which may indicate recurrent palaeoenvironmental or geological events, e.g. cores 36 and 27 to 24 which show anomalously high similarity to 50-6.

The palaeoenvironmental significance of variation in the diversity indices and the similarity (rate of change) index for planktonic foraminifera at Site 289 will be assessed in Chapter VII.

d) Dissolution of Planktonic Foraminifera

Factors causing dissolution in deep sea planktonic foraminiferal assemblages have previously been discussed (Chapter II). It is important to assess the extent to which such factors have altered an assemblage prior to a palaeoenvironmental and palaeoecological interpretation of the data.

According to BERGER (1979), deep sea assemblages exposed to dissolution processes are characterised by a preponderance of heavy, non-spinose forms, a lack of spinose forms (i.e. low diversity) and an increase in the proportion of benthonic foraminifera. Other evidence can be gained from the preservation of individual tests (KU and OBA, 1978). From a consideration of these factors, evidence of dissolution at Site 289 is apparent at two horizons, from cores 50 to 48 and in sample 31-6. The lack of fragile, solution susceptible forms within the former interval has already been noted (Chapter IV). Samples from cores 50 to 48 are also characterised by low diversity and domination by robust globoquadrinids. Throughout most of the studied sequence, the proportion of planktonic to benthonic foraminifera is almost always in excess of 98%, while in sample 50-4 the percentage of planktonics falls to 95%.

In sample 31-6, the majority of G. cultrata individuals have lost much of the intercameral test wall by some corrosive or erosive process (pl.II, fig.1d). In controlled experiments involving calcareous ooze, KU and OBA (1978) suggest a similar degree of attrition to G. cultrata tests is accompanied by up to 70% weight less of original $CaCo_3$. However, BERGER (1970) regards modern individuals of G. cultrata as possessing a high resistance to dissolution and it is curious that other taxa in sample 31-6, such as solution susceptible Globigerinoides spp. (BERGER, 1970) do not display dissolution features of even similar magnitude. Further, the sample is not characterised by an increase in the percentage of benthonic foraminifera.

It is possible that the G. cultrata individuals from 31-6 which show evidence of partial destruction were subject to a short lived, isolated dissolution event during a mono-specific population bloom.

The main interval believed to have undergone noticeable, consistent dissolution of planktonic foraminiferal tests at Site 289 is that incorporating cores 50 to 48. Elsewhere,only limited dissolution is assumed.

The cause of the dissolution at Site 289 is discussed in Chapter VII following a consideration of the palaeoenvironmental conclusions for the sequence.

ii. Radiolaria

a) General features

The relative distribution of all the radiolarian taxa encountered in all samples at Site 289 is given in fig.30a-d.In view of the limitations associated with the radiolarian assemblages from section samples at Site 289 (Chapter I, p.14-16), the following descriptive account will only consider taxa and assemblages from core catcher samples. Fig.31 illustrates the distribution of those taxa which constitute at least 3% of a radiolarian assemblage in at least one sample.

Several general distributional features, also evident in the planktonic foraminifera, are apparent from this composite histogram:

a. Taxa which tend to dominate the assemblages, such as Stichocorys delmontensis and Trisolenia spp., also range throughout the studied sequence.

b. Variations in the relative abundance of particular forms may be gradual (continuous) e.g. spyrids; abrupt (discontinuous) e.g. S. delmontensis; or a combination of both, e.g. Trisolenia spp..

c. Many taxa, while never present in large abundance in any one sample, are continually encountered in almost every sample within their range e.g. Carpocanistrum spp.

b) Distribution of Individual Taxa

Outlined below is a brief description of the relative distribution of the more numerically important taxa at Site 289. Terms of relative abundance (rare, few, etc.) relate to similar values as used in the taxonomy section (see Introduction, Appendix I).

The distribution of individual taxa has been plotted seperately to give a more detailed account than that offered in fig.31.

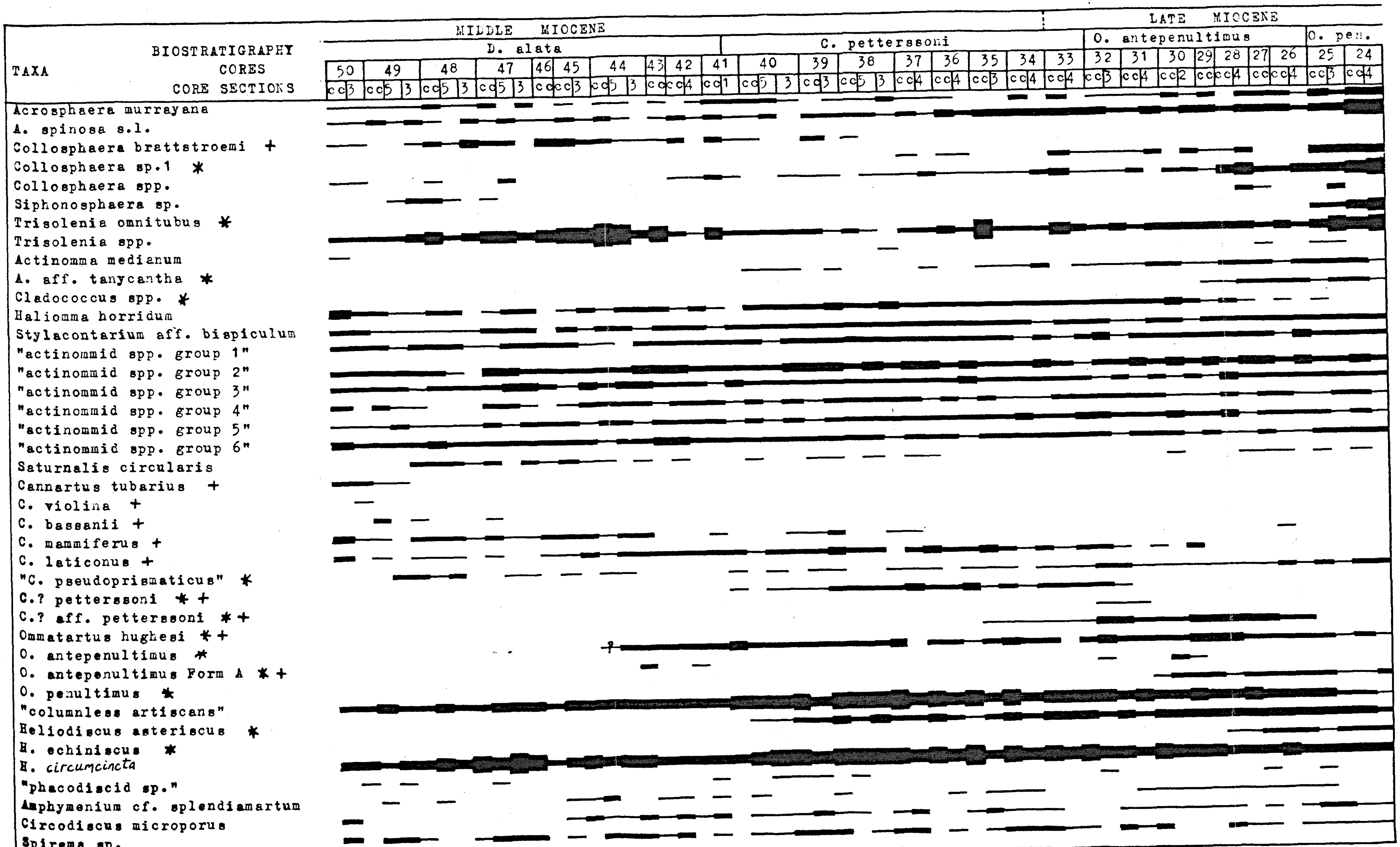


Fig. 30a Percentage abundance of all radiolarian taxa at DSDP Site 289 (continued on Figs. 30b-d)

Key:- present — 0.1-1.0 ▬ >1-5 ▬ >5-10 ▬ >10-20 ■ >20-30 ■ >30-40 ■ >40 ■

*+ appearance and extinction events used for the consideration of evolutionary trends at Site 289 (see Chapter VII)

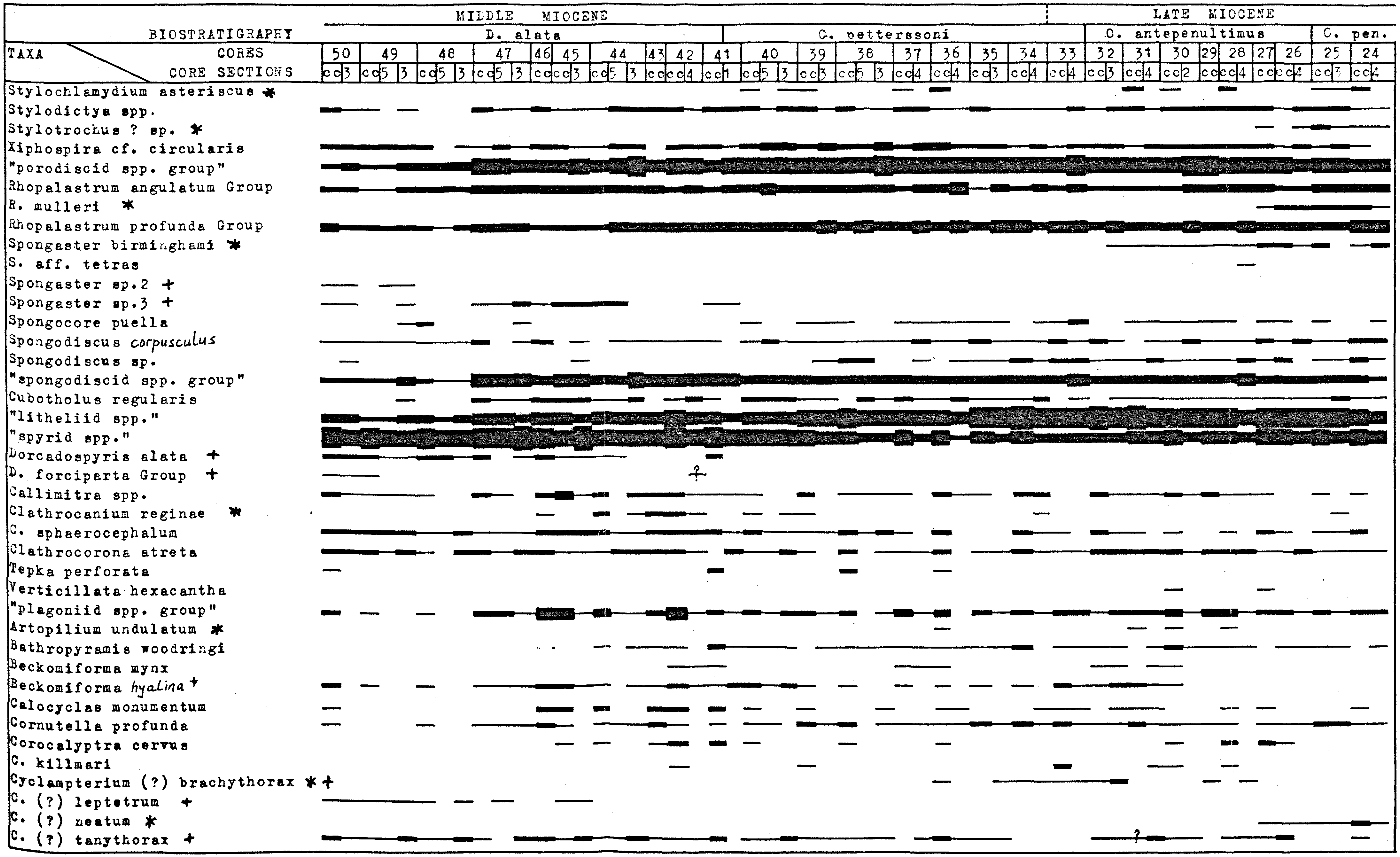


Fig. 30b Percentage abundance of all radiolarian taxa at DSDP Site 289 (continued on Figs. 30c - d)

Key:-	present	0.1-1.0	>1-5	>5-10	>10-20	>20-30	>30-40	>40-
	—	▬	■	■	■	■	■	■

* + evolutionary and extiction events used for the consideration of evolutionary trends at Site 289 (see Chapter VII)

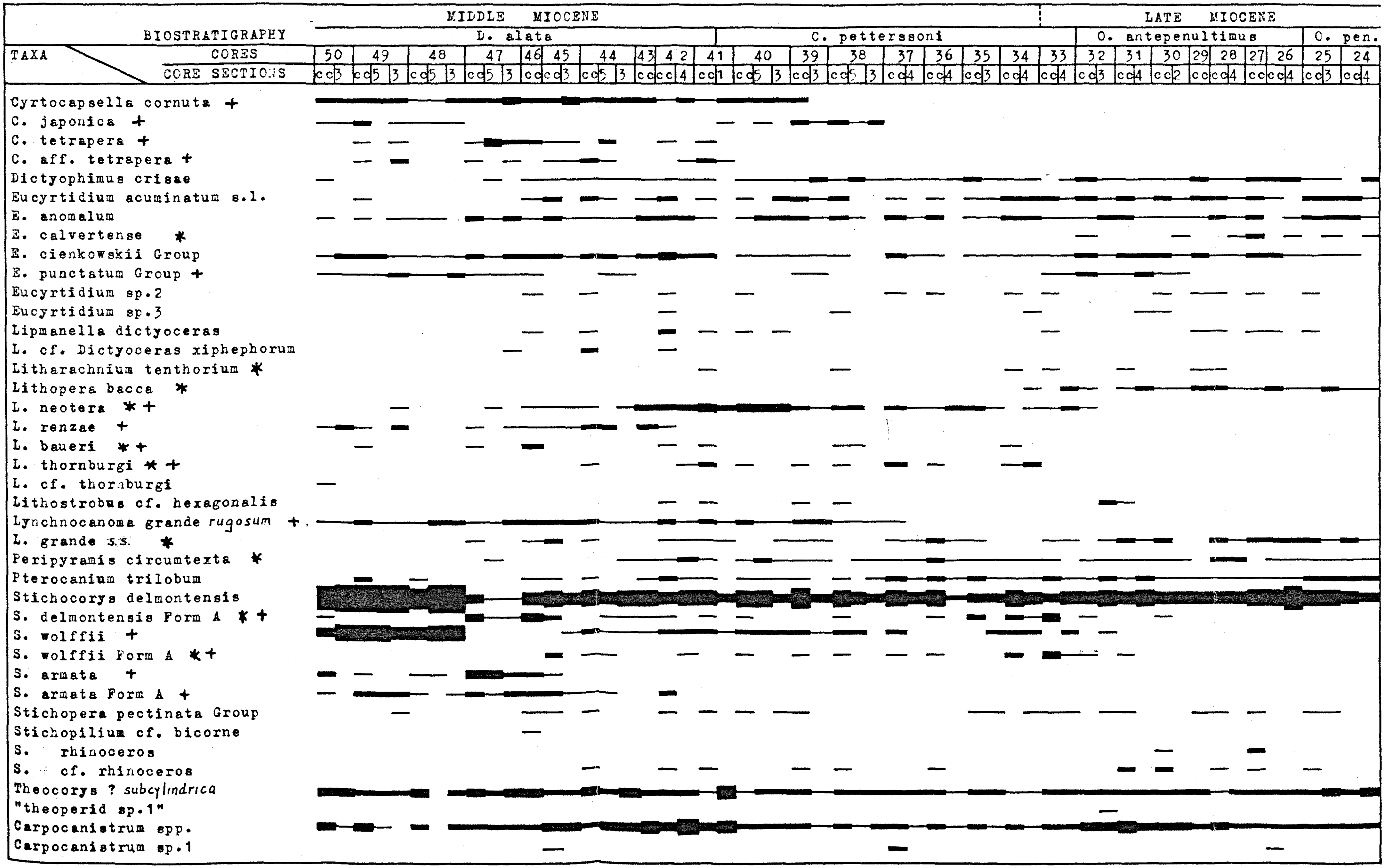


Fig.30c Percentage abundance of all radiolarian taxa at DSDP Site 289 (continued on Figs. 30d)

Key:- present — ; 0.1-1.0 ▬ ; >1-5 ▬ ; >5-10 ■ ; >10-20 ■ ; >20-30 ■ ; >30-40 ■ ; >40 ■

* + evolutionary and extinction events used for the consideration of evolutionary trends at Site 289

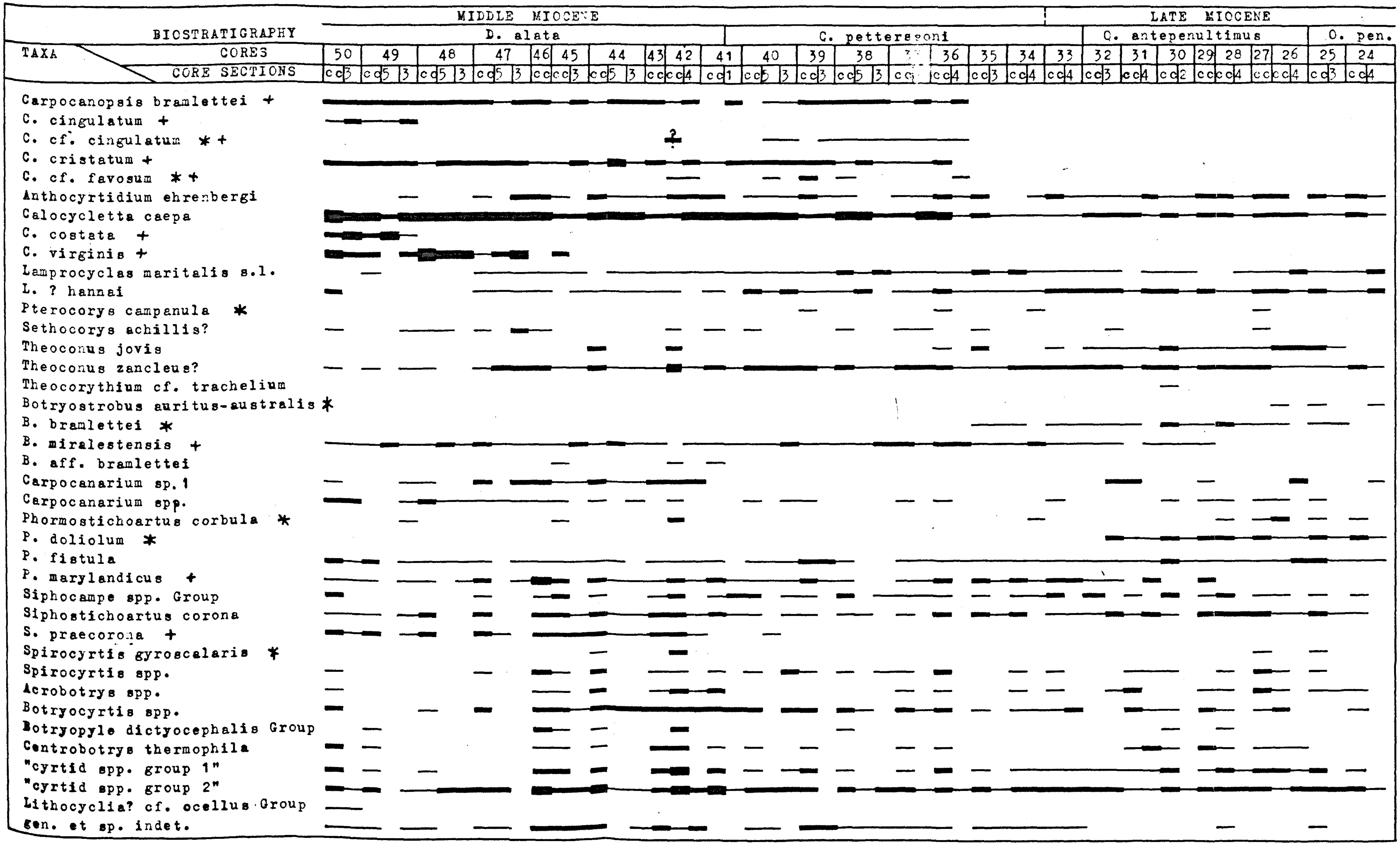


Fig. 30d Percentage abundance of all radiolarian taxa at DSDP Site 289

Key:-

	0.1-	>1-	>5-	>10-	>20-	>30-	>40
Present	1.0	5	10	20	30	40	
—	▬	▬	▬	■	■	■	■

* + evolutionary and extinction event used for the consideration of evolutionary trends at Site 289

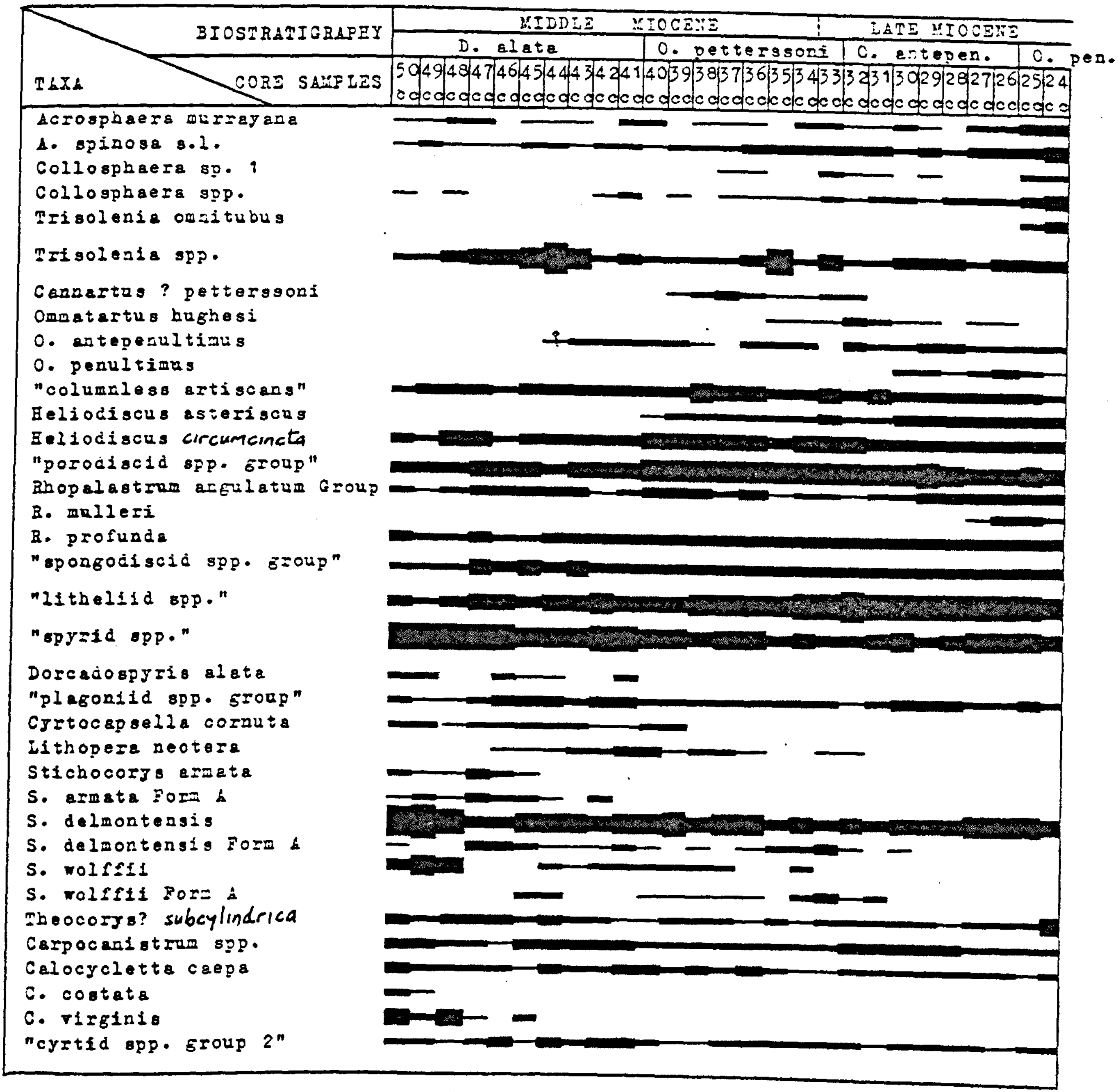


Fig.31 Percentage abundance of selected radiolarian taxa at DSDP Site 289 (core catcher samples only)

Key:-

—	▬	▬	▬	■	■	■	■	■
present	0.1-1.0	>1-5	>5-10	>10-15	>15-20	>20-30	>30-40	>40

Calocycletta caepa (fig.32) exhibits a steady, gradual decrease in abundance from common at the base of the Middle Miocene to rare within the Late Miocene.

The distribution of *Carpocanistrum spp.* (fig.32) reveals a distinct bimodal pattern. Two peaks of abundance within the *Dorcadospyris alata* and *Ommatartus antepenultimus* Zones of the Middle and Late Miocene respectively, in which the taxon is common, are isolated by intervals in which abundance falls to rare or few.

The distribution of *S. delmontensis* (fig.33) is particularly variable over the studied sequence although it is sufficiently consistent over short intervals to allow the recognition of distinct trends. Three peaks of abundance, at the base of the *Dorcadospyris alata*, *Cannartus? petterssoni* and *Ommatartus penultimus* Zones are seperated by discrete intervals of reduced values. The termination of the first peak, in which values decrease rapidly, from very abundant to few, is of particular importance because the event corresponds with the appearance of *S. delmontensis* FORM A (see Appendix I). Elsewhere, the distribution trends are more continuous, especially in the Late Miocene.

S. delmontensis FORM A appears as two discrete peaks of abundance within the *Dorcadospyris alata* Zone and across the *Cannartus? petterssoni/ Ommatartus antepenultimus* zonal boundary respectively, where it is rare to few (fig.33). Elsewhere, the taxon is very rare or absent.

The distribution of *S. wolffii* is similar in many respects to that of *S. delmontensis*, although values are always much smaller (fig.33). The base of the *Dorcadospyris alata* Zone is characterised by relatively high abundance (few to common) although thereafter the species rapidly becomes absent or very rare. Nevertheless, within this sequence, two further small 'peaks' can be recognised.

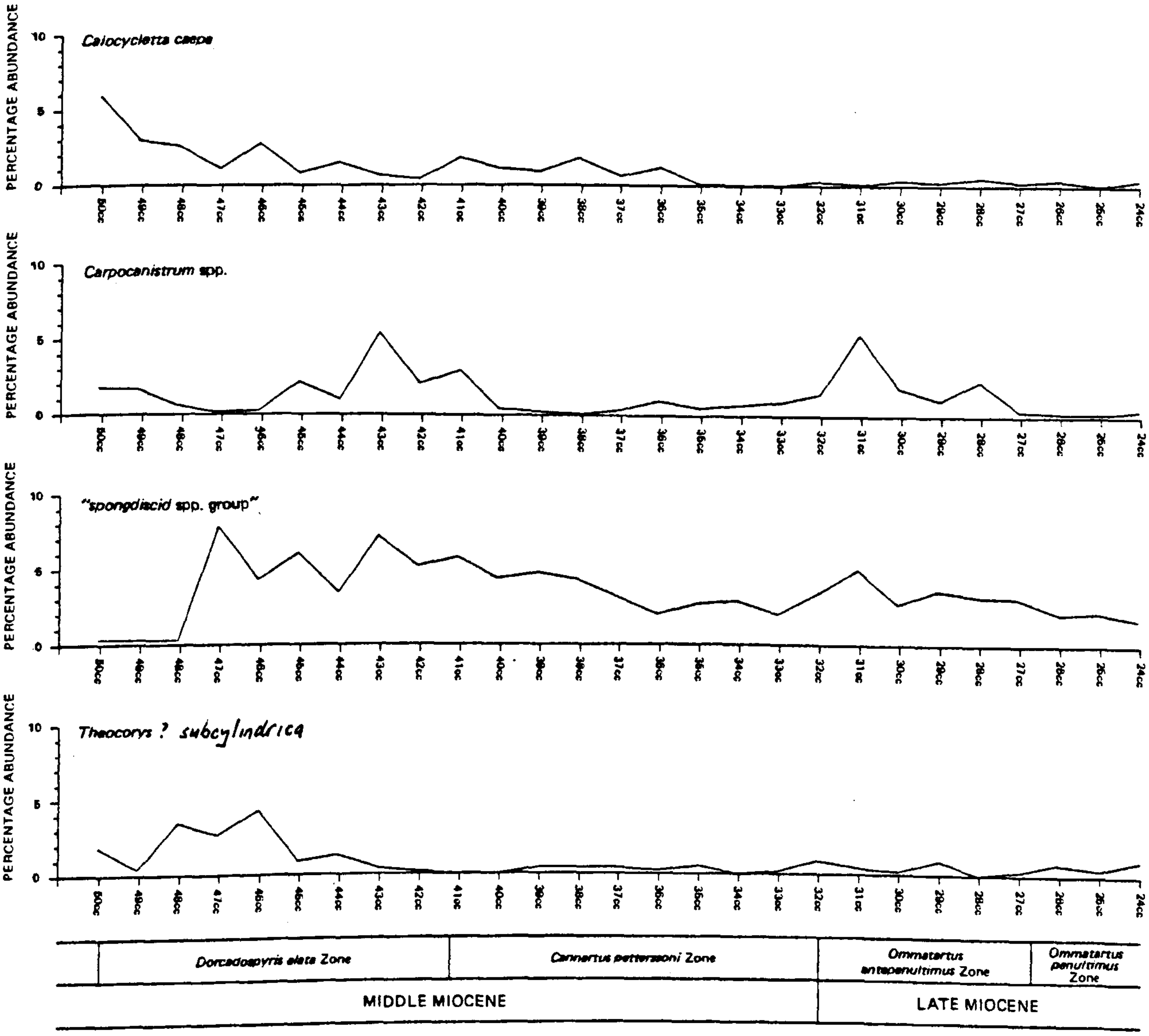


FIGURE 32 RELATIVE DISTRIBUTION OF RADIOLARIAN TAXA, DSDP SITE 289

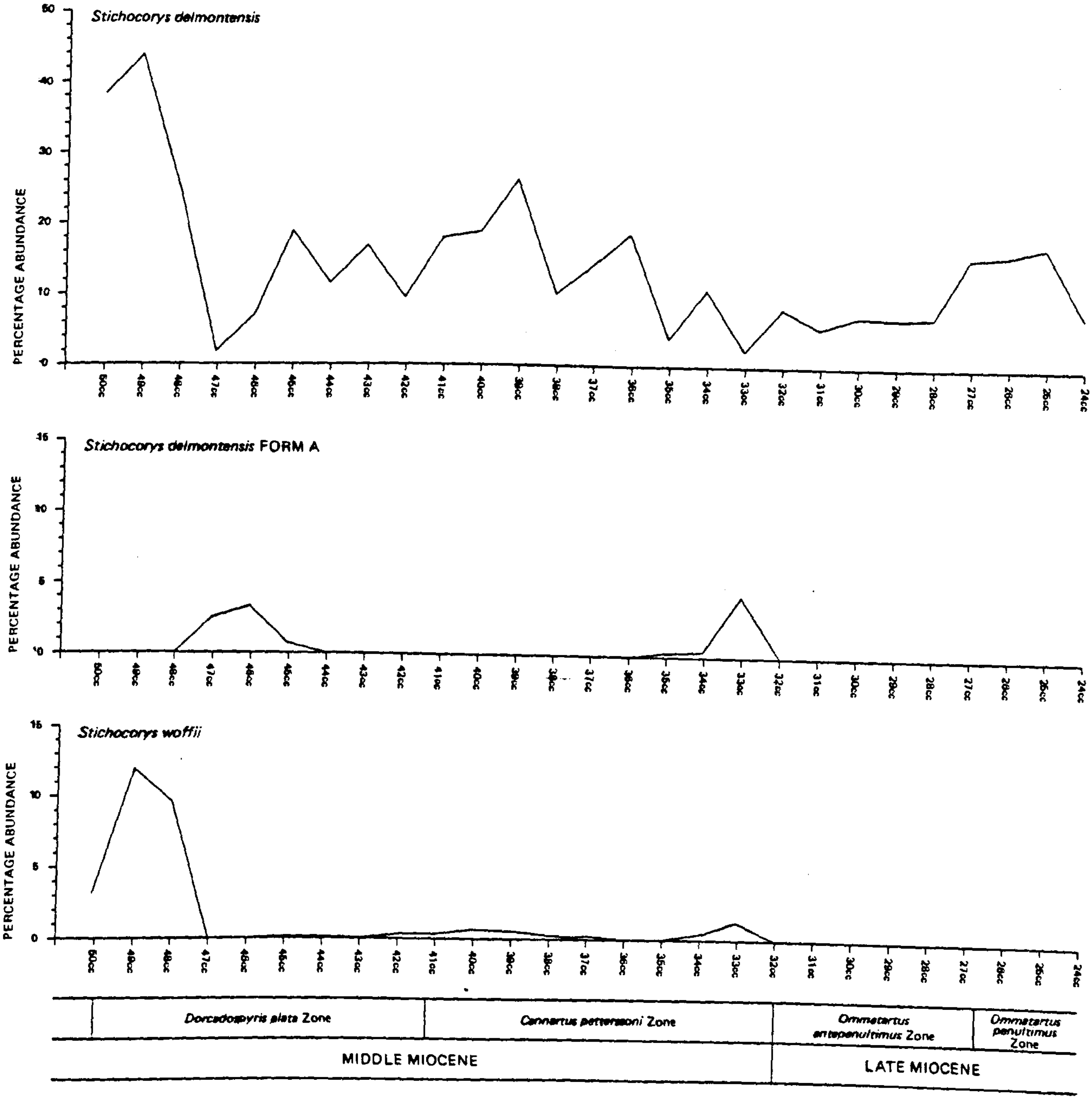


FIGURE 33 RELATIVE DISTRIBUTION OF RADIOLARIAN TAXA, DSDP SITE 289

Theocorys? subcylindrica exhibits relatively high abundance (few) near the base of the *Dorcadospyris alata* Zone and low abundance through the remainder of the studied sequence, where values range from absent to rare (fig.32).

The distribution trend of *"Cyrtid spp. group 2"* (fig.34)indicates peak abundance in a broad interval spanning the *Dorcadospyris alata/Cannartus? petterssoni* zonal boundary.

"Plagoniid spp. group" exhibits four discrete abundance peaks throughout the studied sequence (fig.34).

"Spyrid spp." is one of the more numerically important taxa at Site 289 (fig.34). Most of the Middle Miocene interval is characterised by relatively high abundance with two well defined peaks in the *Dorcadospyris alata* and *Cannartus? petterssoni* Zones. In the late Middle and Late Miocene, abundance is reduced and the distribution is less well defined.

The distribution of "columnless artiscans" is given in fig.35. The trend approximates a 'normal distribution' pattern with low abundance at each end of the sequence (*Dorcadospyris alata* and *Ommatartus antepenultimus/ Ommatartus penultimus* Zones) and high abundance in the middle (*Cannartus? petterssoni* Zone).

Collosphaera spp. is absent, very rare or rare through most of the studied sequence but exhibits a marked increase in abundance in the *Ommatartus penultimus* Zone, where the taxon becomes common (fig.36).

The distribution of *Acrosphaera spinosa* is generally similar to that of *Collosphaera spp.* (fig.36), with low abundances (absent, very rare to few) through most of the sequence and high abundance (very common) within the *Ommatartus penultimus* Zone.

Trisolenia spp. (fig.36) displays a distinct bimodal distribution

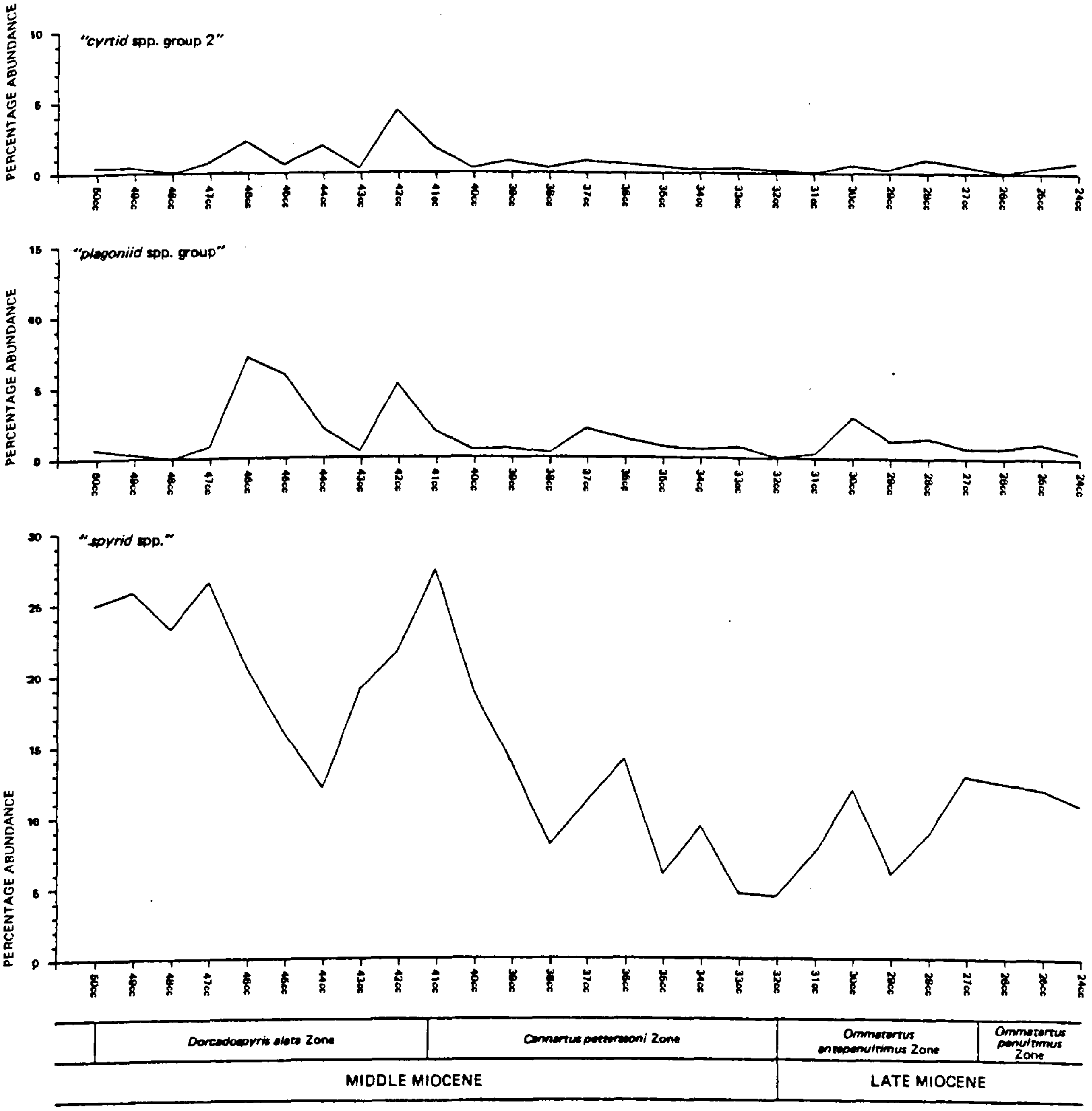


FIGURE 34 RELATIVE DISTRIBUTION OF RADIOLARIAN TAXA, DSDP SITE 289

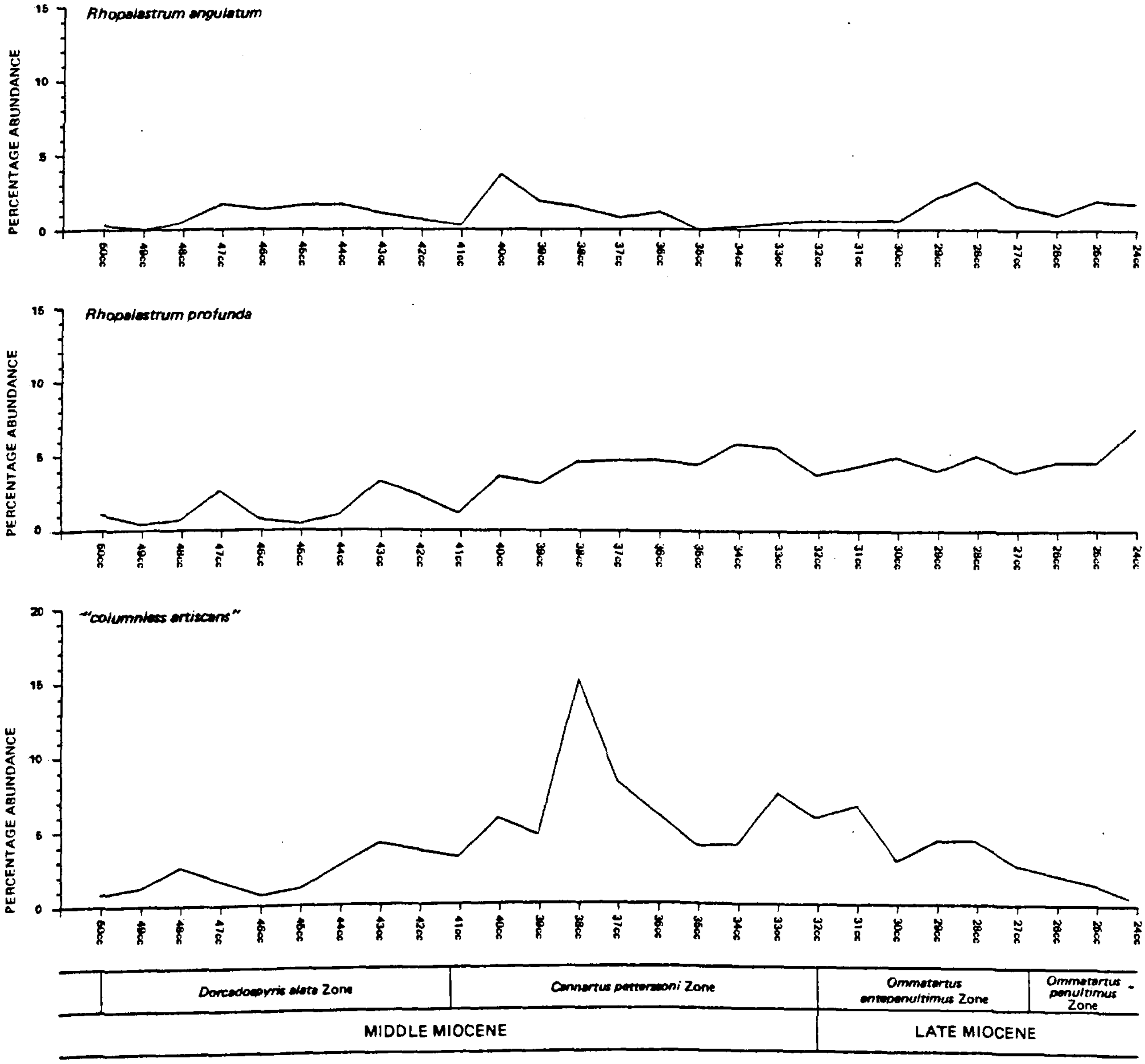


FIGURE 35 RELATIVE DISTRIBUTION OF RADIOLARIAN TAXA, DSDP SITE 289

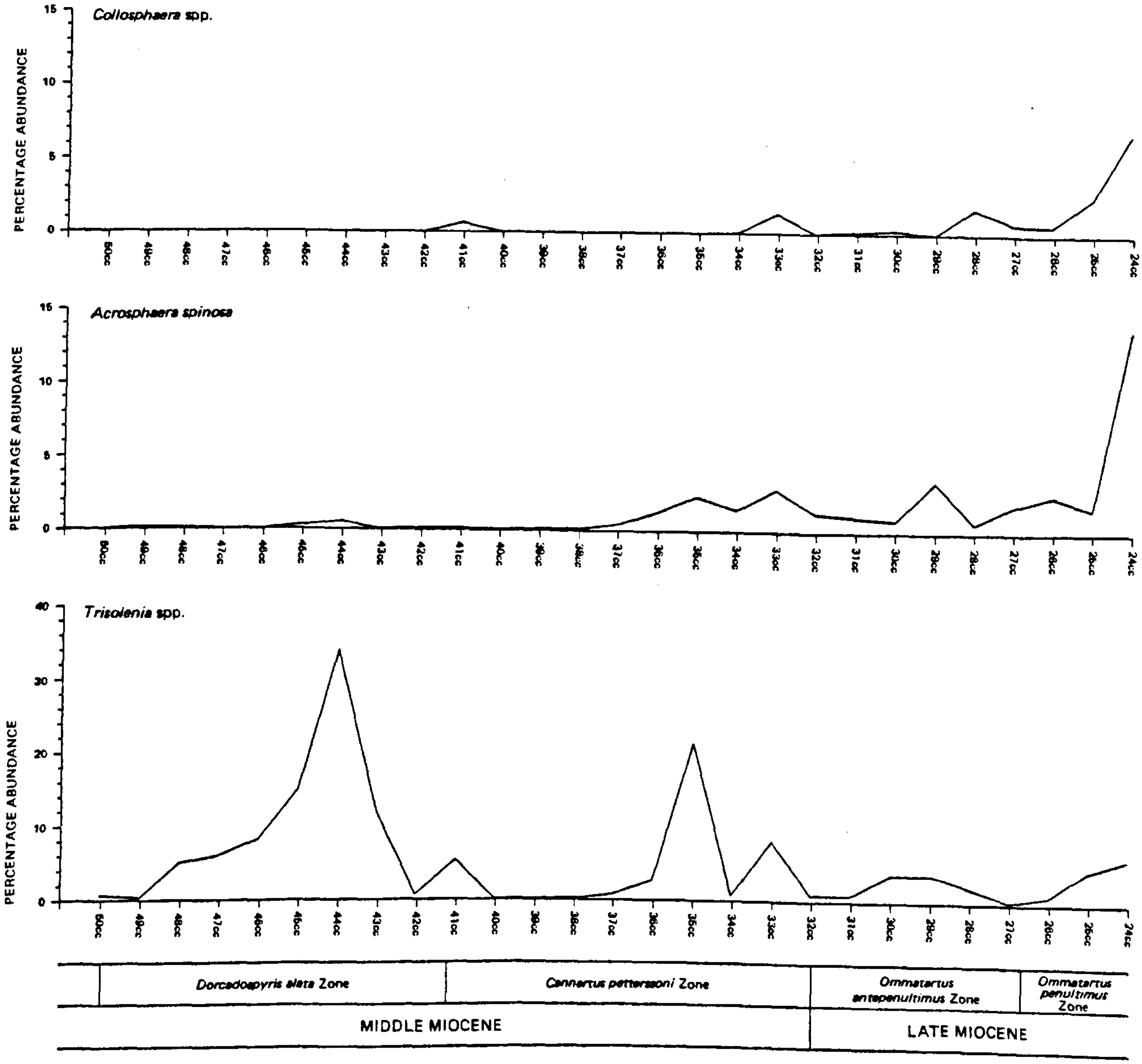


FIGURE 36 RELATIVE DISTRIBUTION OF RADIOLARIAN TAXA, DSDP SITE 289

pattern with very high values (very common to abundant) seperated by intervals of low abundance (rare to few). The first peak, near the top of the *Dorcadospyris alata* Zone, follows an interval in which abundance increases very gradually whilst the second peak, near the top of the *Cannartus? petterssoni* Zone appears to be more sudden.

The distribution of *Rhopalastrum profunda* (fig.35) is generally constant with a gradual but small overall increase in abundance through the sequence.

Rhopalastrum angulatum (fig.35) exhibits a rather more varied distribution with small discrete peaks present in the *Cannartus? petterssoni* and *Ommatartus antepenultimus* Zones.

The distribution of *Heliodiscus circumcincta* is dominated by an abundance peak of relatively large stratigraphic duration within the *Cannartus? petterssoni* and *Ommatartus antepenultimus* Zones (fig.37). A shorter interval of high abundance is also present with the *Dorcadospyris alata* Zone.

The following three taxonomic groups have proved difficult to differentiate below the family level but are numerically important throughout most of the studied sequence at Site 289.

"Porodiscid spp. group" is present in low abundance (rare) near the base of the studied sequence although thereafter, despite quite large variation, values are generally high (common to very common). Distinct trends involve a peak within the *Dorcadospyris alata* Zone and a gradual increase through the *Cannartus? petterssoni* to within the *Ommatartus antepenultimus* Zones. Abundance declines markedly throughout the top of the *Ommatartus antepenultimus* and following *Ommatartus penultimus* Zones (fig. 37).

The distribution of *"Spongodiscid spp. group"* (fig.32) reveals similar low abundance near the base of the *Dorcadospyris alata* Zone. A

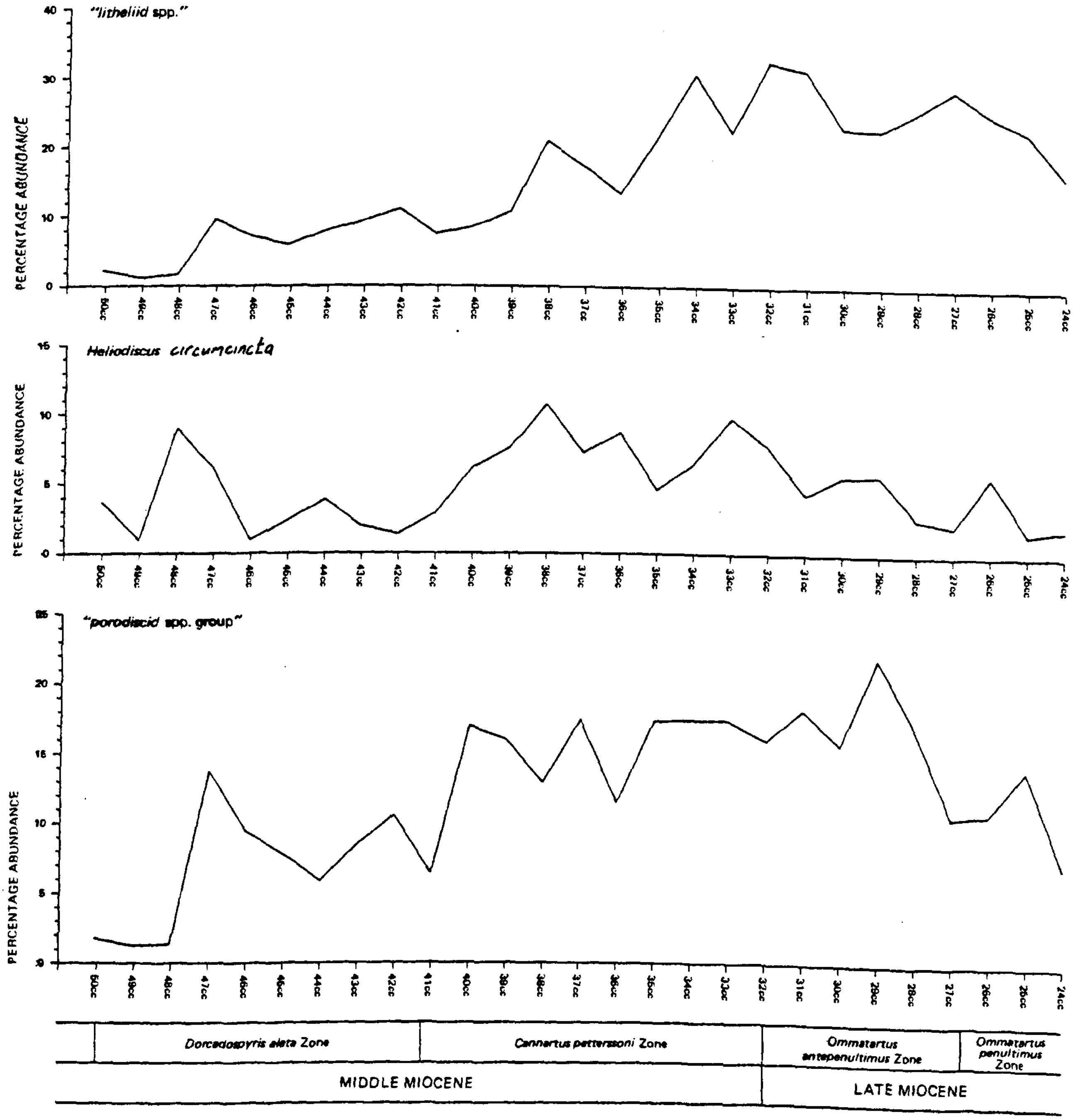


FIGURE 37 RELATIVE DISTRIBUTION OF RADIOLARIAN TAXA, DSDP SITE 289

subsequent peak within most of this zone is followed by declining abundance over the rest of the sequence.

Following low but increasing abundance throughout the *Dorcadospyris alata* Zone, the distribution patterns of *"Lithellid spp."* (fig.37) is dominated by a gradual trend towards maximum abundance within the *Ommatartus antepenultimus* Zone with decreasing values in the subsequent *Ommatartus penultimus* Zone.

A comparison of the various distributional histograms for individual taxa reveal normal correlations between several pairs of taxa, although these relationships have not been quantified by statistical analysis.

The close similarity in the distributional trends between *Stichocorys delmontensis* and *S. wolffii* and between *Acrosphaera spinosa* and *Collosphaera spp.* has already been mentioned. Normal correlation in the distribution of these pairs of taxa can be partly explained by close phylogenetic relationships and/or high morphological similarily which tends to intergrade taxonomic boundaries and render objective discrimination difficult (see Appendix I). The following pairs of taxa also reveal close similarities in their quantitative distributional patterns: *"Plagoniid spp. group"* and *"Spyrid spp"* (fig.34), *"Plagoniid spp. group"* and *"Cyrtid spp. group 2"* (fig.34) and *"Spongodiscid spp. group"* and *Carpocanistrum spp.* (fig.32). In addition, the following four taxa also generally show a 'normal correlation' in distributional trends: "*columnless artiscans*", *Heliodiscus circumcincta*, *"Porodiscid spp. group"* and *"Lithellid spp."*(figs.35,37). *Stichocorys delmontensis* and *"Spyrid spp."*, exhibit close similarities in their distribution for most of the studied sequence only(fig.33,34). *Stichocorys delmontensis* and *S. delmontensis* FORM A show distribution trends which appear to exhibit an inverse relationship.

c) Diversity and Similarity Indices

The Fisher α Index plots for radiolarian assemblages at Site 289 are given in fig. 38. The core cather and section samples are treated seperately in view of the difference in preservation caused by inconsistent washing proceedures. Although the Fisher α Index is generally lower in section samples compared to core catcher samples, there is nevertheless a good normal relationship between the trends (fig. 38). Diversity values in section samples 49-5 and 40-3 appear to be rather anomalous and are close to the diversity values of adjacent core cather samples (fig. 38). In these examples, preservation is similar to that seen in core cather samples and suggests that only negligable test loss prevailed during sample washing.

Fig. 38 also includes taxon density values for each sample. This allows a comparison with the Fisher α Index values. For both core catcher and section samples, it is evident that similar trends prevail. The use of the Fisher α Index is necessary however because total number of radiolarian individuals identified in each sample varied considerably (Appendix II).

The Fisher α Index for core cather samples varies from 7 to 16. Several trends, to be discussed below, are evident.

The Shannon-Wiener Index (H(S)) has been computed from the percentage abundance data in each sample (fig. 38). Values vary from 1.47 to 2.73.

A comparison of both diversity indices used at Site 289 for radiolarian assemblages reveals a good aggreement in the trends (fig. 38).

In the interval from 50cc to 42cc, diversity values fluctuate quite markedly and several trends are apparent. From 41cc to 24cc however,

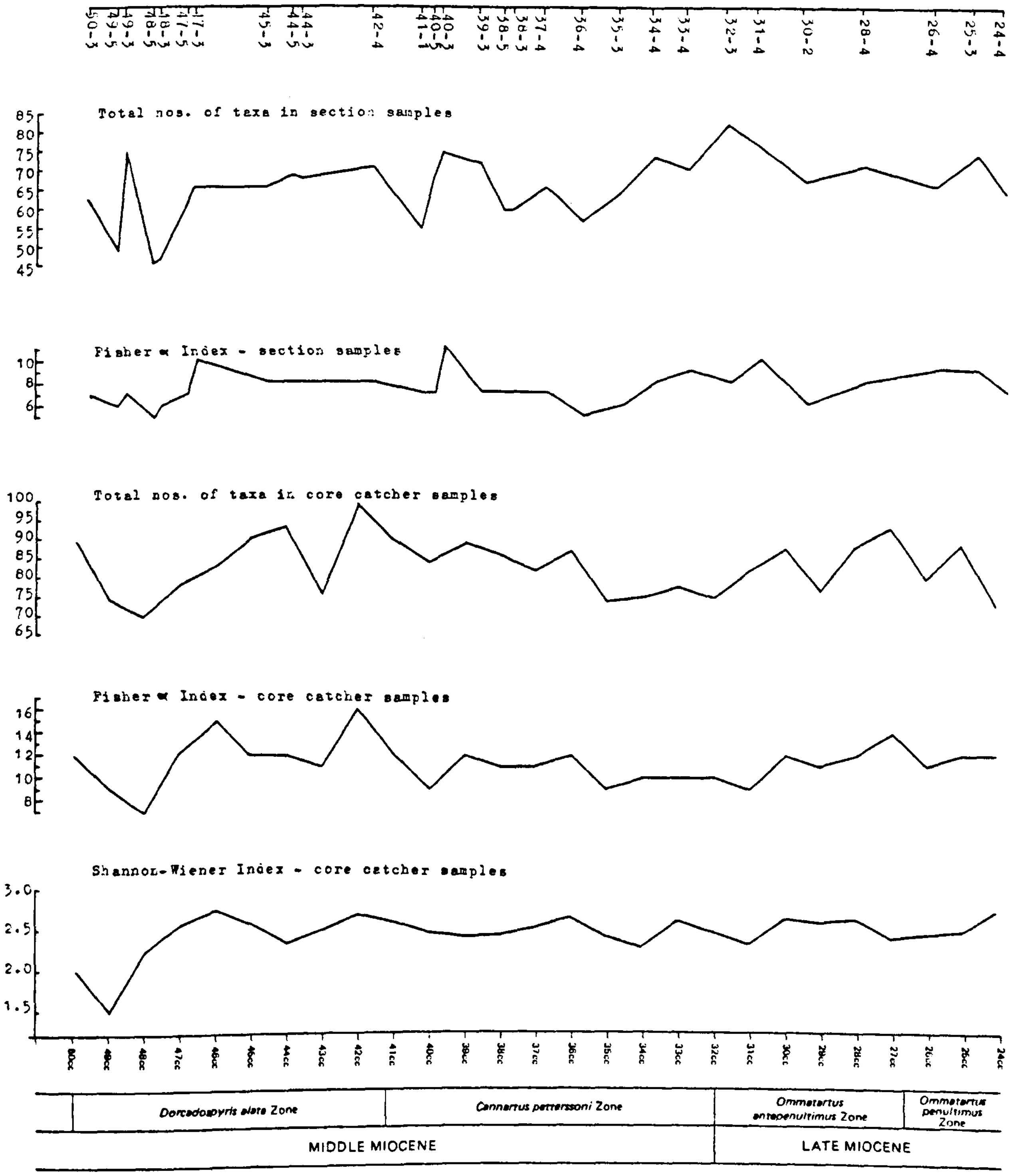


Fig. 38 Diversity Indices for Radiolaria at Site 289

diversity values are relatively stable and trends are more difficult to discern.

Low values of diversity characterise 50cc to 48cc (within the Dorcadospyris alata Zone) where the assemblages are strongly dominated by Stichocorys delmontensis, S. wolffii and Spyrid spp. (fig.31).

A strong rise in diversity is evident in 47cc and 46cc (within the Dorcadospyris alata Zone). A trend towards greater species equitability is apparent in these assemblages where many taxa are present in similar abundance (fig.31).

Decreasing diversity in 45cc to 43cc is followed by increased values in 42cc (all within the Dorcadospyris alata Zone). Assemblages in 45cc to 43cc are characterised by increased abundance of Trisolenia spp., a feature of species dominance which contributes towards decreased diversity.

From 41cc to 24cc, diversity values do not fluctuate markedly although several features are apparent, including increased values in 39cc to 36cc and 30cc to 27cc and decreased values in 40cc, 35cc to 34cc, 31cc and 26cc (fig.38). In this interval, the percentage abundance of individual taxa does not vary considerably (fig.31).

Fig.39 illustrates the similarity of all samples to the sample at the base of the studied sequence (50cc). As with that exhibited by planktonic foraminifera, the pattern is variable although a general trend of decreasing similarity to sample 50cc through the sequence is evident.

Intervals characterised by sharp changes, such as those between 48cc and 47cc, and 39cc and 38cc indicate changes in the relative abundance of radiolarian taxa within the assemblages. Intervals characterised by near horizontal profiles, such as those between 47cc and 39cc indicate taxonomic stability.

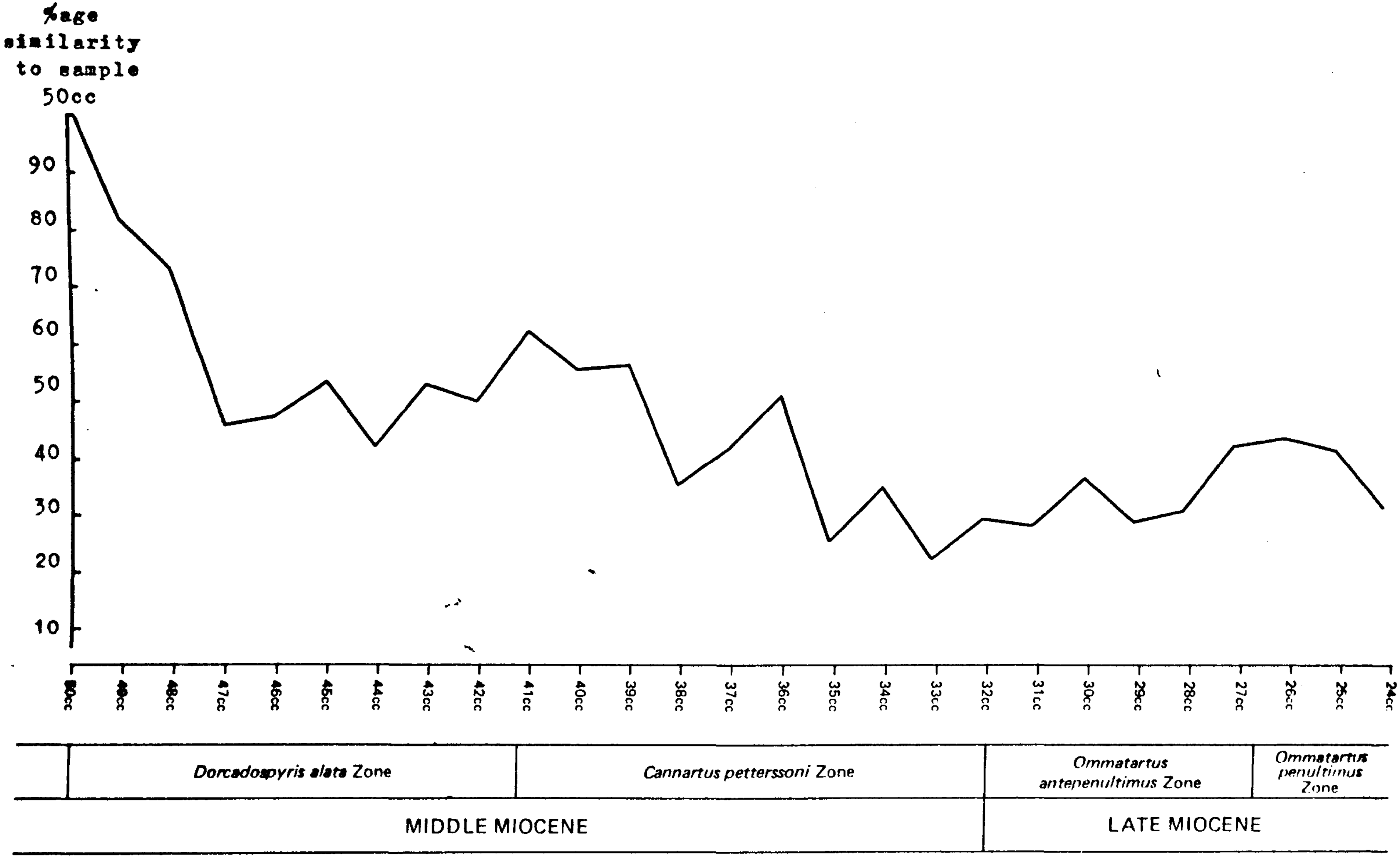


Fig. 39 Similarity Index (Rate of Change) - radiolaria, Site 289

As with planktonic foraminifera, the use of the similarity index serves to unambiguously define the stratigraphical horizons where greatest change occurs, although in many instances this is self evident in fig.31. It is of further use however, in the recognition of subtle cyclic features which may indicate recurrent palaeoenvironmental or geological events, e.g. in samples 36cc and 27cc to 25cc, which show anomalously high similarity to 50cc.

The palaeoenvironmental significance of variation in the diversity indices and the rate of change index for radiolaria at Site 289 will be assessed in Chapter VII.

d) Dissolution of Radiolaria

Factors causing dissolution in deep sea radiolarian assemblages have already been discussed (Chapter II). As previously noted for planktonic foraminiferal assemblages, it is of utmost importance to discriminate changes caused by dissolution from changes caused by palaeoenvironmental and palaeoecological factors. From the distribution and ecology of radiolaria in plankton and surface sediments from the Central Pacific, RENZ (1976) concluded that the factors that control the distribution of radiolaria in the plankton differ from those that control their distribution in the sediments. By identifying and allowing for changes in the assemblages caused by dissolution, other variation caused by palaeoenvironmental and palaeoecological factors can thus be more easily interpreted.

HOLDSWORTH and HARKER (1975) have considered variation of dissolution intensity in radiolarian assemblages at Site 289. A simple model, in which high relative abundances of spyrid and collosphaerid radiolarians were assumed to have been concentrated in solution resistant lag assemblages, was used to indicate increased dissolution.

Intensification of bottom water currents were suggested as the most possibly cause. HOLDSWORTH and HARKER (1975) identified several intervals of 'increased dissolution' at Site 289, one of which, between samples 47cc and 38-3 in the Middle Miocene, falls within the studied sequence herein.

In the present study, the premise used by HOLDSWORTH and HARKER (1975), concerning high relative abundances of spyrids and collosphaerids as indicative of high dissolution, is questioned and an alternative method, which yields conflicting results, is outlined. In view of the results of RENZ (1976), the overall character of the assemblages, expressed in a parameter such as diversity, may yield more information on dissolution than methods utilizing particular taxa only. Intervals which have suffered high dissolution intensity would be reasonably expected to yield lower radiolarian diversity values than surrounding intervals because of preferential destruction of fragile species and concomitant concentrations of robust forms. By this method, intervals where dissolution would appear to have influenced the assemblages to the greatest extent would be from samples 50cc to 48cc, 45cc to 43cc, 40cc, 35cc to 34cc, 31cc and 26cc (see fig.38). This interpretation can be tested by an independant means involving the distribution of solution-prone taxa. Of all the forms identified, the following sixteen species were selected because of their particularly fragile test structure and assumed susceptibility to dissolution (see JOHNSON, 1974 and plate figures herein).

Artopilium undulatum

Corocalyptra cervus

C. killmari

Eucyrtidum sp. 2

Lipmanella dictyoceras

L. sp. cf. dictyoceras xiphephorium

Litharachnium tenthorium

Lithopera thornburgi

Stichopera pectinata

Stichopilium sp. cf. S. bicorne

S. rhinoceros

S. sp. cf. S. rhinoceros

Lithostrobus sp. cf. L. hexagonalis

Botryocyris spp.

Verticillata hexacantha

Clathrocanium reginae

Fig. 40 illustrates the qualitative distribution (presence/absence) of these taxa at Site 289. It is acknowledged that few of the taxa naturally range throughout the time interval in question and that in some cases, absence in parts of the sequence may be because the taxa had yet to evolve or had become extinct. Nevertheless, because distribution of the taxa within their respective ranges at Site 289 is believed to have been primarily controlled by the relative intensity of dissolution, the method is considered valid, particularly in view of the number of taxa outlined.

Intervals where the forms are scarce or absent include 50cc to 47cc, 45cc, 43cc, 37cc, 35cc to 34cc, 32cc and 26cc to 24cc. These samples are also often characterised by low overall diversity and suggests that preferential removal of fragile forms by dissolution is reflected in overall diversity trends.

A comparison of the simple diversity trend (fig. 41) with the relative distribution of Spyrid spp. (a dissolution indicator of HOLDSWORTH and HARKER, 1975) reveals an almost consistent normal

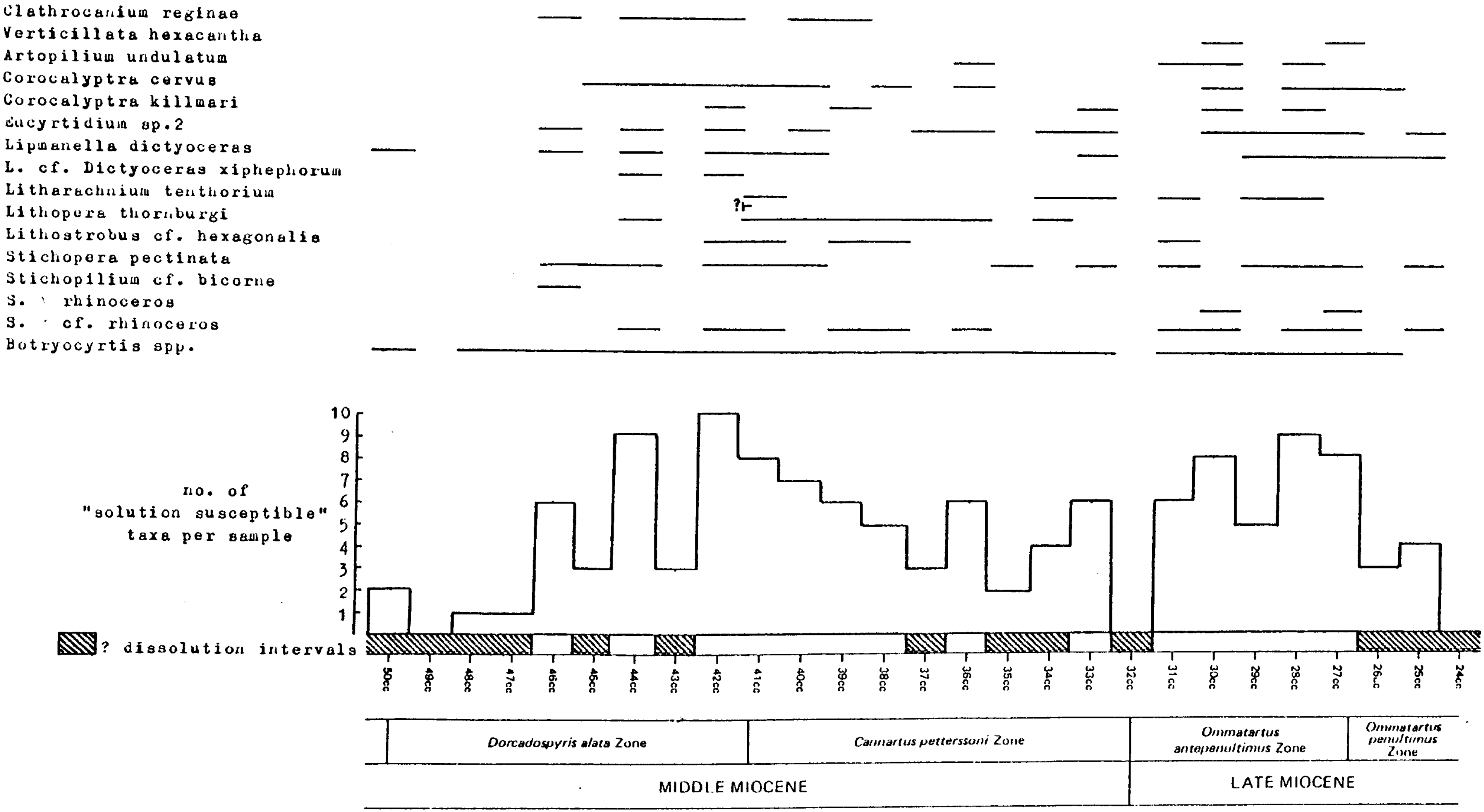


Fig.40 The distribution of fragile radiolarian taxa at Site 289 as a possible indication of increased dissolution

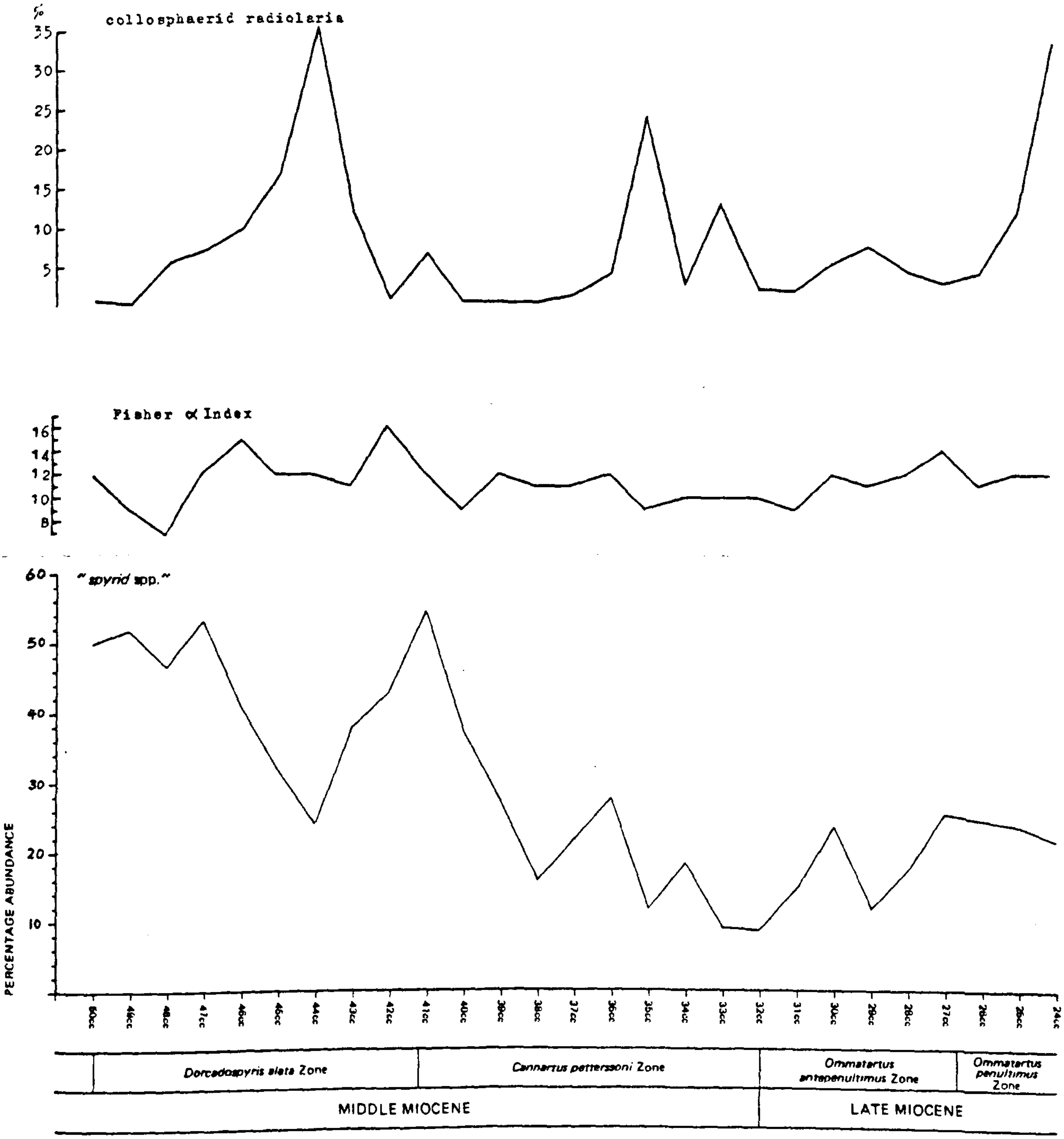


Fig. 41 A comparison of the relative distribution of spyrid and collosphaerid radiolaria with the simple diversity (Fisher α Index) trend at Site 289

relationship. According to the argument propounded herein, low diversity and therefore high dissolution, corresponds to low spyrid concentrations while high diversity and low dissolution, corresponds to high spyrid concentrations. The proposed relationship between dissolution intensity and spyrid abundance is in fact opposite to that suggested by HOLDSWORTH and HARKER (1975). In retrospect, HOLDSWORTH (pers. comm.) suggests that the use of abundance of all spyrid taxa as an indication of dissolution was perhaps misconceived since many species are probably solution prone rather than solution resistant. Nevertheless, it is reasonable to assume that concentrations of spyrid tests, involving heavy solution resistant forms only, such as some of those witnessed by HOLDSWORTH and HARKER (1975) at particular horizons within the Cenozoic interval at Sites 289 and 288 serve as a reliable index of increased dissolution.

The relationship between diversity trends and collosphaerid abundance is not straightforward (fig. 41). High collosphaerid percentages occur in sample 35cc where low diversity suggests increased dissolution although elsewhere a correlation is absent. Evidence outlined in Chapter VII suggests that in the main, the distribution of the taxon is primarily influenced by palaeoenvironmental and palaeoecological factors.

The intervals/samples which are believed to have been subject to increased dissolution of biogenic silica are 50cc to 48cc, 45cc to 43cc, 40cc, 35cc to 34cc, 31cc and 26cc (cf. 47cc to 38-3 by HOLDSWORTH and HARKER, 1975). Evidence for dissolution can also be gained from the overall nature of the assemblages present in some of the intervals, e.g. samples 50cc to 48cc are dominated by heavy robust individuals of Stichocorys delmontensis, in which the more fragile, post-abdominal segments are generally missing. This interval was probably subject to maximum solution intensity within the studied sequence. It is interesting to note that this interval is the only one in the studied sequence in which high percentages of spyrids accompany low diversity values.

Although several independant and/or interrelated environmental and geological factors influence the diversity and overall distributional trends in fossil planktonic foraminiferal and radiolarian assemblages, those involving dissolution appear to be particularly important at certain horizons at Site 289. Further, it is perhaps not coincidental that apparent maximum dissolution of both fossil groups under consideration occur within the same interval, i.e. within cores 50 to 48.

The cause of increased dissolution of biogenic calcium carbonate and silica within the studied sequence at Site 289 will be considered in Chapter VII following a palaeoenvironmental reconstruction for the studied sequence.

3. DSDP SITE 71

i) Planktonic Foraminifera

a) General features

The relative distribution of the thirty four species and subspecies of planktonic foraminifera encountered at Site 71 is given in fig.42. Several distributional features are apparent from this composite histogram:

a. Most taxa range throughout the studied sequence.

b. The relative distribution of most taxa remains comparatively stable throughout.

c. The assemblages are dominated by Globoquadrina spp., particularly G. venezuelana, and by Globorotalia siakensis.

b) Distribution of Individual Taxa

The distribution of individual taxa at Site 71 is self-evident

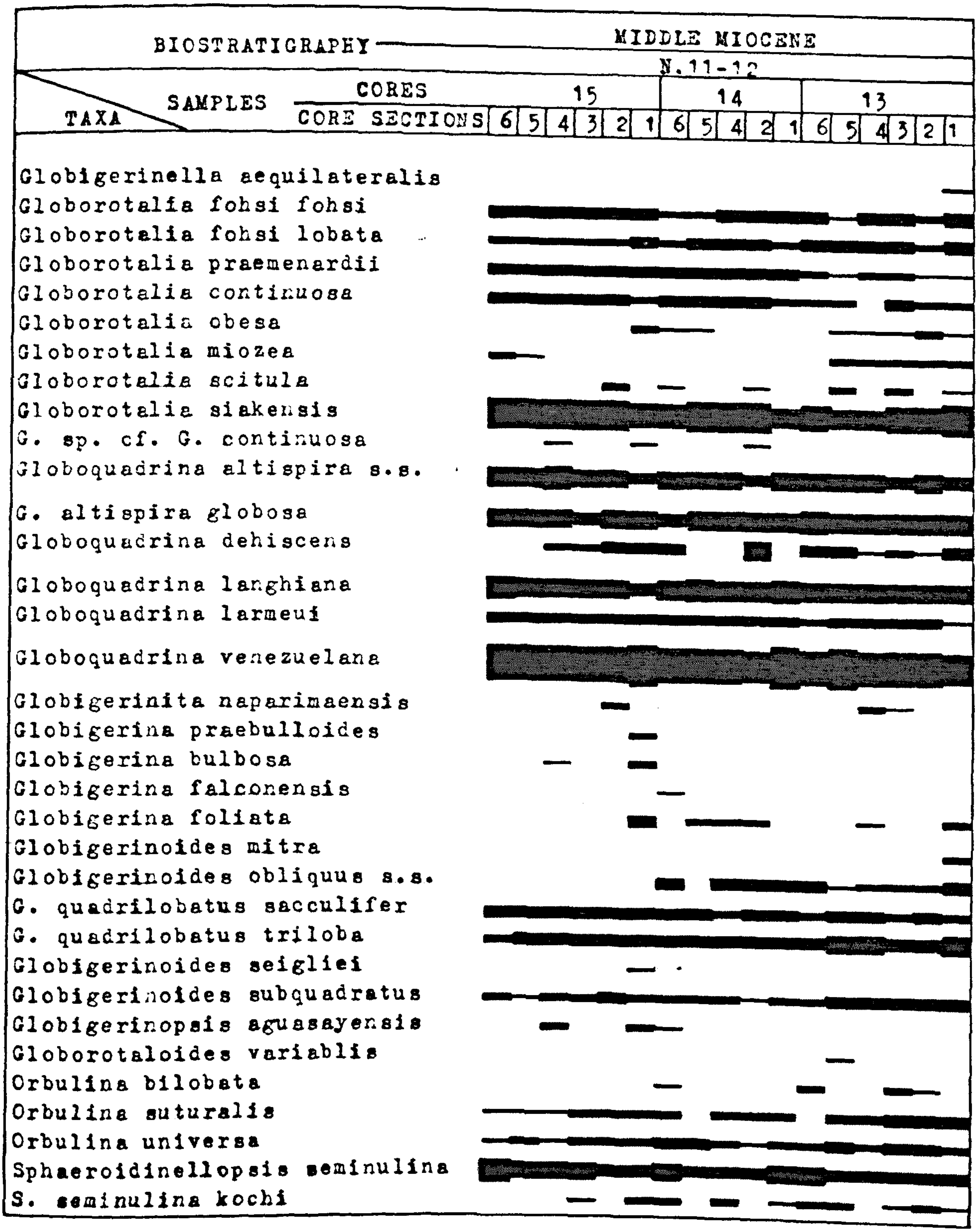


Fig.42 Percentage distribution of planktonic foraminiferal taxa, DSDP Site 71

key :-

present	0.2- 1.0	>1- 5	>5- 10	>10- 20	>20- 30	>30- 40	>40
—	▬	▬	■	■	■	■	■

from fig. 42 and little more may be gained by detailed descriptions. Nevertheless, certain features deserve attention. While most taxa exhibit stable distributions, several display significant fluctuations (fig. 42).

G. venezuelana exhibits a twofold increase in numbers through the sequence from very common to very abundant although this overall trend is interrupted by several temporary falls in abundance (fig.43).

The distribution of G. siakensis is relatively stable through the lower part of the sequence but displays a large drop and subsequent re-establishment of abundance in the latter half of the interval (fig.43).

The distribution of Globorotalia continuosa and G. praemenardii is low but stable through most of the sequence but falls to rare or absent in the latter samples (fig.43).

G. subquadratus (fig.43) is rare or absent through most of the sequence but increases noticeably in the latter samples.

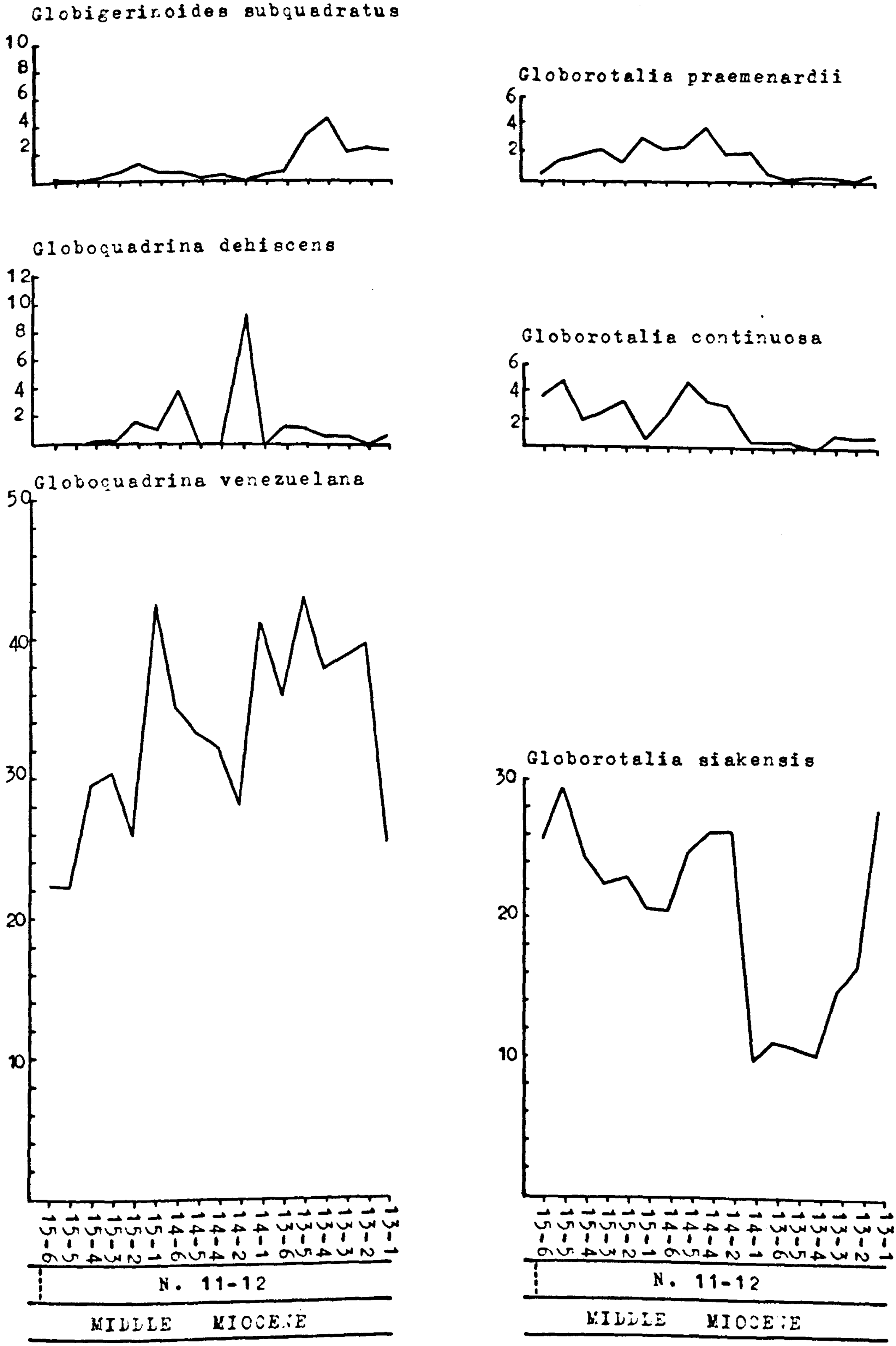
The distribution of Globoquadrina dehiscens is conspicuous by its variability (fig.43). The species is few to absent through most of the interval except for an anomalous single sample peak in mid-sequence.

c) Diversity and Similarity Indices

Both simple and compound indices were used as in the case of assemblages from Site 289.

The number of species within each sample at Site 71 is given in fig.44b. The values only relate to those species encountered in each subsample of 500 individuals. The number of taxa per sample varies from fourteen to twenty three. Within the sequence can be discerned two discrete trends of increasing diversity.

The Shannon-Wiener diversity Index (H(S)) was computed from the relative distribution data and is plotted in fig.44b. Values vary from 1.98 to 2.40 and the trend is rather variable with several one point



Globigerinoides subquadratus

Globorotalia praemenardii

Globoquadrina dehiscens

Globorotalia continuosa

Globoquadrina venezuelana

Globorotalia siakensis

Fig. 43 Percentage abundance of some planktonic foraminiferal taxa at Site 71

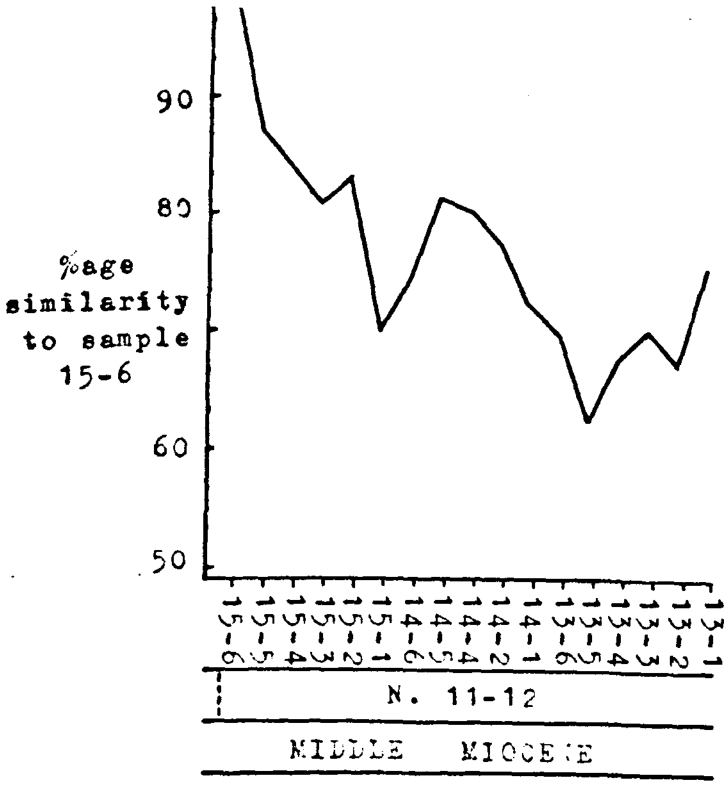


Fig. 44a Similarity Index (Rate of Change) - planktonic foraminifera, Site 71

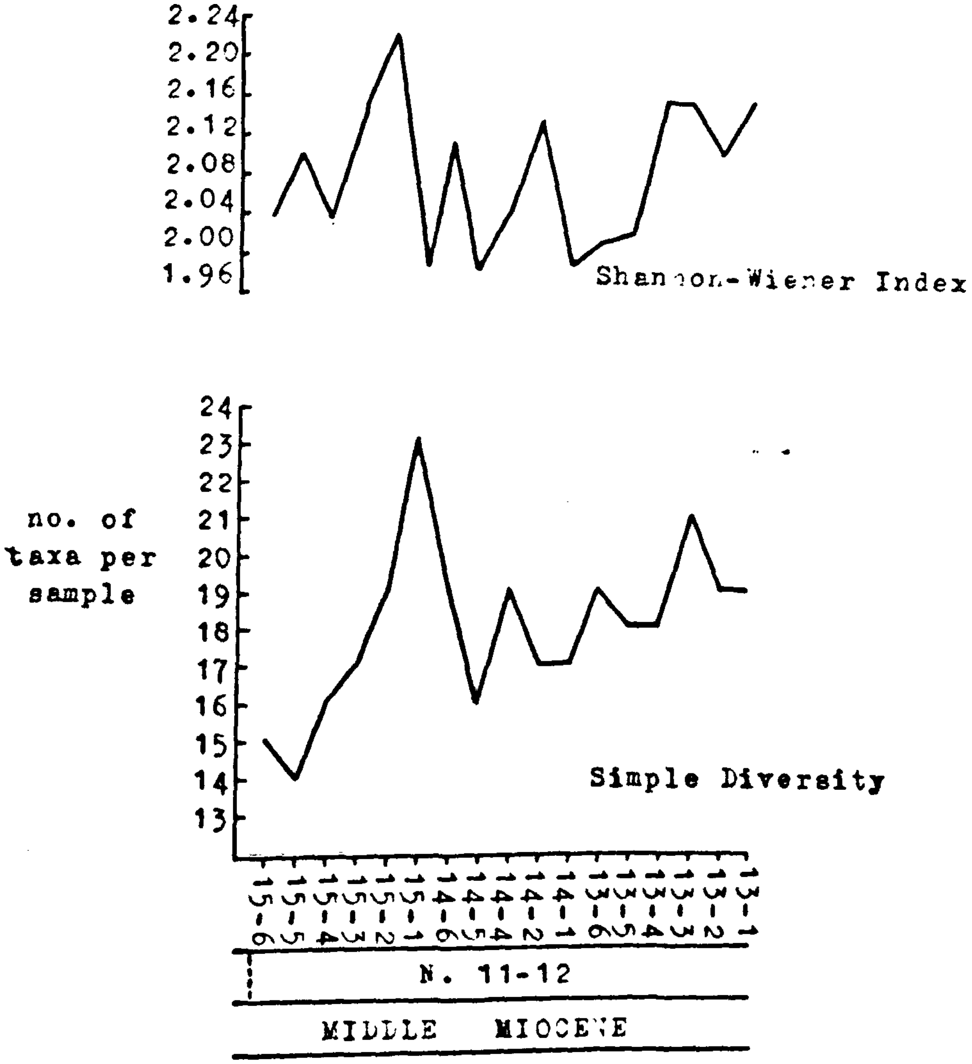


Fig. 44b Diversity Indices of planktonic foraminifera at Site 71

peaks. Consequently, there is only limited correlation between the simple and compound diversity trends (fig.44b).

The similarity index used at Site 71 is the same as that used for planktonic foraminiferal assemblages at Site 289. Fig.44a illustrates the similarity of all samples to that at the base of the studied sequence (15-6). The trend reflects a general decrease in similarity to sample 15-6 through the sequence, although this relationship is accentuated by more rapid declines at certain samples.

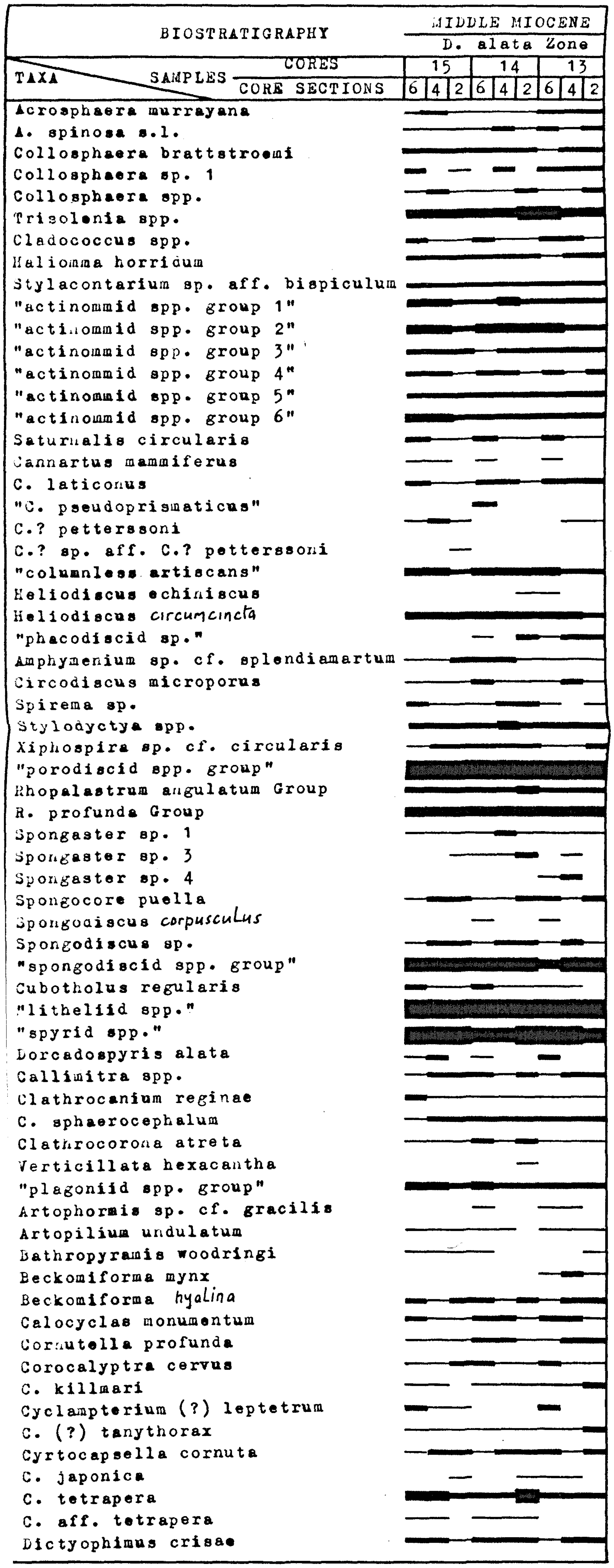
d) Dissolution of Planktonic Foraminifera

The preservation of planktonic foraminiferal assemblages at Site 71 is generally of a lower quality to time equivalents at Site 289 (cores 47 to 44 - see below) and most similar to those assemblages which are believed to have suffered greatest dissolution (i.e. 289, cores 50 to 48). Although most tests are whole, absolute abundances are relatively low and many individuals show signs of corrosion. Robust globoquadrinids dominate the assemblages throughout and those forms which were regarded as solution susceptible at Site 289, such as Globigerinoides obliquus s.s., G. mitrus, Globigerina foliata, Globorotalia obesa, Globigerinita naparimaensis, Orbulina suturalis and O. bilobata, are poorly represented at Site 71. The preservation of the assemblages appears to be consistent with a depositional environment deeper than that at Site 289. The present day water depth of 4419 metres is below the level of the lysocline and it is suggested that perhaps comparable depths prevailed during the Middle Miocene.

ii. Radiolaria

a) General Features

The relative distribution of all radiolarian taxa present is given in fig.45. Several distributional features are apparent from this



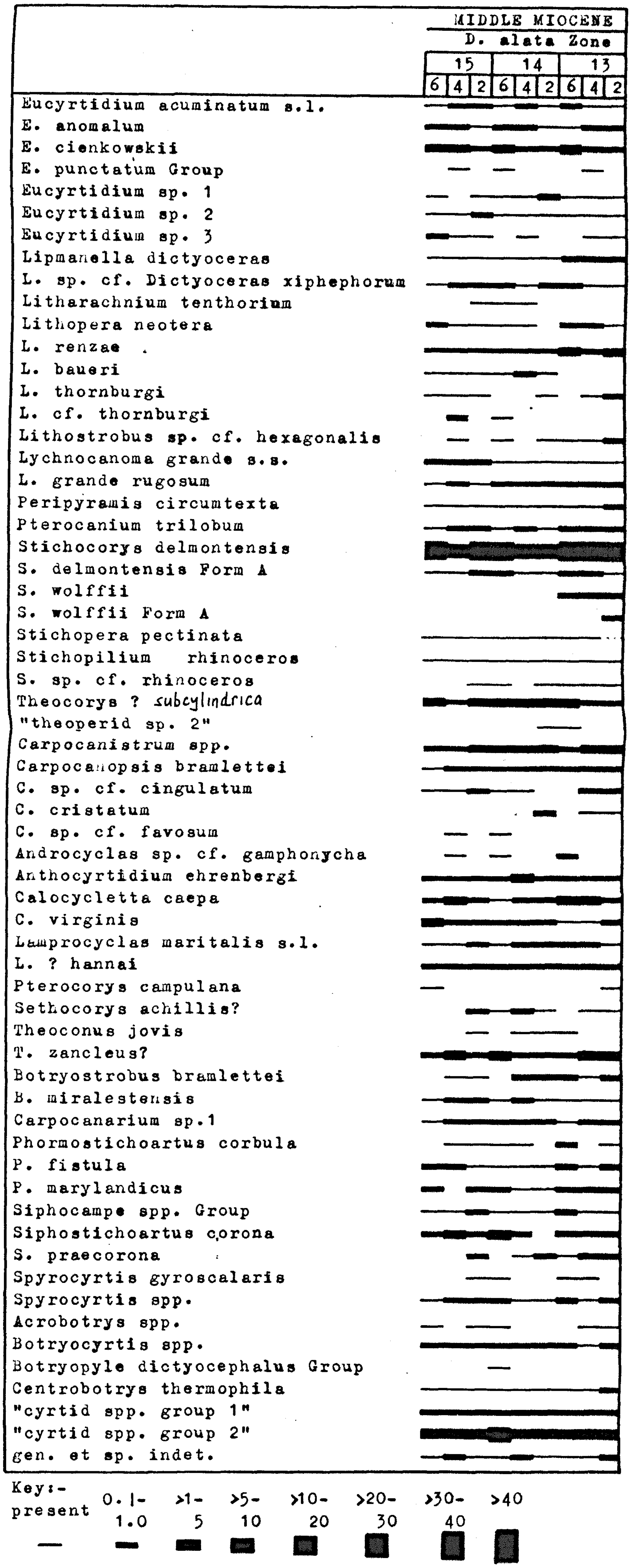


Fig. 45 Percentage distribution of radiolarian taxa, DSDP 71

composite histogram:

a. Most taxa range throughout the studied sequence.

b. The relative distribution of most taxa remains comparatively stable throughout.

c. The assemblages are dominated by Stichocorys delmontensis, "Spyrid spp.", "Porodiscid spp. gp.", "Litheliid spp." and "Spongodiscid spp. gp.".

b) Distribution of Individual Taxa

The distribution of individual taxa at Site 71 is self-evident from fig.45 and little more may be gained by detailed descriptions. Nevertheless, certain features deserve attention. The distribution of S. delmontensis reveals two well defined abundance peaks within the studied sequence (fig.45). S. delmontensis FORM A is present in all samples although abundance is always very rare to rare.

c) Diversity and Similarity Indices

Both simple (taxon density and Fisher α) and compound (Shannon-Wiener) indices were used as in the case of assemblages from Site 289.

The number of taxa per sample varies from 98 to 110 (fig.46b). The Fisher α Index is also plotted in fig.46b. Values vary from 14 to 18 and generally increase through the sequence.

The Shannon-Wiener diversity Index (H(S)) for each sample (fig.46b) indicate that values vary from 2.52 to 2.78. There is no consistent correlation between the simple and compound diversity plots.

The similarity index used at Site 71 is the same as that used for Site 289 radiolarian assemblages. Fig.46a illustrates the similarity of all samples to that at the base of the studied sequence (15-6). The plot, which approximates a very shallow gradient, reflects the small changes in the assemblages as indicated in the composite taxonomic histogram

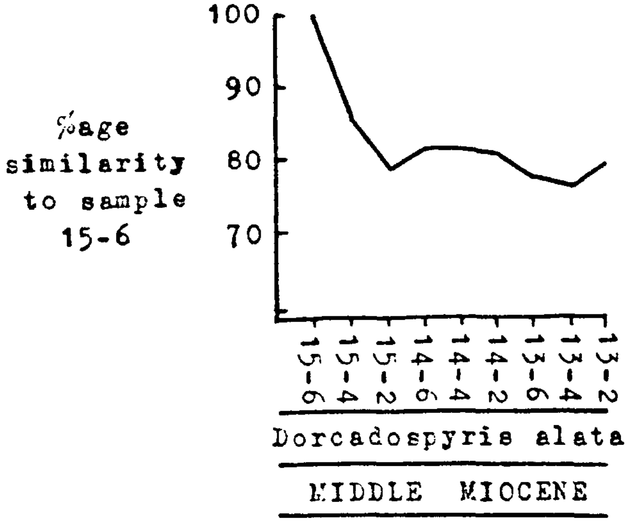


Fig.46a. Similarity Index (Rate of Change) - radiolaria, Site 71

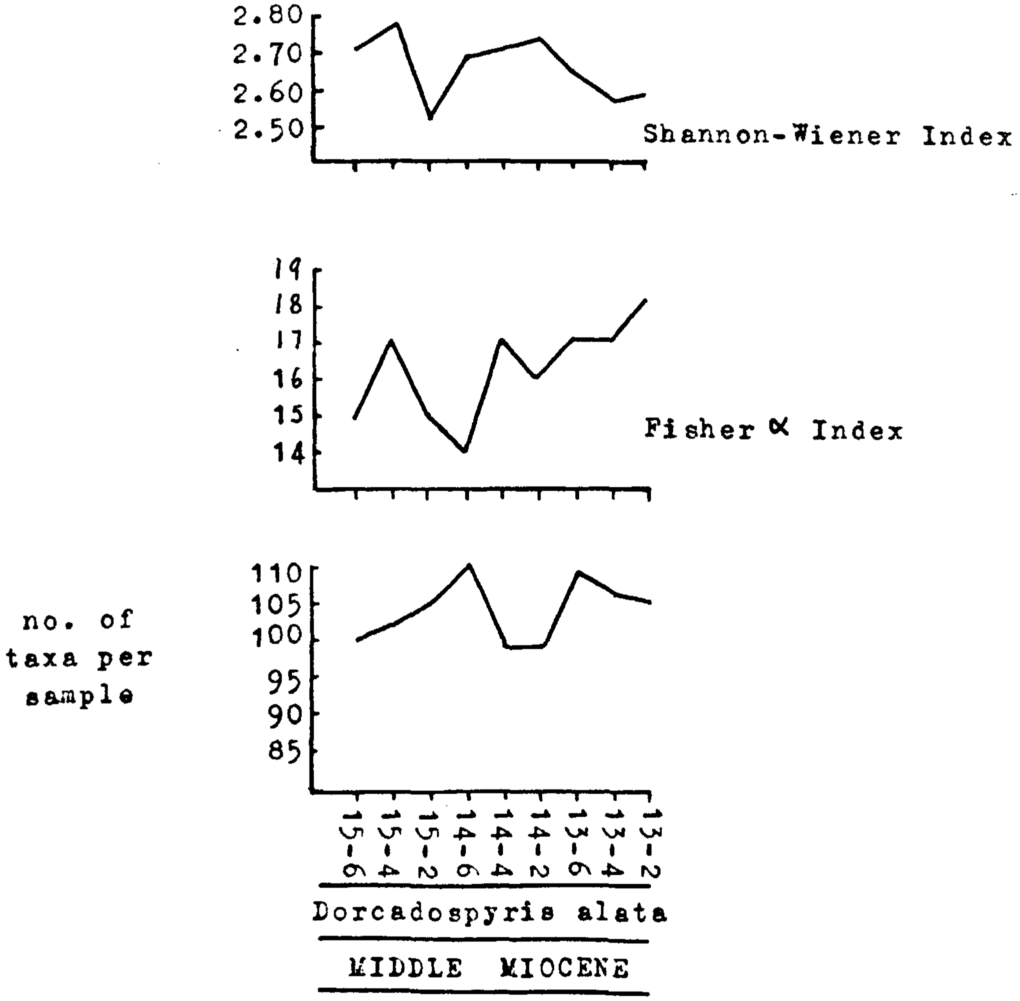


Fig.46b Diversity Indices of radiolaria at Site 71

(fig.45).

d) Dissolution of Radiolaria

The preservation of radiolaria at Site 71 is good to excellant and is generally of a higher quality than time equivalent assemblages at Site 289. Delicate forms and structures are common, simple diversity is high and the assemblages are accompanied by frequent diatoms. The higher diversity assemblages at Site 71 compared to time equivalents at Site 289 deserved discussion (total nos. range from 98 to 110 at Site 71 and from 77 to 92 at Site 289; α ranges from 14 to 18 at Site 71 and from 12 to 15 in the corresponding interval at Site 289 (within the <u>Dorcadospyris alata</u> Zone - see below)). High diversity at Site 71 may be caused by several factors, involving differences in the life environment, sedimentation rate, dissolution, laboratory proceedures and downhole contamination.

The present day overlying surface waters at Site 71 differ from those at Site 289 with respect to temperature (colder) and biological productivity (higher). Colder temperatures may produce decreased diversity in life assemblages (see Chapter II). However, it has been suggested that high productivity may increase the preservation potential of radiolarian tests in the sediment and thus increase diversity of fossil assemblages (DIESTER-HAASS and SCHRADER, 1979). The relationship between temperature, productivity and diversity is thus complex and difficult to rationalise with regard the differences between the two sites.

The sedimentation rate of biogenic ooze is lower at Site 71. The Middle Miocene sequences, which are complete at both sites, comprise 170 metres (approx.) of nanno-foram ooze and chalk at Site 289 but only 100 metres (approx.) of radiolarian-nannofossil ooze at Site 71 (ANDREWS PACKHAM <u>et al.</u> 1975; TRACEY <u>et al.</u>, 1971 respectively). Lower rates of carbonate sedimentation, probably due to accumulation near the lysocline, may account for both the decrease in thickness and increase in the percentage of radiolaria tests in Middle Miocene sediment from Site 71 compared to that from Site 289. Strewn slide studies show an average of 25% radiolaria in Middle Miocene ooze from Site 71 but only 1-5% radiolaria in the equivalent sediment from Site 289 (TRACEY et al., 1971; ANDREWS, PACKHAM et al., 1975). Since similar sized samples from Site 71 will represent a larger time interval than those from Site 289, higher diversity in radiolaria may be expected.

Less dissolution of radiolaria at Site 71 may account for the differences, although the cause is uncertain but may involve the chemistry of percolating pore water.

Washing proceedures in the laboratory may concievably create the differences in diversity. Samples from Site 71 were processed by the current author during the course of this study. In view of the preservational differences between core catcher and section samples at Site 289, which have been attributed to variation in pocessing methods at different laboratories, particular care was taken when washing and sieving samples from Site 71, especially with regard the use of water spray. Nevertheless, because the core catcher samples of Site 289 were not processed by the present author, differences in appearance compared to Site 71 samples is possible.

Downhole contamination of radiolarian tests has been suggested for the occurrence of Cannartus? petterssoni in samples from the Dorcadospyris alata Zone at Site 71. Many other taxa present at Site 71 are absent from the time equivalent section but present in younger horizons at Site 289 (figs. 30, 45). These taxa are Collosphaera sp. 1, Cladococcus spp., Cannartus petterssoni Form A, Heliodiscus echiniscus, Verticillata hexacantha, Artopilium undulatum, Stichopilium ?rhinoceros, Pterocorys campanula and Botryostrobus bramlettei. It is therefore possible that high diversity at Site 71 may be caused by unrecognised downhole contaminants, involving taxa whose true biostratigraphical limits are unknown.

In evaluating the various factors which may account for the diversity differences between radiolarian assemblages at Site 289 and 71, it is suggested that those involving decreased rates of carbonate sedimentation, concurrent condensing of radiolarian assemblages and downhole contamination are perhaps most important. Nevertheless, suggested discrepencies in processing methods and differences in palaeoenvironments cannot be ignored as possible contributory factors.

4. CORRELATION OF SITE 71 WITHIN SITE 289

The correlation of the studied sequence at Site 71 within the larger stratigraphical interval at Site 289 is important for an appreciation of palaeoenvironmental and palaeoecological aspects discussed in the following chapters.

The sequence at Site 71 was selected for study following detailed analysis of the planktonic foraminifera and radiolaria at Site 289. At this latter site, particular interest was expressed in the interval spanning cores 48 and 47 (within N.11-12). Within this short sequence, large scale changes occur in both planktonic foraminiferal and radiolarian assemblages. In the planktonic foraminifera, a major change occurs between cores 48 and 47 which heralds the incoming of high diversity assemblages rich in globorotaliids (G. fohsi s.l., G. siakensis). There is also a radiolarian event at the same horizon which is similarly characterised by an increase in diversity and is largely defined by remarkable changes in Stichocorys delmontensis populations (see this Chapter and Appendix I for details). The transformations are partly due to a decrease in the dissolution of biogenic calcium carbonate and silica (this Chapter) although evidence also suggests major palaeoenvironmental (palaeoecological) influences (Chapter VI). In order to test the palaeogeographical extent of this major event, a time equivalent interval (near base of N.11-12; Dorcadospyris alata Zones) was selected from Site 71. The biostratigraphical accounts in the Initial Reports volume for planktonic foraminifera (BECKMANN, 1971) and radiolaria (MOORE, 1971) were used to sample the base of Zone N.11-12. BECKMANN (1971) indicates the base of the zone to occur between cores 15 and 16 although incomplete recovery of core 16 hinders accurate positioning of the boundary (TRACEY et al., 1971).

The three cores selected, 15, 14 and 13, lie within and near the base of Zone N.11-12 and could therefore be approximately correlated to Site 289 prior to the present study.

Means of correlating the studied sequence at Site 71 within that at Site 289 is offered in fig.47. In the diagram, planktonic foraminiferal and radiolarian events are independantly correlated with those at Site 289. The events used include first appearances of G. fohsi lobata, the last appearance of Cyclampterium leptetrum, relative abundance of G. siakensis and diversity trends in both planktonic foraminifera and radiolaria. The relative distribution of G. siakensis was used because at Site 289, the species exhibited stable abundance over long stratigraphic intervals which were puntuated by rapid and large percentage changes. If widespread and isochronous, these events may prove useful because of ease of identification. However, the primary tools for correlation are the well documented and more reliable first and last appearances (Chapter IV).

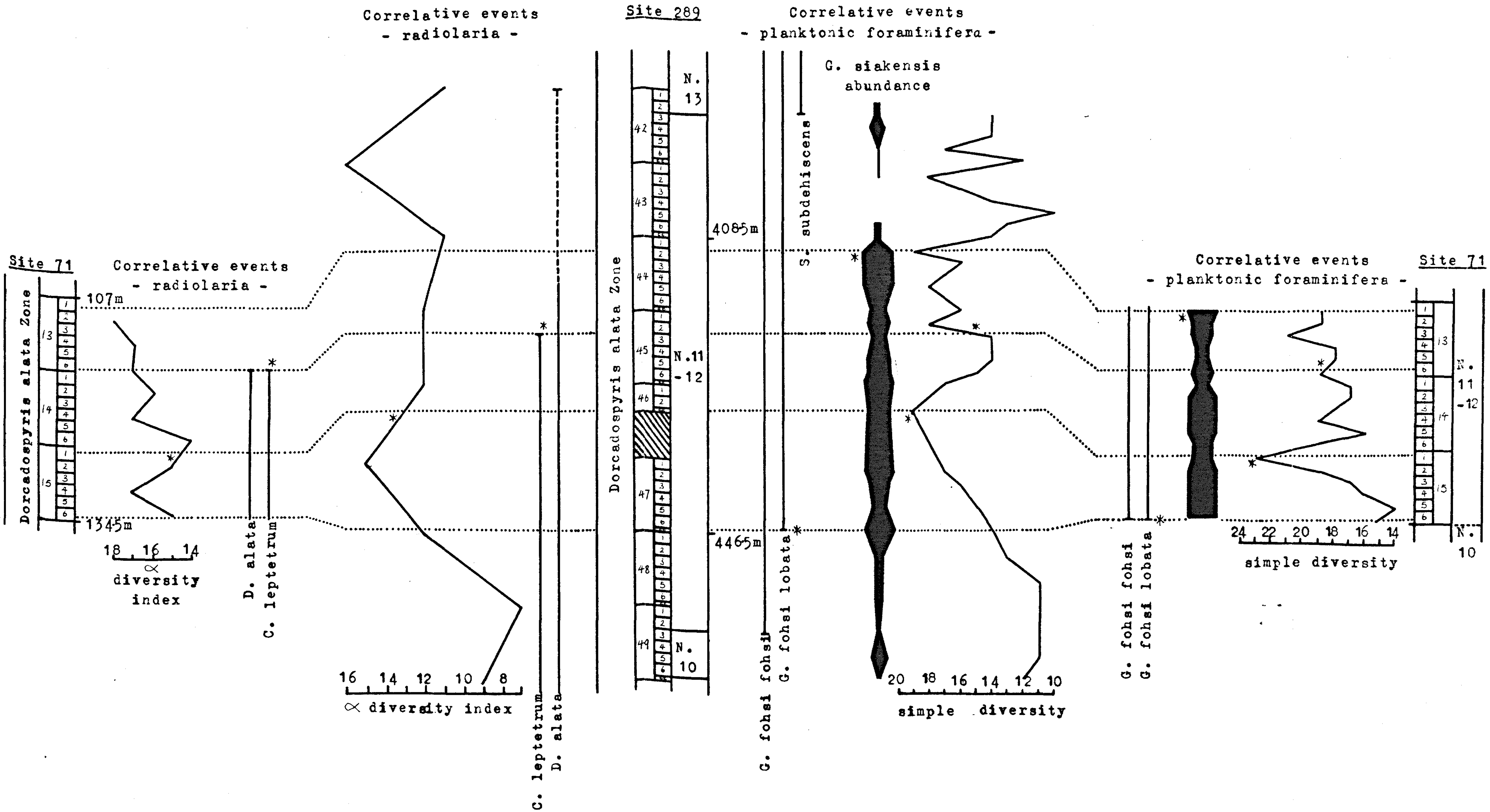


Fig. 47 A biostratigraphical correlation of the studied sequences at Sites 71 and 289 (······· = correlation lines ; * = specific features)

The correlation of quantitative events such as diversity and relative abundances must be treated with caution because they may reflect only local palaeoenvironmental events which can migrate in a diachronous fashion. Consequently, such events are not used as primary correlative tools herein but are provided to verify and substantiate results based on more reliable methods.

The presence of G. fohsi fohsi and G. fohsi lobata throughout cores 15 to 13 at Site 71 suggests the base of the sequence is not older than the base of core 47 at Site 289. The base of core 15 and 47 are correlated on the basis of subsequent (uphole) similarities in planktonic foraminiferal and radiolarian diversity trends (fig.47). The base of core 13 is correlated within core 45 at Site 289 on the basis of the last appearance of C. leptetrum (fig.47). This horizon also links diversity troughs in planktonic foraminifera at Sites 289 and 71 although a similar relationship is not apparent in corresponding radiolaria trends. The presence of the C. leptetrum and D. alata extinction datums within the same horizon at Site 71 is thought to reflect inadequate sampling intervals. According to abundance trends in G. siakensis, the top of core 13 is suggested to be no younger than the top of core 44 at Site 289. Assuming continuous sedimentation and extrapolating from the proportional rate of accumulation between both sites, the top of core 13 is correlated within core 44 (44-2) at Site 289. The time interval represented between cores 15 to 13 inclusive at Site 71 is thus thought to correspond to the time interval represented from the base of core 47 to within core 44 (44-2) at Site 289 (within N.11-12). The greater sedimentary thickness at Site 289 (approximately 34 metres against approximately 28.5 metres at Site 71) is consistent with the accumulation rate and overall thickness differences between the two complete sequences (TRACEY et al., 1971;

ANDREWS, PACKHAM et al., 1975).

5. A COMPARISON OF TIME EQUIVALENT ASSEMBLAGES FROM SITES 289 AND 71

A comparison of the corresponding planktonic foraminiferal and radiolarian assemblages from time equivalent intervals at Sites 289 and 71 can be used to indicate differences and similarities in the factors (palaeoenvironmental and post-mortal) responsible for their formation.

i. Planktonic Foraminifera

An approximate comparison of the taxonomic composition of assemblages and the relative distribution of individual species from 47-6 to 44.2 at Site 289 with those from 15.6 to 13.1 at Site 71 can be made from figs. 22 and 42.

There are many similarities between assemblages from the two sites. Globoquadrinids and Globorotalia siakensis dominate throughout while Globigerinoides spp., Orbulina spp., Sphaeroidinellopsis sp. and Globigerina spp. are always relatively low in abundance. Both sequences are characterised by stable assemblages throughout. The relative distribution of individual taxa at both intervals is generally similar in most cases although noticeable differences occur, e.g. higher abundance of Globoquadrina venezuelana and lower abundance of Fohsella spp. in assemblages from Site 71 compared to those from Site 289. Higher abundance of the robust form G. venezuelana at Site 71 is believed to reflect in part increased dissolution relative to the equivalent interval at Site 289.

Although there is a good normal correlation between simple diversity trends in time equivalent intervals at Sites 289 and 71, values are generally higher in the latter sequence (14 to 24 taxa per sample at Site 71 against 10 to 20 taxa at Site 289). Thirty four species and subspecies were encountered at Site 71 while only twenty eight were present in the corresponding sequence at Site 289. The difference can be attributed to the absence of Globorotalia (F.) peripheroacuta in the studied sequence at Site 71 and to the absence of Globigerina falconensis, Globigerinoides seigliei, Globorotalia miozea, Globorotaloides variablis, Globigerinella aequilateralis, Globigerinopsis aguasayensis and Globigerinita naparimaensis from the corresponding interval at Site 289. This relationship is difficult to reconcile in view of the increased dissolution proposed herein for the interval at Site 71 relative to the correlated sequence at Site 289. However, several species present at Site 71 are also found at Site 289 in horizons younger than the corresponding interval (i.e. G. seigliei, G. variablis, G. aequilateralis, G. aguasayensis and G. naparimaensis). The anomaly may therefore be caused by downhole contamination at Site 71 as suggested for the radiolarian Cannartus? petterssoni. Alternatively, palaeoenvironmental variations between the two sites may have created the diversity differences. It is suggested that a combination of these two factors is responsible for the anomaly between simple diversity values. In contrast, the Shannon-Wiener Index values are similar and range from 2.00 to 2.20 at both sites.

A discussion of the palaeoenvironmental implications of the similarities and differences in planktonic foraminifera assemblages at Sites 289 and 71 is given in Chapter VII.

ii) Radiolaria

An approximate comparison of the taxonomic composition of assemblages and the relative distribution of individual species from 47-6 to 44-2 at Site 289 with these from 15-6 to 13-1 at Site 71 can be made from figs. 31 and 45.

There are several similarities between assemblages from both sites, e.g. *Stichocorys delmontensis*, *"Spyrid spp."*, *Trisolenia spp.*, *"Porodiscid spp."*, *"Litheliid spp."* and *"Spongodiscid spp."* occur in relatively high abundance throughout. Both sequences are also characterised by relatively stable assemblages(figs. 39, 46a). The relative distribution of individual taxa at both intervals is similar in many cases, although noticeable differences occur with regard *S. delmontensis*, *"Porodiscid spp."*, *"Litheliid spp."* and *"Spongodiscid spp."* which are all more abundant at Site 71 and *Trisolenia spp.*, which is more abundant at Site 289.

Higher simple diversity values in assemblages from Site 71 compared to those from Site 289 have been discussed previously in this chapter. Shannon-Wiener Index values from assemblages at both sites are however quite similar (2.52 to 2.78 at Site 71; 2.55 to 2.73 at the corresponding interval at Site 289).

A discussion of the palaeoenvironmental implications of the similarities and differences in radiolarian assemblages at Site 289 and 71 is given in Chapter VII.

CHAPTER VI

A PALAEOENVIRONMENTAL (PALAEOTEMPERATURE) RECONSTRUCTION OF THE MIDDLE TO LATE MIOCENE SEQUENCE AT SITE 289

1. INTRODUCTION

The palaeoenvironmental reconstruction attempted for the Middle to Late Miocene sequence at Site 289 relates primarily to changing temperature in the epipelagic zone (upper 300m) of the water column.

The palaeotemperature reconstruction is based on distributional trends exhibited by a limited number of planktonic foraminifera. Response of the entire planktonic foraminifera and radiolaria biota to the suggested palaeotemperature changes at Site 289 is discussed in Chapter VII. An integrated palaeoenvironmental/palaeoecological interpretation for Site 289 in the western equatorial Pacific is then used as a basis for discussion of some distribution of taxa in the Middle Miocene at Site 71 in the central equatorial Pacific.

2. PALAEOTEMPERATURE RECONSTRUCTION: A DISCUSSION

Previous ecological studies reveal how the quantitative and qualitative distribution of Recent planktonic foraminifera and radiolaria from both the water column and surface sediments can be related to oceanic conditions, in particular of temperature, salinity and nutrient content (BÉ, 1977; CASEY, 1977; see Chapter II herein). By assuming that extant taxa were similarly influenced in the geological past, many studies have attempted Pleistocene palaeoceanographic reconstructions using the distribution of fossil planktonic taxa in deep sea sediments (CLIMAP, 1976).

Palaeotemperature studies of Pleistocene cores using planktonic foraminifera in particular have enjoyed increasing popularity since the pioneering work of SCHOTT (1935) (see BOLTOVSKOY and WRIGHT, 1976, p. 348, for a review and extensive bibliography). Recent studies have also demonstrated the utility of radiolaria for Pleistocene palaeotemperature reconstructions (NIGRINI, 1970; KEANY and KENNETT, 1972, 1975). However, although temperature exerts a vital role in determining the distribution pattern of many planktonic groups (MCGOWAN, 1971), CIFELLI (1971) highlights several important aspects of planktonic foraminiferal distribution that do not appear to be primarily governed by temperature. Nevertheless, the success of multidisciplined projects such as CLIMAP (CLIMAP, 1976; CLINE and HAYS, 1976) indicate that considerable palaeotemperature information can be extracted from distribution trends in planktonic foraminifera and radiolaria. Palaeotemperature reconstructions for the Pleistocene are based on the assumption that cold and warm water assemblages migrate with time in response to water mass and isotherm movements initiated by periodic large scale glacial pulses from polar regions.

Miocene deep sea sequences have not been subjected to the kind of voluminous palaeotemperature work that has been focused on Pleistocene sections. INGLE (1967), KENNETT (1968), KENNETT and VELLA (1975) and KELLER (1980) have attempted palaeoclimatic reconstruction be means of planktonic foraminifera,while CASEY (1970, 1972) and CASEY, PRICE AND SWIFT (1972) present palaeoclimatic curves using radiolaria. SANCETTA (1978) utilised several microfossil groups to formulate a general palaeoceanographic/palaeoclimatic model throughout the Pacific Ocean during the entire Neogene. A palaeoceanographical and palaeotemperature reconstruction for the Miocene is the current aim of the CENOP programme

(HAQ et al., 1980; KEIGWIN and SHACKLETON, 1980; VINCENT, KILLINGLEY and BERGER, 1980).

The successful reconstruction of Miocene oceanic palaeotemperatures by means of distribution trends in planktonic foraminifera and radiolaria must overcome a number of problems not encountered in studies involving more recent environments.

The ecological preferences of Recent taxa can be ascertained by direct observation. Such information forms the basis of palaeotemperature reconstruction in Pleistocene sequences. However, extant species of planktonic foraminifera and radiolaria rarely range below the Pliocene (BLOW, 1969; RIEDEL and SANFILIPPO, 1977). In the present study, only ten planktonic foraminifera encountered in the Middle to Late Miocene sequence actually range into the Recent (see Appendix I). The palaeoecology of the majority of Miocene forms cannot be based on empirical observation as in the case of Recent taxa. Palaeotemperature reconstruction of Miocene oceans by means of distributional patterns in planktonic foraminiferal and radiolarian taxa are therefore restricted by limited ecological knowledge of the taxa encountered. Conclusions must be based on the assumption that the ecology of those Miocene forms still living has not changed with time. Supporting evidence may be gained from extinct species whose distribution patterns outlined in previous studies strongly suggest a preference for a particular thermal regime (see SANCETTA, 1978).

Palaeotemperature reconstructions of Pleistocene deep sea sequences have been confidently made because the period was subject to extreme palaeoclimatic fluctuations which, it has been assumed, are clearly reflected in contemporaneous microfossil assemblages. A problem associated with the present study in particular is the relatively slight palaeotemperature fluctuations which may be anticipated for the western and central equatorial Pacific Ocean during the Miocene, with the possibility that such environmental changes are unreflected in the microfossil assemblages. Observed quantitative and qualitative changes in such assemblages may be due to changes in environmental factors such as salinity or nutrient content, which, because of limited knowledge, are difficult to identify.

A palaeotemperature reconstruction for the Middle and Late Miocene at Site 289 is attempted by means of the following distribution features:

i) mean size distribution in Orbulina universa.

ii) the relative abundance of keeled globorotaliids:

- a. Globorotalia fohsi s.l.
- b. Globorotalia cultrata group.

iii) coiling direction changes in the G. cultrata group.

The palaeotemperature conclusions derived by these means may be regarded as unsatisfactory as they reflect trends exhibited by a small number of taxa only. However, of all the forms encountered in the present study, those used are the only taxa which previous studies suggest a strong relationship between (palaeo)temperature and distribution, and which occur in sufficient numbers in the present study to render significant conclusions possible.

3. SPECIFIC PRINCIPLES

i) Orbulina universa

Orbulina universa is a spherical species which is ubiquitous in tropical to subpolar planktonic foraminiferal assemblages of all oceans (BÉ, 1977). Biometric studies indicate that mean size in the taxon is a good indicator of contemporaneous surface water temperatures in both Recent and Pleistocene oceans.

BÉ, HARRISON and LOTT (1973) undertook a statistical analysis of size in O. universa from plankton and surface sediment samples throughout the Indian Ocean. The strong inverse correlation between test size and latitudinal occurrence demonstrated a direct correlation between mean test diameter and surface water temperature. Populations with large tests (mean diameter >650µ) are present in tropical areas with temperatures greater than 25°C. Test sizes average less than 450µ within the Subtropical-Subantarctic Transition zone (the Subtropical Convergence) and in Subantarctic areas with temperatures lower than 14°C. A marked decrease in mean test size from 550µ to 450µ occurs in a relatively narrow belt in mid-latitudes. BÉ et al. (1973) suggest test size is also influenced by salinity, although the relationship is not consistent. Maximum abundance of the species occurs in subtropical waters and in areas of current upwelling and convergence in relatively cool waters (BÉ et al., 1973). Under these so-called 'optimum conditions', O. universa attains medium size. BÉ et al. (1973) suggest that the occurrence of large and small sizes in so-called 'marginal areas' is due to delayed maturation during ontogeny in equatorial waters and stunted growth in subpolar waters respectively.

BÉ and DUPLESSY (1976) applied the concept to the fossil record. In Pleistocene cores from under the subtropical convergence, the O_2 isotope and micropalaeontological transfer function palaeotemperature records indicate a sequence of glacial and interglacial events for the past 500,000 years. Mean size distribution of O. universa over the interval demonstrates a good correlation with these trends and indicates the promise of this taxon as a tool for independent palaeoclimatic reconstruction.

MALMGREN and HEALY-WILLIAMS (1978) compared O. universa mean size distribution with palaeoclimatic changes derived from O_2 isotope and transfer function techniques in Late Quaternary cores from the Gulf of Mexico. An inconsistent relationship observed between the two trends is thought to reflect the lack of sharp water mass boundaries and the maintenance of uniform temperatures in the Gulf region (MALMGREN and HEALY-WILLIAMS, 1978).

However, further investigtions by ROTTMAN (1979) and COLOMBO and CITA (1980) in Pleistocene sequences from the western Pacific and Atlantic Oceans respectively correlate mean size distribution trends with glacial and interglacial stages and reaffirm the potential of the species for palaeotemperature interpretation in oceanic regions.

ii) Abundance of keeled Globorotaliids

The distribution of dorso-ventrally flattened planktonic foraminifera possessing peripheral keels is thought to be strongly related to temperature (FRERICHS, 1971). So-called 'keeled globorotaliids' are presently found in abundance only in tropical and subtropical oceanic regions (BÉ, 1977). Consequently, the expansion and contraction of an equator-centred belt as defined by distribution limits of fossil keeled forms has been used as a palaeoclimatic indicator throughout the Late Cretaceous and Tertiary (BANDY, 1960, 1968).

Keeled globorotaliids are well represented in the Middle to Late Miocene sequence at Site 289 by *Globorotalia fohsi* s.l. and *G. cultrata* group. *G. fohsi* s.l. ranges from Zone N.11-12 to within Zone N.13 while *G. cultrata* group ranges from within Zone N.11-12 to beyond the upper limit of the studied sequence and is presently extant. Evidence from previous studies that these forms preferred warm, tropical regions is given in the taxonomic section of this thesis (Appendix I).

Variations in abundance of G. cultrata group[1] in Pleistocene deep sea sequences have been used extensively as palaeotemperature indicators, allowing the recognition of glacial and interglacial stages.

SCHOTT (1935) was the first to conclude that vertical variations in the abundance of G. cultrata in cores from the equatorial Atlantic probably correspond to alternating climatic conditions during the Pleistocene, with high abundance indicating interglacials and low abundance indicating glacials.

ERICSON and WOLLIN (1956, 1968) using a frequency to sediment weight ratio method, derived climatic curves from variations in the "G. menardii complex" (including G. tumida) from several cores in the Atlantic Ocean. ERICSON and WOLLIN (1956) reported a close correlation in the climatic curve derived from this method with the O_2 isotope palaeotemperature trends derived from some of the cores by EMILIANI (1955), although the relationship was not entirely consistent. The climatic zones of ERICSON and WOLLIN (1956, 1968) were used to erect a Pleistocene stratigraphy for deep sea sediments in which warm and cold intervals, defined by high and low abundance of "G. menardii complex", and designated by the notations Z to Q, were believed to correspond to continental glacial and interglacial stages respectively. Support for this concept is offered by HAYS et al. (1969) who investigated the $CaCO_3$ content of Pliocene to Recent sequences from the equatorial Pacific and, following ARRHENIUS (1952), correlated high percentages with the glacial intervals of EMILIANI (1966) and ERICSON and WOLLIN (1968).

In the Gulf of Mexico, BEARD (1969) demonstrates the use of G.

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[1] often reported as G. menardii (see Appendix I)

cultrata abundance for recognising Pleistocene climatic cycles. Intervals of low G. cultrata abundance (cold periods) correlate well with water depth changes in the shallow shelf environment which are interpreted as representing glacially induced eustatic sea level falls and are believed to represent glacial stages recognised on the North American continent. According to STAINFORTH et al. (1975), oil company palaeontologists working the coastal part of the Gulf of Mexico routinely record and correlate palaeotemperature fluctuations recognised by warm and cold species abundance alternations with eustatic cycles and continental glacial/interglacial stages.

Further use of the abundance of G. cultrata for palaeoclimatic interpretation is demonstrated by BOLTOVSKOY (1974b) for the Pleistocene of the Indian Ocean.

Perhaps the most convincing evidence as to the reliability of abundance variation in G. cultrata for palaeotemperature interpretation is offered by IMBRIE, Van DONK and KIPP (1973) who undertook a palaeoclimatic investigation of a Late Pleistocene Caribbean deep sea core. Primary palaeotemperature curves were derived from O_2 isotopic and transfer function methods using planktonic foraminifera. The general patterns of palaeotemperature recorded by these methods were also well reflected in abundance variation in G. cultrata.

Recently however, doubt has been cast on the use of G. cultrata group as a palaeotemperature indicator as practised by ERICSON and WOLLIN (1956, 1968) and LAMB (1969). THIEDE (1975) studied living populations of G. cultrata in surface waters off the coast of West Africa. Maximum abundances were found in a cold upwelling zone, casting doubt on the use of maximum abundance of the species as a warm water indicator in areas of Pleistocene upwelling.

VALENCIA (1977) investigated the Pleistocene stratigraphy of cores from the Ontong Java Plateau, located close to Site 289. VALENCIA (1977) postulated a correlation between glacial stages and high frequencies of the G. cultrata group which resulted from the initiation of upwelling in surface waters of the western equatorial Pacific. However, the proposed relationship was not consistent in all cores studied.

The apparent ambiguity concerning the relationship of temperature and abundance in G. cultrata group is further highlighted by the work of ERICSON and WOLLIN (1970). From a comparison of Pleistocene climatic records defined by variation in abundance of G. cultrata gp. in cores from the southeastern Pacific with similar records in cores from the Atlantic, the authors concluded that times of warm suface water in the Pacific were at least partly synchronous with times of cool water in the Atlantic.

A relationship between abundance of G. fohsi s.l. and palaeotemperature has not been commonly applied in previous studies, although presence of the taxon has been used to infer a warm, tropical influence (see Appendix I).

OLSSON (1972) has, however, related maximum size of subspecies in the group to the peak of a warming cycle and suggests that the evolution of the taxon can be viewed as a response to a climatic warming trend, while the extinction of the lineage can be regarded as a response to climatic cooling. In the present study, the relative abundance of G. fohsi s.l. is regarded as a measure of its evolutionary success, which is itself related to palaeotemperature in the sense of OLSSON (1972).

iii) Coiling Direction in Globorotalia cultrata Group

Planktonic foraminifera usually possess trochospiral tests which, when viewed on the spiral surface, show coiling either to the left (sinistral) or to the right (dextral). Coiling direction changes in particular species have been widely used in biostratigraphical and palaeoclimatic studies (see KENNETT, 1976 for a major review). However, the biological reasons why a species should switch dramatically from one mode of coiling to another remains obscure. LIPPS (1979) considered sixteen "causes" of coiling direction changes which have been proposed by various workers, giving particular credence to temperature control and reproductive strategy. The cause of coiling direction in G. cultrata group will be considered further in Chapter VII in light of the palaeoenvironmental conclusions of this study.

Environmental and palaeoenvironmental studies involving coiling direction changes in planktonic foraminifera have been made with particular reference to the extant form, Neogloboquadrina pachyderma (Ehrenberg). Sinistral and dextral forms of this species presently predominate on opposite sides of the 7.2°C surface isotherm in the North Atlantic, the 9°C surface isotherm in the South Atlantic and the 6.5 to 6.8°C surface isotherm in the South Pacific (BOLTOVSKOY and WRIGHT, 1976; KENNETT, 1976). The close relationship between sinistral forms and polar waters has been used in palaeoclimatic studies involving Late Miocene to Recent deep sea sequences from middle and high latitudes (JENKINS, 1967; BANDY, 1972; KEANY and KENNETT, 1972).

Several studies have documented coiling direction changes in G. cultrata group from the Middle Miocene to Recent. The taxon has displayed a strong preference for either sinistral or dextral coiling and rarely exhibits a random mode.

ROBINSON (1969) and BOLLI (1971) for the Caribbean and tropical Pacific, SRINIVASAN and AZMI (1978) for the Indian Ocean and BEARD and LAMB (1968) for Venezuela and the Gulf of Mexico, indicate that coiling direction is predominantly sinistral during the Middle Miocene, both sinistral and dextral during the Late Miocene, predominantly dextral during the Pliocene and exclusively sinistral during the Pleistocene to Recent. The lack of dextral forms in modern oceans prevents any empirical investigation regarding a relationship between temperature and coiling direction in G. cultrata. However, evidence from the stratigraphic distribution of fossil forms suggests coiling preference may have been controlled by palaeotemperature.

The switch from predominantly dextral to exclusively sinistral forms near the Pliocene/Pleistocene boundary has been well documented. ERICSON, EWING and WOLLIN (1963) defined the boundary in deep sea sequences on several critera, one of which was the coiling direction change in "G. menardii complex". The authors further believed the horizon coincided with climatic deterioration associated with the first Pleistocene continental glaciation. However, subsequent investigations indicate that the switch from dextral below to sinistral above coincides with climatic warming (AKERS, 1965; MCINTYRE et al., 1967; POAG and AKERS, 1967; GLASS et al., 1967). GLASS et al. (1967) date the event by radiometric methods at approximately 2.3 m.y. B.P., an age subsequently confirmed by BEARD (1969) and STAINFORTH et al. (1975). The stratigraphic position of the event relative to the Pliocene/Pleistocene boundary has been subject to debate, a full discussion of which is considered beyond the scope of the present study. In brief, Gulf coast palaeontologists place the boundary at 2.8 m.y. B.P., below the horizon at which the coiling switch occurs. This proposed boundary coincides with a horizon indicating major climatic deterioration assumed to reflect the onset of the first Pleistocene continental glaciation in North America, i.e. the Nebraskan stage (BEARD, 1969; BEARD and LAMB, 1968; STAINFORTH et al., 1975). BEARD (1969) correlates the coiling direction change with the boundary between the first Pleistocene glacial stage of the North American continent (the Nebraskan) and the younger interglacial (the Aftonian). BEARD and LAMB (1968) had earlier associated this horizon with the replacement of cold water planktonic foraminiferal faunas of the Nebraskan stage by warmer planktonic facies characterised by abundant sinistral *G. menardii* populations of the Aftonian stage. The record in the Gulf of Mexico therefore suggests an association of right and left coiled *G. cultrata* with cold and warm climatic intervals respectively. Other schools place the Pliocene/Pleistocene boundary at approximately 1.8 m.y. B.P. based on evolutionary rather than environmental evidence (GLASS *et al.*, 1967; BERGGREN and Van COUVERING, 1974). Nevertheless, GLASS *et al.* (1967) correlate the coiling direction switch with a change from cold to warm conditions within the Late Pliocene. It is thus evident that despite differences of opinion regarding the placement of the Pliocene/Pleistocene boundary, several authors independantly associate the final switch from predominantly dextral coiling to exclusively sinistral coiling in *G. cultrata* group with a change in climatic conditions from cold to warm at approximately 2.3 m.y. B.P.

BOLLI (1971) offers evidence that connects coiling direction changes in *G. cultrata* with palaeotemperature variation in the Middle to Late Miocene. The author considers coiling direction changes in two wells from the tropical Pacific (Bodjonegoro-1 of Java) and the Caribbean (Cubagua-1). The evidence shows that preferred coiling direction and changes from sinistral to dextral and back to sinistral in *G. cultrata* are not always synchronous between the two sections. In the late Middle and Late Miocene especially, there are several coiling changes in the Cubagua section while at the same time the species continues to coil sinistrally at Bodjonegoro. BOLLI (1971) suggests that if water temperature influenced coiling direction of G. cultrata at that time, then the southern part of the Caribbean Sea would seem to have had several marked temperature changes during the Middle to Late Miocene. At the same time, the temperature would seem to have remained more stable in the tropical Pacific. By inference, because the surface waters of the Java region were probable warmer than those of the Caribbean, as is the case today, the increase in the incidence of dextral forms in the latter region would be associated with cooler waters. This proposed relationshipn between dextral forms and decreased water temperatures during the Miocene is consistent with that discussed above for the Late Pliocene/Early Pleistocene. BOLLI (1971) suggests that the sporadic occurrence of the tropical species, Globorotalia tumida s.l. in the Cubagua-1 is further evidence for cooler conditions relative to the Bodjonegoro-1 section.

4. DISCUSSION OF DATA

i) Orbulina universa

The quantitative distribution of Orbulina universa at Site 289 is given in fig.22. The species ranges throughout the studied sequence and is present in almost all samples. Abundance is consistently low and varies from very rare to few.

Eighty-three samples, from cores 50 to 24, were used from the sequence for the biometric study. In addition, a further fourteen samples were analysed throughout the remaining late Late Miocene in order to infer the palaeoclimatic history throughout the entire Middle and Late Miocene sequence.

The calculated mean diameter for each sample is plotted in fig.48. Several distinct trends are evident. Following a rise and fall within Zones N.11-12 to within N.13 (cores 45 to 40), there is an overall

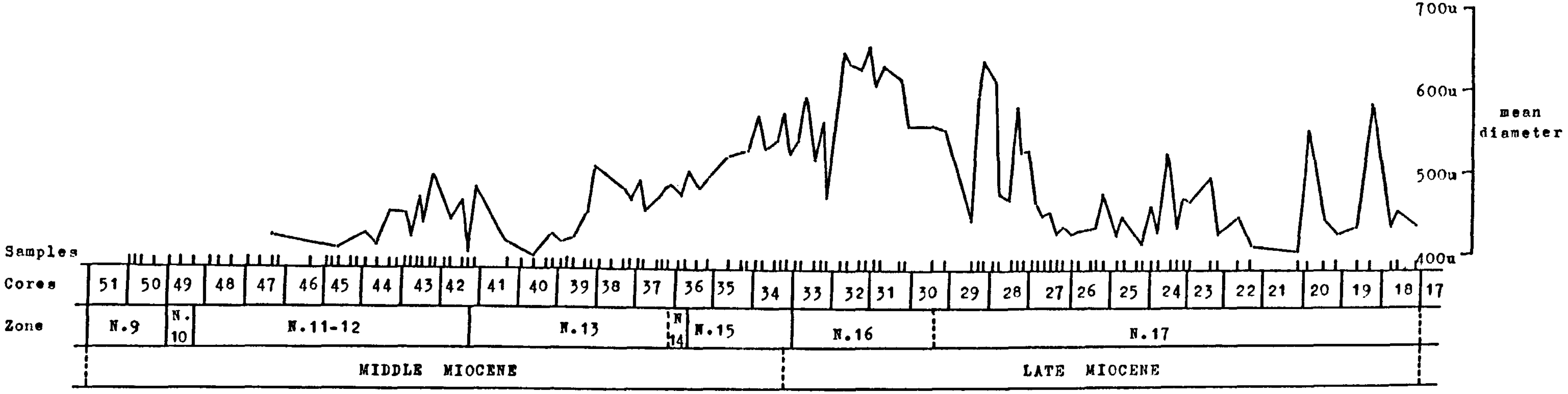

Fig. 48 Mean size distribution in <u>Orbulina universa</u> at Site 289 (only those samples with more than ten specimens are included)

tendency of gradually increasing mean diameters from within Zones N.13 to N.16 (cores 39 to 31). A large drop in mean diameters occurs in a short stratigraphical interval within Zone N.16 to early N.17 (cores 31 to 27). Thereafter, mean diameters are generally low though punctuated at certain horizons by increased values. Superimposed on this general outline, discrete intervals of relatively high mean diameters can be distinguished from intervening intervals of relatively low mean diameters:

High mean diameters: within cores 44 to 42, 39 to 37, 35 to 33, 32 to 30, 29 to 28, 24 to 23, 20 and within core 19.

Low mean diameters: within cores 47 to 45, 41 to 39, 37 to 36, 33, 30 to 29, 27 to 25, 22 to 21, 20 to 19 and within core 18.

The highest mean diameter is 642μ at sample 31-1 while the lowest mean diameter is 386μ at sample 39-5. The largest individual encountered measured 897μ (sample 31-1) while the smallest individuals measured 295μ (samples 37-5, 33-1, 23-3, 20-1).

The variation in the mean diameter of O. universa illustrated in fig.48 may reflect one or more of the following factors: bottom water velocity at the time of deposition, dissolution, unknown ecological factors, or palaeotemperature.

Variation in the size sorting potential of bottom currents during sedimentation may easily account for changes in the mean size of O. universa individuals. Such a mechanism would be difficult to demonstrate with the limits of the present study however, and since no sedimentary structures other than parallel laminae are apparent in the studied sequence (ANDREWS, PACKHAM et al., 1975; see Chapter I), the role of changing bottom water velocities in creating mean size variation is assumed to be negligible.

BÉ et al. (1973) suggest that large tests may possess thinner walls than small tests. If this relationship is correct, dissolution would tend to concentrate small forms. Intervals of increased dissolution of calcium carbonate are thought to be generally restricted to cores 50 to 48 (Chapter V). Although this sequence is characterised by no or very rare O. universa individuals, subsequent intervals of low mean diameters are not accompanied by evidence of dissolution in the overall planktonic foraminiferal assemblages. That variation in mean diameter does not primarily reflect dissolution intensity is further substantiated by variation in the relative abundance of keeled globorotaliids (see p.159, this chapter).

Variation in mean size may reflect unknown ecological factors such as salinity or nutrient content, although the extent of such a relationship is virtually impossible to measure without independent evidence for correlative purposes.

Mean size variation in O. universa is thus assumed to primarily reflect palaeotemperature changes as shown for extant individuals and the palaeotemperature reconstruction undertaken in this study is partly based on this hypothesis. The assumption is substantiated by the correlation of palaeotemperature trends as interpreted from other unrelated sources, i.e. relative abundance and coiling direction in Globorotalia cultrata group, discussed later in this chapter.

Intervals of high and low mean diameter, as shown on fig.48, are thus believed to indicate 'high' and 'low' palaeotemperatures respectively.

In order to help assess the validity of the mean size/palaeotemperature hypothesis, it may be useful to consider some relationships between size and abundance and within mean size itself.

The highest mean diameter present in the studied sequence (642μ) is less than those suggested by BÉ et al. (1973) to represent tropical surface waters of the Indian Ocean (>650μ). By 'Recent' standards, the highest mean values at Site 289 are equivalent to those present in sediments underlying the Central Water Mass (Subtropical) of the Indian Ocean while lowest mean values are equivalent to those present in sediments underlying the Subantarctic Water Mass (BÉ et al.,1973). The lower values present in the Middle to Late Miocene at Site 289 compared with those found at equivalent latitudes at the present time may possibly be attributed to one of three main factors: temperature differences, dissolution or evolution. Lower temperatures in equatorial regions during the Middle and Late Miocene compared with the present time may be responsible for smaller O. universa individuals. However, O_2 isotope palaeotemperature data suggest that Recent equatorial surface water temperatures attained their approximate values at or near the Early/Middle Miocene boundary (SAVIN et al., 1975).

The preferential dissolution of large tests in Miocene sediments would create spuriously low values. Although obvious dissolution is only apparent in the earliest Middle Miocene, a certain degree of dissolution, however mild, may have inevitably operated during sinking and accumulation of the tests (BERGER, 1979).

An evolutionary trend involving a net increase in mean size with time would account for the differences in the mean size between Miocene and Recent individuals, although such a suggestion is difficult to prove in the present study. If such a trend has operated however, then palaeotemperature inferences in the present study based on mean size distribution in O. universa must assume that the temperature/mean size relationship has always existed, in spite of any overall evolutionary size increase.

A comparison of mean size distribution and relative abundance in O. universa at Site 289 is given in fig.49. Such a comparison may be used to test the hypothesis of BÉ et al. (1973) that optimum conditions for the species are in subtropical waters where temperature and size is intermediate and abundance is greatest. At Site 289 there appears to be a normal correlation between maximum size (warmest, tropical/equatorial conditions?) and maximum abundance (fig.49). This correlation is not consistent, but nevertheless serves to illustrate the complexity of the temperature/size relationship in the species.

The biometric data may be considered in terms of size frequency distribution histograms for individual samples. BÉ et al. (1973) published frequency distribution graphs from diameter measurements of living O. universa individuals in the Indian Ocean. In view of the temperature/size relationship demonstrated by BÉ et al. (1973), size frequency distribution histograms may be useful as an indication of the relative influence in a sample, of individuals from different water masses. The graphs of BÉ et al. (1973, fig. 12) mostly show unimodal 'normal distributions' and suggest that all individuals are autochthonous to the water mass sampled. The only exception involves an area containing an oceanic water mass boundary west of Australia (between lats. 30°S and 35°S). Here the size frequency distribution is bimodal and may reflect individuals from two distinct water masses, although BÉ et al. (1973) do not comment on this possibility.

Size frequency distribution histograms were prepared on all samples from Site 289. Many distributions are unimodal and 'normal' although most are polymodal and skewed. Since the interpretation of such histograms remains rather speculative and uncertain, they are not all reproduced in this thesis. Nevertheless, several examples which

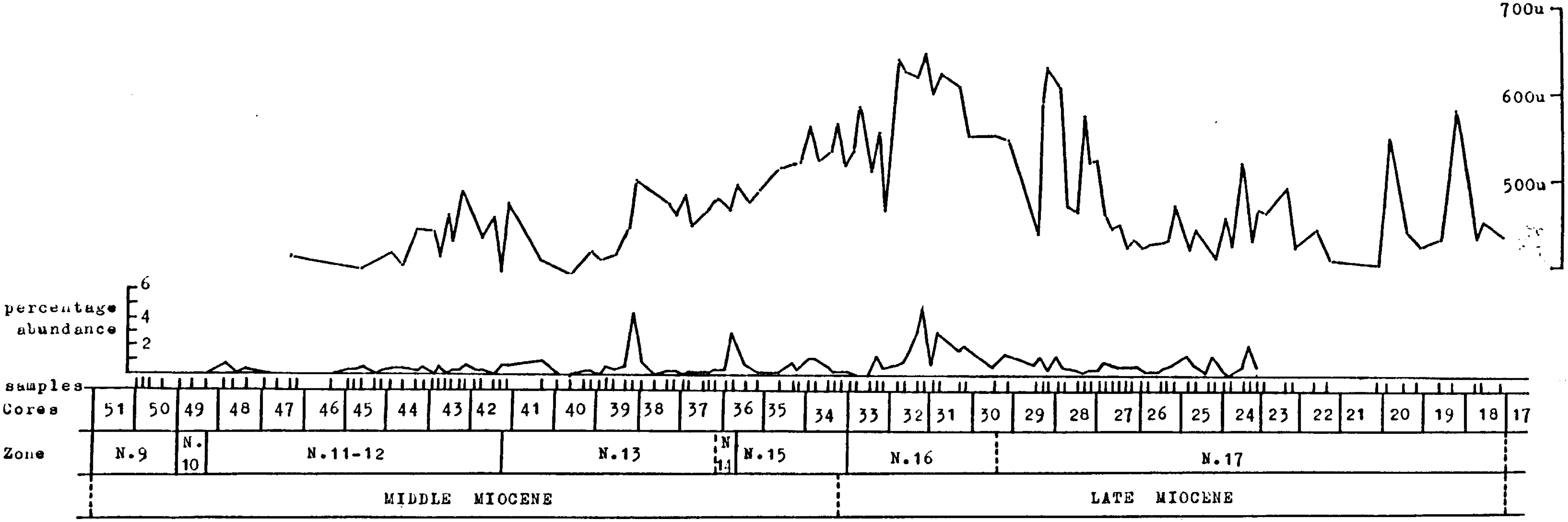

Fig. 49 Mean size distribution and percentage abundance of Orbulina universa at DSDP Site 289

illustrate the range of distribution types are included. The property of skewness was quantified by computer analysis using the numerical measure of moments (BLATT, MIDDLETON and MURRAY, 1972). Moment measures of skewness measure the asymmetry of a distribution, i.e. the deviation from a normal distribution. Such techniques are normally applied to grain size distribution studies of sediments.

Samples displaying a normal, unimodal distribution with a skewness value approximating zero includes 31-2 (fig.50). Those samples which are polymodal and negatively skewed (i.e. a bias towards larger sizes) includes 32-4 and 28-6 (fig.50). Those samples which are polymodal and positively skewed (i.e. a bias towards smaller sizes) includes 41-2 and 25-5. Further work on size frequency distribution patterns in plankton and underlying sediment samples is needed to clarify the possible relationship between polymodal distributions and different water mass populations in O. universa. Meanwhile the possibility that polymodal distributions in O. universa size frequency histograms at Site 289 represent the influence of different water masses cannot be ignored.

ii) Abundance of keeled globorotaliids and coiling directions in Globorotalia cultrata group

The abundance of keeled globorotaliids (G. fohsi s.l. and G. cultrata gp.) and coiling direction in the keeled Globorotalia cultrata group are considered together because of the intimate relationship apparent in the two phenomena for the G. cultrata group.

The abundance of G. cultrata group and G. fohsi s.l. from the Middle to Late Miocene sequence at Site 289, involving cores 50 to 24, has already been described (see Chapter V, p.110 , figs.26,27) and will be further considered during the course of the palaeotemperature reconstruction later in this chapter. For the purposes of the

Sample 31.2 : normal unimodal distribution
n = 58
mean = 601u
skewness = -0.28

Sample 32.4 : polymodal, negatively skewed
n = 32
mean = 618u
skewness = -0.99

Sample 28.6 : polymodal, negatively skewed
n = 55
mean = 602u
skewness = -0.65

Sample 25.5 : polymodal, positively skewed
n = 30
mean = 416u
skewness = 1.00

Sample 41.2 : polymodal, positively skewed
n = 41
mean = 408u
skewness = 0.87

250-275u	276-300u	301-325u	326-350u	351-375u	376-400u	401-425u	426-450u	451-475u	476-500u	501-525u	526-550u	551-575u	576-600u	601-625u	626-650u	651-675u	676-700u	701-725u	726-750u	751-775u	776-800u	801-825u	826-850u	851-875u	876u +

Fig. 50 Size frequency histograms for Orbulina universa at Site 289

reconstruction, the relative abundance of G. cultrata group is considered throughout the entire Middle and Late Miocene interval, including cores 23 to 18. It is only necessary here to reiterate that the main distributional feature apparent in keeled globorotaliids, particularly G. cultrata group, is the strong cyclicity in abundance.

The coiling direction record for G. cultrata group at Site 289 is given in fig.51. It is apparent that a strong preference for sinistral or dextral coiling is usual while random coiling is rare. Consequently, changes in coiling direction tend to be rapid over a short stratigraphical interval. An initial mode of sinistral coiling during the Middle Miocene is quickly replaced by an interval within N.13 in which the mode is usually dextral but punctuated by intervals of random coiling. Throughout the remainder of the Middle Miocene to within N.17 of the Late Miocene, coiling is strongly sinistral. The remainder of the Late Miocene and Early Pliocene is characterised by several switches from sinistral to dextral and back again. Dextral coiling predominates through most of the Pliocene while the latest Pliocene and entire Pleistocene is characterised by an exclusively sinistral mode.

The pattern of coiling direction switches in G. cultrata group described above for Site 289 is essentially similar to those described by ROBINSON (1969), BEARD and LAMB (1968), BOLLI (1971) and SRINIVASAN and AZMI (1978) from tropical sequences situated worldwide (see p. 149). The global pattern varies in the Middle and Late Miocene where the number of switches from dextral to sinistral modes differs according to locality. The Caribbean record, as reported by BOLLI (1971), is similar to that present at Site 289 and is characterised by several switches during the Late Miocene. In the Java region (BOLLI, 1971) and tropical Indian Ocean (SRINIVASAN and AZMI, 1978) however, coiling directions are more stable

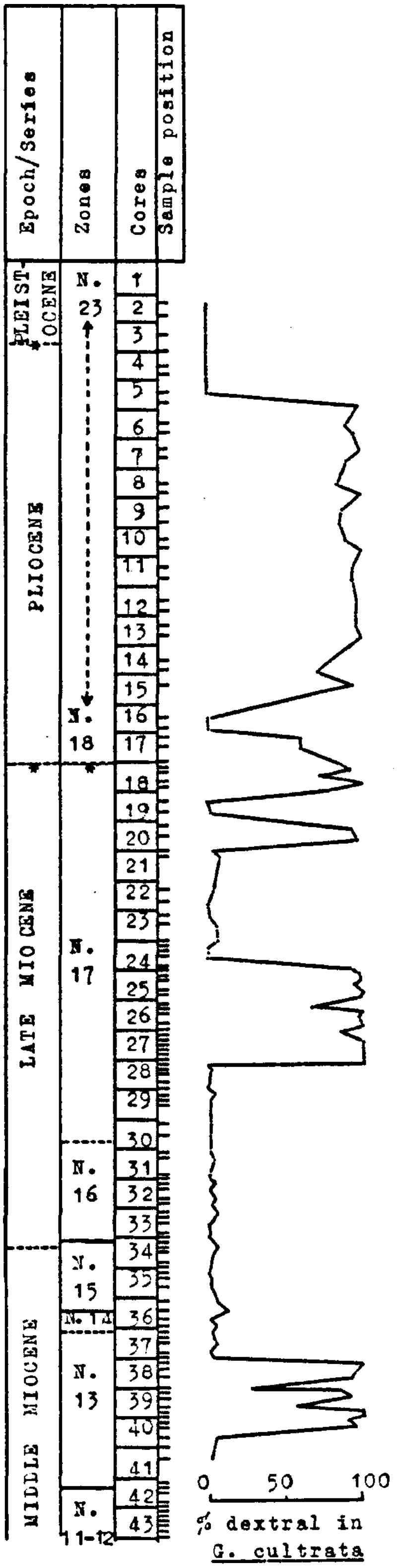

Fig. 51 Coiling trends in *Globorotalia cultrata* group at Site 289 (* = from Andrews, Packham *et al.*, 1975)

and switches less frequent in the corresponding interval.

As in the case of mean size in O. universa, the abundance of keeled globorotaliids may reflect one or more of the following factors: bottom water velocity during sedimentation, dissolution, unknown ecological factors or palaeotemperature.

Evidence is available, however, to suggest that the first two factors, involving current velocity and dissolution, were not significant in the case of the variation at Site 289.

A comparison of relative distribution and coiling direction in G. cultrata group serves to help eliminate the role of current sorting as an important contributary factor to abundance in keeled globorotaliids. In the interval within cores 28 to 27, sinistral forms undergo a massive and very rapid decrease in abundance from over 50% to less than 1% of the planktonic foraminiferal assemblages (see fig. 52). Dextral forms, however, are entirely unaffected by this event and remain consistently low in abundance within the same interval (fig.52). Since the forms are identical except for coiling mode, it is unlikely that any current regime could selectively remove sinistral forms only from the sediment. Thus, in this particular instance, within cores 28 to 27, a palaeoenvironmental factor is likely to be responsible for the changes in abundance of G. cultrata group coiling variants.

The role of dissolution in modifying planktonic foraminiferal assemblages at Site 289 and in particular within cores 50 to 48 has been previously discussed (see Chapter V). According to the dissolution rank of BERGER (1970) high abundance of keeled globorotaliids in sediments may indicate high dissolution. Meanwhile for O. universa, BÉ et al. (1973) suggest that large tests may generally possess thinner walls than smaller tests, which if correct, suggests that dissolution would tend to concentrate small forms. Increased dissolution at Site 289 should therefore expect to produce high abundance of keeled globorotaliids and low mean diameter in O. universa. However, instead of inverse correlation, the consistent association is that of a normal correlation, with high abundance in keeled globorotaliids and high mean diameter in O. universa (see below). Moreover, evidence discussed in Chapter V suggests the first major influx of G. fohsi s.l. within core 47 coincides with decreased dissolution. Such compound evidence suggests dissolution has not played a primary role in controlling the distributions discussed for O. universa and keeled globorotaliids.

As in the case of O. universa, variation in the relative abundance of keeled globorotaliids may be controlled by unknown palaeoecological factors, although in the absence of substantiating evidence only tentative speculation is possible.

The observed changes in abundance of keeled globorotaliids and coiling direction modes in G. cultrata group is thus taken to reflect changes in palaeotemperature, as indicated from previous studies. The palaeotemperature reconstruction is partly based on this hypothesis, which is substantiated by the correlation of palaeotemperature trends interpreted from an unrelated source (mean size in O. universa).

5. AN INTEGRATED PALAEOTEMPERATURE INTERPRETATION

A palaeotemperature curve for the Middle to Late Miocene sequence at Site 289 has been established from an interpretation of the data described above involving mean size distribition in O. universa, relative abundance of G. cultrata group and G. fohsi s.l. and coiling direction changes in G. cultrata group.

The palaeotemperature curve is believed to indicate palaeotemperature variations in the epipelagic zone of the palaeo-water column. A composite diagram (fig.52) outlines the method. Data from the three sources are displayed side by side against the stratigraphic column. The relative abundance of G. cultrata group has been split into dextral and sinistral abundance in view of the significance of coiling direction in this taxon. Since coiling preference in the group is rarely random, but usually strongly biased towards one of two modes, it follows that distribution in the two forms is usually almost mutually exclusive. However, plotting the separate distribution of sinistral and dextral forms clearly allows a comparison in the rate of abundance variation and facilitates interpretation of controlling factors.

The strongest evidence for palaeotemperature variation is offered by a comparison of mean size distribution in O. universa and the relative distribution of sinistral and dextral forms of G. cultrata group. Previous studies indicate that high mean size in O. universa and high relative abundance in sinistral forms of G. cultrata group is related to high oceanic surface water temperatures. A comparison of both distribution reveals an excellent normal correlation in the trends (fig.52). The correlation is clearly apparent to the eye and has not been statistically quantified. The trends exhibit the following properties which stratigraphically coincide.

a) a gradual increase in values during the late Middle and early Late Miocene (from cores 39 to 28) which culminate in distinct peaks within Zone N.17 (within cores 29 and 28). Within this interval, the increase in values is discontinuous and characterised by horizons of reduced values (within cores 40, 38, 37, 33, and 30 to 29).

b) a large and rapid reduction in values within the Late Miocene to produce a distinct trough within N.17 (within cores 27 to 24).

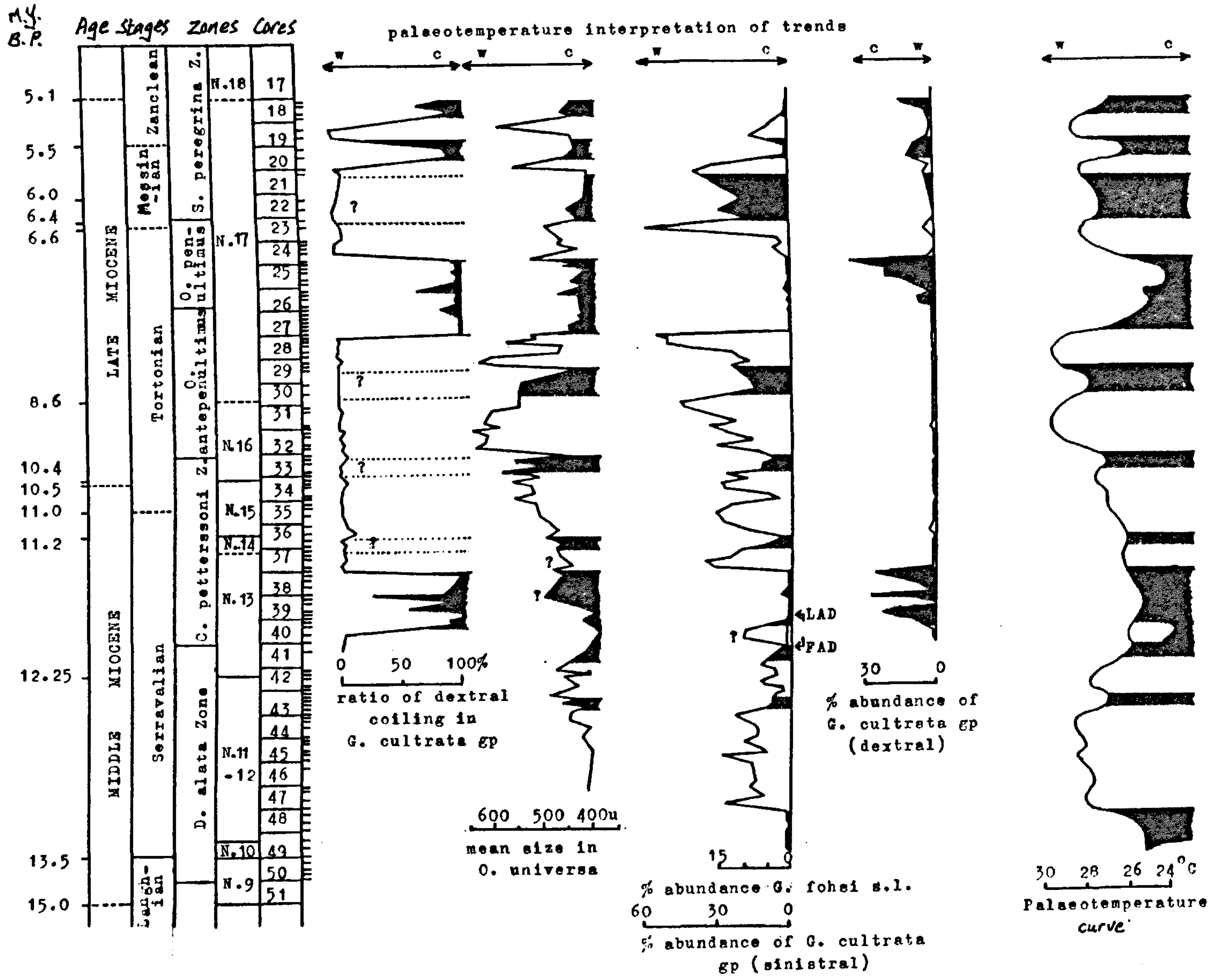

Fig. 52 Palaeotemperature interpretation for the Middle to Late Miocene at Site 289

LAD = last appearance datum of G. fohsi s.l.
FAD = first appearance datum of G. cultrata gp.
▨ = upwelling signal inferred in trends;
■ = interval of upwelling inferred in model
? = no correlation with other trend(s)

c) rapidly fluctuating values in the late Late Miocene to produce several distinct peaks (within cores 24 to 23, 21 to 20 and 19) and troughs (within cores 23 to 21, 20 to 19 and 18).

The normal correlation between the two trends is not absolutely consistent however; a drop in abundance in sinistral G. cultrata group forms within core 35 is accompanied by an increase in mean size in O. universa.

Previous studies also indicate that low mean size in O. universa and a strong preference for dextral coiling in G. cultrata group is related to reduced oceanic surface water temperatures. A comparison of both features at Site 289 reveals a close association (fig.52). Horizons where dextral forms dominate over sinistral forms are usualy accompanied by low mean size in O. universa (within cores 39, 38, 27 to 25, 20 and 18). A correlation between low mean size in O. universa and a predominance of dextral forms in G. cultrata group is not entirely consistent however, e.g. within cores 29 and 23 to 21, where while a large decline in values occurs in the former, sinistral coiling continues in the latter (fig.52).

The relative distribution of G. fohsi s.l. generally approximates a normal distribution within its stratigraphic occurrence in the early Middle Miocene (fig.52). For most of this sequence the mean size distribution data for O. universa are too sparse to make any significant comparison in trends similar to that possible between G. cultrata group and O. universa. However, a well defined peak in mean size of O. universa coincides with a small peak in abundance of G. fohsi s.l. within cores 43 and 42 (fig.52).

Palaeotemperature trends reflected by the "compound curve" are interpreted as follows:

The rapid evolution of G. fohsi s.l. in terms of sub-speciation and increased relative abundance within Zone N.11-12 reflects a major increase in palaeotemperature. The general amelioration recorded by cores 47 to 44 is interrupted by minor palaeotemperature deterioration indicated by decreased abundance of G. fohsi s.l.

Decline and eventual extinction of G. fohsi s.l., indicated by a gradual decrease in relative abundance starting in Zone N.11-12 (core 43) and terminating in Zone N.13 (core 40) reflects a gradual decrease in palaeotemperature. Within the interval, a temporary increase in the relative abundance of G. fohsi s.l. coincides with a peak in mean size of O. universa and represents a temporary palaeotemperature improvement (within core 42). Subsequent palaeotemperature deterioration within Zone N.13 is indicated by low mean size in O. universa (within cores 40 to 39) and an influx of dextral G. cultrata group (within cores 39 to 38). The extinction of the keeled globorotaliid G. fohsi s.l. coincides with the evolutionary appearance of a homeomorphic taxon, G. cultrata group. It is suggested that these events constitute evolutionary palaeoecological replacement by a more versatile keeled species which could respond to palaeotemperature deterioration with a dextral morphotype.

The subsequent reappearance of sinistral dominance and gradual increased abundance in G. cultrata group and the concomitant increase in mean size of O. universa from within Zone N.13 to within Zone N.17 suggests gradually increased palaeotemperatures over the interval. Temporary intermittent palaeotemperature deterioration is indicated at several intervals where both mean size in O. universa and relative abundance of G. cultrata group decrease in value (within cores 36, 33 and 30 to 29).

The large decline in mean size of O. universa and relative abundance in dextral G. cultrata group within Zone N.17 (within core 27) of the Late Miocene represents a major, rapid decrease in palaeotemperature. This interpretation is substantiated by a subsequent gradual increase in dextral G. cultrata group forms.

Eventual palaeoclimatic amelioration is suggested by an increase in the mean size of O. universa and the relative abundance of sinistral individuals of G. cultrata group (within cores 24 to 23). Subsequent trends in the remaining Late Miocene interval indicate rapid fluctuations in palaeotemperature with two peaks (within cores 21 and 19) intercalated with three lows (within cores 22, 20 and 18).

Although amplitudes and wavelengths within the palaeotemperature curve are derived from quantitative data, no statistical principles have been applied in their construction, and the curve may be regarded as tentative and subjective. Nevertheless, because the curve is based on sympathetic trends observed in unrelated taxa, it is regarded as representative of true palaeotemperature variation in at least a qualitative sense.

To introduce a quantitative aspect, a temperature scale has been applied to the curve (fig.52). The calibration is not, however, intended to be definitive; it is merely used to indicate the possible range of palaeotemperature variation and must be regarded as extremely tentative. The calibration of a temperature scale has been attempted from evidence offered by previous studies. The O_2 isotope record was interpreted by SAVIN et al. (1975) as showing that equatorial Pacific surface water palaeotemperatures rose rapidly during the late Early and early Middle Miocene, from approximately 20°C to 28°C. The authors indicate a 3°C increase during the early Middle Miocene (see Chapter III, p.60). These conclusions have been applied in the present study for palaeotemperature increases postulated for the early Middle Miocene at Site 289 (fig.52). In the Late Miocene, a palaeotemperature scale has been derived from the results of BÉ and DUPLESSY (1976). Variation in mean size diameter of _O. universa_ of approximately 200μ during the Pleistocene are related to temperature changes of between 4° and 6°C (see this chapter, p.144). Such a change in size occurs at Site 289 in the Late Miocene (cores 29 to 27, fig.52), where a similar temperature range is inferred.

Thus palaeotemperatures of surface waters at Site 289 in the western equatorial Pacific are thought to have varied from approximately 24°C to 29°C during the Middle to Late Miocene.

6. THE CAUSE OF THE PALAEOTEMPERATURE VARIATION

Chapter III considers the cause of palaeotemperature variation in surface waters of the equatorial Pacific during Pleistocene glacial events. It is believed that glacially induced intensification of atmospheric and oceanic circulation and eustatic sea level fluctuation increased equatorial upwelling in the eastern equatorial Pacific and introduced the phenomenon to the western equatorial Pacific (ARREHENIUS, 1952; HUTCHINSON, 1950, 1952; QUINN, 1971; VALENCIA, 1977; see also p.67 herein). The increased glacial development of the Antarctic continent during the Early and Middle Miocene is believed to have established a permanent glacial mode with "Pleistocene type" climatic variations and equatorial upwelling since the early Middle Miocene (SAVIN _et al._, 1975; Van ANDEL _et al._,1975; BERGER, 1979; KENNETT, 1978; SHACKLETON, in press; see also Chapter III, p.65-66).

At Site 289, cooling events postulated for the Middle and Late Miocene are considered to reflect the temporary development of upwelling in the epipelagic surface waters (upper 300m) of the western equatorial

Pacific. The stratigraphic occurrence of such events is indicated by the shaded intervals in fig.52. The cause of the upwelling during the Middle to Late Miocene is thought to have been similar to that during the Pleistocene, i.e. increased atmospheric and oceanic circulation and eustatic sea level lows initiated by periodic glacial accretion on and around the Antarctic continent (see above and Chapter III, p. 67).

The effect of upwelling and associated palaeotemperature variations on the palaeoecology and assemblage statistics of planktonic foraminifera and radiolaria at Site 289 is considered in Chapter VII. The relationship of palaeotemperature trends postulated in the present study to those developed in previous studies of the Middle and Late Miocene is discussed in Chapter VIII.

CHAPTER VII

THE DISTRIBUTION OF PLANKTONIC FORAMINIFERA AND RADIOLARIA IN RELATION TO THE PALAEOTEMPERATURE INTERPRETATION

1. INTRODUCTION

The quantitative distribution of planktonic foraminifera and radiolaria at Sites 289 and 71 can now be assessed in relation to the palaeotemperature interpretation for the Middle to Late Miocene at Site 289. The assessment is based on the assumption that maximum abundances of species to a large extent indicate the optimum environment in terms of temperature (BRADSHAW, 1959; BÉ and TOLDERLUND, 1971; HECHT, 1976; BÉ, 1977). Where distribution of taxa appear to be related to palaeotemperature events, certain conclusions may be reached as to the probable palaeoecology of these forms.

Information concerning the palaeoecology and optimum environments for Miocene planktonic foraminiferal and radiolarian taxa is either rudimentary or negligible (see Appendix I). In this study, the recognition of palaeoenvironmental preferences in particular species is intended to enlarge our palaeoecological understanding of the assemblages.

The palaeotemperature curve for the Middle and Late Miocene at Site 289 indicates variation from a maximum of approximately 29°C to a minimum of approximately 24°C. By assuming that latitudinal provincialism in planktonic faunas developed during the Early Miocene (see Chapter III), the palaeotemperature range should generally maintain dominantly tropical to subtropical assemblages according to the biogeographical schemes of McGOWAN (1974), BÉ (1977) and CASEY (1977) for the Recent.

Although a palaeotemperature interpretation is presented for the entire Middle and Late Miocene interval at Site 289 (cores 50 to 18), a comparison with the relative distribution of all taxa is only offered for the Middle to within the Late Miocene (cores 50 to 24).

2. PLANKTONIC FORAMINIFERA : SITE 289

A consideration of the palaeogeographical distribution of the taxa encountered at Site 289, as indicated in previous studies (see Taxonomy, Appendix I) reveals that most species are either restricted to low or middle latitudes e.g. *Globorotalia fohsi* s.l., *G. cultrata* group, *Globoquadrina altispira* s.l., *Globigerinoides obliquus* s.l., or are cosmopolitan, e.g. *Globorotalia acostaensis* s.l., *G. scitula*, *G. siakensis*, *Globoquadrina dehiscens*, *G. langhiana* group, *Orbulina spp.*, *Sphaeroidinellopsis spp.* The occurrence at Site 289 of species normally associated only with high latitudes is rare and is characterised by very low abundances e.g. *Globigerina bulloides*, *G. decoraperta*, *G. falconensis*. In addition, certain high latitude Miocene species are never encountered at Site 289, e.g. *Globorotalia miotumida* s.l., *G. conomiozea*, *G. panda*, *Globigerina quinqueloba*, *Neogloboquadrina pachyderma* (VINCENT, 1974; HOSKINS, 1978).

Variation in the relative abundance of species at Site 289 which can be related to palaeotemperature trends, should therefore distinguish those forms whose optimum environment appear to have existed within non-upwelling tropical waters characterised by high surface palaeotemperatures, from those forms whose optimum environment appear to have existed within upwelling tropical to subtropical waters characterised by cooler surface palaeotemperatures.

In the following account, several aspects of the foraminiferal assemblages are considered against the proposed palaeotemperature curve.

The palaeotemperature curve is compared to the relative distribution of the fifteen most abundant taxa and to the absolute distribution (i.e. presence and absence) in some of the less common forms. From these comparisons it can be possible, where appropriate, to infer a broad palaeoecology and optimum environment for certain taxa. Subsequently a palaeoenvironmental/ palaeoecological model is developed for the epipelagic zone at Site 289 which attempts to explain some of the major quantitative taxonomic variation of means of periodic upwelling.

In view of their possible palaeoenvironmental significance, trends of diversity and similarity in planktonic foraminifera are matched against the palaeotemperature curve to seek correlation.

Finally, in order to briefly consider a possible relationship between palaeoenvironment and adaptive radiation in planktonic foraminifera, the palaeotemperature curve is compared to the distribution of evolutionary events (appearances and extinctions) throughout the studied sequence.

i) Individual Taxa

A comparison of distribution of the fifteen most abundant taxa with the palaeotemperature curve is given in figs.53-57.

The distribution of Globorotalia fohsi fohsi, G. fohsi lobata and G. cultrata gp. [1] are intimately related to the palaeotemperature curve and the close normal correlations are as expected, with high abundance corresponding to increased palaeotemperatures and low abundance corresponding to decreased palaeotemperatures (fig. 53, 54).

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[1] fig.54 represents both sinistral and dextral variants of G. cultrata group.

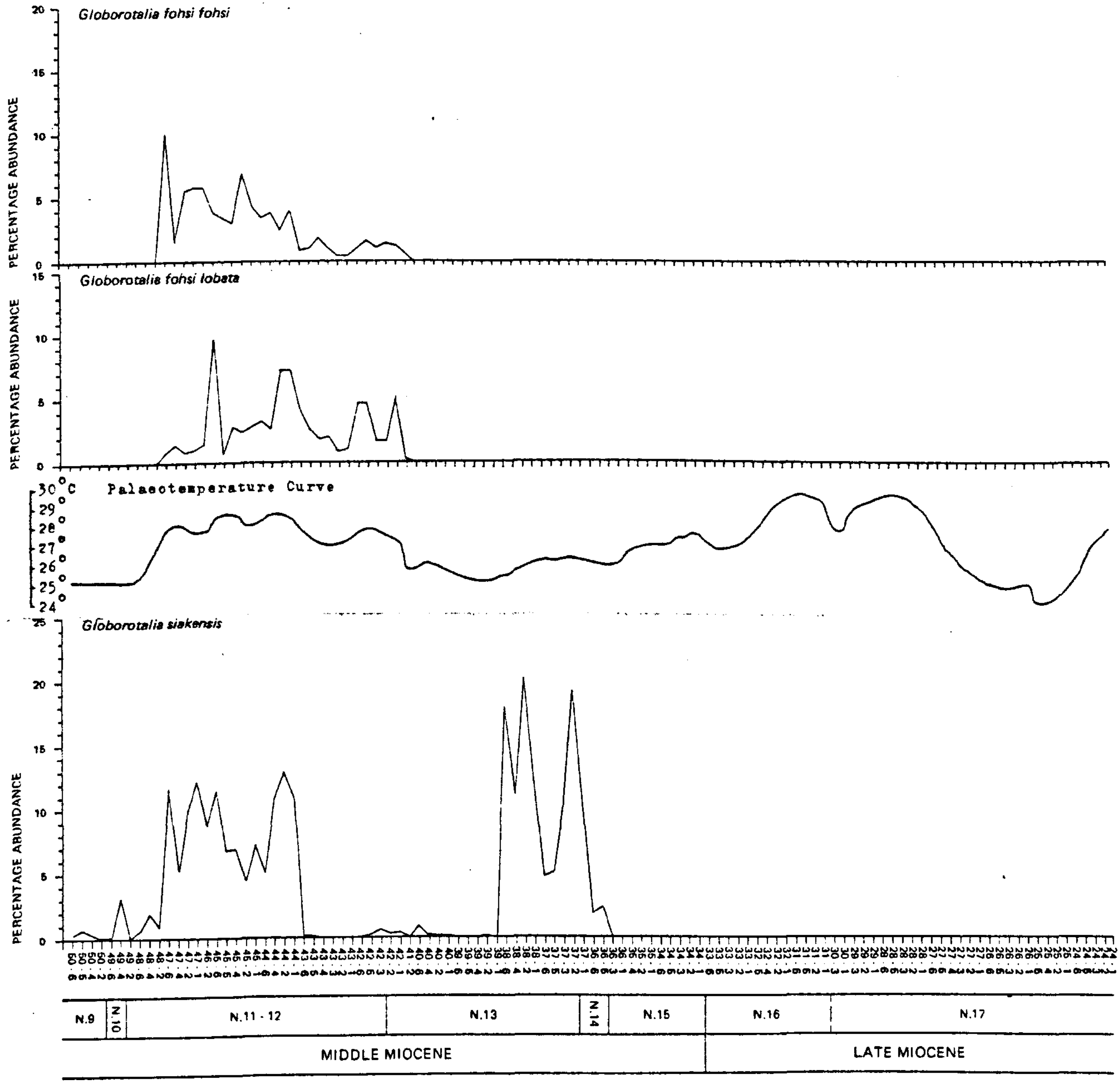


Fig. 53 Relative distribution of planktonic foraminiferal taxa compared to palaeotemperature curve, Site 289

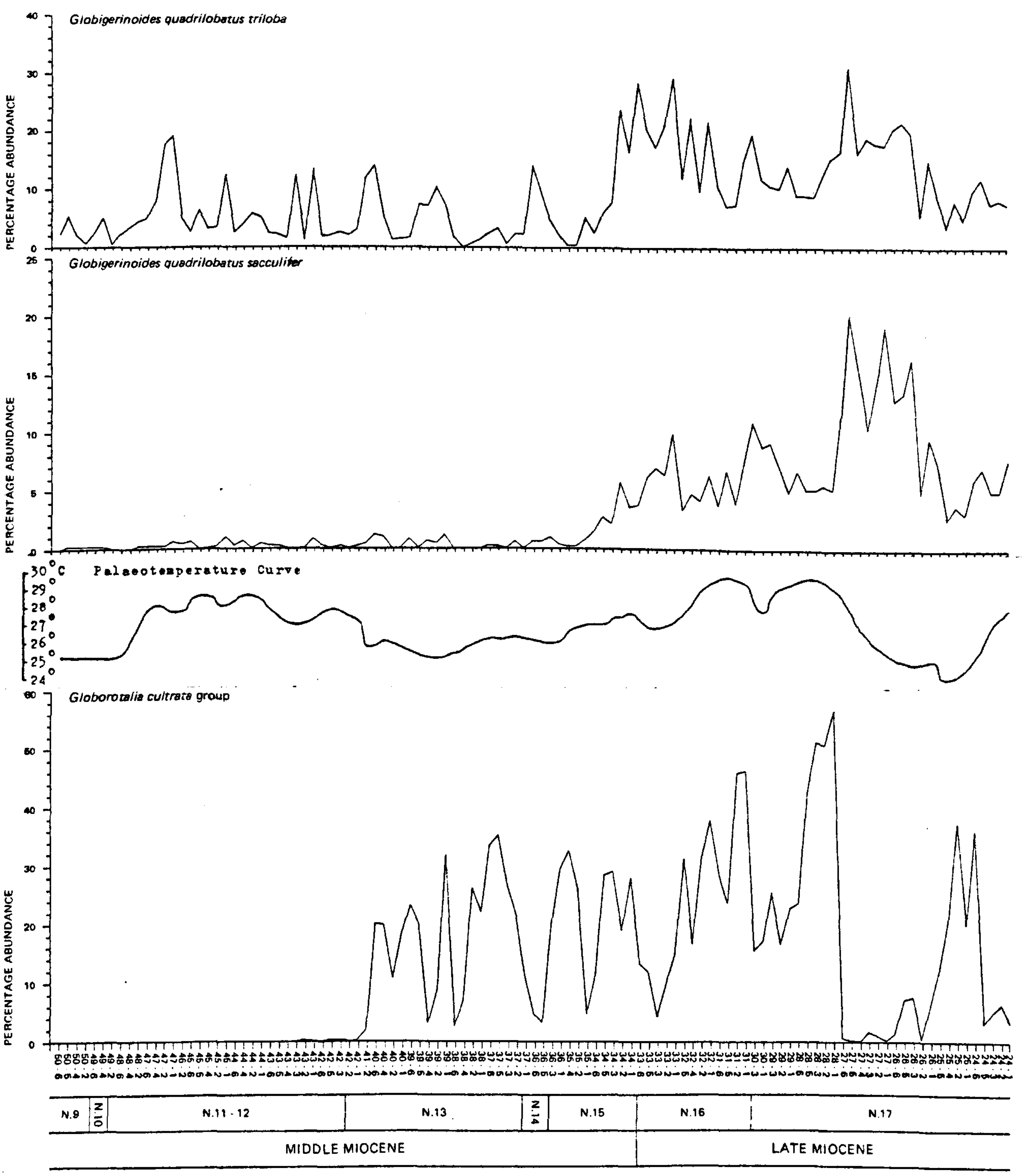


Fig. 54 Relative distribution of planktonic foraminiferal taxa compared to palaeotemperature curve, Site 289

The distribution of *Globorotalia siakensis* and *G. continuosa* is closely related and similarly show a good normal correlation with palaeotemperature trends (fig.53,55). The horizons where abundance increases dramatically in these taxa are generally characterised by increasing palaeotemperatures while the horizons where abundance decreases dramatically, including the final extinction datum of *G. siakensis*, are generally associated with decreasing palaeotemperatures. Beyond Zone N.14 however, a relationship between palaeotemperature trends and distribution in *G. continuosa* is not evident.

A comparison of abundance in *Sphaeroidinellopsis seminulina* s.l. with the palaeotemperature curve indicates a good normal correlation (fig.56). Although the trends are not entirely sympathetic in intensity, high abundance in the species is generally associated with increased palaeotemperature while low abundance is generally associated with decreased palaeotemperature.

The distribution of *Globoquadrina venezuelana* exhibits a consistent inverse relationship with palaeotemperature trends (fig.56). High abundance is usually accompanied by decreased palaeotemperatures while low abundance generally corresponds with increased palaeotemperatures.

The interval of high abundance in *Globoquadrina dehiscens* coincides with decreased palaeotemperatures (fig.55). However, an inverse relationship is not apparent throughout the entire sequence and several intervals of low palaeotemperatures are unaccompanied by increased abundance in the species.

In general, the distribution of *Globigerinoides quadrilobatus triloba*, *G. quadrilobatus sacculifer* and *G. obliquus* s.s. reveal an inverse relationship with palaeotemperature trends, in which high

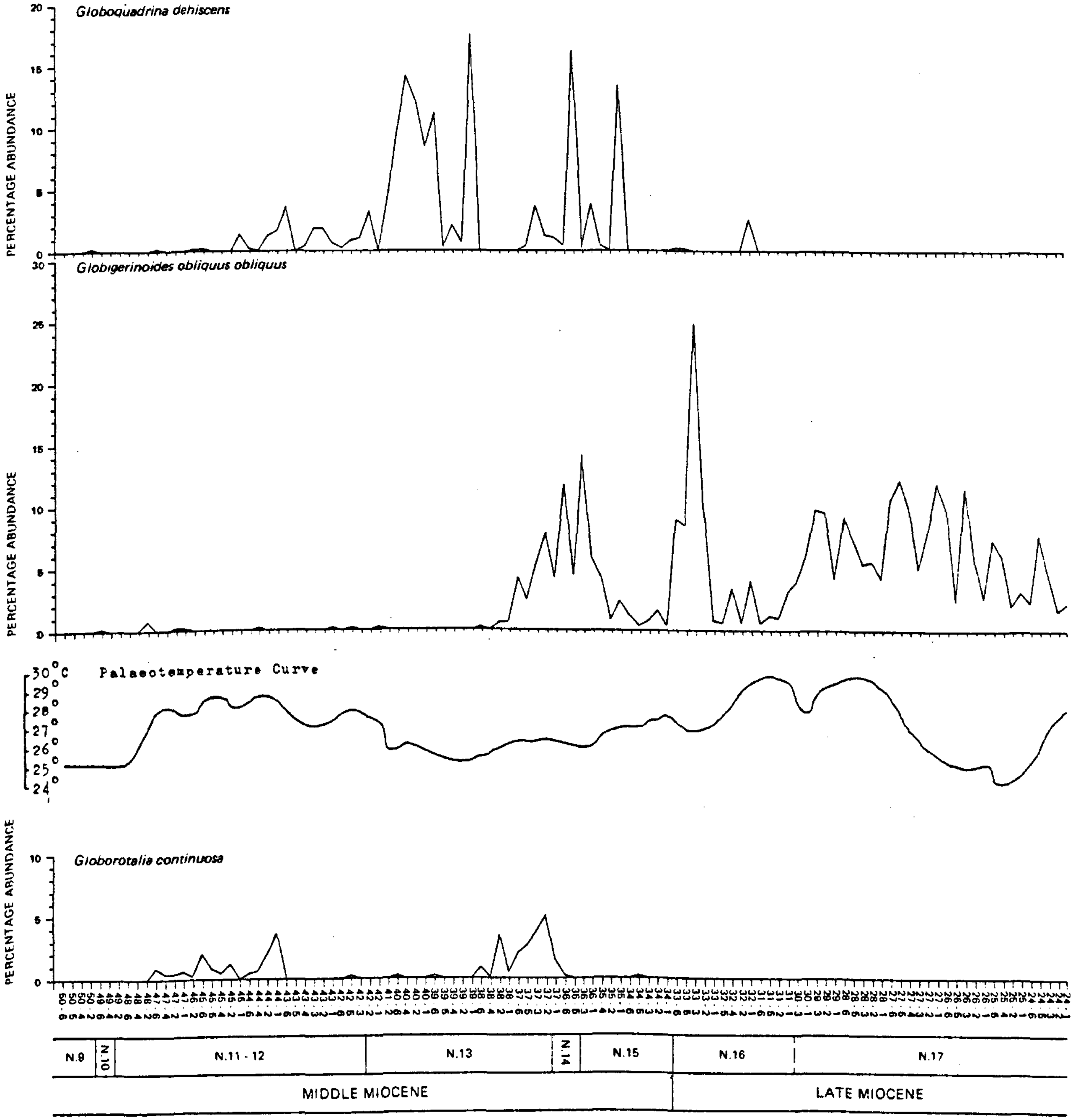


Fig. 55 Relative distribution of planktonic foraminiferal taxa compared to palaeotemperature curve, Site 289

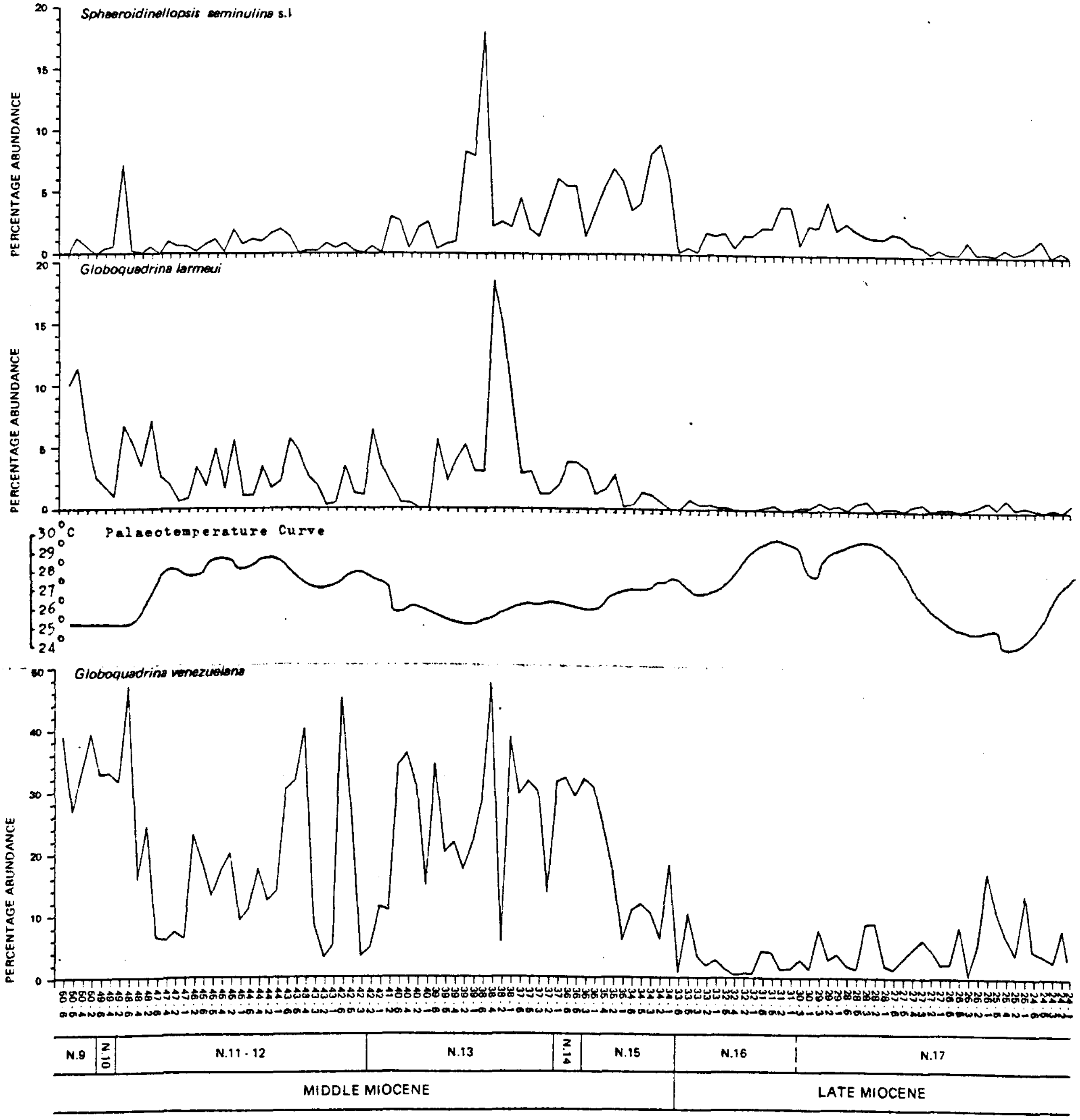


Fig. 56 Relative distribution of planktonic foraminiferal taxa compared to palaeotemperature curve, Site 289

abundance corresponds to decreased palaeotemperatures and low abundance corresponds to increased palaeotemperatures (fig.54,55). However, the pattern is not entirely consistent, especially for *G. quadrilobatus* s.l. in the early Middle Miocene, where dissolution is thought to have adversely affected abundance (see Chapter V).

The distributions of *Globoquadrina altispira altispira*, *G. altispira globosa*, *G. langhiana* group and *G. larmeui* do not appear to be related to the palaeotemperature trends (fig.56,57).

The relative distributions of several abundant taxa at Site 289 therefore appear to be generally influenced by palaeotemperature trends. Together with *G. cultrata* gp. (sinistral) and *G. fohsi* s.l., optimum palaeoenvironments for *G. siakensis*, *G. continuosa* and *S. seminulina* s.l. appear to have been those within a non-upwelling, warm, tropical epipelagic zone. Conversely, together with *G. cultrata* group (dextral), optimum palaeoenvironments for *G. venezuelana*, *G. dehiscens*, *G. quadrilobatus triloba*, *G. quadrilobatus sacculifer* and *G. obliquus* s.s. appear to have been those within an upwelling cooler tropical to subtropical epipelagic zone.

The distribution of *G. altispira* s.l., *G. langhiana* group and *G. larmeui* appear to have been influenced by factors other than palaeotemperature (?salinity etc.). Similar conclusions may be drawn for *G. continuosa* and *G. dehiscens* in those intervals where distribution appears to be unrelated to palaeotemperature.

The quantitative distribution of several taxa at Site 289 is difficult to compare with the palaeotemperature curve because the forms are consistently present in low abundance e.g. *Globorotalia obesa*. However, the behaviour of species which are discontinuously distributed throughout the sequence can be more easily compared to the

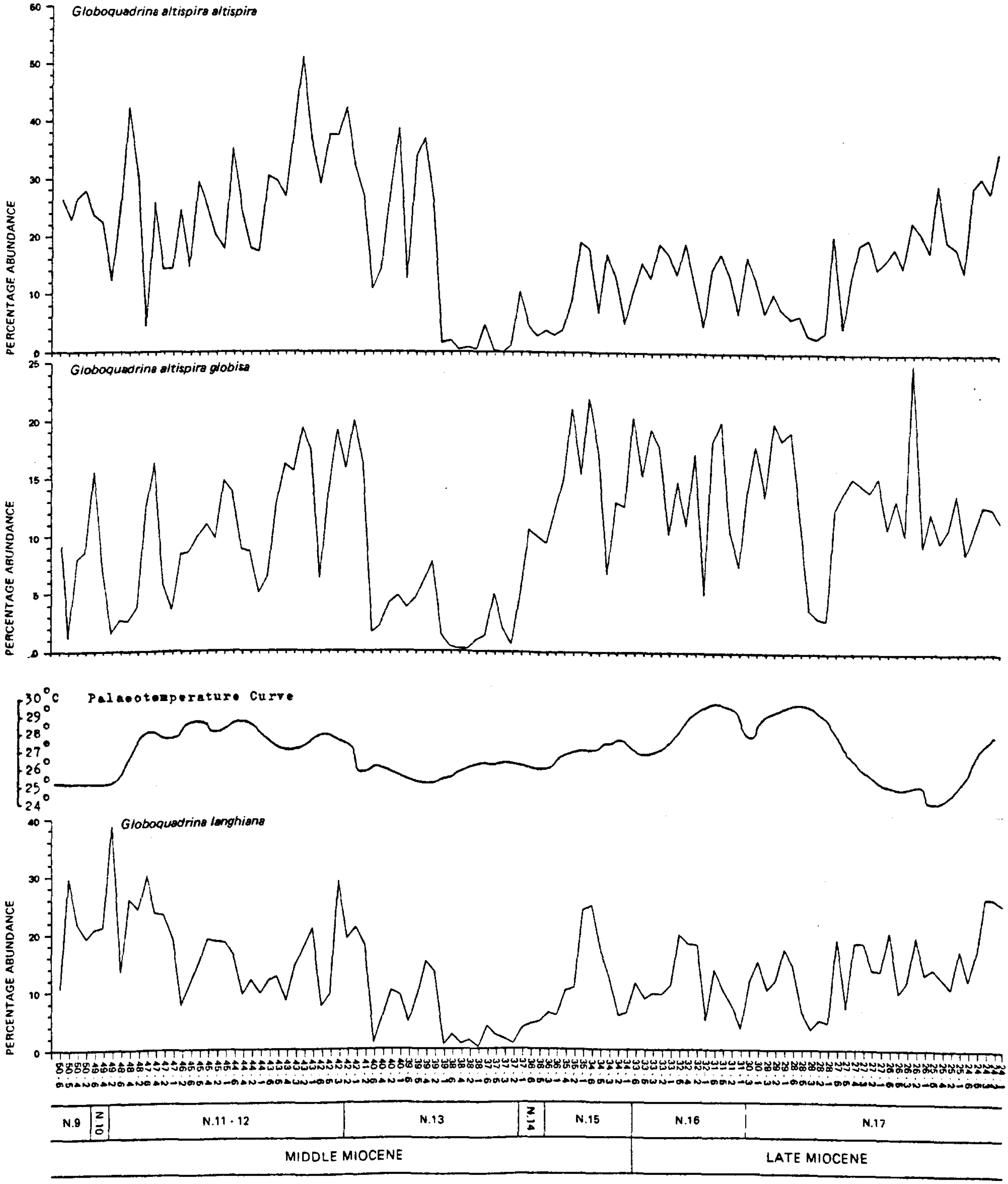


Fig. 57 Relative distribution of planktonic foraminiferal taxa compared to palaeotemperature curve, Site 289

palaeotemperature curve and allows an assessment of palaeoenvironmental preferences based on qualitative criteria (presence or absence). The distribution of several rare forms is given in fig.58. A comparison with the palaeotemperature trends indicates a correlation in certain instances. For *Globorotalia sp. cf. G. merotumida*, *G. sp. cf. G. multicamerata* and *Globigerinoides ruber*, presence in the sequence generally coincides with increasing palaeotemperatures. Favourable palaeoenvironments for these forms appear to include those of a warm, non-upwelling,tropical,epipelagic zone. In *Globigerina bulloides* and *G. falconensis*, presence in the sequence generally coincides with decreasing palaeotemperatures. Favourable palaeoenvironments for these forms appear to include those of a cooler, upwelling tropical to subtropical epipelagic zone.

The qualitative distribution of *Globigerina foliata*, *G. nepenthes*, *G. praebulloides* and *G. calida praecalida* appears to have been influenced by factors other than palaeotemperature (?salinity etc.).

In order to test their validity, conclusions made herein concerning the palaeoenvironmental preferences of particular taxa can be compared to preferences indicated by palaeobiogeographical distribution (see Appendix I).

Apart from *Globorotalia fohsi* s.l. and *G. cultrata* group (sinistral), six taxa appear to exhibit a preference at Site 289 for warm, non-upwelling, tropical waters:

Globorotalia siakensis
G. continuosa
G. sp. cf. G. merotumida
G. sp. cf. G. multicamerata
Sphaeroidinellopsis seminulina s.l.
Globigerinoides ruber

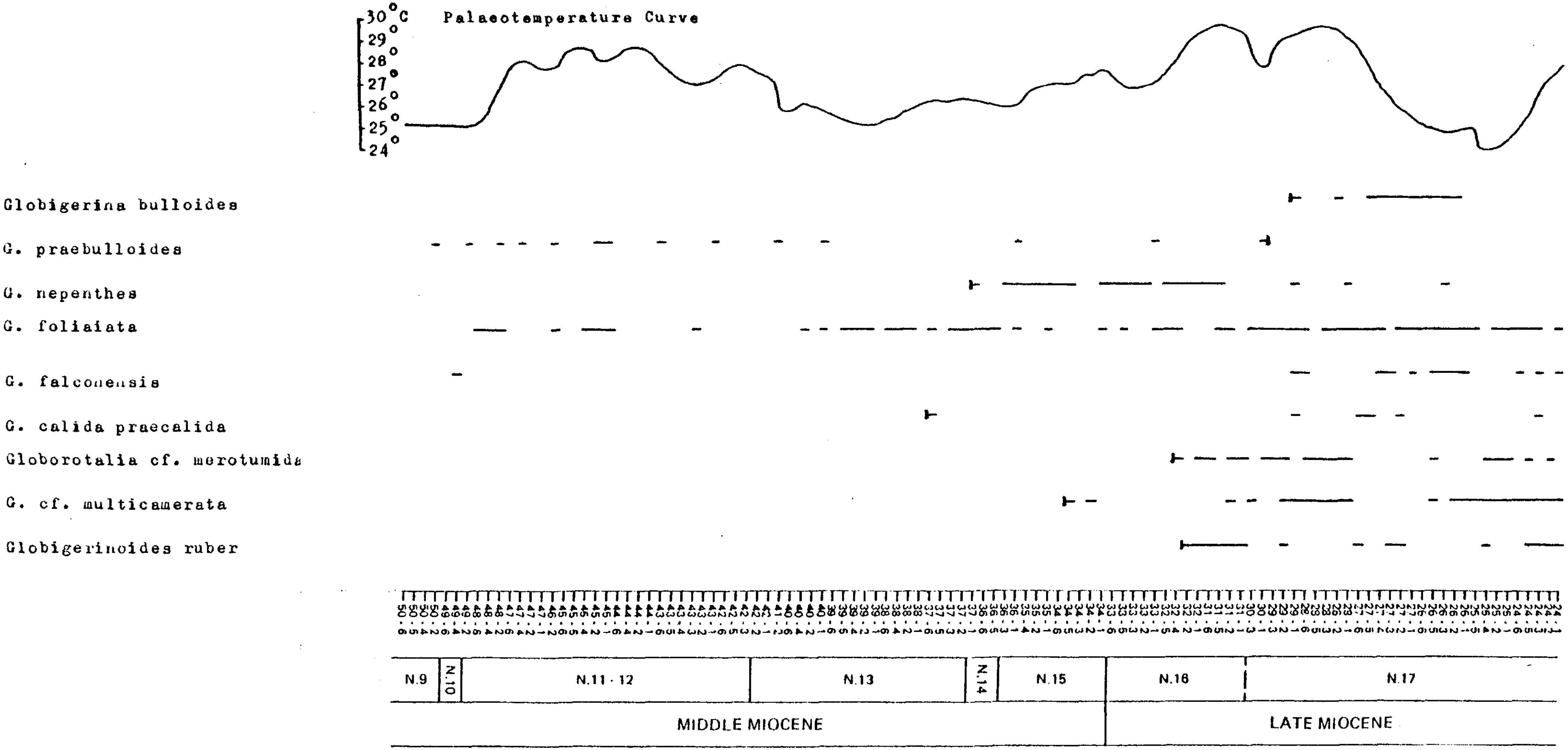


Fig.58 The distribution of rare planktonic foraminiferal taxa compared to the palaeotemperature curve at Site 289

Palaeogeographical distributions outlined from previous studies suggests a cosmopolitan occurrence in the first two taxa but a distinct preference for tropical and subtropical regions in the latter four taxa (see Appendix I).

Apart from G. cultrata group (dextral), seven taxa appear to exhibit a preference at Site 289 for cooler upwelling, tropical to subtropical waters:

Globoquadrina venezuelana

G. dehiscens

Globigerinoides obliquus s.l.

G. quadrilobatus triloba

G. quadrilobatus sacculifer

Globigerina bulloides

G. falconensis

Palaeobiogeographical distributions outlined from previous studies suggests a cosmopolitan occurrence with a preference for tropical to subtropical regions in the first four taxa, a distinct preference for high latitude temperate regions in the latter two taxa but a definite preference for warm tropical regions in G. quadrilobatus sacculifer (see Appendix I).

Thus a comparison of palaeoenvironmental preferences for particular taxa deduced from this study, with preferences suggested from previous studies, reveals both complementary and conflicting as well as neutral results.

ii) Cycles of Upwelling during the Middle and Late Miocene: A Palaeoenvironmental/Palaeoecological Model

An environmental and ecological model for the epipelagic zone at Site 289 is now developed to attempt to explain some of the major quantitative taxonomic variations, particularly at generic level. Periodic upwelling is invoked.

Ecological studies of modern planktonic foraminifera indicate a significant taxonomic depth stratification in the epipelagic zone of the water column (see Chapter II, p.36-37). Depth distribution is believed to be closely related to thermohaline density stratification of sea water. Greatest development of vertical seperation of species occurs in non-upwelling tropical regions where temperature and salinity variation in the upper few hundred metres of water results in a wide range of water densities available for habitation. The variety of environmental niches which exist in the epipelagic zone of tropical oceans may account for the high taxonomic diversity of these regions (DOUGLAS and SAVIN, 1978).

The following model attempts to relate the quantitative distribution of some planktonic foraminiferal taxa at Site 289 to the development and destruction of habitable niches due to periodic upwelling.

The vertical temperature profiles of the western and central equatorial Pacific Ocean are characterised by the development of a thermocline (see Chapter II, p.29). Palaeoceanographic studies suggest that this feature has existed since the beginning of the Middle Miocene (SAVIN et al., 1975; Van ANDEL et al., 1975; DOUGLAS and SAVIN, 1978; see Chapter III, p.60). Moreover, the taxonomic depth stratification during the Miocene is also believed to have been quite similar to that of the present time. DOUGLAS and SAVIN (1978) have undertaken an oxygen isotope analysis of several species of Middle Miocene age (Zone N.12). The isotopic temperature ranking of the Miocene genera is similar to that observed for the same genera in modern oceans. Species of Globigerinoides yielded the warmest isotopic temperatures (shallow depth) while species of Globorotalia (Fohsella) gave the coldest isotopic temperatures (increased depths). DOUGLAS and SAVIN (1978) conclude that these isotopic differences probably reflect differences in depth habitats similar to those observed for modern foraminifera.

Fig.59 indicates the quantitative distribution of Globorotalia spp. (turborotaliids and keeled globorotaliids) and Globigerinoides spp. in the Middle to Late Miocene at Site 289. Although the stratigraphical distribution of turborotaliids is restricted, abundance in this group reveals a good normal correlation with that of the keeled globorotaliids. Conversely, a detailed examination and comparison of the distribution of keeled globorotaliids with Globigerinoides spp. indicates a good inverse correlation. However, because the data is expressed in relative abundance, a large decrease in an abundant form may often tend to increase the abundance of all other taxa. If there is no intimate relationship involved, all other taxa should increase in equal proportions, according to the original percentage abundances. Nevertheless, in several instances, a decrease in the relative abundance of keeled globorotaliids is accompanied by a disproportionately high increase in the percentage of Globigerinoides spp. e.g. within cores 34 to 33. Thus there appears to be an intimate relationship between the relative abundance of keeled globorotaliids and Globigerinoides spp. which is not an artifact of data presentation and which probably reflects changes in absolute numbers.

A palaeoenvironmental/ palaeoecological model for the epipelagic zone of the western equatorial Pacific (Site 289) under non-upwelling and upwelling conditions during the Middle to Late Miocene is given in fig.60. This is intended to explain, in very broad terms, variation in the quantitative distribution of several taxa, including Globorotalia spp. and Globigerinoides spp., by reference to the availability of habitable niches. Particular attention is paid to these taxa because they appear to

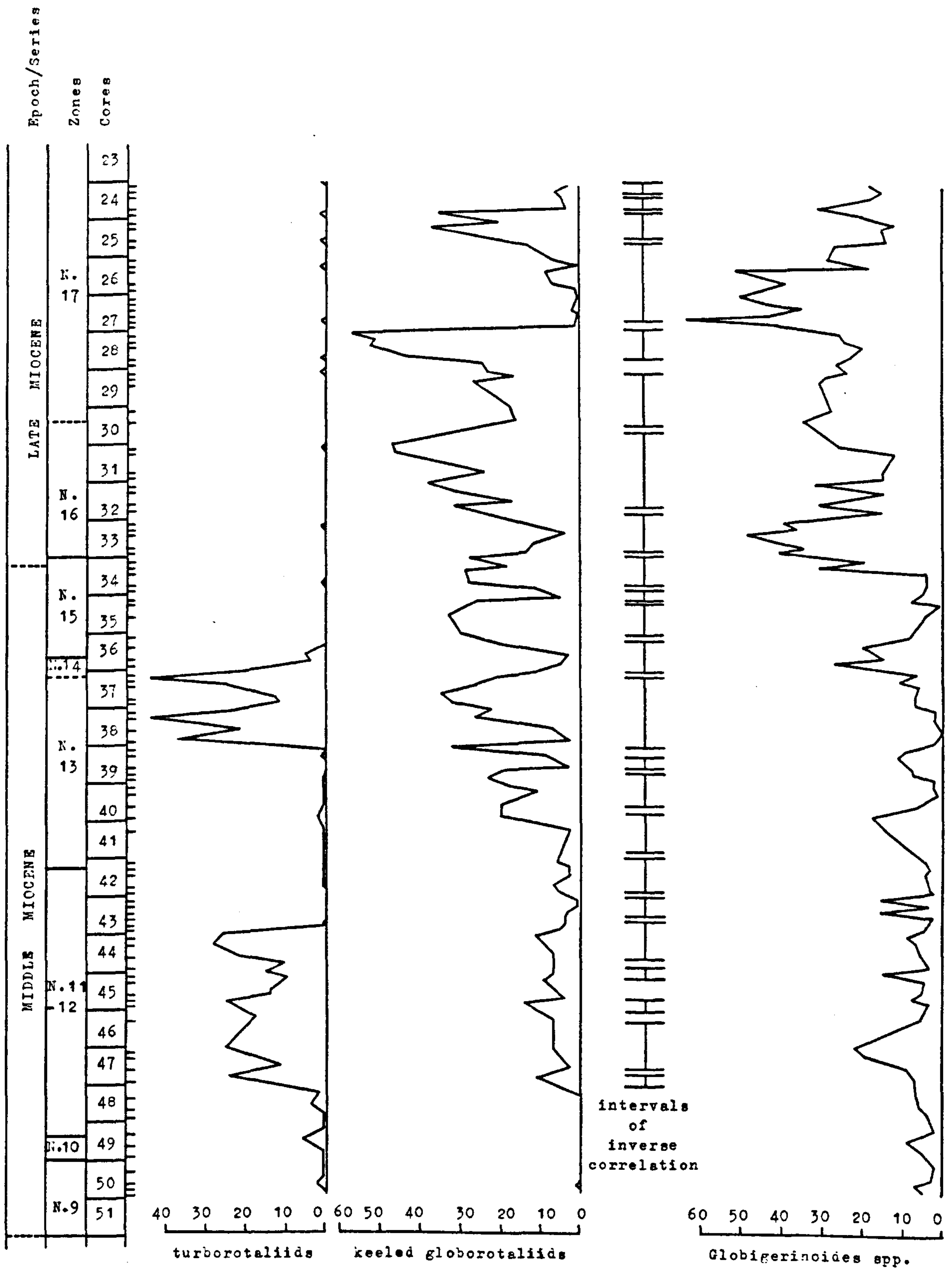
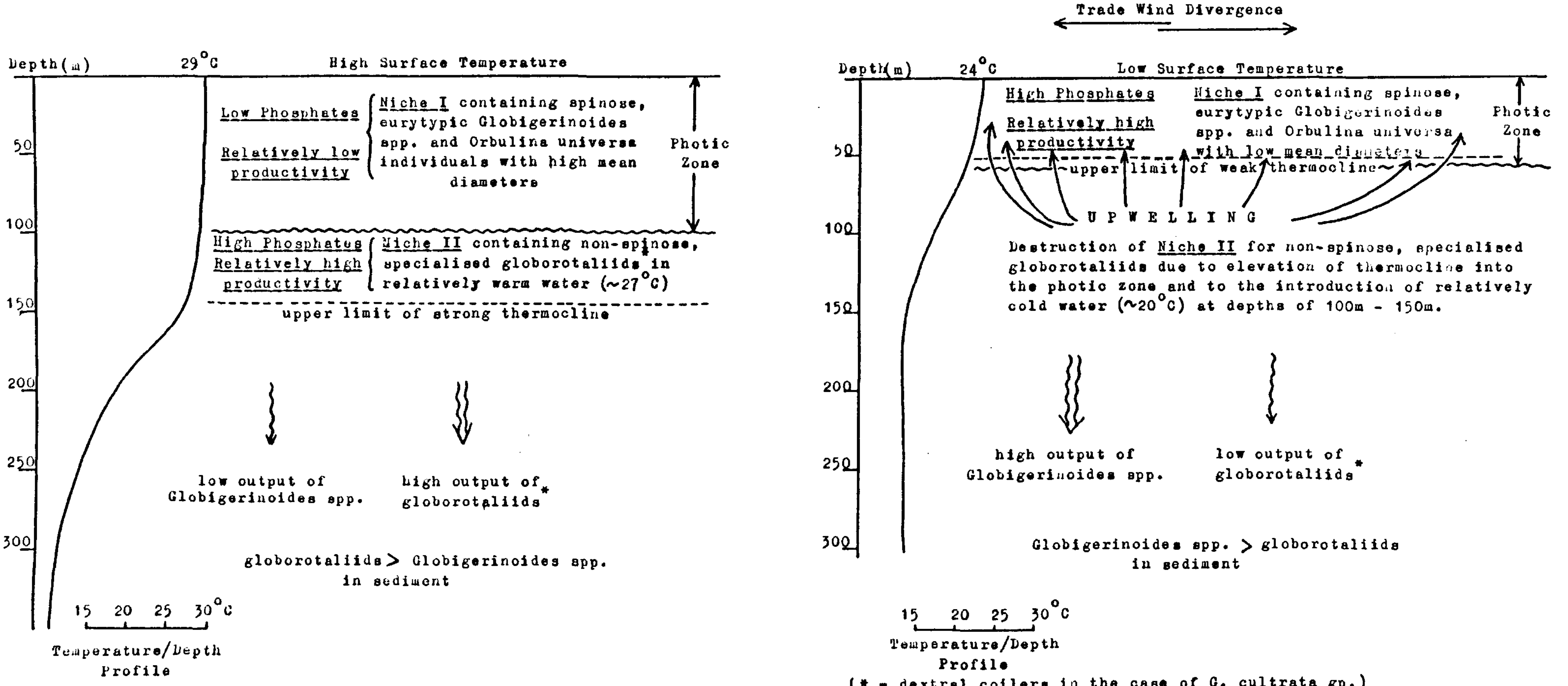


Fig.59 Percentage abundance of turborotaliids, keeled globorotaliids and Globigerinoides spp. at DSDP 289

exhibit well defined depths preferences in both modern and Miocene oceans (Chapter II, p.36-37; DOUGLAS and SAVIN, 1978; see above).

Fig.60 illustrates the proposed situation under non-upwelling conditions. The temperature/depth profile is that of the present day (Chapter II, p.30). Surface temperatures are high (29°C) and there is a well defined thermocline, the upper limit of which reaches a depth of 150 metres. In these circumstances, there is little upward movement of nutrients so that surface waters are relatively depleted. The photic zone is taken to extend to a depth of 100 metres. Under these conditions, values of temperature and nutrients, and, although not illustrated, salinity, O_2 content and density, all exhibit strong depth gradients (see Chapter II). The presence of a permanent thermocline ensures stability of the upper 150 metres of the water column. The epipelagic zone is thus stratified with respect to various physical and chemical parameters.

The stratification is reflected in biological distribution, according to the conclusions of BÉ (1977) regarding the depth distribution of modern planktonic foraminifera. The photic zone is inhabited by spinose Globigerinoides spp. that appear to rely on symbiotic algae for some metabolic processes. Morphology in this genus is relatively simple and geographical distribution is wide. The genus can therefore be regarded as eurytypic with a broad adaptive range, i.e. it is unspecialised and not restricted to narrow environmental conditions. In contrast, Globorotalia spp. tend to concentrate at depth, in or around the thermocline. Morphology in this genus is more specialised and geographical distribution, particularly in keeled forms, is narrower. The genus can therefore be regarded as specialised and stenotypic with a narrower adaptive range, i.e. it is restricted to particular environmental conditions (DOUGLAS and SAVIN, 1978). In the proposed model under non-


A/ No Upwelling : Epipelagic Zone Stratified : Surface Temperature High

B/ Upwelling : Epipelagic Zone Mixed and Homogenised : Surface Temps. Low

(* - sinistral coilers in the case of G. cultrata gp.)

(* - dextral coilers in the case of G. cultrata gp.)

Fig. 60 A model to explain the inverse relationship between the relative abundance of globorotaliids and Globigerinoides spp. at DSDP Site 289 upwelling conditions, the Globigerinoides spp. habitat is situated within the photic zone and is designated 'niche I'. The Globorotalia spp. habitat is situated below the photic zone and above or within the thermocline and is designated 'niche II'. It is suggested that Globigerinoides spp. are restricted to 'niche I' because of their dependance on the photosynthetic activities of symbiotic algae. Globorotalia spp. are believed to be restricted to 'niche II' because they have developed a specialisation for deeper, colder and denser waters below the competetive environment of the photic zone, where they feed on organic detritus. This situation is envisaged for those stratigraphic intervals at Site 289 where lack of upwelling is believed to have created high surface palaeotemperatures (fig.60). Due to these high surface palaeotemperatures, mean size in O. universa would increase. The presence of a well developed 'niche II', together with an overall lack of nutrients in 'niche I', may be responsible for the greater net output of Globorotalia spp. compared to Globigerinoides spp. apparent in the sediment (fig.59).

Fig.60 also illustrates the situation proposed under conditions of upwelling. The temperature/depth profile is similar to that of the present day central equatorial Pacific where, because of upwelling, surface temperatures are relatively low and the thermocline is weakly developed and elevated towards the surface into the photic zone (Chapter II, p.30). Further effects of upwelling include a decrease in surface water temperatures and an increase in the availability of nutrients in surface waters. Due to increased tubulence, the photic zone may contract. Although not illustrated in fig.60, O_2 and salinity values of surface waters are decreased while density values are increased. (see Chapter II). Due to the lack of a strong thermocline, variation in the physical and chemical parameters of the epipelagic zone are homogenised and stratification is reduced.

A significant effect of upwelling on 'niche I' would be to increase biological productivity because of the greater availability of nutrients transported from below. It is suggested that this productivity increase would offset any decrease caused by a contraction of the photic zone. Since the forms endemic to 'niche I', i.e. Globigerinoides spp., are eurytypic, wide ranging and unspecialised, the effects of decreased temperature should not be detrimental. It is thus proposed that upwelling would increase the net output of Globigerinoides spp. to the sediment by increasing biological productivity in the photic zone. Simultaneously, mean size in O. universa would decrease due to decreased surface water palaeotemperatures. Meanwhile, the elevation of the upper limit of the thermocline into the photic zone would integrate 'niche II' into 'niche I' and eliminate the former as a seperate, discrete habitat. To survive, Globorotalia spp. would need to ascend into the photic zone to follow their optimum environment defined by particular values of temperature, salinity, density and nutrient content. However, the stenotypic genus is not adapted for existence in the highly competitive photic zone. In addition, the normal optimum environment for the taxon ('niche II') would be diluted by water-mass mixing and by the introduction of relatively cold ascending waters. It is thus suggested that members of the genus would fail to overcome the demands induced by upwelling so that net productivity and output into the sediment would decrease. This situation is envisaged for those stratigraphic intervals at Site 289 where the introduction of upwelling is believed to have created low surface palaeotemperatures (see figs.59).

iii) Coiling direction in Globorotalia cultrata gp. : A

possible cause

The observed changes in coiling direction in *Globorotalia cultrata* gp., which appear to reflect palaeotemperature variation, can be tentatively explained by reference to the palaeoenvironmental/palaeoecological model at Site 289.

The factors proposed for the cause of coiling direction changes in planktonic foraminifera have been reviewed by THIEDE (1971), KENNETT (1976) and LIPPS (1979).

Temperature control of coiling direction has been suggested based on empirical observations in modern seas (see Chapter VI). However, LIPPS (1979) offers an alternative explanation involving reproductive strategies under changing trophic conditions. The hypothesis suggests that the two coiling modes represent microspheric and megalospheric generations which result from asexual and sexual reproduction respectively. This situation is similar to that observed in some benthonic foraminifera (KENNETT, 1976). LIPPS (1979) implies that under conditions of ecological stress (poor nutrient supply), a slow reproductive mode (sexual) would be advantageous so that one particular coiling type would predominate. Conversely, when optimum environmental conditions prevail (good nutrient supply), forms would tend to reproduce rapidly (asexual) and the alternative coiling mode would predominate. This hypothesis suggests therefore that coiling ratio changes in time and space may indicate changes in trophic supply. LIPPS (1979) suggests an increase in oceanic fertility caused by upwelling may preferentially produce microspheric forms exhibiting an exclusive coiling mode.

However, the reproductive strategy explanation of LIPPS (1979) is difficult to demonstrate because of the problem of distinguishing megalospheric from microspheric morphotypes in planktonic foraminifera

(KENNETT, 1976). Moreover, it is difficult to reconcile particular aspects of certain taxa, including G. cultrata gp., with the basic concept. For instance, in Neogloboquadrina pachyderma, KENNETT (1976), following VELLA (1974), indicates how coiling ratios differ according to the size fraction examined. This observation strongly suggests preferential mortality during ontogeny caused by genetically induced environmental selection. The size/coiling ratio relationship in this species is difficult to explain in terms of the preferential production of asexual or sexual morphotypes where ratios should remain constant during ontogeny. In addition, if one assumes that changes in coiling mode follow the explanation of LIPPS (1979), it is similarly difficult to reconcile the lack of dextral forms in G. cultrata gp. since 2.3 m.y. B.P. (see Chapter VI, p.150). If coiling direction or reproductive mode is controlled by trophic conditions, then because these conditions are not everywhere uniform and tend to exhibit large geographical variation, alternative morphotypes should exist at any one time. This is not the case with G. cultrata gp. during the Pleistocene to Recent.

Those workers who advocate the control of coiling direction by temperature tend to suggest a genetic relationship. Temperature changes may trigger certain genes controlling coiling (BANDY, 1960; Van VALEN, 1969). Alternatively, genes may be intimately linked so that the gene which confers the ability to thrive in 'warm' temperatures only may be linked to the gene which induces a particular mode of coiling, while the gene which confers the ability to thrive in 'cold' temperatures' only may be linked to the gene which induces the alternative mode of coiling. These gene pairs may be both present in the diploid genotype but with only one pair expressed in the phenotype. This latter hypothesis may apply to the palaeoenvironmental/palaeoecological model at Site 289 in the case of

G. cultrata gp. Under non-upwelling conditions, with relatively high palaeotemperatures both at the surface and within 'niche II', sinistral forms possessing an operational gene confering the ability to thrive in 'warm' palaeotemperatures only would dominate within the taxon (fig.60). Conversely, under conditions of upwelling with relatively low palaeotemperatures throughout, dextral forms possessing an operational gene confering the ability to thrive in 'cold' palaeotemperatures only would dominate within the taxon (fig.60). This situation could explain any coiling ratio/size relationship which may exist in G. cultrata gp. by assuming that those dextral forms produced in conditions of 'warm' palaeotemperatures would be eventually eradicated from the population during ontogeny by the forces of natural selection. However, the enigmatic lack of dextral forms during the Pleistocene to Recent cannot easily be explained within a gene-linkage hypothesis and further investigation is needed to formulate a suitable thesis. Such a hypothesis may involve a complex unification of the reproductive strategy theory of LIPPS (1979) and a variation of the gene-linkage explanation offered herein.

iv) The Palaeoenvironmental/Palaeoecological Model : A Conclusion

Changes in the quantitative distribution of individual taxa have been explained in this Chapter by reference to variations in palaeotemperature. The palaeoenvironmental/palaeoecological model discussed above however indicates that variation in abundance may be caused by a complex interaction of limiting factors associated with changes in the structure of the epipelagic zone, rather than palaeotemperature only. As well as temperature, such changes would affect salinity, density, nutrient supply and biological competition, all of which can exhert important influences on planktonic foraminifera (BÉ, 1977). However, since palaeotemperature is the only factor which can be quantified in this study, possible unwarrented emphasis is unavoidable.

v) Whole Assemblage Analysis

Trends relating to the quantitative nature of the planktonic foraminiferal assemblages as defined by the diversity and similarity indices can be compared to the palaeotemperature curve to indicate and consider any correlations of possible palaeoenvironmental significance.

a) Diversity Indices

The significance of diversity in planktonic foraminifera as an indicator of palaeoenvironment (palaeotemperature; palaeoceanography) has been briefly considered in Chapter V (p.104).

A comparison of simple diversity in planktonic foraminifera at Site 289 with the palaeotemperature curve reveals no clear consistent relationship (fig.61). Both normal and inverse relationships are apparent at particular intervals. A normal relationship, in which increased diversity accompanies increased palaeotemperature and decreased diversity accompanies decreased palaeotemperature, occurs within cores 50 to 46, 40 to 37 and 32 to 26. This relationship may derive from increased niche availability during times of warm surface waters with the development of a stratified epipelagic zone. Nevertheless, a direct relationship between increased palaeotemperature and diversity may not have been particularly significant, for example, within cores 50 to 46, although increased palaeotemperatures are believed to be related to increased diversity e.g. via evolutionary subspeciation in the Fohsella group, the correlation is exaggerated by a gradual decrease in dissolution intensity over the interval (see Chapter V, p.115). Elsewhere, there exist horizons where palaeotemperature trends vary inversly with diversity e.g. within cores 37

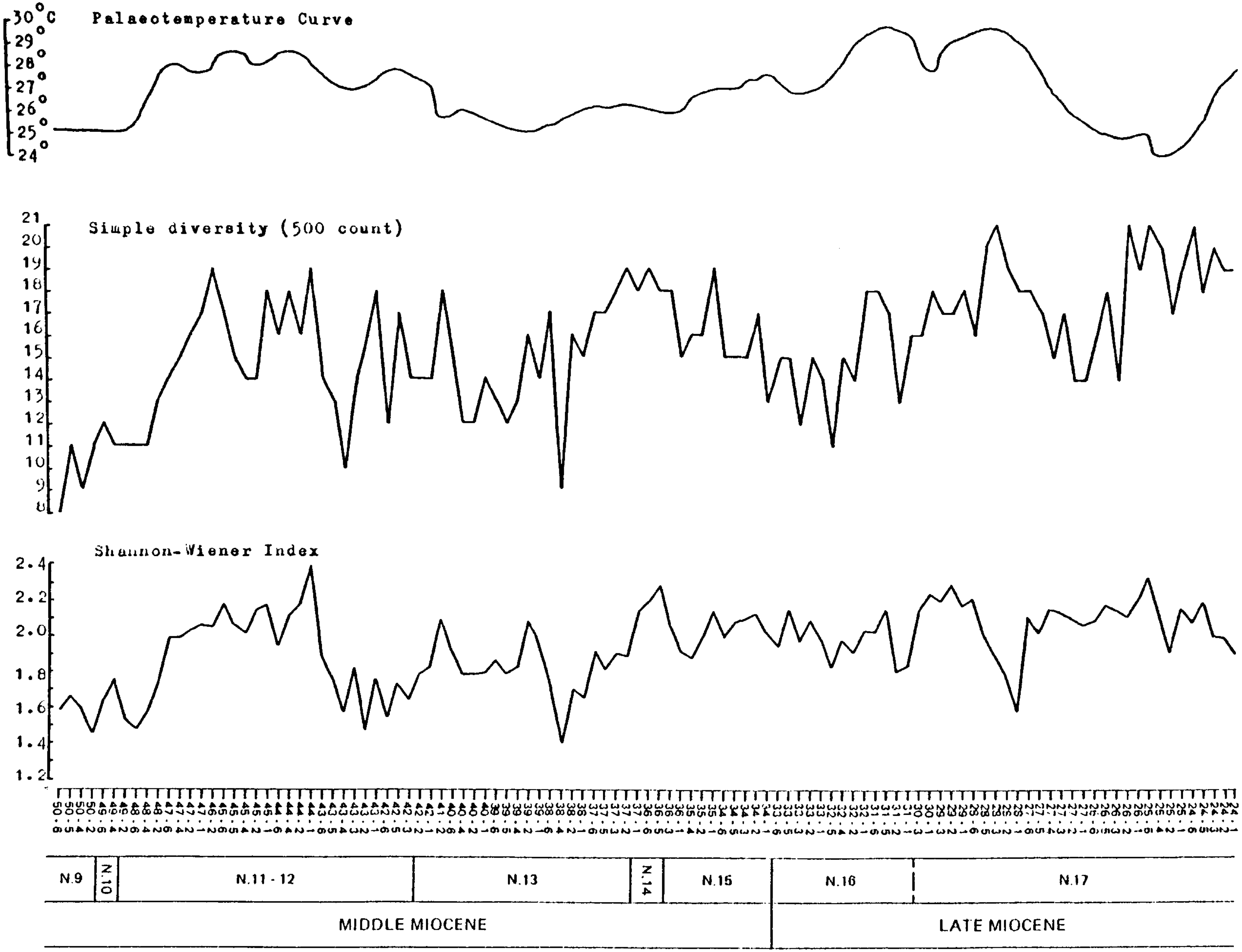


Fig. 61 Diversity Indices in planktonic foraminifera compared to the palaeotemperature curve at Site 289

to 36 and 26 to 25, where low palaeotemperatures coincide with increased diversity.

Thus no consistent relationship exists between palaeotemperature and simple diversity in planktonic foraminifera at Site 289. An explanation may involve the biogeographical location of the site. The present day surface water temperatures in the western equatorial Pacific are the highest throughout the ocean. Assuming this was the case during the Miocene, a drop in palaeotemperature in the region may allow the existence of taxa normally restricted to cooler water masses but retain those taxa specialised to warmest temperatures because warmer waters may not exist elsewhere. It is therefore concievable that, in contrast to elsewhere, decreased temperature in the western equatorial Pacific may sometimes cause an increase, rather than a decrease, in simple diversity.

A comparison of compound diversity (Shannon-Wiener) in planktonic foraminifera at Site 289 with the palaeotemperature curve is given in fig.61. As with simple diversity, only a limited correspondance exists between high and low diversity and high and low palaeotemperature respectively. Moreover, interpreted maximum palaeotemperature values for the sequence, which occur within core 28 (where sinistral Globorotalia cultrata gp. reach maximum abundance), compute as low diversity on the H(S) index because of high species dominance.

In the present study, the application of diversity indices in planktonic foraminifera for palaeoenvironmental interpretation appears to be limited. The apparent inconsistent relationship between diversity and palaeotemperature may reflect palaeoecological complications associated with the biogeographical position of Site 289.

b) Similarity Index

The similarity index, which illustrates the 'rate of change' in the planktonic foraminiferal assemblages at Site 289, may distinguish intervals of taxonomic consistency from intervals of taxonomic instability. Since the base sample (50-6) can be partly regarded as representing a 'cold-water' (upwelling) assemblage, similarities to and deviations from this 'standard' in subsequent samples can be interpreted as an indication of palaeotemperature variation. The rate of change index may therefore serve as a useful indicator of palaeoenvironment.

A comparison of the 'rate of change' index with the palaeotemperature curve at Site 289 is given in fig.62. Major deviations in similarity to sample 50-6 tend to coincide with increased palaeotemperature (within cores 47 to 44, 37, 32 and 29 to 28). Conversely, intervals of increased similarity to sample 50-6 tend to coincide with decreased palaeotemperature (within cores 43, 36 and 27 to 24). The relationship is not entirely consistent however and interference in the trend may be caused by the strong influence of dissolution in the 'standard sample' and by the subsequent evolutionary introduction of new forms.

c) Evolutionary Events

Throughout the main studied sequence at Site 289 (cores 50 to 24), many evolutionary events involving the appearance and extinction of numerous planktonic foraminiferal taxa were encountered. A brief comparison of this information with the palaeotemperature curve may indicate the extent to which evolutionary appearances and extinctions are related to the palaeoenvironmental changes envisaged for the sequence.

The number of appearances and extinctions per core is plotted separately in fig.63. The taxa used to compile these graphs are indicated in fig.16 by an asterisk (appearance) and a cross (extinction). In almost all cases, the stratigraphical position of the datums correspond to known

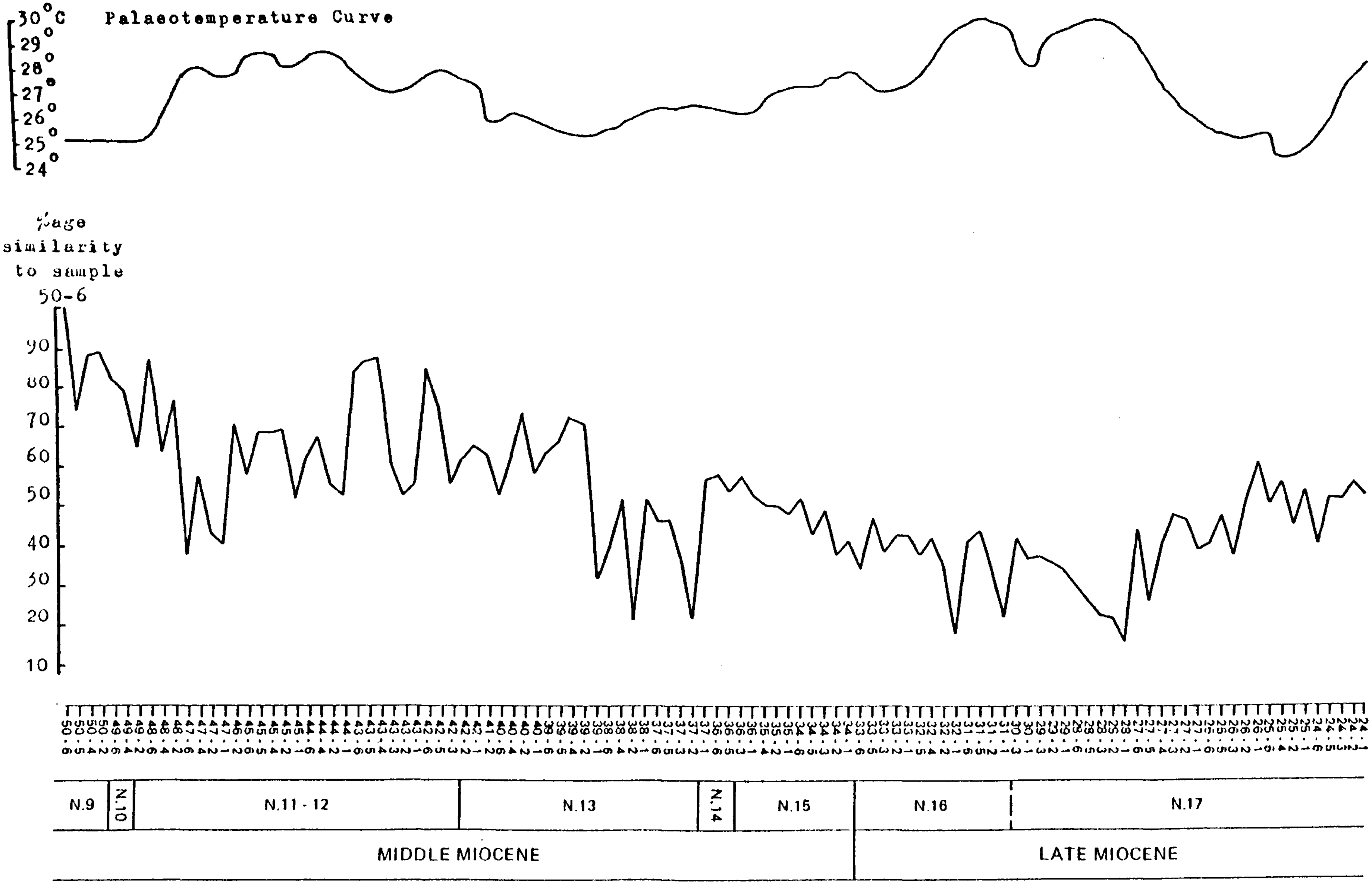


Fig. 62 Similarity Index for planktonic foraminifera compared to the palaeotemperature curve, Site 289

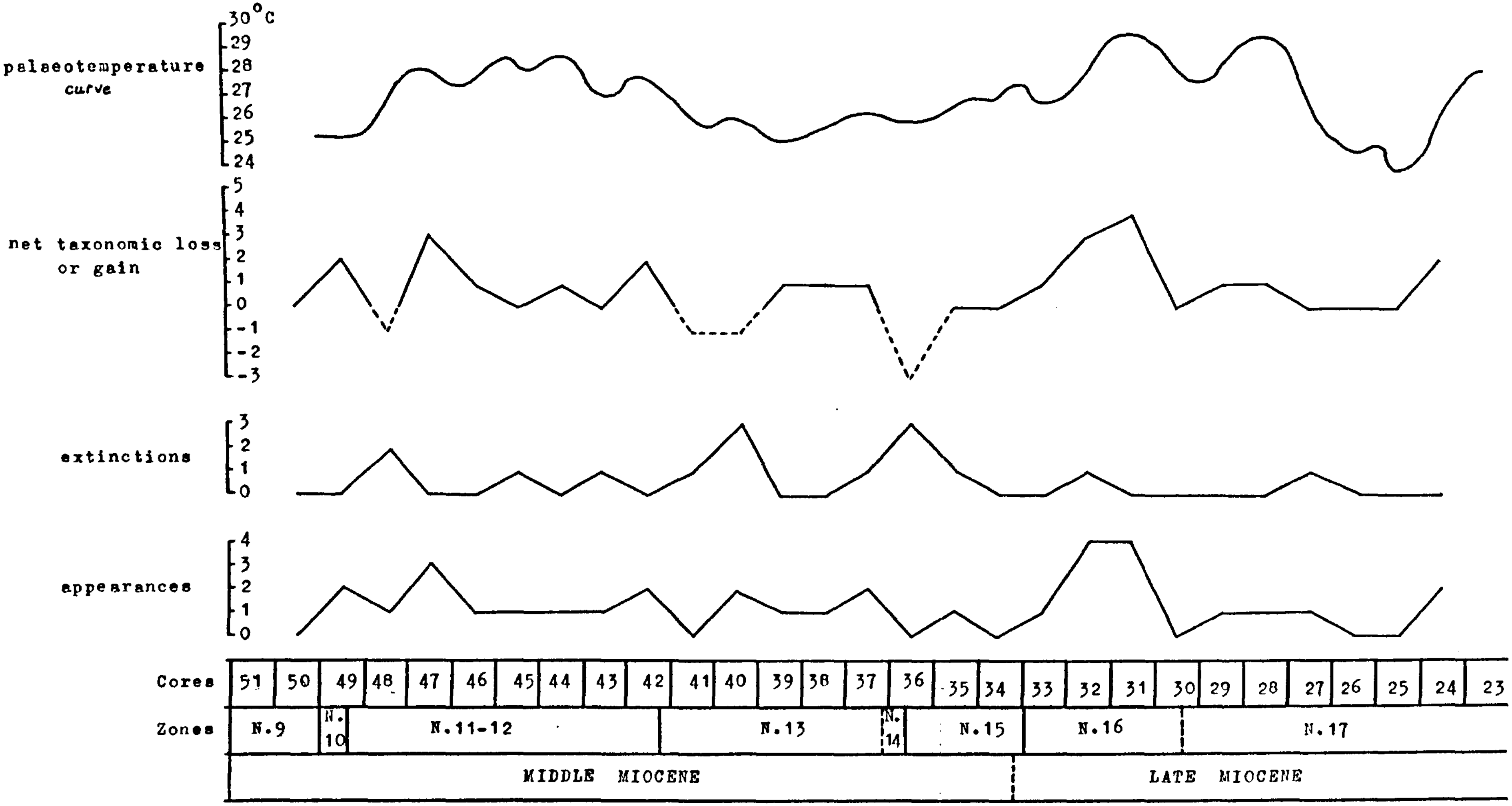


Fig. 63 Evolutionary events in planktonic foraminifera at Site 289

ranges (see Appendix I). In some taxa, ranges at Site 289 are much shorter than apparent elsewhere and may reflect local palaeoenvironmental conditions e.g. Globorotalia continuosa, G. scitula and Globorotaloides variabils. In these instances, initial evolutionary appearance appears to have occurred elsewhere at an earlier time. Subsequent appearance at Site 289 does not necessarily involve evolutionary processes and may simply indicate migration into the region following development of favourable conditions.

The appearance/extinction data is combined in fig.63 to indicate net taxonomic loss or gain per core. A comparison of this plot with the palaeotemperature curve reveals an interesting correlation. Intervals of increased palaeotemperature are characterised by net taxonomic gain i.e. an increase in the diversity potential of planktonic foraminiferal assemblages e.g. within cores 47 to 42 and 33 to 28. Conversely, intervals of decreased palaeotemperature are characterised by taxonomic stability or a net taxonomic loss i.e. a decrease in the diversity potential of planktonic foraminiferal assemblages e.g. within cores 41 to 40, 36, and 27 to 25.

As previously discussed, high surface water palaeotemperatures are believed to reflect steep vertical temperature and density gradients in the epipelagic zone and the existance of a strong thermocline. Under these stratified conditions, the number of different ecological niches available for exploitation by planktonic organisms would be expected to increase. Increased niche availability has been regarded as the catalyst for increased speciation and diversity in planktonic foraminifera (DOUGLAS and SAVIN, 1978). This concept would seem to be supported by the evidence presented from Site 289. Decreased surface water palaeotemperatures are believed to reflect upwelling and the homogenisation of temperature and density gradients. The decrease in niche types associated with this process would presumably initiate extinction of the less competitive taxa.

Although the data is rather sparce and is presented in a simplified, generalised manner, this brief comparison of evolutionary events with palaeotemperature trends appears to support a stratigraphical relationship between increased niche creation and increased speciation in planktonic foraminifera.

3. RADIOLARIA : SITE 289

Knowledge concerning the palaeoecology of Miocene radiolaria is particularly limited (see Appendix I). In this study, variation in the relative abundance of certain taxa can be related to palaeotemperature trends in a similar manner to that carried out for planktonic foraminifera. It is thus possible to indicate and distinguish those forms whose optimum environment appear to exist within non-upwelling tropical waters characterised by high surface palaeotemperatures from these forms whose optimum environment appear to exist within upwelling tropical to subtropical waters characterised by cooler surface palaeotemperatures. However, for those taxa (known and unknown) whose presence in tropical sediments is due to mesopelagic and bathypelagic submergence from high latitude surface waters (CASEY, 1977; see Appendix I), palaeoenvironmental variation within the epipelagic zone would probably exert little or no influence.

In the following account, several aspects of the radiolarian assemblages are considered against the proposed palaeotemperature curve.

The palaeotemperature curve is compared to the relative distribution of the nineteen most abundant taxa and to the absolute distribution (i.e. presence and absence) of some of the less common forms.

From these comparisons it can be possible, where appropriate, to infer a broad palaeoecology and optimum environment for certain taxa.

Stichocorys delmontensis s.l. exhibits gross variation in morphology and numerical distribution at Site 289. A biometric study is presented to indicate the relationship between size and palaeotemperature in this species.

In view of their possible palaeoenvironmental significance, trends of diversity and similarity (see Chapter V) are compared to the palaeotemperature curve to seek correlation.

Finally, to briefly consider a possible relationship between palaeoenvironment and adaptive radiation in radiolaria, the palaeotemperature curve is compared to the distribution of evolutionary events (appearances and extinctions) throughout the studied sequence.

i) Individual Taxa

A comparison of distribution in the nineteen most abundant taxa with the palaeotemperature curve is given in figs.64-69.

Relative distribution within each of the following taxa generally reveals a good normal correlation with the palaeotemperature trends:

Carpocanistrum spp.
"Spongodiscid spp. group"
"Plagoniid spp. group"
"Litheliid spp."
"Porodiscid spp. group"
Stichocorys delmontensis Form A

In addition, relative distribution within Trisolenia spp., "Cyrtid spp. group 2" and Theocorys? subcylindrica also appears to be related to the palaeotemperature curve, although good, normal correlations are not so consistent.

In these nine taxa, an increase in relative abundance is generally accompanied by an increase in palaeotemperature, whereas a decrease in relative abundance is generally accompanied by a decrease in palaeotemperature.

Relative distribution in Stichocorys delmontensis s.s. reveals a good inverse correlation with the palaeotemperature trends. In S. wolffii, relative distribution similarly appears to be related to the palaeotemperature curve, although a good, inverse correlation is not so consistent. In these species, an increase in relative abundance is generally accompanied by a decrease in palaeotemperature, whereas a decrease in relative abundance is generally accompanied by an increase in palaeotemperature.

In the following taxa, no relationship between relative distribution and the palaeotemperature curve at Site 289 is apparent:

Calocycletta caepa
Heliodiscus circumcincta
Rhopalastrum angulatum
Rhopalastrum profunda
"columnless artiscans"
"Spyrid spp."
Collosphaera spp.
Acrosphaera spinosa

The relative distribution of several abundant taxa at Site 289 therefore appears to be generally influenced by palaeotemperature trends. Therefore, optimum palaeoenvironments for Carpocanistrum spp., "Spongodiscid spp. group", "Plagoniid spp. group", "Litheliid spp.", "Porodiscid spp. group", Stichocorys delmontensis Form A, Trisolenia spp., "Cyrtid spp. group 2" and Theocorys? subcylindrica appear to have been

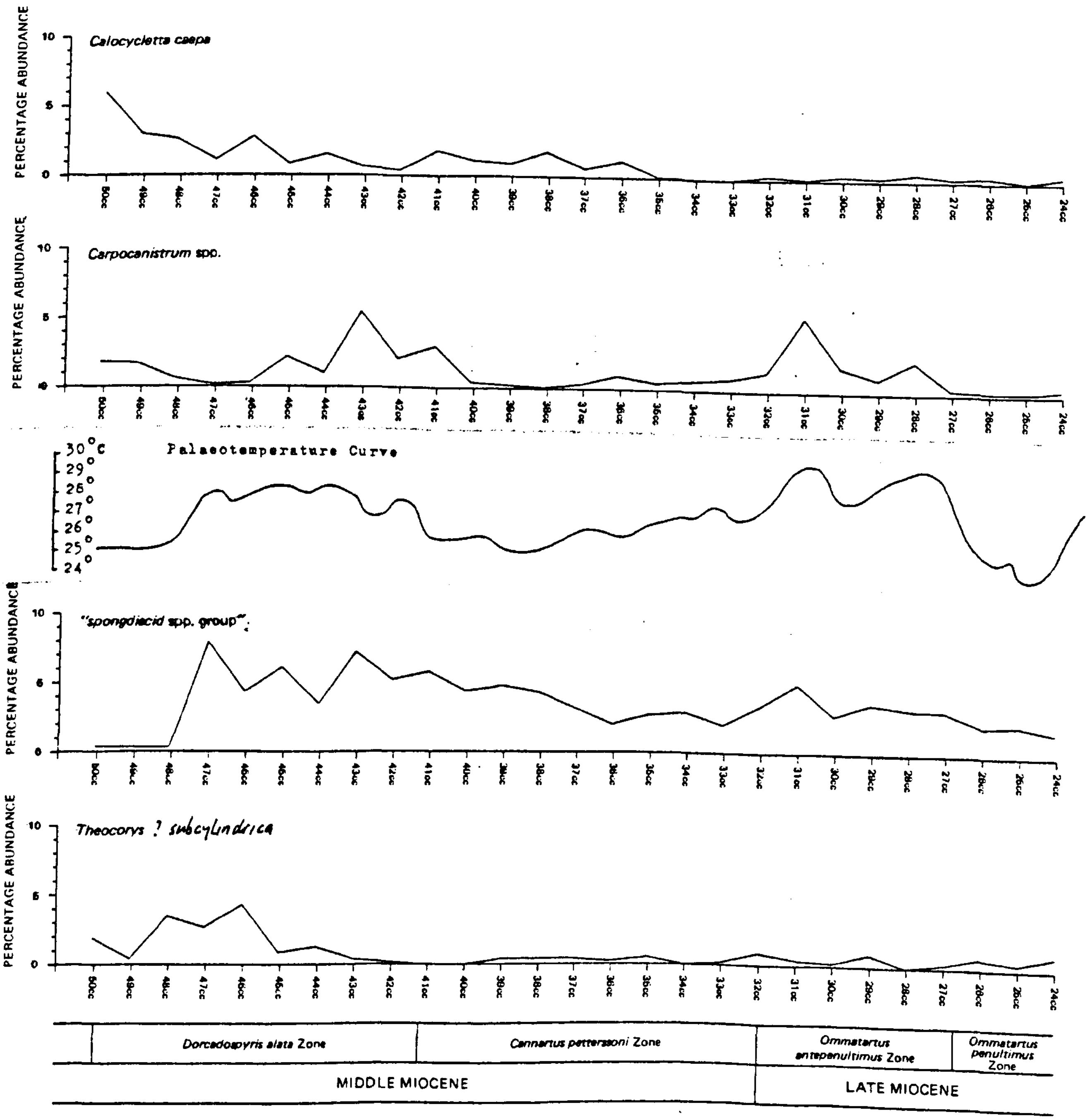


Fig. 64 Relative distribution of raciolarian taxa compared to palaeotemperature curve, Site 289

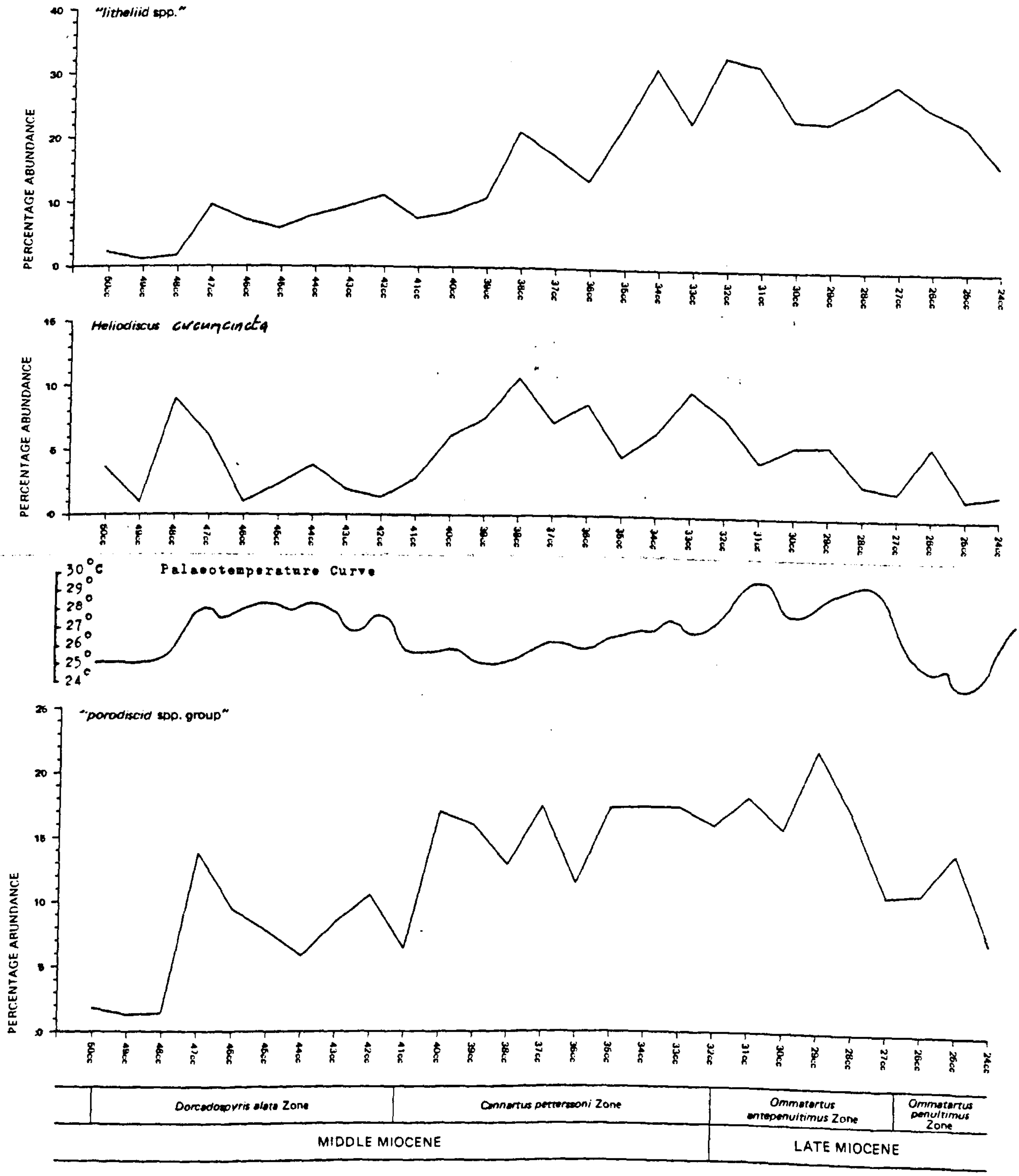


Fig. 65 Relative distribution of radiolarian taxa compared to palaeotemperature curve, Site 289

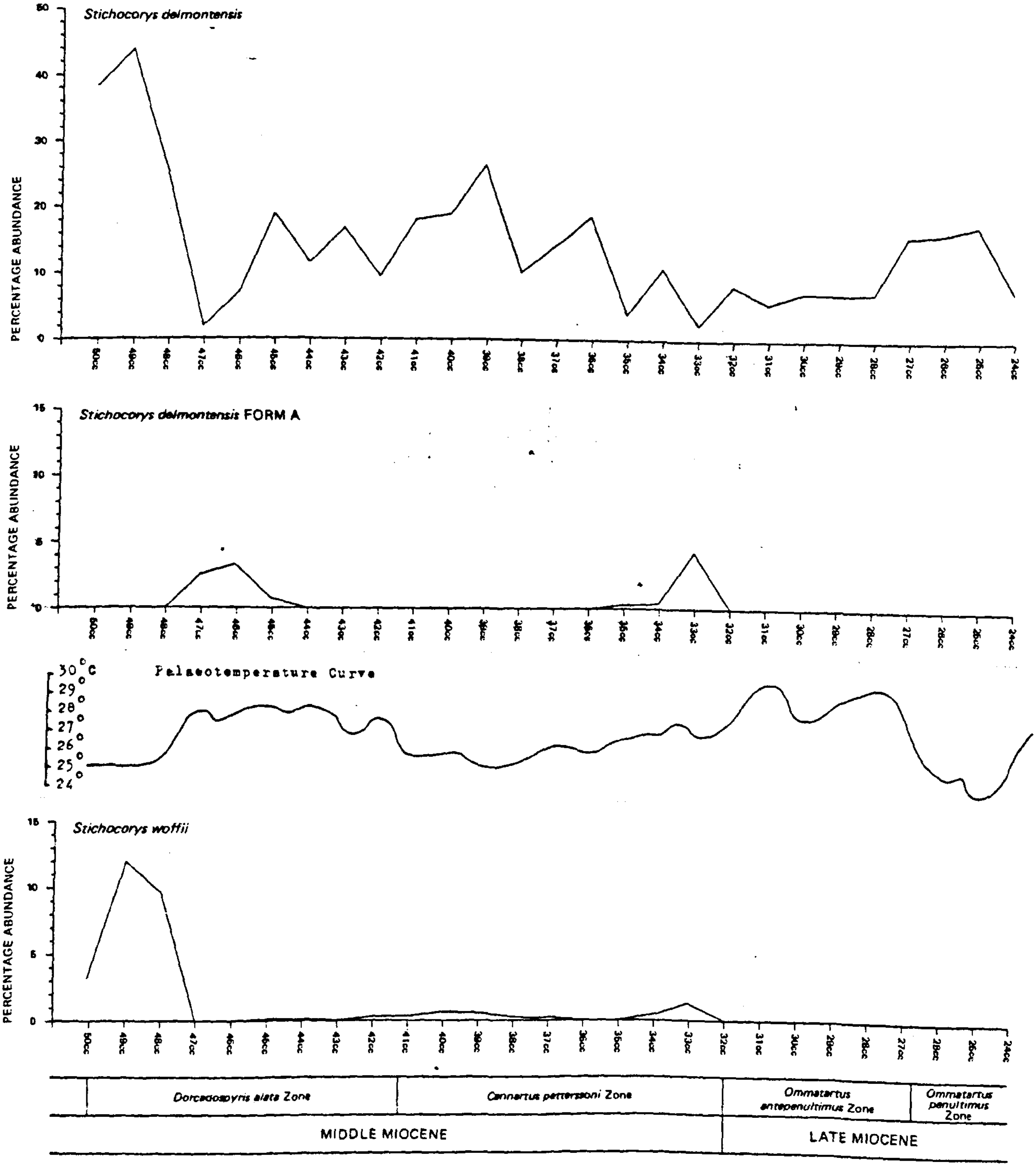


Fig. 66 Relative distribution of radiolarian taxa compared to palaeotemperature curve, Site 289

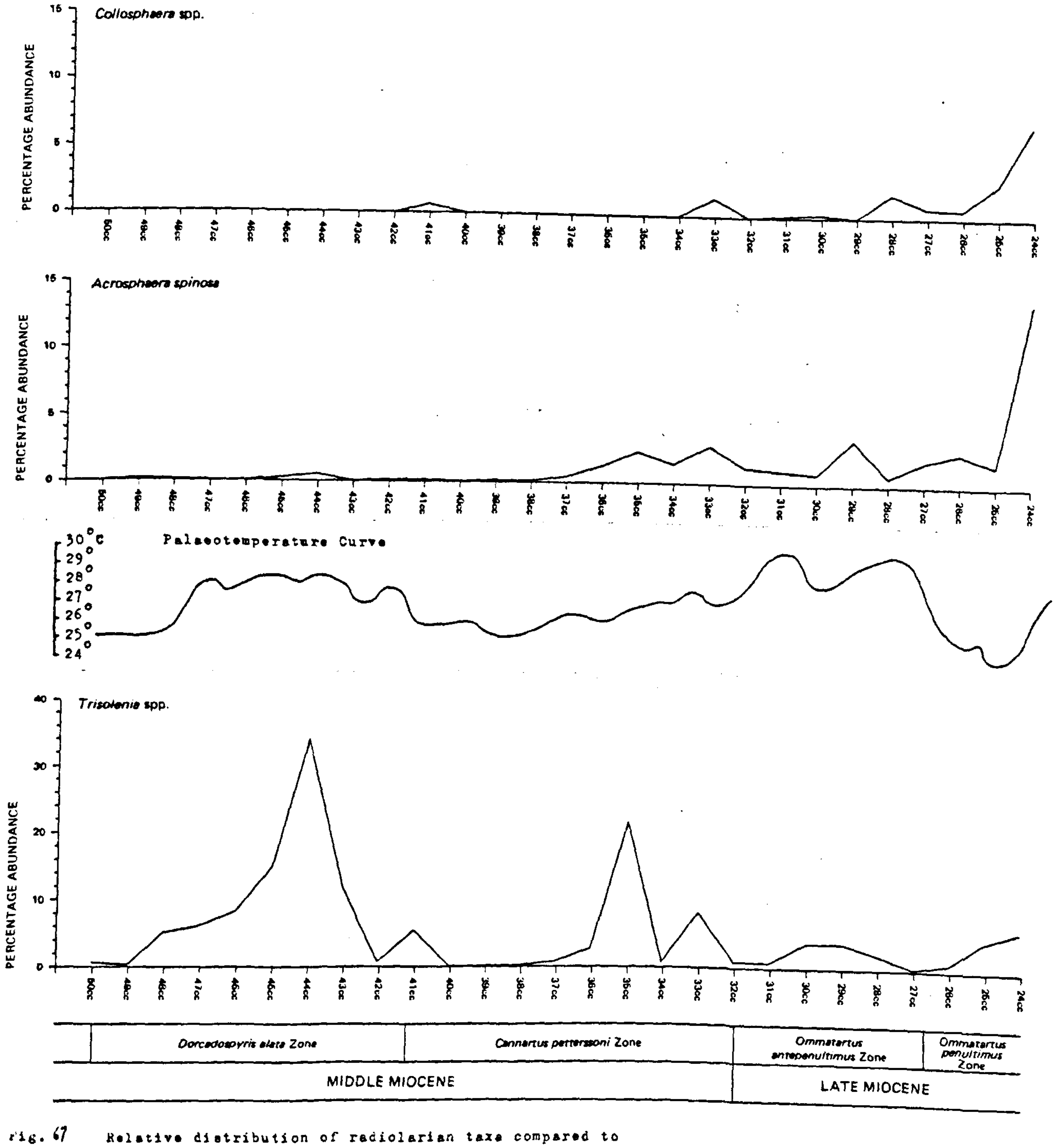


Fig. 67 Relative distribution of radiolarian taxa compared to palaeotemperature curve, Site 289

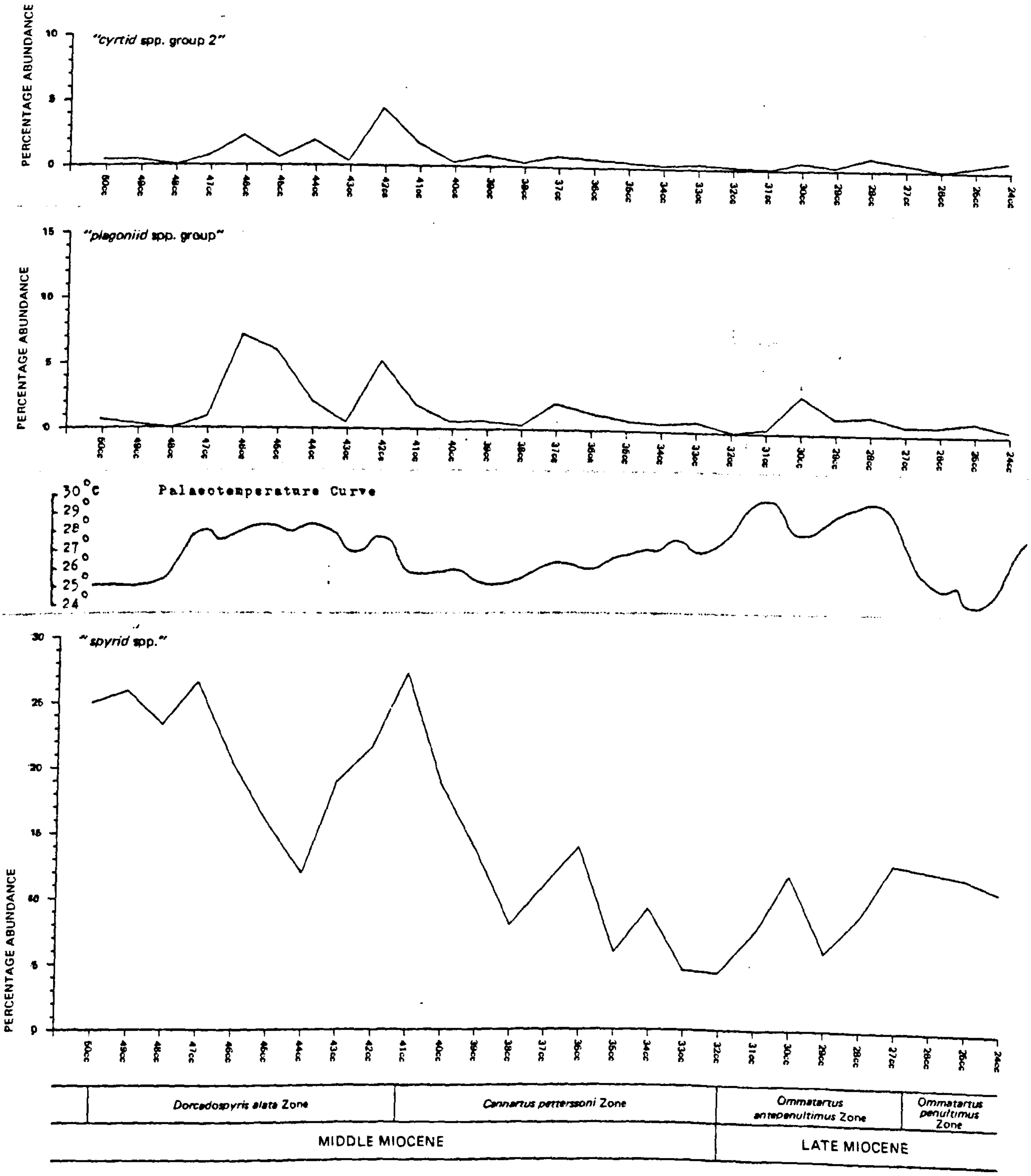


Fig. 68 Relative distribution of radiolarian taxa compared to palaeotemperature curve, Site 289

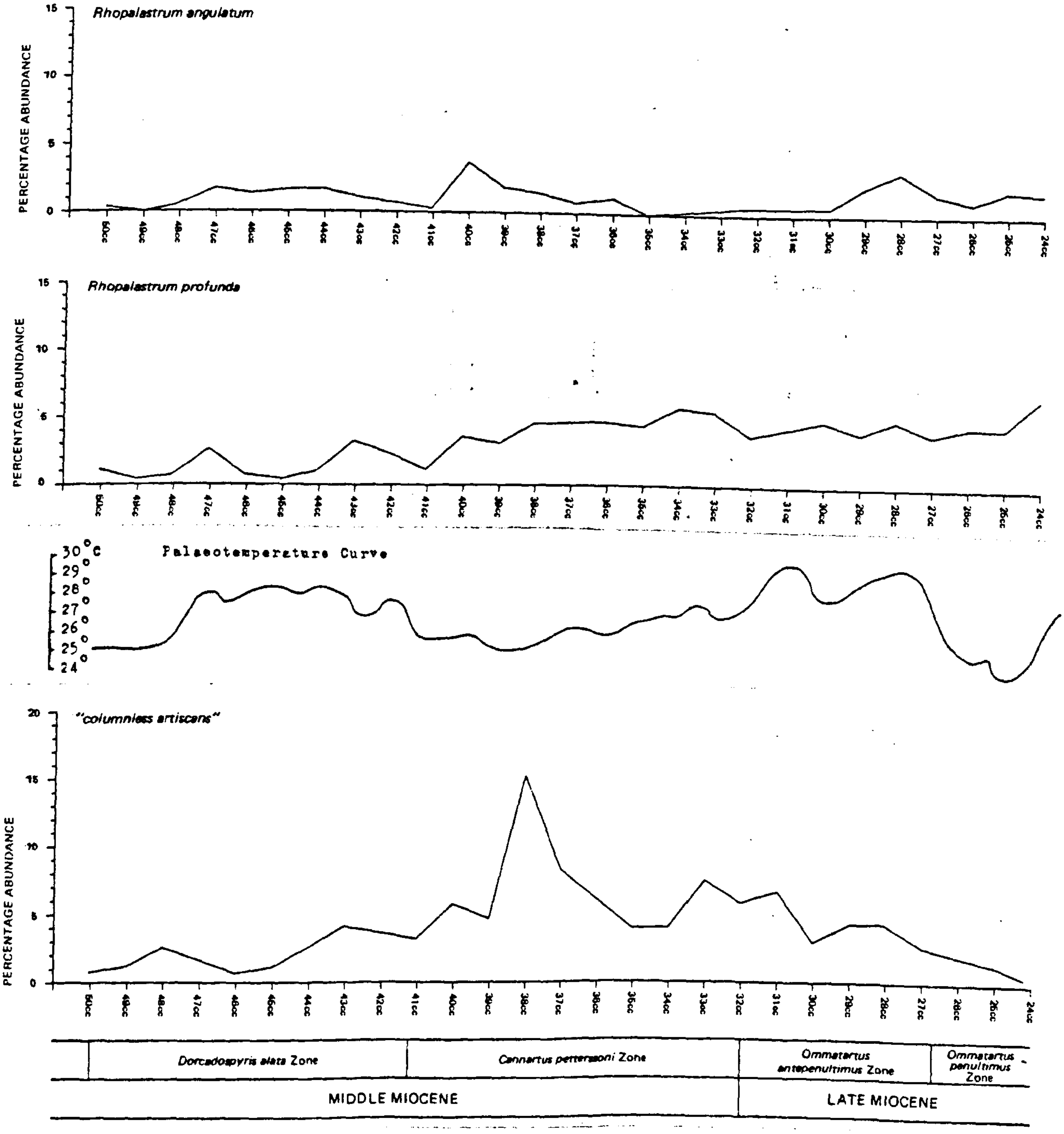


Fig. 69 Relative distribution of radiolarian taxa compared to palaeotemperature curve, Site 289

those within a non-upwelling, warm, tropical epipelagic zone. Conversely, optimum palaeoenvironments for Stichocorys delmontensis and S. wolffii appear to have been those within an upwelling, cooler, tropical to subtropical epipelagic zone.

The distribution of the remaining taxa considered above appears to have been influenced by factors other than palaeotemperature (?salinity etc.).

The quantitative distribution of many taxa at Site 289 is difficult to compare with the palaeotemperature curve because the forms are consistently present in low abundance e.g. Botryocyrtis spp., Eucyrtidium cienkowskii, Ommatartus antepenultimus (see Appendix I and fig.30). However, those taxa that are discontinuously distributed throughout the sequence can be more easily related to the palaeotemperature record and allow an assessment of palaeoenvironmental preferences based on qualitative criteria (presence or absence).

The distribution of several rare forms is given in fig.70. A comparison with the palaeotemperature curve indicates a correlation in certain instances. In Centrobotrys thermophilia, presence in the studied sequence tends to coinside with increased palaeotemperatures, while in Cyrtocapsella japonica and Actinomma medianum, presence tends to coincide with decreased palaeotemperatures. In these examples, data is sparse and interpretation may be regarded as subjective. However, the limited evidence suggests that distribution in these taxa may have been controlled by the process of upwelling. A consideration of the results of previous studies in the case of C. thermophilia and A. medianum tentatively support these conclusions (see Appendix I).

For most of the taxa listed in fig.70, distribution does not appear to correlate with the postulated palaeotemperature trends and

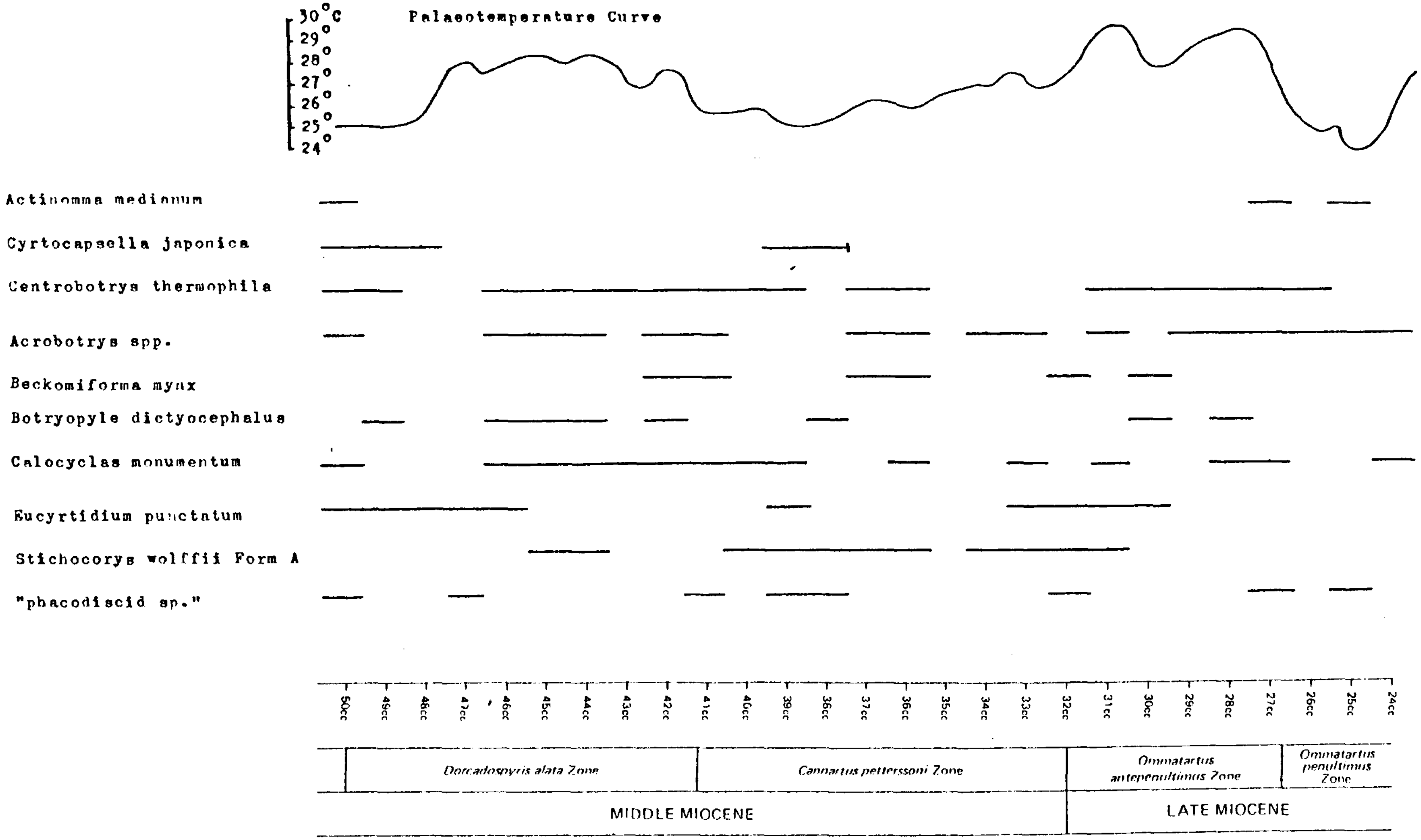


Fig. 70 The distribution of rare radiolarian taxa compared to the palaeotemperature curve, Site 289

alternative, unknown factors are considered to have been important (?salinity, etc; dissolution, see Chapter V).

A comparison of distribution in both abundant and rare taxa with the palaeotemperature trends indicates that normal and inverse correlations exist in several instances. However, the distribution of many forms exhibits no apparent relationship with the palaeotemperature record.

As in the case of planktonic foraminifera, changes in the quantitative distribution of individual taxa have been explained by reference to palaeotemperature, although other limiting factors may be involved. Changes in the structure of the epipelagic zone would be accompanied by changes in salinity, density, nutrient supply and biological competition, all of which can exhert important influences on radiolaria (CASEY, 1977).

ii) Stichocorys delmontensis s.l. : A Biometric Analysis

Stichocorys delmontensis s.l. is an important taxon within the radiolarian assemblages at Site 289 where it exhibits large scale variation in relative abundance and morphology. A brief outline of these changes is considered in Chapter V and Appendix I respectively. The relative distribution of S. delmontensis s.s. has been shown to vary inversely with palaeotemperature trends at Site 289 (fig.66). Conversely, the appearance of S. delmontensis Form A generally coincides with increased palaeotemperature (fig.66). Normal S. delmontensis morphotypes appear to be associated with upwelling in the epipelagic environment whereas S. delmontensis Form A, a small, stunted morphotype, seems to represent an ecophenotypic variant which appears with the development of warmer surface palaeotemperatures and a non-upwelling,stratified epipelagic zone.

Throughout the sequence at Site 289 there exist intervals where both morphotypes may either be clearly distinguishable or appear to intergrade. Due to its possible use as a palaeoenvironmental indicator, the morphological variation exhibited by the species is quantified by a biometric analysis.

Between 30 and 40 individuals were randomly selected in each core catcher sample from 50cc to 24cc, using a micrometer eyepiece at x100 magnification. The following measurements were taken:

i. combined length of the first three segments (cephalis, thorax and abdomen).

ii. maximum test width across the abdominal segment.

Length x width graphs for each sample are given in fig.71a-b. Measurements within approximately 6μ are grouped .

Since the two morphotypes can be normally distinguished by eye, they are also differentiated on the graphs by open and closed squares. Mean size in each sample is also indicated.

Samples 50cc, 49cc and 48cc indicate an exclusive presence of large, robust 'normal-forms'. Sample 47cc contains the first major development of 'Form A'. This morphotype, together with the few 'normal-forms' that are present, is clearly smaller than 'normal-forms' of preceeding samples.

From sample 46cc to 32cc, both morphotypes generally co-occur although differences in abundance, which are not truely represented in these plots, can be substantial (fig.30c). Size differentiation in these samples is usually apparent e.g. 44cc, although in several samples both morphotypes tend to intergrade e.g. 43cc, 32cc. From 31cc to 24cc, only 'normal-forms' are present.

Size variation in <u>S. delmontensis</u> through the studied sequence can

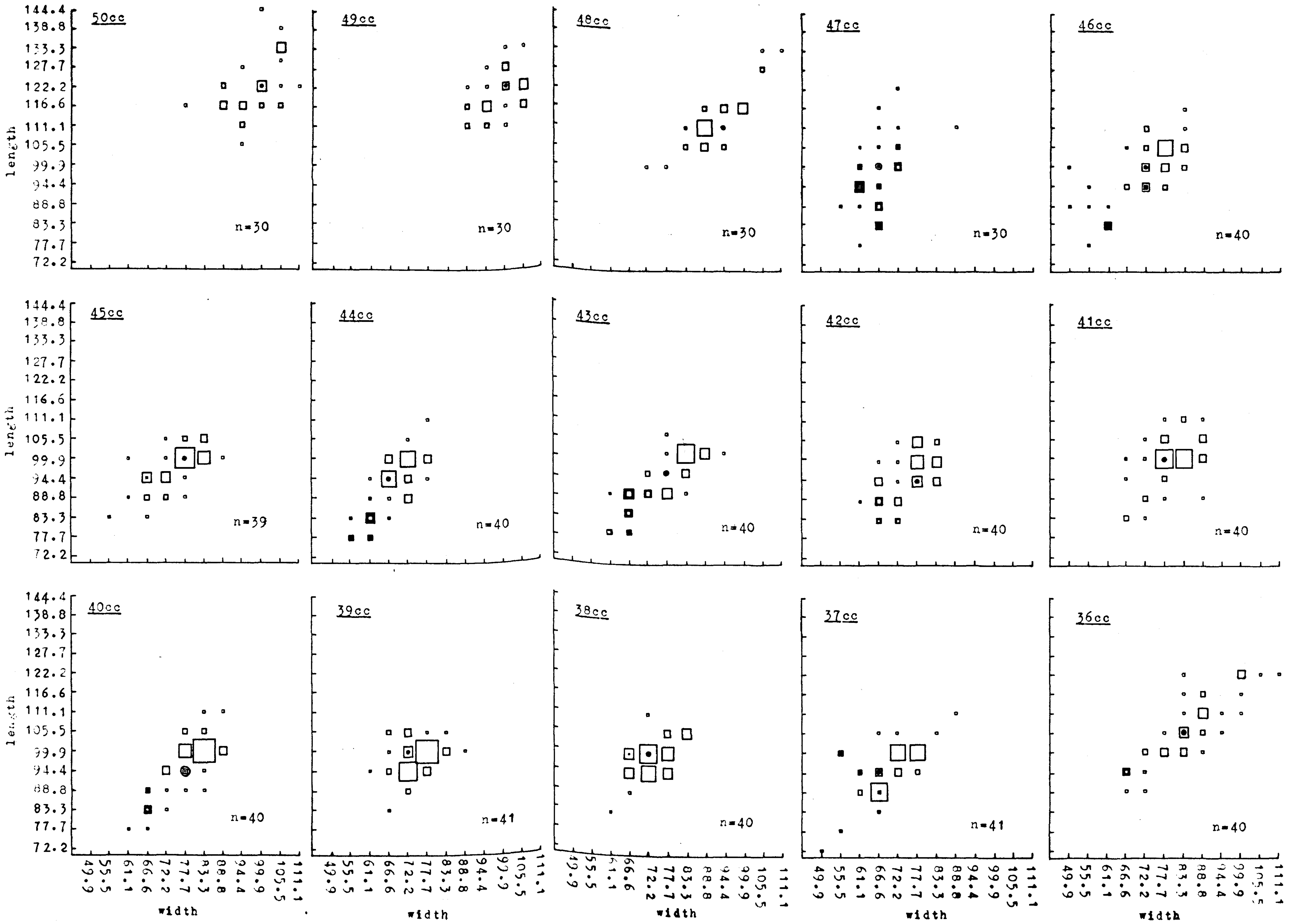
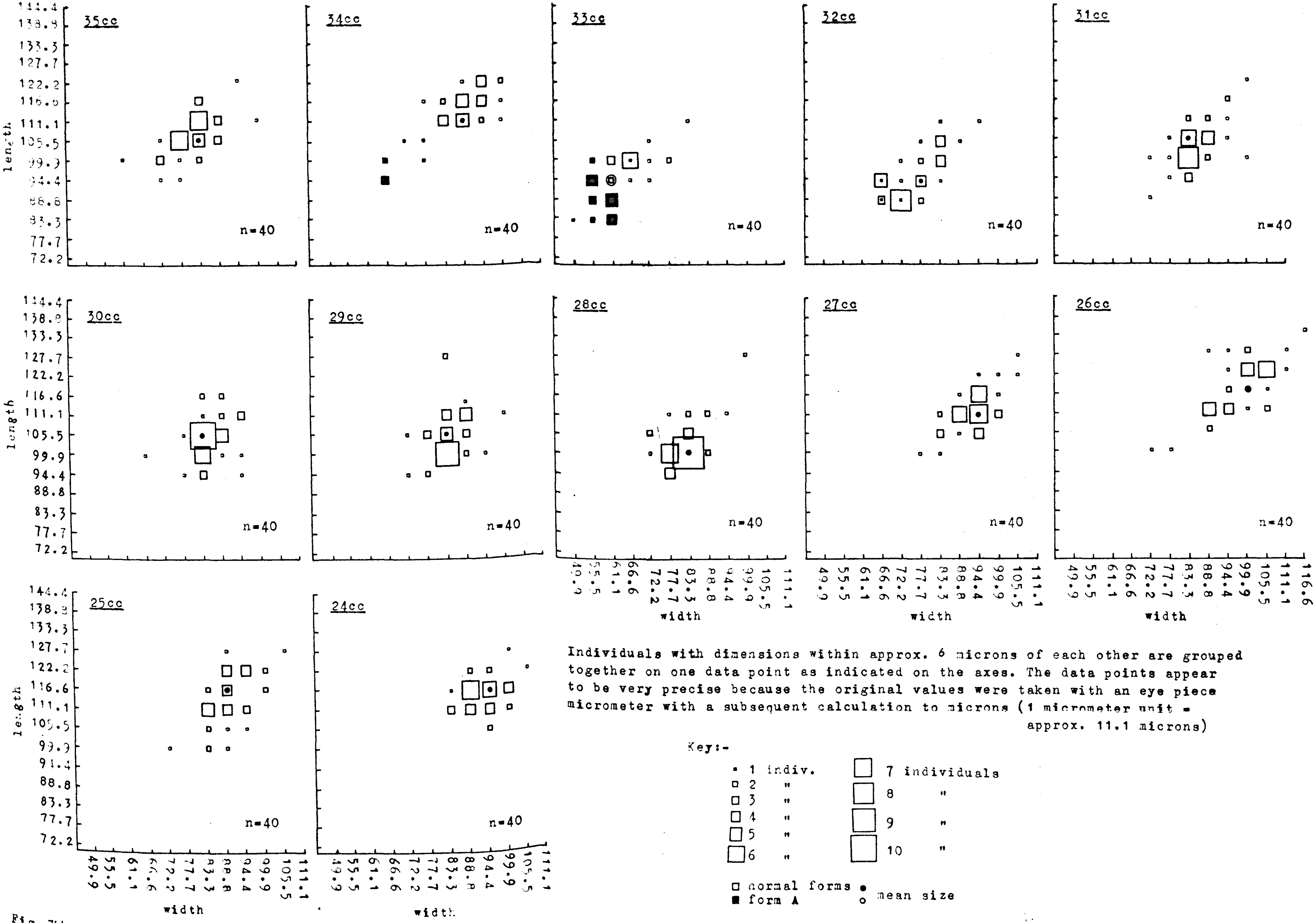


Fig. 7/4 Size frequency distribution in <u>Stichocorys delmontensis</u> s.l. within each sample at Site 289 (see Fig. 7/b overleaf for key)



Individuals with dimensions within approx. 6 microns of each other are grouped together on one data point as indicated on the axes. The data points appear to be very precise because the original values were taken with an eye piece micrometer with a subsequent calculation to microns (1 micrometer unit = approx. 11.1 microns)

Fig. 7b Size frequency distribution in *Stichocorys delmontensis* s.l. within each sample at Site 289 be represented by a plot of mean size per sample. The mean size represents two variables however (length and width), which, for the purpose of this histogram, must be represented by a single parameter. If the mean size for a sample is plotted on triangular graph paper, the distance from the co-ordinate to the base apex can be considered as a simple approximate indication of size (fig.72).

The relative distance in each sample is plotted in fig.73, where the trend is compared to the palaeotemperature curve. The vertical scale representing 'm' is only relative. No consistent relationship is apparent, although highest mean sizes co-exist with lowest palaeotemperatures (within cores 50 to 48; 27 to 24) while decreased mean sizes accompany increased palaeotemperatures (within cores 47 to 42, 33 and 28). Elsewhere however, an increase in mean size may not be associated with decreased palaeotemperatures (within cores 36 to 34 and 31) while increased palaeotemperatures may not be associated with a decrease in mean size and the development of 'Form A' morphotypes (within cores 32 to 28).

Size variation in S. delmontensis may be a function of selective sorting by current activity or dissolution. Intervals where increased dissolution of radiolaria tests are postulated, i.e. within cores 50 to 48 and 27 to 24, are certainly characterised by large, robust 'normal-forms'. However, the clear distinction of two seperate morphotypes, particularly in the interval from 48cc to 46cc, within which a large and sudden palaeoceanographical (palaeotemperature) change is postulated, suggests an important palaeoenvironmental influence.

The lack of a consistent relationship between mean size distribution in S. delmontensis s.l. and palaeotemperature trends at Site 289 may reflect the combined influence of palaeoenvironmental and

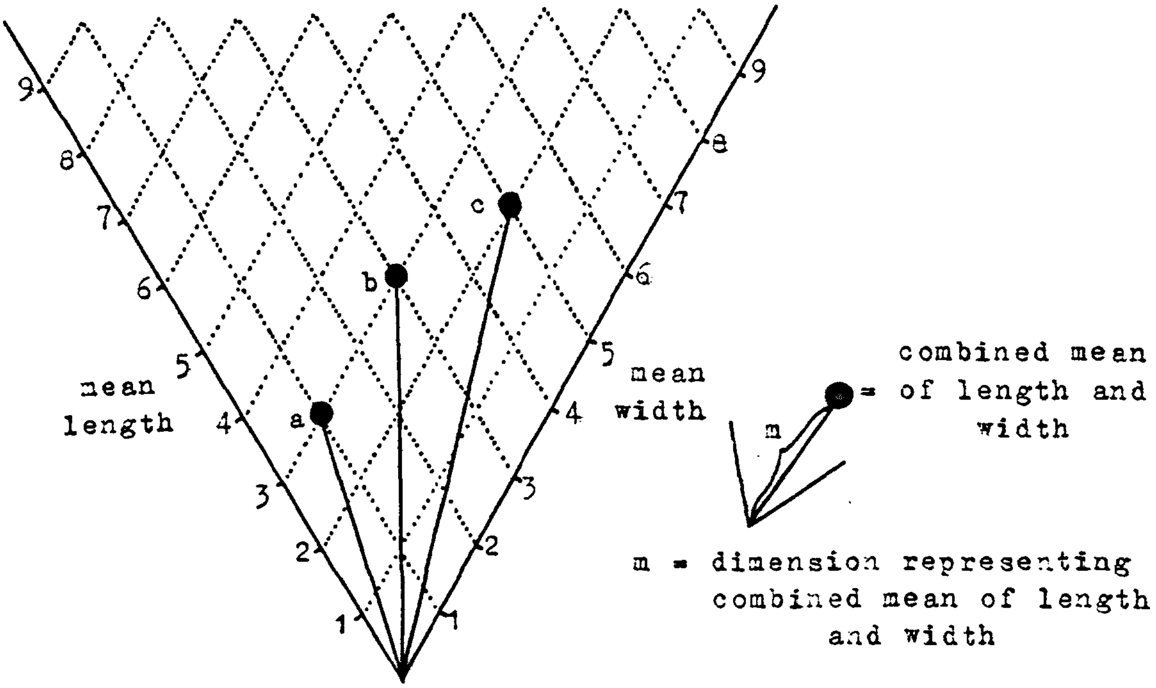


Fig. 72 The definition of dimension m as a representation of the combined mean of length and width

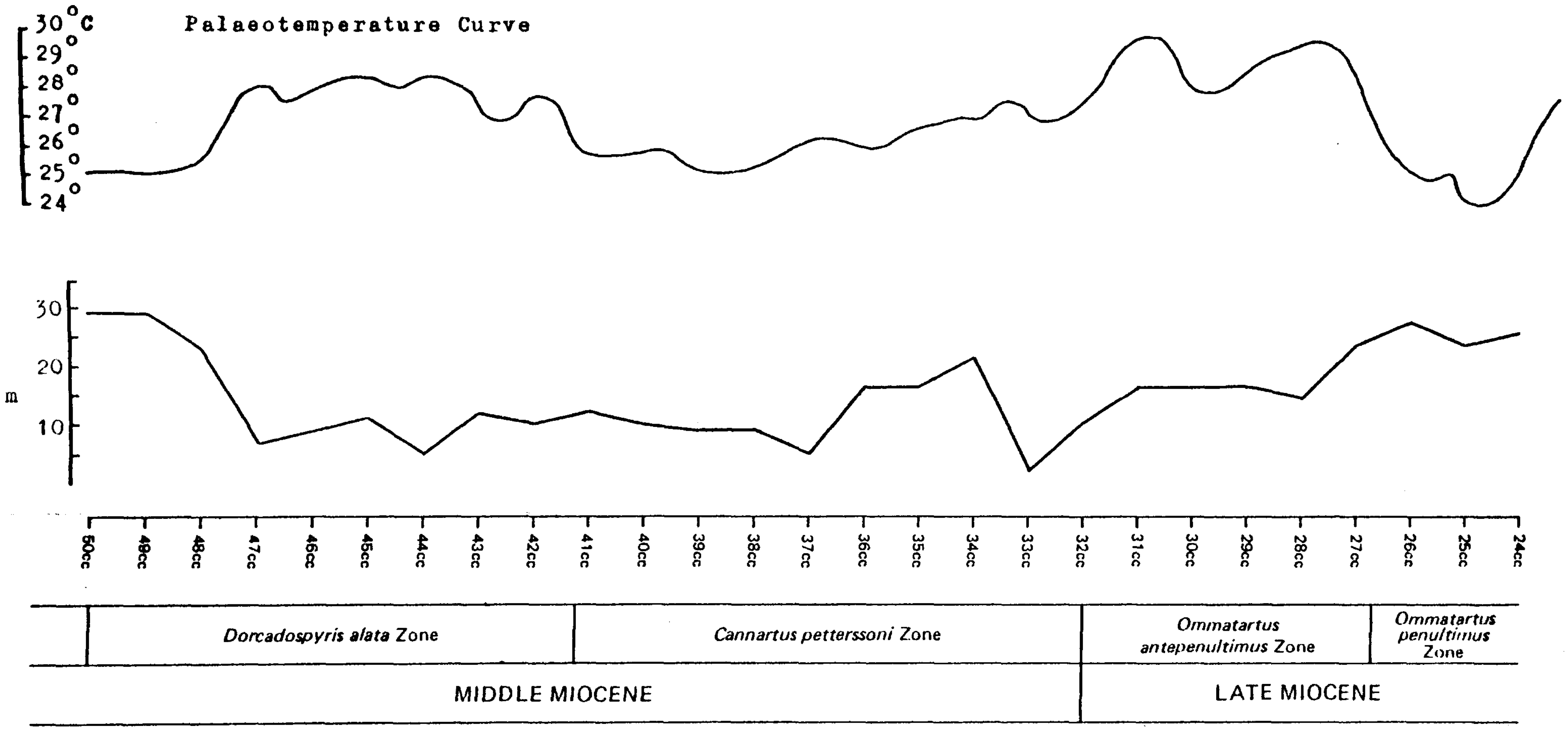


Fig.73 'Mean Size' (m) in <u>Stichocorys delmontensis</u> s.l. compared to the palaeotemperature curve at Site 289 post-mortal disruptive factors. Nevertheless, the distinction between large, robust 'normal-forms' and small, stunted 'Form A' morphotypes does appear to reflect palaeoceanographical processes. Intervals within which the distinction between both morphotypes is clear probably indicates a sharp change between upwelling and non-upwelling palaeoenvironments (e.g. 48cc to 47cc), whereas intervals within which the distinction is gradual, via intermediate forms, probably reflects more gradual transformations (e.g. 43cc).

The intraspecific variation in S. delmontensis s.l. which appears to be related to palaeotemperature trends, may be possibly associated with a functional morphology.

Planktonic organisms may transgress or migrate across particular density defined environmental niches by modifying their bouyancy (BÉ, 1977). If, because of unknown reasons (light?), S. delmontensis s.l. is restricted to a relatively narrow depth range, then a bouyancy regulating mechanism would be necessary to maintain this depth when density values are fluctuating because of upwelling induced changes in temperature. The morphological variation apparent at Site 289 may reflect attempts to maintain the species at certain depths.

The large, robust and heavy 'normal-forms' may be adapted to maintain a particular depth within cold, upwelling waters. Should upwelling cease and temperatures increase, the waters would become less dense. To maintain its position and prevent sinking, the species would need to become more bouyant. The small, stunted and lighter 'Form A' may reflect this requirement.

Consideration of functional morphology in radiolaria is highly speculative and is not enhanced by the massive range of morphological types encountered in a single assemblage and derived from a limited range of environments. Further, the role of test morphology may be secondary to that of cytoplasmic adaptations to a planktonic mode of life. Speculation as to the causes and consequences of dimorphism in S. delmontensis is further complicated since the variation may be due to periodic depletion of available silica in the water column, although within the interval at Site 289 where S. delmontensis undergoes greatest changes i.e. from 48cc to 47cc, no similar phenomenon is apparent in any other radiolarian genus. Nevertheless, any possible relationship between temperature controlled density changes and functional morphology must be regarded as tentative.

Though not investigated in detail herein, dimorphism in S. armata and S. wolffii is superficially similar to that seen in S. delmontensis and may be of similar significance.

iii) Diversity Indices

The significance of diversity in radiolaria as an indicator of palaeoenvironment (palaeotemperature; palaeoceanography) is considered in Chapter II.

A comparison of simple diversity (absolute numbers; α index) in radiolaria at Site 289 with the palaeotemperature curve reveals a weak normal correlation (fig.74). Increased diversity and palaeotemperature coincide within cores 47 to 42 and 30 to 27. The relationship is more evident between palaeotemperature and the α diversity index (the more reliable of the two) and may derive from increased niche availability during times of warm surface waters with the development of a stratified epipelagic zone. The simple diversity trend may also reflect changes in dissolution intensity however (see Chapter V). The relative influence of palaeotemperature and dissolution to the diversity of radiolarian assemblages at Site 289 cannot be accurately assessed, although from evidence discussed in Chapter V, it is probable that dissolution is more

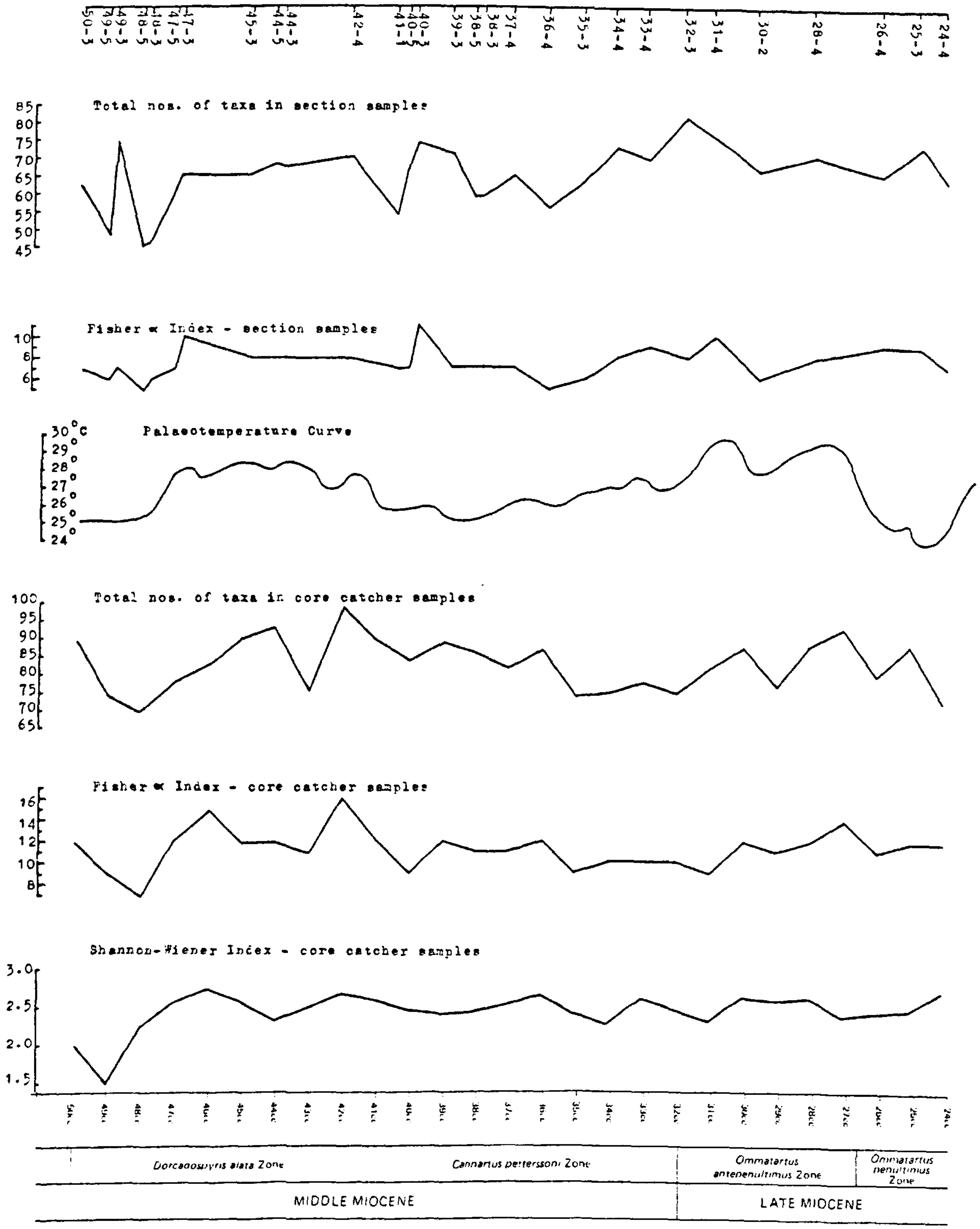


Fig.74 Diversity Indices in radiolaria compared to the palaeotemperature curve at Site 289

important.

A comparison of compound diversity (Shannon-Wiener) in radiolaria with the palaeotemperature curve at Site 289 is given in fig.74. A limited normal correlation is also evident with increased diversity accompanying increased palaeotemperature and decreased diversity accompanying decreased palaeotemperature.

In the present study, the application of diversity indices in radiolaria for palaeoenvironmental interpretation appears to be useful although the influence of fluctuations in dissolution intensity must be strongly considered.

iv) Similarity Index

The similarity index which illustrates the 'rate of change' in the radiolarian assemblages at Site 289 may distinguish intervals of taxonomic consistency from intervals of taxonomic instability. Since the base sample (50cc) can be partly regarded as representing a 'cold-water' (upwelling) assemblage, similarities to and deviations from this 'standard' in subsequent samples can be interpreted as an indication of palaeotemperature variation. The 'rate of change' index may therefore serve as a useful indicator of palaeoenvironment.

A comparison of the 'rate of change' index with the palaeotemperature curve at Site 289 is given in fig.75. Major deviations in similarity to sample 50cc tend to coincide with increased palaeotemperature (from samples 47cc to 43cc, 38cc to 37cc and 33cc to 28cc). Conversely, intervals of increased similarity to sample 50cc tend to coincide with decreased palaeotemperature (from samples 42cc to 39cc, 36cc and 27cc to 24cc). The relationship is not entirely consistent however and interference in the trend may be caused by the strong influence of dissolution in the 'standard sample' and by the subsequent

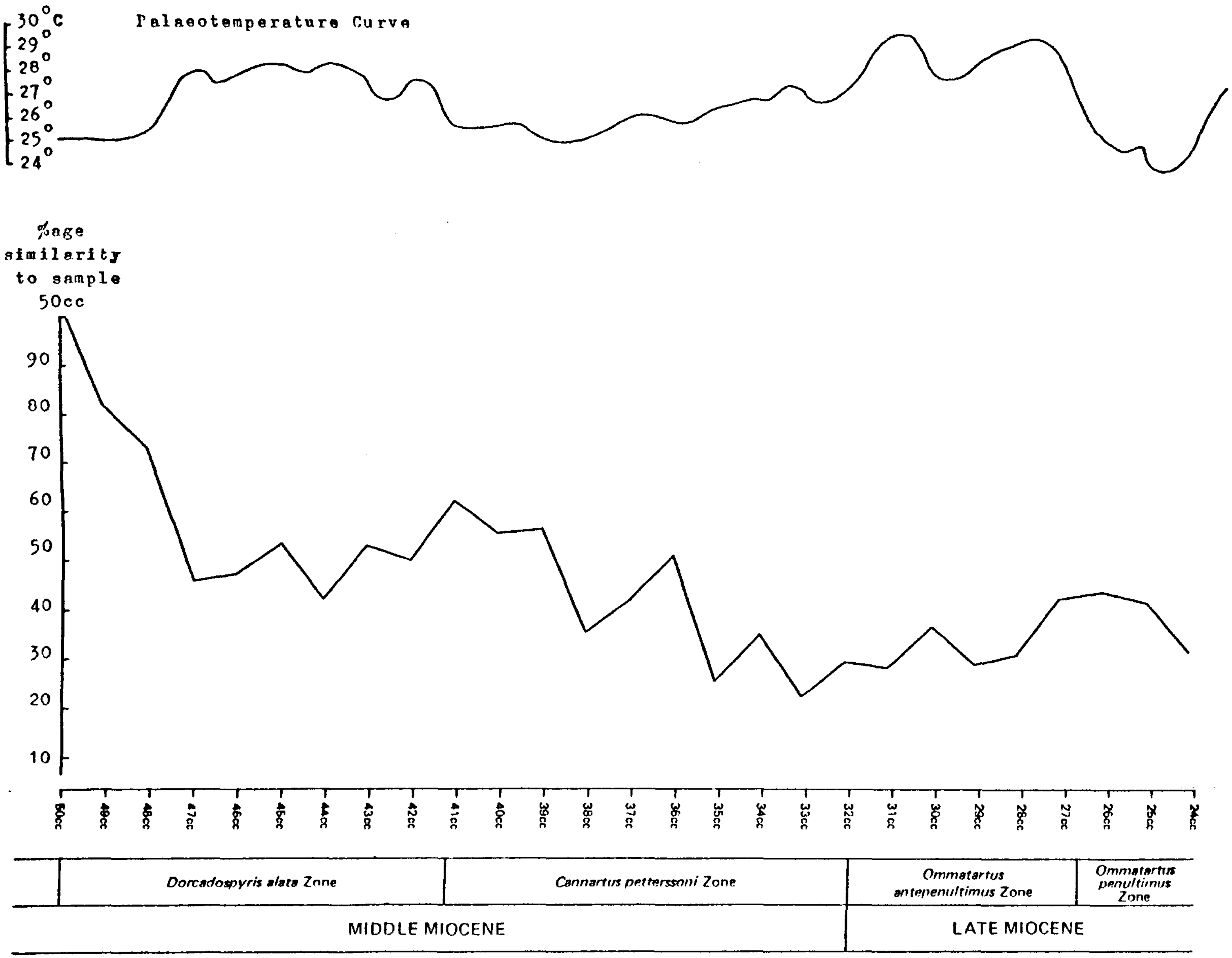


Fig. 75 Similarity Index for radiolaria compared to the palaeotemperature curve, Site 289

evolutionary introduction of new forms.

A comparison of the similarity indices in planktonic foraminifera and radiolaria generally indicates a normal correlation in the tends (compare fig.62 and 75). This relationship suggests that the same factor governs the nature of both the planktonic foraminiferal and radiolarian assemblages. This major factor appears to be palaeotemperature.

v) Evolutionary Events

Throughout the main studied sequence at Site 289 (cores 50 to 24), many evolutionary events involving the appearance and extinction of numerous radiolarian taxa were encountered. A brief comparison of this information with the palaeotemperature curve may indicate the extent to which evolutionary appearances and extinctions are related to the palaeoenvironmental changes envisaged for the sequence.

The number of appearances and extinctions per core is plotted separately in fig.76. The taxa used to compile these graphs are indicated in fig.30a-d by an asterisk (appearance) and a cross (extinction). In many cases, the stratigraphical position of the datums correspond to known ranges (see Appendix I). In some taxa, ranges at Site 289 are far different than those apparent elsewhere and may reflect local palaeoenvironmental conditions e.g. Botryostrobus miralestensis, Eucyrtidium punctatum and Heliodicus asteriscus.

The appearance/extinction data is combined in fig.76 to indicate net taxonomic loss or gain per core. A comparison of this plot with the palaeotemperature curve reveals a good correlation (fig.76). Intervals of increased palaeotemperature are generally characterised by net taxonomic gain i.e. an increase in the diversity potential of radiolarian assemblages e.g. within cores 47 to 44, 40, 35 and 32. Conversely, intervals of decreased palaeotemperature are characterised by net

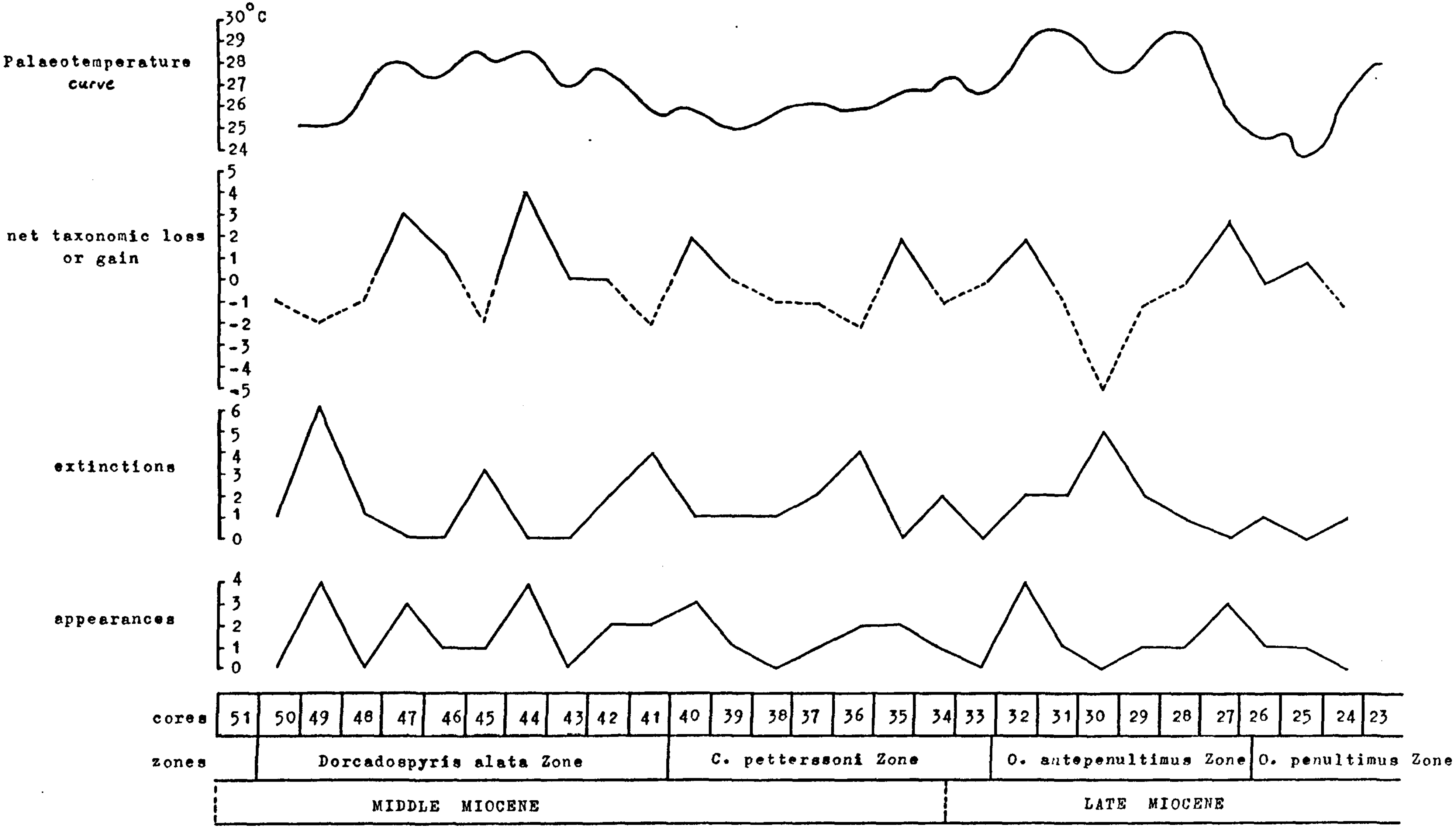


Fig. 76 Evolutionary events in radiolaria at Site 289

taxonomic loss i.e. a decrease in the diversity potential of radiolarian assemblages e.g. within cores 49 to 48, 41, 39 to 36, 30 and 29 and 24. The relationship is not entirely consistent however as high palaeotemperatures within core 28 are unaccompanied by a significant increase in potential diversity.

As in the case of planktonic foraminifera at Site 289, evolutionary radiation in radiolaria seems to be related to palaeoenvironment, with appearances tending to coincide with an increase in niche availability caused by the development of non-upwelling, stratified, epipelagic environments. Conversely, most extinctions tend to coincide with a decrease in niche availability caused by the development of upwelling and homogenisation within the epipelagic environment.

vi) Dissolution of Planktonic Foraminifera and Radiolaria : A Possible Cause

The dissolution of planktonic foraminifera and radiolaria at Site 289 is considered in Chapter V. Noticeable dissolution of planktonic foraminifera is apparent within cores 50 to 48 and in 31-6, while dissolution of radiolaria is apparent in samples 50cc to 47cc, 45cc, 43cc, 37cc, 35cc, 34cc, 32cc and 26cc to 24cc. Although the dissolution of calcareous and siliceous tests is governed to a great extent by different factors (see Chapter II), it is evident that major dissolution of planktonic foraminifera occurs in approximately the same stratigraphical interval as that of radiolaria. The converse does not hold however, although the limited correlation nevertheless suggests a common cause.

The dissolution of planktonic foraminifera and radiolaria is partly controlled by surface water productivity, which is itself a reflection of climate (see Chapter II). A comparison of dissolution intervals at Site 289 with the palaeotemperature curve may therefore indicate a relationship (fig. 77).

Intervals of prolonged dissolution, i.e. within cores 50 to 48 and 26 to 24, coincide with reduced palaeotemperatures. BERGER (1979) has reviewed the observed relationship between palaeoclimate and dissolution of planktonic foraminifera in Cenozoic deep sea sequences of the Pacific Ocean (see ARRHENIUS, 1952; HAYS <u>et al</u>., 1969; BERGER, 1973; HEATH, MOORE and Van ANDEL, 1977). Briefly, the onset of a cold (glacial) event may affect dissolution in two ways :

i) the associated increase in ocean fertility via the intensification of upwelling may increase the sedimentation rate of pelagic deep sea carbonates and decrease dissolution of planktonic foraminifera by decreasing the exposure time at the sediment/water interface.

ii) Alternatively, the associated increase in the intensity of corrosive bottom water flow may increase the dissolution of planktonic microfossils and the mechanical breakdown of all sedimentary grains by reducing sedimentation rates and extending exposure time at the sediment/water interface.

At Site 289, the correlation between decreased palaeotemperature and poor preservation of planktonic foraminifera and radiolaria within cores 50 to 48 and 26 to 24 suggests a possible detrimental influence of corrosive bottom currents. Increased bottom water activity and surface water upwelling may result simultaneously from high latitude glacial activity (Chapter II). The corrosive activity of bottom water currents would tend to decrease the sedimentation rate in a pelagic carbonate sequence. At Site 289, reduced sedimentation is postulated within cores 50 to 48, where dissolution of calcareous and siliceous microfossils is evident (see Chapter IV, fig.19).

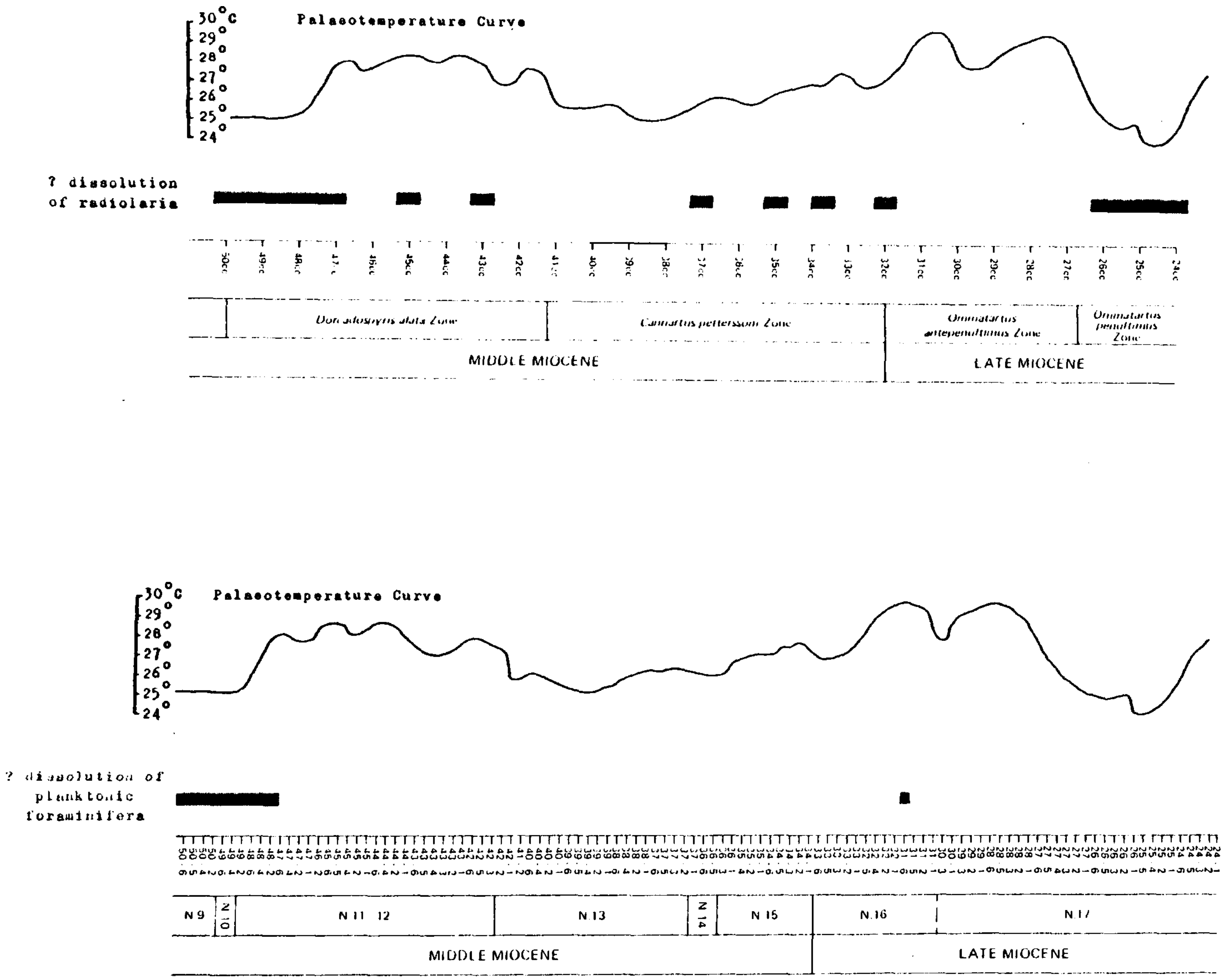


Fig. 77 A comparison of possible dissolution intervals with the palaeotemperature curve at Site 289

However, the relationship between dissolution and palaeoclimate at Site 289 is not straightforward, since poor preservation also coincides with increased palaeotemperatures (within cores 35, 32 and 31).

In this case, decreased biological productivity within the epipelagic zone related to the cessation of upwelling may be responsible.

From a consideration of the stratigraphical distribution of increased radiolaria dissolution at both Sites 288 and 289 on the Ontong Java plateau, HOLDSWORTH and HARKER (1975) indicate that local current activity may have played a significant role.

It is therefore apparent that dissolution of microfossils at Site 289 may be caused by different factors at different times. Although a possible relationship between palaeoclimate and dissolution has been considered, other factors such as variation in local bottom current activity, changes in water depth or diagenetic effects may be very important but are difficult to demonstrate herein.

4. DSDP SITE 71

The palaeoenvironmental/palaeoecological interpretation at Site 289 in the western equatorial Pacific, together with a consideration of present day environmental features in the western and central equatorial Pacific, can be used to speculate as to the cause of some taxonomic distributions in planktonic foraminifera and radiolaria in the Middle Miocene at Site 71.

At the present time, there are several environmental differences between the epipelagic zones at Sites 289 and 71 (see Chapter II, fig.10). Site 71, in the central equatorial Pacific, is characterised by lower surface temperatures (25.5°C against 29.5°C) and a weaker (thinner) thermocline. The area around Site 71 approximately marks the maximum westerly extension of equatorial upwelling at the present time. These differences in oceanic characteristics between Sites 289 and 71 are believed to have existed since the beginning of the Middle Miocene (Van ANDEL et al., 1975). Consequently the differences should be reflected in the nature of the planktonic assemblages, both fossil and living.

The studied sequence at Site 71 is correlated with the interval from within cores 47 to 44 at Site 289 (Chapter V). The palaeotemperature interpretation for Site 289 in this interval indicates high surface water palaeotemperatures and the development of a stratified epipelagic zone with no indication of significant upwelling until the top of the sequence (Chapter VI, fig.52).

A comparison of taxonomic distribution in the equivalent intervals at Site 289 and 71 is given in Chapter V. The overall similarity in planktonic foraminiferal and radiolarian assemblages between the two sites suggests that palaeoenvironmental differences were not large. Nevertheless, noticeable discrepencies in the relative and absolute distribution of particular taxa tend to indicate differences in surface water palaeotemperature between both sites.

i) Planktonic Foraminifera

Planktonic foraminiferal assemblages of the Middle Miocene interval at Site 71 differ from contemporaneous equivalents at Site 289 in several points:

Globoquadrina venezuelana is more abundant while Globorotalia fohsi s.l. in less abundant; Globigerina falconensis and Globorotalia miozea are only found at Site 71 while Globorotalia peripheroacuta is only found at Site 289.

A consideration of palaeoecological conclusions made for these species at Site 289 and from previous work (see this Chapter and Appendix palaeotemperatures relative to Site 289. However, Site 71 is also characterised by increased abundance of the 'warm-water' forms, 'Porodiscid spp. gp.', 'Lithellid spp.' and 'Spongodiscid spp. gp.'. Thus the increased relative abundance of some radiolarian taxa which are believed to indicate 'warm' surface water palaeotemperatures is inconsistent with the decreased palaeotemperature postulated for Site 71 relative to Site 289.

iii) Stichocorys delmontensis s.l. : A Biometric Analysis

Variation in abundance and size of S. delmontensis at Site 289 appears to partly reflect changes in palaeotemperatures within the epipelagic zone. A biometric analysis of individuals similar to that carried out at Site 289 is offered for those at Site 71. A comparison of results between both sites may therefore indicate the extent of palaeotemperature differences.

Although 'normal forms' and 'Form A' individuals can be visually differentiated, they tend to continuously intergrade in most samples (fig.78).

A plot of mean size per sample is given in fig.79. A comparison of this plot with that of the equivalent time interval at Site 289 (cores 47 to 44) reveals the range of mean size to be approximately similar.

Size frequency histograms for all individuals measured within equivalent time intervals at Site 289 and 71 is given in fig.80. The graphs indicate that Site 289 differs from Site 71 in that S. delmontensis 'Form A' individuals tend to include smaller forms. If S. delmontensis 'Form A' is an ecophenotypic variant which develops as a response to increased surface water palaeotemperatures, this would seem to indicate warmer palaeotemperatures at Site 289 relative to Site 71.

An overall consideration of the distribution of those planktonic

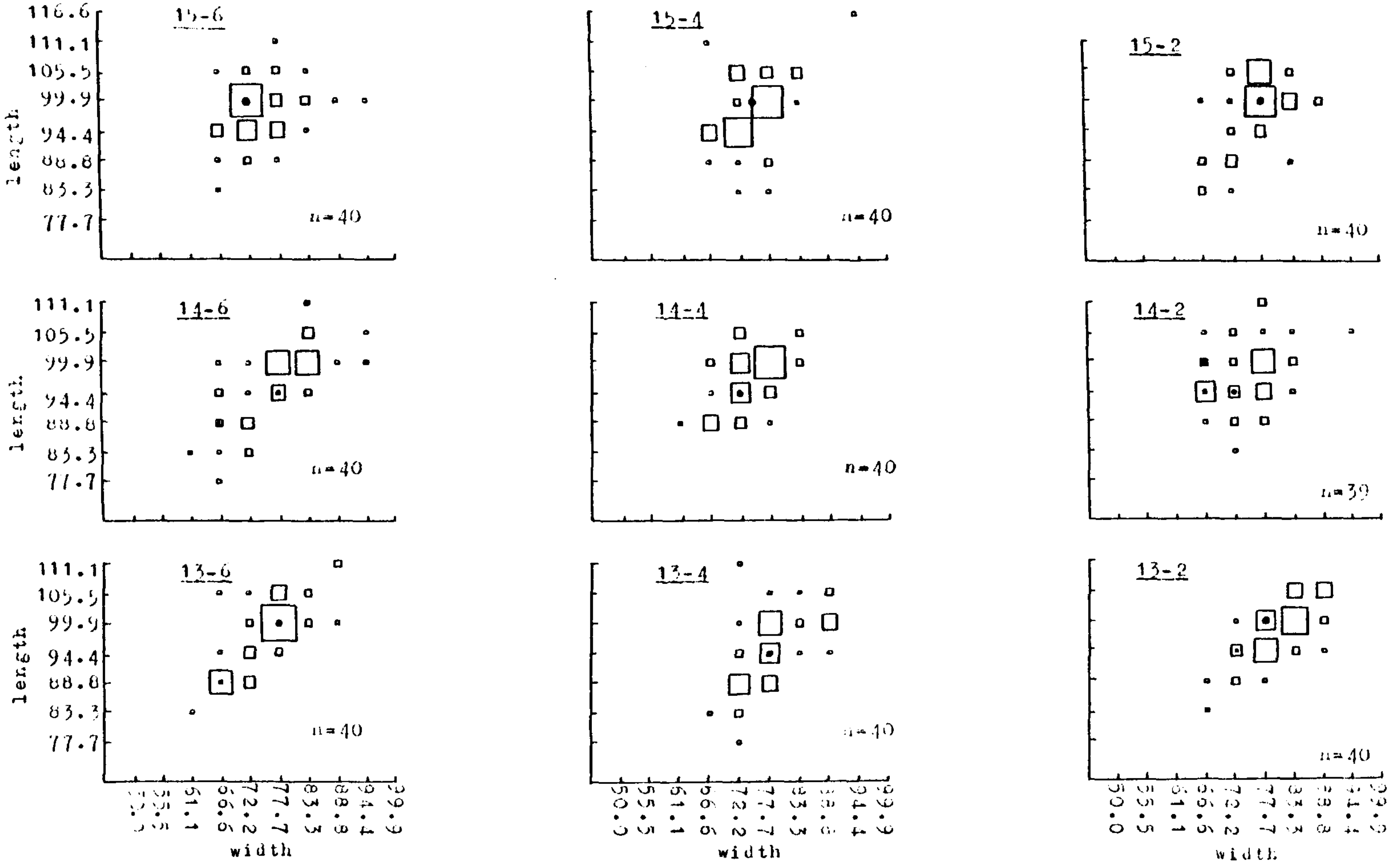


Fig.7B Size frequency distribution in Stichocorys delmontensis s.l. within each sample at Site 71

Individuals with dimensions within approx. 6 microns of each other are grouped together on one data point as indicated on the axes.

Key :-

● mean size

▪ 1 indiv.

□ 5 "

□ 8 "

▫ normal forms

• form A

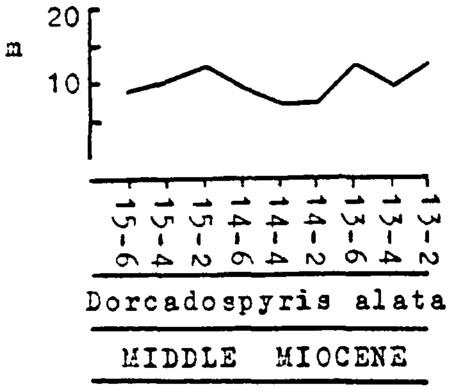


Fig.79 'Mean Size' (m) in *Stichocorys delmontensis* s.l. at Site 71

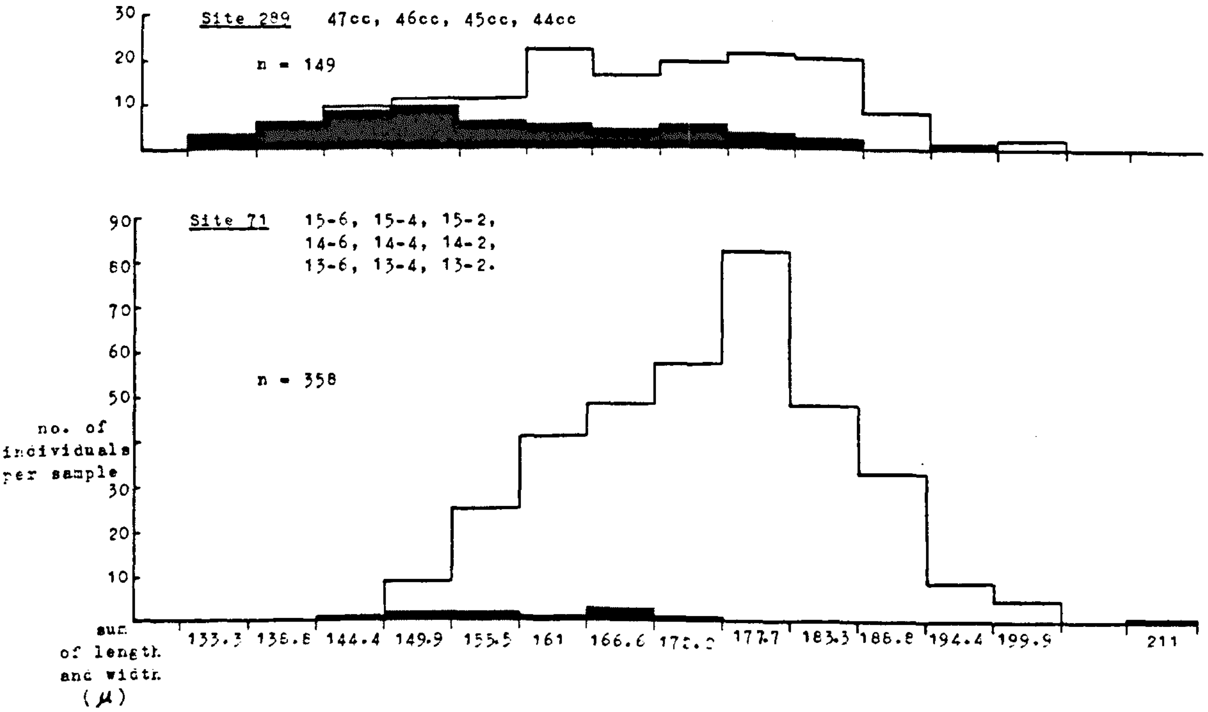


Fig. 30 Size frequency distribution histograms for *Stichocorys delmontensis* s.l. at Sites 289 and 71

▬ = Form A individuals

For convenience, the classes are composite with each including all individuals whose sum of length and width are equal eg. class 149.9μ includes individuals with a range of length : width values as follows :- 88.8 : 61.1 ; 83.3 : 66.6 and 77.7 : 72.2μ. These dimensions appear to be very precise because the original values were taken with an eye-piece micrometer with a subsequent calculation to microns (1 micrometer unit = approx. 11.1μ) foraminiferal and radiolarian taxa thought to be of value as palaeotemperature indicators within time equivalent intervals of the Middle Miocene at Sites 289 and 71 suggests that as in the present time, surface water palaeotemperatures were warmer at the former site. During this period, when surface water palaeotemperatures were believed to be generally high, the differences probably reflect the greater influence of upwelling at Site 71. 'Anomalously' high abundance at Site 71 of those radiolaria taxa which seem favoured by high palaeotemperatures probably reflects an incomplete understanding of the palaeoecology of these forms.

CHAPTER VIII

THE PALAEOTEMPERATURE RECORD AT SITE 289: REGIONAL PERSPECTIVE AND SIGNIFICANCE

1. GENERAL DISCUSSION

The surface water palaeotemperature record at Site 289 can be compared to Middle and Late Miocene oceanic palaeotemperature reconstructions of previous studies in order to assess its validity and consider its regional significance. Because the interpretation offered herein has been established from one locality only, it may represent only local palaeoceanographical events confined to the western equatorial Pacific. In such circumstances, many of the palaeoecological conclusions reached for planktonic foraminiferal and radiolarian taxa would probably be of only limited application. It is therefore important to test the interpretation for regional applicability.

The palaeotemperature curve is plotted on a linear absolute time scale by utilising the geochrongological framework applied to the planktonic foraminiferal biostratigraphical zonation as outlined in Chapter IV (fig.81). The palaeotemperature trends are thus independant of any distortion resulting from inconsistent rates of sedimentation, dissolution or compaction.

The interpretation for the Middle Miocene indicates initially cool surface water values throughout Zones N.9 to N.10 (∼14-13 m.y. B.P.). A sudden rise and subsequent persistence of high values characterises Zones N.11-12 (∼13-12.25 m.y. B.P.) and is followed by a second cool period throughout Zones N.13 and N.14 (∼12.25 to 11.2 m.y. B.P.).

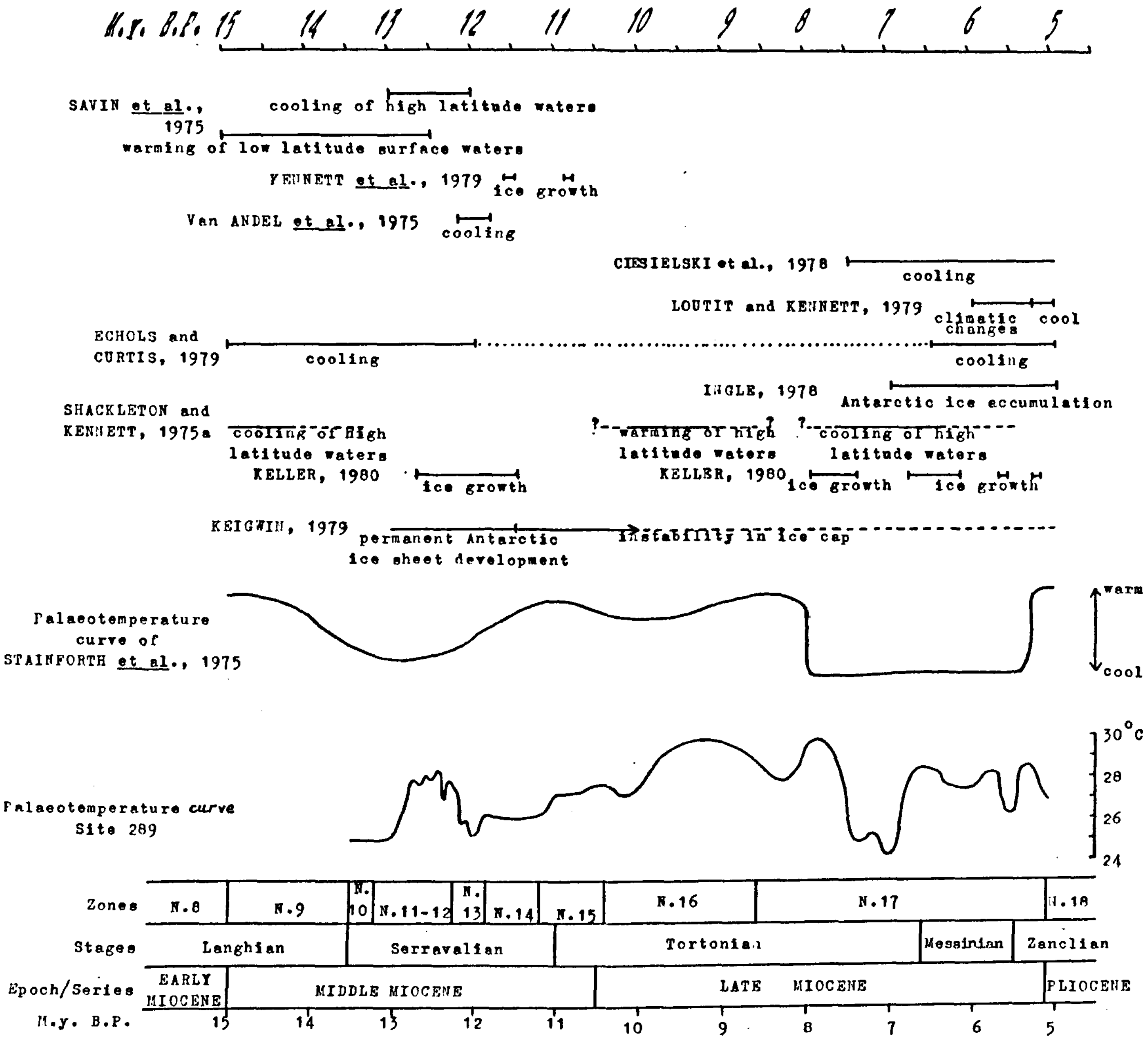


Fig. 81 A comparison of the palaeotemperature curve at Site 289 with the palaeoclimatic conclusions of previous studies

Palaeotemperatures gradually increase over the Middle/Late Mioceneboundary to attain peaks in Zones N.16 and early N.17 (∽11.2-?8 m.y. B.P.). Following a small drop near the N.16/N.17 zonal boundary, palaeotemperatures drop dramatically within Zone N.17 and thereafter undergo rapid fluctuations involving several warm and cool intervals up to the base of Zone N.18 at the Miocene/Pliocene boundary (fig.81).

Palaeoceanographical and palaeotemperature reconstructions of the Pacific Ocean during the Middle and Late Miocene have been briefly considered in Chapter III. Major palaeotemperature changes during this interval are believed to have occurred near the start of the Middle Miocene and towards the end of the Late Miocene. In the Middle Miocene event, high latitude surface palaeotemperatures are believed to have decreased while low latitude surface palaeotemperatures are believed to have increased. The mechanism suggested to trigger the palaeotemperature changes involves continental redistribution in the Antarctic region which caused palaeoceanographical circulation adjustment and established the thermal isolation of Antarctica by the formation of the circum-Antarctic current (see Chapter III, p.60), (fig.14).

The early Middle Miocene palaeoceanographical event produced a circulation and thermal regime similar to that of today. Subsequent palaeotemperature changes, such as those of the Late Miocene and Pleistocene, are believed to reflect variations in the size of high latitude glacial masses (see Chapter III, fig.14).

STAINFORTH _et al._, (1975) have integrated various palaeoclimatic data to develop an empirical worldwide sea temperature curve for the Middle Miocene to Pleistocene (fig.81). The trends indicate high palaeotemperatures during the early Middle Miocene (∽16-14 m.y. B.P.) and in the late Middle and early Late Miocene (∽11-8 m.y. B.P.). Low palaeotemperatures are indicated within the Middle Miocene (∿14-12 m.y. B.P.) and in the late Late Miocene (∿8-6 m.y. B.P.).

KELLER (1980) has recently presented a palaeoceanographical reconstruction for the North Pacific during the Middle and Late Miocene. Using evidence afforded by variation in the quantitative distribution of planktonic foraminiferal taxa, the O_2 isotope record and the stratigraphical distribution of erosion and dissolution horizons (increased bottom water flow), KELLER (1980) identified palaeotemperature oscillations which are attributed to changes in the proportions of Arctic and Antarctic ice masses. Cool intervals are postulated within the Middle Miocene (Zone N.14; ∿12.7-11.5 m.y. B.P.) and within the Late Miocene (Zone N.16, ∿8-7.5 m.y. B.P.; Zone N.17, 6.8-6.4 m.y. B.P.). Further cool periods are suggested for the interval spanning the Miocene/Pliocene boundary (∿5.7 m.y. B.P.; 5.3 m.y. B.P.).

KELLER (1980) concluded that the similarity between planktonic foraminiferal faunas of the N.W. and S.E. Pacific Ocean indicates that the climatic events were of global proportions.

Further evidence for a Middle Miocene growth in the Antarctic ice sheet and associated drop in oceanic palaeotemperatures is offered by the O_2 isotope records presented by SHACKLETON and KENNETT (1975a) (see Chapter III), KEIGWIN (1979) and KENNETT _et al._ (1979). KEIGWIN (1979) suggests a permanent Antarctic ice sheet developed late in the Middle Miocene (∿13 to 11.5 m.y. B.P.) while KENNETT _et al._ (1979) refer to oscillations in the O_2 isotope signal which probably reflect partial melting and, in particular, growth of the ice cap at 11.5 m.y. and 10.8 m.y. B.P.

A latest Miocene glacial event has also been recognised worldwide by SHACKLETON and KENNETT (1975a), CIESIELSKI _et al._ (1978), INGLE (1978), KENNETT (1978), WISE (1978), ECHOLS and CURTIS (1979), FRAKES (1979) and LOUTIT and KENNETT (1979). KENNETT (1978) and LOUTIT and KENNETT (1979) associate the event with the European Messinian and the New Zealand Kapitean stages. The palaeoclimatic events described above are compared to the palaeotemperature model at Site 289 in fig.81.

Most of the palaeoclimatic evidence from previous studies is given on an absolute time scale. The means by which these ages are determined may, however, be inconsistent from study to study and a degree of flexibility must be applied during any comparison. This consideration must apply to those instances where similar events coincide in time as well as in those instances where similar events appear to be out of phase in time.

The palaeotemperature trends at Site 289 can be seen to coincide with similar trends from unrelated evidence in many instances. During the early Middle Miocene a palaeotemperature increase postulated at Site 289 coincides with similar trends suggested by SAVIN et al. (1975) for low latitude waters, although SHACKLETON and KENNETT (1975a) and ECHOLS and CURTIS (1979) indicate decreased palaeotemperatures within this interval.

A cooling event during the mid-Middle Miocene at Site 289 appears to reflect a well documented near-synchronous trend reported by SAVIN et al.(1975), STAINFORTH et al. (1975), Van ANDEL et al. (1975), ECHOLS and CURTIS (1979), KENNETT et al. (1979), KEIGWIN (1979) and KELLER (1980).

A general trend of increased palaeotemperatures in the late Middle and early Late Miocene at Site 289 is similar to that given by SAVIN et al. (1975) and SHACKLETON and KENNETT (1975a).

In the late Late Miocene, palaeotemperatures at Site 289 appear to be unstable and subject to large fluctuations in value. These trends are also widely reported elsewhere by SAVIN et al. (1975), SHACKLETON and

KENNETT (1975a), INGLE (1978), CIESIELSKI et al. (1978), ECHOLS and CURTIS (1979), LOUTIT and KENNETT (1979) and KELLER (1980).

It is thus apparent that the palaeotemperature trends at Site 289 generally reflect contemporaneous and similar palaeoclimatic events elsewhere in the worlds oceans. In particular, evidence for growth of the Antarctic ice sheet appears to coincide in time with the development of equatorial upwelling at Site 289. A relationship between high latitude glaciation and a eustatic fall in sea level with upwelling in the western equatorial Pacific during Pleistocene glacial intervals has been considered in Chapter III. The close correlation between Antarctic glacial events and a contemporaneous reduction in surface palaeotemperatures (upwelling) at Site 289 supports the view that a similar relationship existed during the Middle and Late Miocene.

Site 289 may therefore be considered to have monitored and recorded palaeoceanographic change as it occurred throughout the equatorial and south Pacific Ocean during the Middle to Late Miocene.

The warm interval from within Zone N.11-12 may mark the full development of the circum-Antarctic current during the early Middle Miocene. The partial separation of high latitude water masses from mid- and low latitude water masses via the maximum development of the current would increase the thermal isolation of high and low latitude regions and induce Antarctic glaciation and equatorial warming (see Chapter III and fig.14).

This phenomenon would create a circulation and thermal regime in the Pacific Ocean not unlike that of the present time. Subsequent palaeotemperature fluctuations at Site 289 in the late Middle and Late Miocene may therefore reflect instability in the size of the Antarctic ice cap (KEIGWIN, 1979).

The palaeotemperature fluctuations of the latest Late Miocene are of particular interest to global palaeoceanography.

During the Late Miocene, the progressive isolation of the Mediterranean basin led to highly restricted circulation which was reflected in the extensive deposition of evaporites (Van COUVERING *et al.*, 1976). The Messinian "Salinity Crisis" involved the deposition of an estimated 10^6 Km^3 of evaporites representing 6% of the salts of the worlds oceans in a time interval of approximately 1.5 m.y. (RYAN *et al.*, 1974; Van COUVERING *et al.*, 1976). The history of dessication is complicated but major evaporite deposition is believed to have occurred in two main phases:

i) large scale plate movements involving the collision of Africa with southern Europe instigated the initial partial isolation of the Mediterranean from the Atlantic from approximately 6.5 to 5.5 m.y. B.P.

ii) superimposed on this event, a glacially induced eustatic fall in sea level promoted the total isolation of the basin (Van COUVERING *et al.*, 1976; ADAMS *et al.*, 1977). The final connection with the Atlantic is believed to have been the Betic Strait entering into the Mediterranean from Andalusia (the "Iberian Portal") (ADAMS *et al.*, 1977).

Evidence for a latest Miocene Antarctic glacial event has been reviewed herein. In addition, ADAMS *et al.* (1977) suggest the event was accompanied by a eustatic fall in sea level of approximately 50 to 70 metres which produced regressive units and unconformities in shallow water sequences during the Late Miocene throughout the world (see also PECK *et al.*, 1979).

The timing and origin of the Late Miocene glacial event is subject to much controversy (see ARTHUR, 1979; WRIGHT and CITA, 1979/1980). RYAN et al.(1974) suggest the expansion of the Antarctic ice sheets may have been triggered by the Messinian evaporite buildup. According to their hypothesis, the tectonic closure of the Mediterranean resulted in the deposition of evaporites from 6.5 m.y. B.P. which reduced oceanic salinities. The salinity decline would induce a chain reaction involving a raised freezing point of sea water, the subsequent expansion of polar pack ice, an increase in the earths albedo, growth of continental glaciers and a eustatic decline in sea level. The hypothesis of RYAN et al. (1974) thus offers an explanation for the initiation of glaciation and has been subsequently supported by CITA and RYAN (1979) who indicate major oceanic cooling within the Messinian stage at approximately 5.6 m.y. B.P.

However, alternative evidence suggests that Antarctic glaciations predated and were independant of Messinian events. Sedimentary sequences from the Southern Ocean show evidence for a strong increase in glacially induced bottom water activity prior to the onset of Messinian evaporite deposition at 6.5 m.y. B.P. (CIESIELSKI et al., 1978). Similarly, INGLE (1978) and KELLER (1980) infer increased ice accumulation from 7 m.y. and 6.8. m.y. B.P. respectively (see fig.81).

The palaeotemperature record at Site 289 may contribute some useful evidence with regard the accurate timing of the Late Miocene glacial event. Assuming the geochronology of the sequence, as considered in Chapter IV, is accurate, the Messinian stage at Site 289 is characterised by variable palaeotemperates. However, greater palaeotemperature variability, which is accompanied by particularly low values is postulated for the late Tortonian stage, immediately prior to the Messinian stage (~7.5-7 m.y. B.P.) (fig.81).

Evidence from Site 289 thus suggests that the Late Miocene

Antarctic glacial event began prior to the Messinian stage and would appear to be independant of salinity reduction induced by evaporite buildup. In this context, a eustatic fall in sea level may have played a significant role in the initial isolation of the Mediterranean basin at the onset of Messinian times.

WRIGHT and CITA (1979/1980) have recently reviewed the various arguements involving the origin of Antarctic glaciation and Mediterranean isolation during the Late Miocene. Their conclusions, which involve a complex interaction of local tectonic, glacial-eustatic and chemical oceanic (salinity) factors, may be highly pertinant to the present study and are worth repeating:

"It would appear as though the Mediterranean was alternatively closed and open to the world ocean prior to the tectonic closure of the Atlantic inlet which completely isolated the area during the latest Messinian. It may be that the evaporitic and glacial events produced a positive feedback mechanism in which glacio-eustatic lowering of sea level (due to extra-Mediterranean causes) isolated the Mediterranean and initiated restriction and eventually evaporite deposition. This deposition and its consequent geochemical imbalances may then have further intensified climatic deterioration".

2. THE PERIODICITY OF MIOCENE PALAEOTEMPERATURE CYCLES AT SITE 289

The palaeotemperature curve at Site 289 displays a series of cycles involving alternating high and low values. The amplitude and wavelength of each cycle varies considerably and it is also possible to differentiate and recognise cycles on more than one scale. The cycles which are considered to be most significant with respect to palaeoceanography and palaeoecology are those in which evidence for upwelling has been postulated (fig.52).

The Middle to Late Miocene interval spans approximately ten million years. At Site 289, there are nine individual cycles involving an upwelling component (fig.52). Although the wavelength of these cycles appears to exhibit a noticeable degree of variation, over the time interval there exists an average periodicity of approximately 1 m.y. The upwelling cycles are superimposed on three larger cycles which are defined by peaks within Zones N.11-12, N.16-17 and N.17 (fig.52). These 'mega-cycles' exhibit an average periodicity of approximately 3.3 m.y. The identification and interpretation of 'mini-cycles' with average periodicities significantly smaller than 1 m.y. is limited by the sampling interval used in this study. The palaeotemperature interpretation was derived using 123 samples with an average sampling interval of approximately 80,000 yrs. In these circumstances, cycles at Site 289 which for example, exhibit a periodicity of approximately 0.1 m.y., would be represented by one-point peaks. Because such trends are weakly defined, interpretation would be ambiguous e.g. adjacent samples in the mean size distribution plot of <u>O. universa</u> (see fig.52).

It is important to determine the extent to which the periodicity of upwelling cycles (approximately 1 m.y.) conform to those postulated from previous studies, in order to assess their significance.

EMILIANI and SHACKLETON (1974), SAVIN <u>et al.</u> (1975), HAYS <u>et al.</u> (1976) and EMILIANI (1978) indicate that glacial events during the Pleistocene exhibit an average periodicity of between 80,000 and 90,000 years. A definite relationship between the glacial and interglacial events of the Pleistocene and astronomical parameters, especially obliquity, has been recently expressed by EMILIANI (1978).

SAVIN <u>et al.</u> (1975) and SHACKLETON (in press) indicate that palaeoclimate events occurred during the Early Miocene which were of similar periodicity but of generally smaller magnitude to those of the Pleistocene (see Chapter III).

MITCHELL (1976) suggests that climate variability is restricted to periods over more than 10^7 years (tectonic effects) and from 10^4 to 10^5years (astronomical factors) without variance in between.

Although Mitchell's (1976) discussion was mostly theoretical, recent practical investigations by SHACKLETON (in press), including the interval spanning the Early/Middle Miocene boundary at Site 289, tend to corroborate his views. Nevertheless, the results of the present study indicate climatic variability over periods of approximately 10^6 years. SHACKLETON (in press) has demonstrated that the oceans have been sensitive to small variation in the seasonal and latitudinal distribution of solar energy resulting from astronomical factors during the Miocene as well as during the Pleistocene. Although astronomical effects involving eccentricity and obliquity during the Neogene are believed to induce climatic cycles over a 10^5 year interval, the results of the present study suggest that cycles over a 10^6 year interval may also have their origin in these phenomena.

CHAPTER IX

SUMMARY

This thesis reports an investigation of planktonic foraminifera and radiolaria of mainly Middle to Late Miocene age from DSDP Sites 289 and 71 in the western and central equatorial Pacific Ocean respectively.

The primary aim of the study was an explanation of the distribution of taxa in terms of pre-mortal (ecological and environmental) and post-mortal (dissolution) factors. This aim was pursued through the following steps:

- the stratigraphic intervals of increased dissolution were identified from the distribution of those planktonic foraminifera and radiolarian taxa thought to be particularly sensitive to dissolution.
- a palaeotemperature interpretation for the Middle and Late Miocene epipelagic zone in the western equatorial Pacific Ocean was derived from the distribution of those planktonic foraminifera at Site 289 which are thought to be particularly sensitive to palaeotemperature variation.
- the relative distribution of individual taxa and changes in the nature of entire assemblages were compared with the palaeotemperature curve. Coincidence between micropalaeontological and palaeoceanographic events was then sought to examine the possibility of ecologically induced changes in the quantitative distribution of particular taxa.

As an essensial precursor to palaeoenvironmental and palaeoecological discussions, aspects of present day Pacific oceanography, planktonic ecology and pelagic (biogenic) sedimentation are reviewed (Chapter II).

The results of previous research concerning the Cenozoic history of the Pacific Ocean is considered in order to create a framework within which the aims and significance of the present study may be viewed. The Cenozoic development of the Pacific Ocean is generally dominated by plate tectonic events which were largely responsible for changing oceanic circulation and gradually deteriorating temperatures. The present day circulation system, water mass distribution, thermal structure and glacial mode appears to have developed by Middle Miocene times. Although extreme glacial and interglacial fluctuations have characterised the earth's climate since the Late Pliocene, O_2 isotope investigations suggest that palaeotemperature variation of approximately similar amplitude and wavelength to Pleistocene events also operated during the Miocene, and further, can be recognised in equatorial regions of the Pacific Ocean (Chapter III).

DSDP Site 289 is located on the Ontong Java Plateau, north of the Solomon Islands. The Plateau possesses an unusually large crustal thickness and has accumulated a thick sequence of flat lying, highly stratified pelagic biogenic carbonates ranging in age from Early Cretaceous to Recent. At Site 289, continuous sedimentation characterises the sequence from the Early Oligocene to Recent, in which the environment of deposition appears to be oceanic, middle bathyal, above the CCD under conditions of high equatorial productivity.

The interval under study at Site 289 can be subdivided into two units : a primary sequence from near the base of the Middle Miocene to within the Late Miocene, and a secondary sequence from within the Late Miocene to the Quaternary. Investigations in the former involve the qualitative and quantitative distribution of all taxa encountered. In the latter sequence, only certain planktonic foraminifera were investigated to furnish additional palaeoenvironmental information.

DSDP Site 71 is located in the central equatorial Pacific, west of the East Pacific Rise, overlying a thick lens of undisturbed Cenozoic biogenic sediments. The Miocene sequence consists of alternating calcareous and siliceous ooozes. The environment of deposition appears to have been similar to that described for Site 289 although accumulation was probably nearer the CCD. The interval under study is a relatively short sequence within the Middle Miocene and was chosen for palaeontological comparison with the contemporaneous sequence at Site 289.

All the planktonic foraminifera and radiolaria encountered in the primary sequence at Site 289 and at Site 71 were subject to taxonomic review (see Appendix I).

Fifty seven species and subspecies of foraminifera were identified while 163 radiolarian taxa were distinguished, including 145 species, four of which are described and named for the first time.

The biostratigraphical zonation schemes of BLOW (1969) and RIEDEL and SANFILIPPO (1978) were applied to the sequences. At Site 289, the Middle to Late Miocene interval was subdivided into eight planktonic foraminiferal zones, from N.9 to N.17, and four radiolarian zones, from the Dorcadospyris alata Zone to the Ommatartus penultimus Zone. Application of the geochronological synthesis of BERGGREN and Van COUVERING (1974) from the available zonations allowed the identification of absolute age datums and the approximate positioning of European stage boundaries (Chapter IV).

An assessment of relative rates of sedimentation was made which suggests a fairly constant rate for the interval studied, apart from reduced values near the base of the sequence, within Zone N.9.

The studied sequence at Site 71 falls within the N.11-12 planktonic foraminiferal zone and the Dorcadospyris alata radiolarian zone of the Middle Miocene.

Palaeontological distribution data is presented in two main quantitative forms : percentage abundance of individual taxa and diversity and similarity indices of entire assemblages. Handled in this way the data helps in formulating palaeoenvironmental conclusions and can be easily used to help assess the palaeoecological preferences of individual taxa and entire assemblages. An important feature evident from the distribution of individual taxa is that percentage abundance may fluctuate quite considerably and often in a cyclic manner, suggesting that the cause is not evolutionary in origin (Chapter V).

The preservation of planktonic foraminifera and radiolaria at Site 289 is generally good and consistent with depths of deposition above the lysocline. Intervals of increased dissolution can be identified however, based on the distribution of solution - susceptible species. Evidence of increased dissolution of both planktonic foraminifera and radiolaria is particularly evident in an interval near the base of the studied sequence, corresponding with reduced rates of sedimentation. Increased dissolution of both groups is apparent elsewhere although not to the same degree and never at the same horizon. Apart from the interval near the base of the studied sequence, distributional trends in planktonic foraminifera and radiolaria do not generally appear to reflect dissolution (Chapter V).

The preservation of planktonic foraminifera at Site 71 is worse than in time equivalent assemblages at Site 289 and is consistent with a depth of deposition nearer the CCD. The preservation of radiolaria at Site 71 is however of a superior quality compared to that of time equivalent assemblages at Site 289, and, moreover, diversity values are consistently higher. The cause of these features may be compound, possibly reflecting geological factors such as differences in rates of sedimentation or artificial factors such as differences in processing methods and downhole contamination.

A high resolution correlation between the studied sequence at Site 71 with that at Site 289 was primarily based on evolutionary datums but also on quantitative features such as relative abundance in taxa and diversity trends. The sequence at Site 71, consisting of 28.5m of sediment, appears to be time equivalent of 34m of sediment within the N.11-12, D. alata Zones at Site 289 (Chapter V).

A comparison of time equivalent planktonic foraminiferal and radiolarian assemblages at Site 71 and 289 indicates a close similarity in terms of quantitatively dominant and subordinate taxa, although certain differences of palaeoenvironmental significance, are apparent (Chapter V).

A palaeoenvironmental reconstruction was attempted for the Middle to Late Miocene sequence at Site 289 and relates primarily to changing temperature in the epipelagic zone of the water column (Chapter VI).

A palaeotemperature curve was based on the following distributional features in planktonic foraminifera:

- Mean size in Orbulina universa.
- Relative abundance of keeled globorotaliids (Globorotalia fohsi s.l. and G. cultrata gp.).
- Coiling direction in G. cultrata gp.

In general, good normal correlation was found between increased mean size in O. universa, increased abundance of keeled globorotaliids and dominantly sinstral coiling in G. cultrata gp. at Site 289. These trends do not appear to result from post-mortal factors and fluctuating palaeotemperatures are assumed to be responsible.

The palaeotemperature curve is constructed by eye without recourse to statistical principles and may be therefore regarded as subjective. However, because the curve is based on sympathetic trends from unrelated sources, it is regarded as a reflection of true palaeotemperature variation in at least a qualitative sense.

The palaeotemperature curve indicates low values at the base of the Middle Miocene, from Zones N.9 to N.10, followed by increased values throughout Zone N.11-12, and decreased values throughout Zones N.13 to N.14. In the late Middle and early Late Miocene, from Zones N.14 to N.16, palaeotemperature values gradually increase. Following a fall and rise near the N.16/N.17 zonal boundary, palaeotemperature falls rapidly. The remaining late Late Miocene interval is characterised by a gradual rise in palaeotemperature followed by fluctuating values.

A temperature scale was applied to the curve. The calibration of the curve was based on the results of previous studies involving O_2 isotope palaeotemperatures of the Middle and Late Miocene, and the range of mean size variation in O. universa associated with palaeotemperature variation during the Pleistocene. The calibration is not intended to be definitive and is used only to indicate the possible range of palaeotemperature variation. The resulting estimates suggest that the palaeotemperature of surface waters at Site 289 during the Middle to Late Miocene varied from approximately 24° to 29°C.

The palaeotemperature variation at Site 289 may have been due to the periodic development of equatorial upwelling. The increased glacial development of the Antarctic continent during the Early Miocene appears to have established a permanent glacial mode with "Pleistocene type" climatic variations and equatorial upwelling since the early Middle Miocene. At Site 289, cooling events during the Middle and Late Miocene may reflect the temporary development of upwelling in the epipelagic waters of the western equatorial Pacific. The cause of upwelling would be similar to that during the Pleistocene, i.e. increased atmospheric and oceanic circulation and a eustatic fall in sea level initiated by periodic glacial advance around the Antarctic continent, which serves to intensify upwelling in the eastern equatorial Pacific and spread the phenomenon to the western equatorial Pacific (Chapter VI).

The palaeotemperature curve was compared to the relative distribution trends in individual taxa. On the assumption that maximum abundance of a species occurs in its optimum environment, the comparison serves to indicate environmental preferences associated with palaeotemperature (Chapter VII).

Variation in the relative abundance of several planktonic foraminifera at Site 289 appears to be related to the palaeotemperature trends. Such relationships indicate preferences for either non-upwelling tropical waters characterised by high surface palaeotemperatures or upwelling, tropical to subtropical waters characterised by low surface palaeotemperatures.

As well as *Globorotalia fohsi* s.l. and *G. cultrata* gp. (sinistral), distribution in the following taxa suggests optimum environments to occur within non-upwelling tropical waters characterised by high surface temperatures:

Globorotalia siakensis
Globorotalia continuosa
Globorotalia sp. cf. G. merotumida
Globorotalia sp. cf. G. multicamerata
Sphaeroidinellopsis seminulina s.l.
Globigerinoides ruber

In contrast, distribution in the following taxa suggests optimum environments to occur within upwelling, tropical to subtropical waters characterised by low surface temperatures:

Globorotalia cultrata (dextral)
Globoquadrina venezuelana
Globoquadrina dehiscens
Globigerinoides quadrilobatus triloba
Globigerinoides quadrilobatus sacculifer
Globigerinoides obliquus s.s.
Globigerina bulloides
Globigerina falconensis

Distribution of taxa does not always correspond to palaeotemperature trends however, and the relative abundances of Globoquadrina altispira s.s., Globoquadrina altispira globosa, Globoquadrina langhiana and Globoquadrina larmeuis appear to reflect factors other than palaeotemperature.

A palaeoenvironmental/palaeoecological model is suggested to explain the distribution of Globigerinoides spp. and globorotaliids in terms of periodic upwelling. Distribution in both taxa is inversely related and does not appear to reflect dissolution. It is suggested that during times of non-upwelling, niche diversity in the epipelagic zone is high and specialised globorotaliids thrive in a well developed specialised habitat below the photic zone, near the thermocline. Conversely, during times of upwelling, niche diversity is low, prohibiting the proliferation of globorotaliids and creating a nutrient rich environment for surface dwelling Globigerinoides spp.

A review of the factors which have been proposed to explain coiling direction changes in planktonic foraminifera, when considered in light of the results of the present study, suggest that coiling changes for G. cultrata gp. may result from linkage of genes confering the ability to survive particular temperature ranges with genes controlling coiling direction. This hypothesis does not fully explain the observed coiling direction trends in the taxon however, and the reproduction strategy theory of LIPPS (1979) may also be of significance in this case.

A comparison of diversity trends with the palaeotemperature curve does not reveal a consistent correlation. The relationship appears to reflect the biogeographic position of Site 289.

The similarity trend appears to relate to the palaeotemperature curve with major deviation from the base sample coinciding with palaeotemperature increase and increasing similarity to the base sample coinciding with palaeotemperature decrease. The relationship may be developed in this manner because the base sample, to which all others are compared, reflects in part an upwelling environment. The correlation indicates an overall close relationship between the planktonic foraminiferal assemblages and the proposed palaeotemperature trends.

A comparison of the palaeotemperature curve with evolutionary events (extinctions and appearances) also indicates a correlation, suggesting that high palaeotemperatures promote speciation via an increase in niche diversity while low palaeotemperatures promote extinction because of a decrease in niche diversity.

Variation in the relative abundance of several radiolaria at Site 289 likewise appears to be related to the palaeotemperature trends. The correlations indicate preferences for either non-upwelling tropical waters characterised by high surface palaeotemperatures or upwelling, tropical to subtropical waters characterised by low surface palaeotemperatures (Chapter VII).

Distribution in the following taxa suggests optimum environments to occur within non-upwelling, tropical waters characterised by high surface temperatures:

- "*Spongodiscid spp.* group"
- "*Porodiscid spp.* group"
- "*Litheliid spp.*"
- "*Plagoniid spp.*"
- *Carpocanistrum spp.*
- *Trisolenia spp.*
- *Stichocorys delmontensis* FORM A
- *Theocorys? subcylindrica*
- *Centrobotrys thermophila*
- "*Cyrtid spp. gp. 2*"

In contrast, distribution in the following taxa suggests optimum environments to occur within upwelling, tropical and subtropical waters characterised by low surface temperatures:

- *Stichocorys delmontensis*
- *Stichocorys wolffii*
- *Cyrtocapsella japonica*
- *Actinomma medianum*

Distribution in other radiolaria shows no apparent relationship with the palaeotemperatre curve and control may be governed by other environmental factors.

A biometric analysis of *Stichocorys delmontensis* s.l. was undertaken to more closely examine the relationship between palaeotemperature and morphology in this species. The results indicate that highest mean sizes occur at times of Low palaeotemperature while lowest mean sizes occur at times of high palaeotemperature, although this relationship is not completely consistant. The relationship may nevertheless indicate a functional morphology associated with the maintanence of constant depths in the water column during times of changing environments.

A comparison of diversity trends in radiolaria with the palaeotemperature curve indicates a close normal correlation although the influence of dissolution may also strongly govern diversity by controlling the distribution of many fragile taxa.

As in the case of planktonic foraminifera, there is a good correlation between similarity and palaeotemperature trends and between evolutionary events and palaeotemperature trends. These aggreements emphasise the strong overall influence of palaeotemperature on abundance distribution and speciation and extinction of individual taxa.

Because variation in climatic factors may control dissolution by affecting productivity and the activity of corrosive bottom waters, the palaeotemperature curve at Site 289 was compared to the stratigraphic distribution of "dissolution intervals" in order to seek any correlation. The results of this comparison are inconsistent and indicate that dissolution of microfossils may be caused by different factors at different times (Chapter VII).

The distribution of planktonic foraminifera and radiolaria at Site 71 in the central equatorial Pacific was considered in the light of the palaeoenvironmental/palaeoecological interpretations at Site 289, together with a consideration of present day environmental differences between the two sites (Chapter VII).

In general, distributions at Site 71 conform with the premise that overall conditions were cooler compared with those at Site 289. Some of the taxa which appear to thrive in non-upwelling conditions at Site 289, such as G. fohsi s.l. and Trisolenia spp., are found in reduced numbers at Site 71. Conversely, some taxa which appear to thrive in upwelling conditions at Site 289, such as Globoquadrina venezuelana and Stichocorys delmontensis, are found in increased abundance at Site 71. Moreover, a biometric analysis of S. delmontensis at Site 71 indicated a lack of the extreme forms of S. delmontensis Form A which are present in contemporaneous assemblages at Site 289, and, together with evidence outlined above, suggests a greater degree of upwelling at Site 71 compared to Site 289 during Zone N.11-12 times of the Middle Miocene.

The surface water palaeotemperature record at Site 289 is compared to Middle and Late Miocene oceanic palaeotemperature reconstructions of previous studies of the Pacific Ocean in order to assess its validity and consider its regional significance (Chapter VIII).

The supposed palaeotemperature trends at Site 289 can be seen to coincide with trends deduced elsewhere from unrelated evidence. Important features are the increase in values during the early Middle Miocene, the cooling event during the mid-Middle Miocene, the palaeotemperature increase during the late Middle and early Late Miocene and the unstable values during the late Late Miocene. Site 289 may therefore be considered to have monitored and recorded palaeoceanographic change as it occurred throughout the Pacific Ocean. Of interest on a global scale is the apparent development of a late Late Miocene palaeotemperature decline at Site 289 prior to Messinian times, suggesting that glacial advance on and around, Antarctica with an associated eustatic sea level fall predates the accumulation of Messinian evaporites and may have even constituted an important factor towards the initial isolation of the Mediterranean basin.

The stratigraphical distribution of upwelling intervals at Site 289 indicates a periodicity of approximately 1 m.y. Although MITCHELL

(1976) suggests that climatic variability is restricted to periods of more than 10^7 years (tectonic effects) and from 10^4 to 10^5 years (astronomical factors), the results of the present study suggest that cycles of more intermediate duration may also be recognised.

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