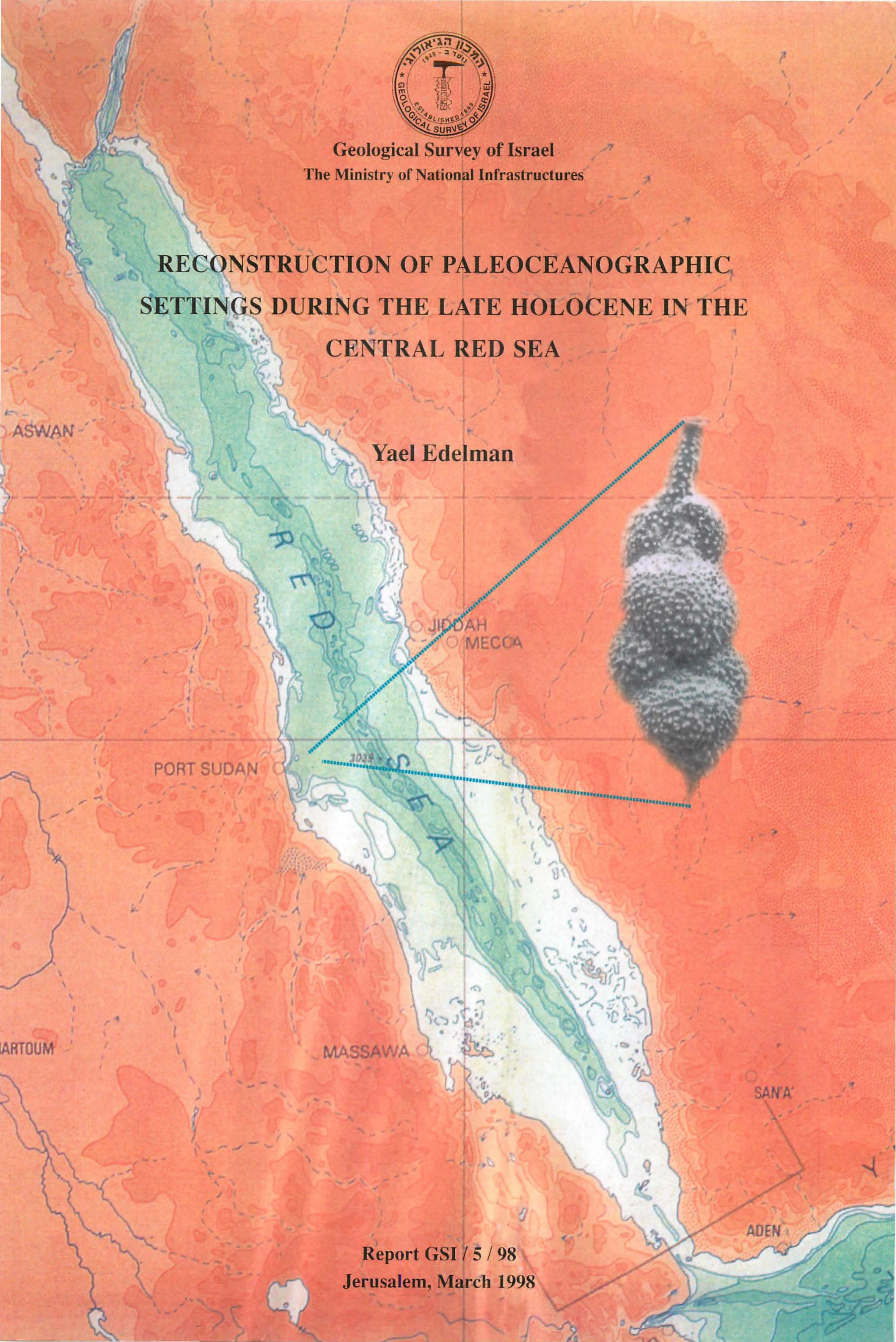
Geological Survey of Israel
The Ministry of National Infrastructures

RECONSTRUCTION OF PALEOCEANOGRAPHIC SETTINGS DURING THE LATE HOLOCENE IN THE CENTRAL RED SEA

Yael Edelman

Report GSI / 5 / 98
Jerusalem, March 1998



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Cover design: Bat-Sheva Cohen

Production: Eltan Communications

Cover: SEM picture of Neouvigerina ampullacea - Benthic Foraminifera
Bathymetric chart of the Red Sea.
(Morcos, S.A. & Varley, A., eds, 1990.
Red Sea, Gulf of Aden and Suez Canal: Bibliography.
Paris, UNESCO/ALECSO, 198 p.)

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RECONSTRUCTION OF PALEOCEANOGRAPHIC SETTINGS DURING THE LATE HOLOCENE IN THE CENTRAL RED SEA

Yael Edelman

Thesis submitted as a M.Sc. Thesis in the Institute of Earth Sciences, the Hebrew University, Jerusalem,

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Acknowledgments

My sincere thanks to Dr. Ahuva Almogi-Labin and to the late Prof. Zeev Reiss for supervising me throughout my thesis project.

Thanks are due to Professor Christoph Hemleben of the Institute und Museum für Geologie und Paläontologie, University of Tübingen, Tübingen, Germany for obtaining the R/V "Meteor" material studied; to Maria Scherbacher, University of Tübingen, for providing information on living and dead benthic foraminifera of the upper 5 cm of the cores studied; to Dr. Bonani, ETH, Zürich, for providing AMS ^{14}C dates; to the laboratory of geochemistry of the Geological Survey of Israel for analyzing the total organic carbon content and calcium carbonate and to the Geological Survey of Israel for providing facilities for carrying out this work.

Financial support for this work was provided by the Israel ministry of Energy and Infrastructure (grant number 032 - 7330) and by a grant from G.I.F, the German Israeli Foundation for Scientific Research and Development.

Abstract

Changes in mixed, intermediate and deep water masses were investigated, as well as changes in the bottom conditions within different depth ranges, in order to reconstruct a more complete paleoceanographic picture for the Late Holocene. Four multi-corers were taken along a west-east transect from the central Red Sea by the German R/V "Meteor" at water depths of 366, 579, 929 and 1782 m. The cores were situated south of the present-day monsoonal border (convergence zone) and represent intermediate and deep water masses. One was taken from the oxygen minimum zone (OMZ), another from the margin of the OMZ and two from deeper and more oxygenated water.

A high resolution record was obtained by sampling at very close intervals (every 2 cm). Samples were soaked, washed, sieved, dried, split and counted in order to study the fossil assemblages of planktic and benthic foraminifera as well as pteropods. The cores were correlated to the dated maximum abundance of the mesopelagic pteropod *Limacina bulimoides* (~4200 years before present [BP]) observed earlier at other Red Sea locations. This abundance peak was not recognized in the shallowest core (MC88, 366 m) and, therefore, could not be correlated with the other three. An average accumulation rate of ~5 cm/1000 years was estimated for the three correlated cores; thus, an age of ~6400 years BP was assessed for the longest core sequence.

Changes found in the abundance and assemblage composition of the planktic groups (in the three deeper cores) reflect variations in the mixed layer and intermediate water column properties. These enabled an ecostratigraphic division into six zones and a paleoceanographic reconstruction of the past ~6000 years. The most prominent downcore changes were attributed to fluctuations in the relative abundance of the epipelagic planktic foraminifera *Globigerinoides ruber* vs. that of the deeper dweller *G. sacculifer*. Changes in stratification of the water column and position of the OMZ, and in the relationship between the depth of the pycnocline and that of the photic zone, probably influenced the optimal reproduction conditions required for *G. sacculifer*.

The *G. ruber* vs. *G. sacculifer* cycle and the frequency and presence/absence pattern of *L. bulimoides* are clearly correlated from ~5300 to ~2400 years BP. This relationship supports a stronger stratification of the water column in the past 3000 years, as compared to the period between ~5300-3000 years BP, especially between ~3000-2700 years BP. This probably reflects climatic fluctuations which strongly affected the northern area of the Red Sea, producing sinking of denser waters to intermediate depths at a time of a more arid climate regime (between ~5300-3000 years BP).

The data concerning the benthic foraminifera distinguishes between three lateral assemblages: The OMZ , OMZ transitional and deeper more aerated assemblage. The organic matter flux and its state of preservation, together with the dissolved oxygen levels in the bottom water and sediment pore water, influence the distribution and abundance pattern of the specific benthic assemblage. The dominant species comprising the OMZ assemblage are the infaunal *Bolivina*, *Bulimina* and *Globocassidulina*; those comprising the OMZ transitional assemblage, the epifaunal to shallow infaunal species of *Neouvigerina* and *Cibicides*; and those comprising the deeper more aerated assemblage, the epifaunal to shallow infaunal species of *Miliolidae*, *Hanzawaia*, *Astrononion* and *Glomospira*.

The total organic carbon, calcium carbonate, >63 μm size fraction and benthic foraminifera assemblage did not change significantly downcore in each of the different cores. These observations indicate that, in general, the deep water body did not undergo major changes during the past ~6000 years, this in contrast to the more significant changes detected in the mixed layer and intermediate waters, as reflected by the changes observed in the planktic assemblages.

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1 - Introduction

1.1 Geological background

The Red Sea is a long (2000 km), narrow (average, 280 km) and deep (maximum, 2900 m) marginal sea situated between latitudes 12°30'N - 30°N and separating Africa from Asia. The Red Sea was created about 25 m.y ago as part of the Syrian-African rift (Braithwaite, 1987). The relatively young tectonics created both the bathymetry and the steep slopes.

The Red Sea is an ocean in creation, with a mid-oceanic ridge. It is separated from the Gulf of Aden by a topographic barrier (oceanographic sill) 137m deep at the Bab-El-Mandeb straits (Locke and Thunell, 1988). There are two gulfs in the north Red Sea: in the northwest the shallow Gulf of Suez (90m deep) and in the north the deep, narrow Gulf of Elat (1830m deep) which is separated from the Red Sea by a barrier 252m deep at the Straits of Tiran. This latter gulf is part of the Dead Sea rift-system (Braithwaite, 1987).

1.2 Climatic settings

The climate in the Red Sea area is arid. Precipitation north of 20°N is 10-25 mm/year, while south of 20°N, during the south-western monsoon, precipitation can be as high as 500 mm/year (Edwards, 1987). Runoff of water into the Red Sea is very scarce and originates from flash floods through large wadies. Very high air temperatures, (which can reach 50°C during summer), very high solar radiation and, during most of the year, low cloudiness are characteristic of the area. Changes in wind direction in the southern Red Sea are according to seasonal and monsoonal vector changes. The border of the northern and southern wind collision is at 20°N which is also the location of the downwelling. As a result of the hot and arid climate, evaporation is very high, about 2-3 m per year (Patzert, 1972; Edwards, 1987).

1.3 The hydrography and circulation pattern

The circulation-regime in the Red Sea is dominated by the winds, evaporation and the monsoon system. During the winter, the deep water flow is southward while the surface water flows from the Gulf of Aden northward against the northernly wind and undergoes cooling (as a result of evaporation) with salinity increase. During summer the circulation pattern is more complex and includes a surface water mass which flows southward from the Red Sea towards the Gulf of Aden (parallel to the wind direction). Beneath this mass there is an undercurrent entering from the Gulf of Aden into the Red Sea while at depth, the deep waters flow southward. Thus a three-layered circulation is produced. The deep waters form as a result of heavy Gulf of Suez waters which sink during the winter to great depths of the Red Sea. The origin of the intermediate waters is from dense, saline waters of the Gulf of Elat and cooled waters from the northern Red Sea which sink and flow southwards (Patzert, 1972; Cember, 1988). The surface waters of the Gulf of Aden enter the Red Sea with a temperature and salinity of 30°C and 36.5‰, respectively. As they flow north they evaporate, undergo cooling and increase in salinity, and reach temperatures and salinity of 22-26°C and 40.5‰, respectively. The deep water body, with a stable and constant temperature and salinity of 21.5°C and 40.6%o, respectively, exists beneath the relatively warm and less saline top (100m) water mass (Patzert, 1972).

The surface waters of the Red Sea are close to oxygen saturation levels ~4.5 ml O_2/l. At a depth of 100-500 meters there is a prominent decrease in the oxygen content with a minimum concentration (at a depth of ~500 m) of 1.5-1.75 ml O_2/l in the north, decreasing towards the south to the level of 0.5 ml O_2/l, at approximately 400 m. (Neumann and McGill, 1962). Ventilation of the intermediate and deep water masses is controlled by the rate of formation of deep waters in the Gulf of Suez, Gulf of Elat and the northern Red Sea itself, and by the residence time (estimated at 150-200 years). In addition, the oxygen content is controlled by the increasing consumption southwards (Patzert, 1972; Cember, 1988 and ref. within). This phenomenon is connected to the higher nutrient levels in the water flowing into the Red Sea from the Gulf of Aden (Weikert, 1987).

1.4 Nutrient levels and water productivity

Table 1:

(Weikert, 1987)

Nutrient salts in oceanic Red Sea water from different regions. Ranges of concentration reflect seasonal fluctuations (modified after Karbe and Lange, 1981). The depth of the surface layer (SL) corresponds to that of the euphotic zone. OM - depth range of minimum oxygen concentrations, DW - deep water.

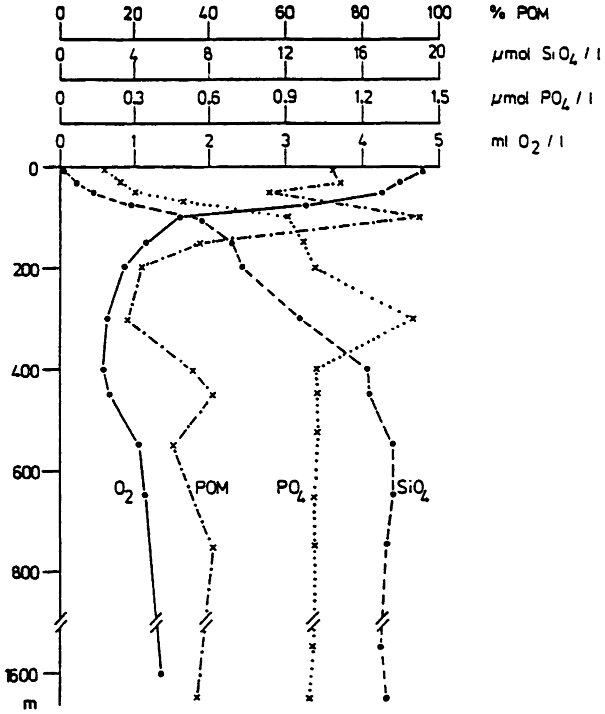
Nutrients	Northern Red Sea			Central Red Sea			Southern Red Sea		
(μmol/l)	SL ⩽100m	OM 400–500m	DW >1000m	SL ⩽100m	OM 350–450m	DW >1000m	SL ⩽70m	OM 300–400m	DW >1000m
Phosphate	0.01–0.05	0.6– 0.8	0.2– 0.5	0.05–0.1	0.8– 1.1	0.6– 0.7	0.1 –0.3	0.9– 1.2	0.6– 0.8
Nitrate	0.1 –0.4	15.5–18.0	8.0–11.9	0.03–0.2	18.1–20.1	11.9–15.0	0.03–0.2	18.9–22.1	14.0–18.2
Silicate	0.2 –0.4	9.0–11.3	5.2– 8.0	0.3 –0.6	10.3–13.6	8.0–10.2	0.4 –0.7	13.6–16.5	10.2–15.5

As seen in Table 1, the nutrient levels are very low, with lower levels in the north compared to the south, and in the top waters compared to the bottom waters. In general, the nutrient content defines the Red Sea as an oligotrophic sea. As a result of its oligotrophy the primary production is low as well. High values of chlorophyll-a are found usually at a depth of 50-100 meters, mostly because of photoinhibition in the clear top waters. The amount of phytoplankton changes throughout the year, but is usually low. The cause of the very deep light penetration is a combination of the low biomass, strong solar radiation, low cloudiness and the absence of significant amounts of suspended abiogenic matter, (Weikert, 1987). The quantitative levels of phytoplankton are larger in the southern Red Sea during the summer monsoon, when the waters flowing in from the Gulf of Aden, are very productive and have a high nutrient content of an upwelling water system. The amount of phytoplankton and the existance of the oxygen minimum zone, control the zooplankton assemblage. One of the factors causing this phenomenon are the high temperatures which cause oxidation of the organic matter at a very high rate. It is important to emphasize that the zooplankton biomass below 400 m is the lowest ever recorded *in any sea* (Weikert, 1987; Wishner, 1979).

The thermocline and halocline behave as barriers between the top and bottom water layers, thus preventing mixing of the deeper water column. Consequently, there is no return of nutrients to the euphotic zone, leading to very low productivity in the top mixed layer, as seen in Fig. 1 (Weikert, 1987).

Fig. 1.

Profiles of dissolved oxygen (O_2), inorganic phosphate (PO_4), silicate (SiO_4) and particulate organic matter (POM) at an oceanic station at the latitude of Gebel Tair, southern Red Sea (Original).



1.5 Planktic foraminifera

The diversity of the planktic foraminifera is low (Almogi-Labin, 1984; Ivanova, 1985; Auras-Schudnagies et al., 1989). The dominant genera are spinose and symbiont bearing. Other genera (non-spinose and symbiont lacking) which may have been transported as nekroplankton appear in very small quantities, mostly in the southern Red Sea (Almogi-Labin, 1984; Ivanova, 1985; Kroon, 1988; Auras-Schudnagies et al., 1989). The dominant species are mostly epipelagic feeding mostly on phytoplankton. The exception is *Globigerinoides sacculifer* which is a carnivore, feeding on copepods. Non-spinose and symbiont lacking species are known in the Red Sea mostly from deeper waters (mesopelagic and bathypelagic) with higher nutrient levels. These species are mostly herbivores (Hemleben et al., 1989).

In the northern Red Sea the dominant species is *Globigerinoides sacculifer* while in the southern part, it is *Globigerinoides ruber* (Auras-Schudnagies et al., 1989). The reasons for this are not yet clear. The relationship between the species dominance and water salinity (Herman, 1968; Berggren and Boersma, 1969) is opposed to laboratory findings, that show the same salinity range and optimum for both species (Bijma et al., 1990). The idea that temperature is the limiting factor is also not in agreement with laboratory findings (Bijma et al., 1990 and compare also Reiss et al., 1980). Species dominance, both in the water column and in the sediment, might be controlled by the fertility of the sea, feeding strategies and reproductive patterns. Thus the life cycle is bi-monthly in the upper waters for *G. ruber* and monthly for *G. sacculifer,* which is also seasonally affected (Almogi-Labin, 1984; Bijma, 1990; Erez et al., 1991).

1.6 Benthic foraminifera

The benthic foraminiferal assemblages of the central Red Sea especially those of the deep waters were not investigated until recently (Scherbacher, 1994). On the other hand, Recent northern Red

Sea and Gulg of Suez benthic foraminifera were studied by Said (1949, 1950) and a more detailed study in the Gulf of Elat was represented by Hottinger and others (1993 with ref.).

1.7 Pteropods

The Red Sea pteropod assemblage is of low diversity, consisting of shallow, epipelagic and deeper mesopelagic species, but lacking bathypelagic ones (Almogi-Labin, 1984). The assemblage is dominated by the migratory mesopelagic species, *Limacina inflata* and *Clio convexa*. The pteropod distribution is controlled mainly by the presence of the oxygen minimum zone, which in turn, controls the vertical distribution of the mesopelagic species. *Limacina inflata* reaches a depth of 400 meters and *Clio convexa* reaches depths of up to 700 meters (Weikert, 1987). The epipelagic species live in the 50-100 top meters and do not migrate. The epipelagic species compose less than 20% of the assemblage and are dominated by *Creseis acicula*, *Creseis virgula virgula* and *Limacina trochiformis*. The species diversity is highest in the Gulf of Aden, less in the Red Sea and the lowest in the Gulf of Elat. The pteropods of the Red Sea are herbivores and therefore are controlled by the relative abundance of the primary producers (Weikert, 1987).

It is important to emphasize, that despite the great depths of the Red Sea and the Gulf of Elat, the pteropods are very well preserved in Recent sediments, probably due to carbonate super-saturation (Herman, 1968; Almogi-Labin, 1982; Krumgalz and Erez, 1984; Ivanova, 1985; Almogi-Labin et al., 1991). The well preserved aragonitic pteropods together with the well preserved low Mg-calcite foraminifera and the low Mg-calcite tests of coccoliths, form the carbonate ooze of the Recent sediments in the Red Sea. The living pteropod population is well reflected in the composition of the pteropod assemblage in the sediment (Almogi-Labin, 1984; Auras-Schudnagies et al., 1989).

1.8 Previous paleoceanographic studies and purpose of the present study

Paleoceanographic reconstructions of the Red Sea based mainly on fossil foraminifera, pteropods and coccolithophorids, as well as stable oxygen and carbon isotopes from core material were published by various authors (Herman, 1968; Berggren and Boersma, 1969; Chen, 1969; Deuser and Degens, 1969; Reiss et al., 1980; Halicz and Reiss, 1981; Almogi-Labin, 1982; Ivanova, 1985; Locke and Thunell, 1988; Auras-Schudnagies et al., 1989; Almogi-Labin et al., 1991 and more). However, information available on the Late Holocene (i.e. younger than 4000 years) is extremely scarce, perticularly because of lack of high resolution studies. Moreover, studies on living populations of foraminifera (mainly planktic ones) and of pteropods, were carried out only fairly recently (Almogi-Labin, 1984; Brummer and Kroon, 1988; Auras-Schudnagies et al., 1989; Bijma et al., 1990).

Detailed taxonomic studies on Red Sea planktic and benthic foraminifera necessary for assessing the paleoceanographic significance of these important sediment constituents, were published only a very short while ago (Hottinger et al., 1993).

Finaly, information on living and dead benthic foraminifera in the top 5cm from short cores in the central Red Sea became lately available (Scherbacher, 1994).

For these reasons it seemed appropriate and feasible to attempt a reconstruction of the Late Holocene in the Red Sea based on foraminifera and pteropods from the same short cores examined.

2 - Material and methods

Four multicores were taken by the R/V "Meteor" (material provided by Prof. Ch. Hemleben from Tübingen University) in the central Red Sea between latitude 19°N and 20°N, at different water depths (366m; 579m; 929m and 1782m) on a W-E transect (Fig. 2).

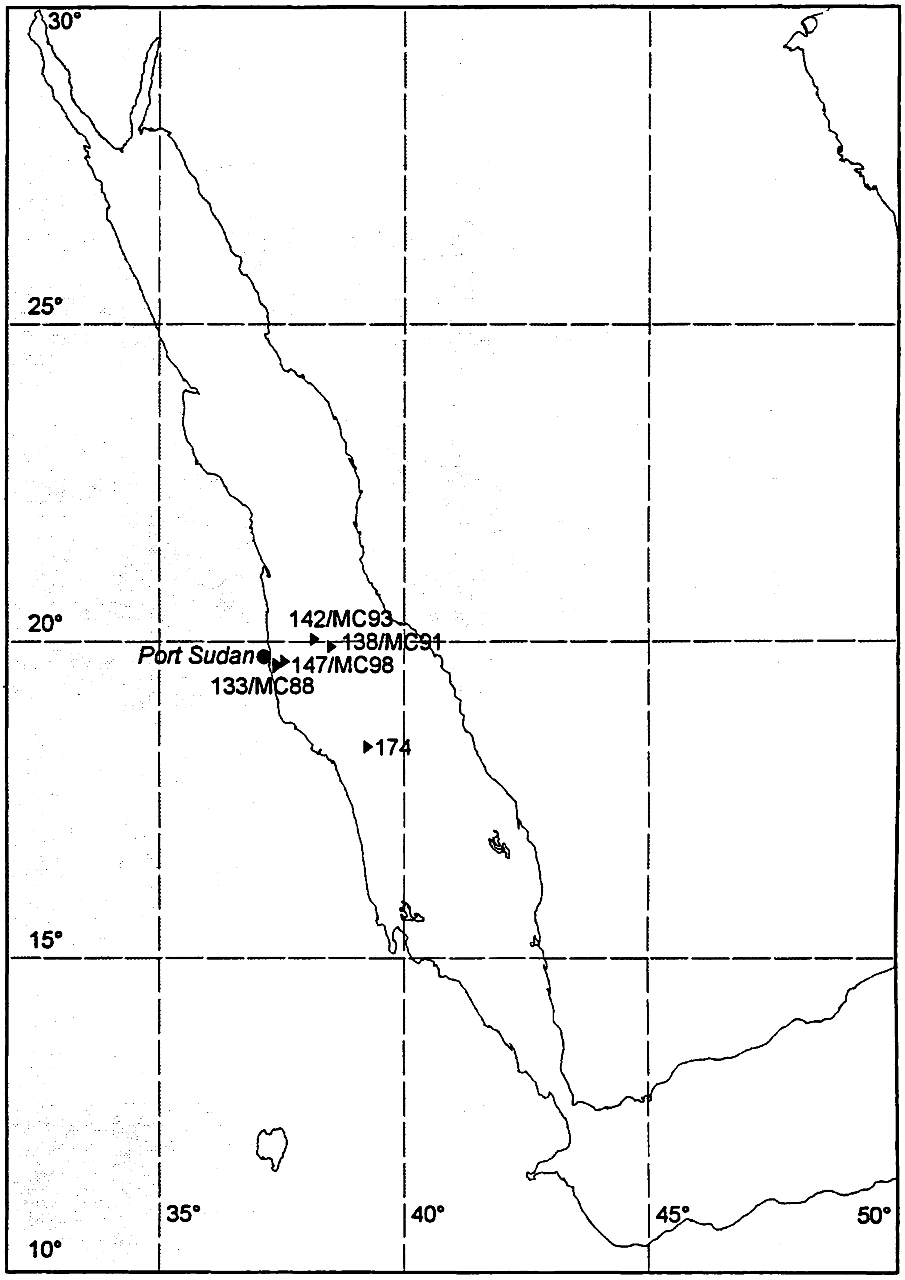


Fig. 2. Location map. The four selected multicores were taken from the following stations (in a W-E transect): MC88 - station 133; MC98 - station 147; MC93 - station 142; MC91 - station 138.

Table 2 Core data:

MC no.	Station	Water depth	Location	Multicore length	No. samples
88	133	366 m	37°15,2'E/19°37,2'N	30 cm	12
98	147	579 m	37°31,7'E/19°43,0'N	32.5 cm	14
93	142	929 m	38°12,6'E/19°59,2'N	30 cm	13
91	138	1782 m	38°27,8'E/19°54,0'N	32 cm	13

Locations were chosen in order to examine Holocene sediments within, at the margin and below the oxygen minimum, as well as from the deepest water mass.

A total of 52 samples were analyzed in order to investigate a closely sampled record contained in these short (about 30cm) deep-sea cores covering the last few thousand years. Core samples taken at 2cm intervals were soaked, washed with tap water through a 63μm sieve, oven-dried at 50°C and dry-sieved to obtain two fractions, 63-149μm and >149μm. The samples were split with a Von Daniels splitter in order to obtain aliquots which contain ~300 specimens of planktic and benthic foraminifera each and ~300 specimens of pteropods. All these specimens were identified and counted under a binocular stereoscopic microscope. Planktic foraminifera and pteropods were studied in the >149μm size fraction. In addition the samples were dry-sieved through a 100μm sieve and the benthic foraminifera were studied in this size fraction. This in order to allow a comparison between this data and that of a contemporaneous study by German colleagues (Prof. Ch. Hemleben and Ms. M. Scherbacher, University of Tübingen) on the top 5cm of the same core set.

The taxonomy of the foraminifera is based mainly on the Atlas of Recent Foraminiferida from the Gulf of Aqaba, Red Sea (Hottinger et al.,1993). The identification of the pteropods is based on Almogi-Labin and Reiss (1977) and on Almogi-Labin (1982). Problematic specimens were investigated under the SEM in order to determine their final identification.

The absolute and relative abundance of the pteropods and foraminifera found in the four cores was documented. Species composing less than 1% of the assemblage were grouped under "others".

The planktic/benthic foraminiferal ratio is given for each core in the size fraction >149μm (calculated as the percent of planktic/planktic + benthic).

The relative abundance of the mesopelagic species was studied in the same size fraction and represent the sum of the mesopelagic species out of the total pteropod assemblage.

3 - Results

The following species were identified:

3.1 Foraminifera

Planktic species
Globigerina bulloides d'Orbigny
Globigerina calida Parker
Globigerinella siphonifera (d'Orbigny)
Globigerinita glutinata (Egger)
Globigerinoides ruber (d'Orbigny)
Globigerinoides sacculifer (Brady)
Globoturborotalita rubescens (Hofker)
Hastigerina pelagica (d'Orbigny)
Orbulina universa d'Orbigny
Orbulina sp. ("small")
Turborotalita clarkei (Rögl and Bolli)
Gallitellia vivans (Cushman)

Benthic species
Abditodentrix rhomboidalis (Millett)
Alliatinella panayensis (McCulloch)
Ammobaculites? sp. (in Hottinger et al., 1993)
Ammodiscus flavians Höglund
Amphistegina radiata (Fichtel and Moll)
Angulogerina angulosa (Williamson)
Anomalinulla glabra (Cushman)
Articulina pacifica Cushman
Assilina ammonoides (Gronovius)
Astacolus sp. A (in Hottinger et al., 1993)
Asterorotalia sp.
Astrononion sp. A (Cushman and Edwards)
Bolivina persiensis Lutze
Bolivina variabilis (Williamson)

Bolivinellina cf. pescicula Saidova

Brizalina striatula (Cushman)

Brizalina subspathulata (Boomgaart)

Bulimina elongata d'Orbigny

Bulimina marginata d'Orbigny

Bulimina striata (d'Orbigny)

Cancris auriculus (Fitchel and Moll)

Caribeanella elatensis Perelis and Reiss

Cassidelina? makiyama (Ishizaki)

Cassidelina spinescens (Cushman)

Challengerella bradyi Billman et al.

Cibicides mabahethi Said

Cibicides sp. A (in Hottinger et al., 1993)

Cibicides tabaensis Perelis and Reiss

Discorbinella? sp.

Discorbinella bertheloti (d'Orbigny)

Discorbinella rhodiensis (Terguem)

Ehrenbergina compressa de Montfort

Elphidium sp.

Epistominella sp.

Eponides pusillus Parr

Evolvocassidulina sp.

Fissurina sp.

Floresina sp. A (in Hottinger et al., 1993)

Fursenkoina sp. A (in Hottinger et al., 1993)

Globocassidelina oriangulata Belford

Globocassidulina sp.

Glomospira charoides Jones and Parker

Glandulina group of G. laevigata d'Orbigny

Gyroidinoides cf. soldanii (d'Orbigny)

Hanzawaia sp. A Asano

Haplophragmoides bradyi (Robertson)

Heterolepa cf. subhaidingerii (Parr) (probably identified as *Cibicidoides pseudoungerianus* by Scherbacher, 1994).

Heterolepa? sp. A

Hyalinea balthica (Schroeter)
Lagena spp.
Lagenammina sp.
Lamarckina ventricosa (Brady)
Lenticulina spp.
Loxostomina limbata (Brady) *costulata* (Cushman)
Loxostomina spp.
Miliolidae div.
Neocorbina marginata Hofker
Neoeponides bradyi (Le Calvez)
Neorotalia sp.
Neouvigerina ampullacea (Brady)
Neouvigerina interrupta (Brady)
Neouvigerina porrecta (Brady)
Neouvigerina porrecta (Brady) *subsp. A* (in Hottinger et al., 1993)
Nodophthalmidium antillarum (Cushman)
Nonion sp.
Patellinella sp.
Pattelina corrugata Williamson
Paracassidulina neocarinata (Thalmann)
Plotnikovina cf. aequa (Cushman)
Porosononion sp. B (in Hottinger et al., 1993)
"Psammosphaera" spp.
Pseudoeponides falsobeccarii Rouvillois (probably identified as *Ammonia sp.* 1 by Scherbacher, 1994)
Pseudononion grateloupi (d'Orbigny)
Pyramidulina catesbyi (d'Orbigny)
Pyrgo spp.
Reophax spp.
Reussella sp.
Robertinoides bradyi (Cushman and Parker)
Rosalina spp.
Rosalina? suezensis (Said)
Rotorbinella cf. lepida McCulloch
Sahulia kerimbaensis (Said)

Siphonaperta horrida (Cushman)

Siphonina tubulosa Cushman

Siphotextularia heterostoma (Fornasini)

Spirillina spp.

Spirophthalmidium sp.

Spirotextularia floridana (Cushman)

Svratkina acuta (Sidebottom)

Textularia cushmani Said

Tretomphalus spp.

Trochammina sp.

Valvobifarina mackinnonii (Millett)

Vertebralina striata d'Orbigny

Vonkleinsmidoides McCulloch

3.2 Pteropoda

Cavolinia sp. (juvenile shells)

Cavolinia longirostris (de Blainville)

Cavolinia uncinata (Rang)

Clio convexa (Boas)

Creseis acicula (Rang)

Creseis chierchiae (Boas)

Creseis virgula virgula (Rang)

Diacria quadridentata (de Blainville)

Hyalocylis striata (Rang)

Limacina bulimoides (d'Orbigny)

Limacina inflata (d'Orbigny)

Limacina trochiformis (d'Orbigny)

Peraclis reticulata (d'Orbigny)

4 - Ecological significance background

4.1 Ecological significance of planktic foraminifera

Globigerina bulloides

A spinose symbiont-lacking, shallow mesopelagic species, living between 50-100 m in the northern Red Sea, but found also down to 400 m. It is strongly dependent upon food-levels and characterizes upwelling situations (Reiss et al., 1974; Almogi-Labin, 1984; Hemleben et al., 1989; Luz and Reiss, 1994, unpublished).

Globigerina calida

A spinose symbiont-bearing, shallow mesopelagic species, living between 50-100 m in the northern Red Sea. It is a warm-water, photic zone species. It is morphologically very closely related to *G. siphonifera* by its test morphology and spine structure (Reiss et al., 1974; Almogi-Labin, 1984; Hemleben et al., 1989; Luz and Reiss, 1994 , unpublished).

Globigerinella siphonifera

A spinose symbiont-bearing, shallow mesopelagic species, living in the northern Red Sea, in the upper 100 m. *G. siphonifera* prefers a carnivorous diet, although it feeds on diatoms and phytoflagellates as well. A dominant species in the Gulf of Elat and northern Red Sea (along with *G. ruber* and *G. sacculifer*). It is frequent during the winter months in the northern Red Sea and at times of high productivity in the Gulf of Elat (Reiss et al., 1974; Almogi-Labin, 1984; Hemleben et al., 1989; Luz and Reiss, 1994 , unpublished).*G. siphonifera* undergoes gametogenesis after sinking and loosing all its spines (Bè and Anderson, 1976; Bijma et al., 1990).

Globigerinita glutinata

A non-spinose, shallow water species, living in the northern Red Sea between 50-100 m. It is a cosmopolitan species and apparently tolerates a rather wide range of temperature and salinity. Its diet consists mainly of diatoms (Reiss et al., 1974; Almogi-Labin, 1984; Hemleben et al., 1989; Luz and Reiss, 1994 , unpublished).

Globigerinoides ruber

A spinose dinoflagellate symbiont-bearing, epipelagic species (the shallowest one) living in the upper 50 m. *G. ruber* is an omnivore but feeds mostly on phytoplankton and has a bi-monthly life-cycle. Its salinity and temperature tolerance is 22-49 ‰ and 13-32°C, respectively (Reiss et al., 1974; Almogi-Labin, 1984; Hemleben et al., 1989; Bijma et al., 1990; Luz and Reiss, 1994 , unpublished).

Together with *G. sacculifer* and *G. siphonifera* it is one of the dominant species in the Gulf of Elat, Red Sea and northeastern Arabian Sea. It is abundant in oligotrophic waters like gyre centers or the south-eastern Levantine Basin, on the other hand, *G. ruber* reaches higher frequencies than *G. sacculifer* in fertile waters according to Bijma et al. (1990). It is more abundant in the southern Red Sea and Gulf of Aden, than in the less fertile waters of the northern Red Sea and Gulf of Elat - where *G. sacculifer* dominates (Zobel, 1971; Kroon, 1988; Auras-Schudnagies et al., 1989; Bijma et al., 1990).

Globigerinoides sacculifer

A spinose dinoflagellate symbiont-bearing, epi to shallow mesopelagic species living between 50-150 m (although, found at depth of 300 m in the Gulf of Elat) mainly inhabiting the chlorophyll maximum. Adult *G. sacculifer* feed mostly on copepods, juveniles on phytoplankton. It exhibits a lunar reproductive cycle, undergoing gametogenesis after sinking and loosing all its spines. Its salinity and temperature tolerance is 24-47 ‰ and 14-31°C, respectively (Reiss et al., 1974; Bè and Anderson, 1976; Almogi-Labin, 1984; Hemleben et al., 1989; Bijma et al., 1990; Erez et al., 1991; Bijma and Hemleben, 1994; Bijma et al., 1994; Luz and Reiss, 1994, unpublished).

It is one of the dominant species in the Gulf of Elat, northern Red Sea and central and southern Arabian Sea (Zobel, 1971; Almogi-Labin, 1984; Kroon, 1988; Auras-Schudnagies et al., 1989).

Globoturborotalita rubescens

A spinose, symbiont-lacking, epipelagic species, easily distinguished by its reddish pigment in its test (Reiss et al., 1974; Almogi-Labin, 1984; Hemleben et al., 1989; Luz and Reiss, 1994 , unpublished).

Hastigerina pelagica

A spinose, deeper water species, living in low quantities in the Gulf of Elat, (Reiss et al., 1974; Almogi-Labin, 1984). Shows a distinct lunar cycle (Hemleben et al., 1989).

Orbulina universa

A spinose dinoflagellate symbiont-bearing, shallow mesopelagic species, living between 50-100 m (although found as deep as 300 m, as well) in the northern Red Sea. High freqencies in surface waters of upwelling regions near continental margins have been reported. Adult *O. universa* are carnivorous while juveniles are herbivorous. It exhibits a lunar reproductive cycle (Reiss et al., 1974; Almogi-Labin, 1984; Hemleben et al., 1989; Luz and Reiss, 1994 , unpublished).

Orbulina sp. ("small")

A spinose dinoflagellate symbiont-bearing species. Very small in size, identified in the Gulf of Elat as well as in the eastern Arabian Sea (Zobel, 1971; Reiss et al., 1974).

Turborotalita clarkei

A very small (< 149µm, which was the size fraction under investigation in the present study) spinose species. It is extremely thickly calcified (Almogi-Labin, 1984; Hemleben et al., 1989; Hottinger et al., 1993).

Gallitellia vivans

A small sized epipalagic species, found in the Indian Ocean associated with upwelling waters (Kroon and Nederbragt, 1988).

4.2 Ecological significance of benthic foraminifera

Ammodiscus spp. - shallow to intermediate infaunal

Live specimens of this genus are most abundant in the sediment at 0-1.5 cm, but found up to 3.5 cm deep (Mackensen and Douglas, 1989).

Astrononion sp. - shallow infaunal

Recorded between 50-200 m, often displaced (Corliss and Chen, 1988). Moderate organic matter fluxes and moderately low O_2 (suboxic indicators, 0.3-1.5 ml O_2/l) are indicated by the common occurrence of *Astrononion* assemblages (Sjoerdsma and Van der Zwaan, 1992; Gooday, 1994; Kaiho, 1994). Found living in the central Red Sea at 0-3 cm and in the deepest MC91 (1782m), down to 5cm (Scherbacher, 1994).

Bolivina spp. - infaunal

Bolivina are omnivores (Keller Grünig et al., in prep.). In general, Bolivinids characterize oxygen-poor (dysoxic indicators, 0.1-0.3 ml O_2/l) environments with high organic carbon levels (Sjoerdsma and Van der Zwaan, 1992; Gupta, 1994; Kaiho, 1994). They are related to sluggish deep-water circulation (Gooday, 1994). *B. persiensis* is known in the Red Sea core tops living at 0-2 cm depth (Scherbacher, 1994).

Bulimina marginata - shallow infaunal

This species is found at 0-2 cm sediment depth. It is a mud-dweller, omnivore, opportunistic species, preferring sediments with high organic content and increased nutrient levels (Corliss and Chen, 1988; Jorissen, 1988; Corliss, 1991; McCorkle et al., 1990; Van der Zwaan and Jorissen, 1991; Keller Grünig et al., in prep.). Occupies a wide depth interval of 50-1200m. It is abundant in low oxygen environments irrespective of depth (Reiss et al., 1984). Recent low oxygen environments with high food-availability are dominated by this and other *Bulimina* species. In the central Red Sea, *Bulimina marginata* was found living in the topmost cm (Scherbacher, 1994).

Cancris auriculus - epifaunal

Only moderately tolerant to oxygen deficiency (Van der Zwaan and Jorissen, 1991). Found in core samples from the northern Red Sea at depth of 30-200m (Said, 1949).

Cibicides mabahethi - epi to infaunal

Scherbacher (1994) records *C. mabahethi* living down to 5 cm depth in the shallow core and down to 3 cm in the OMZ margin. It was found mainly in the top 1 cm in the sediment. This species is found at 512 m in core samples in the northern Red Sea (Said, 1949).

Cibicidoides - epi to shallow infaunal

Found living in the top 1 cm (McCorkle et al., 1990), between oxygen levels of 1.3-6.0 ml O_2/l hence, an oxic indicator (Kaiho, 1994).

Discorbinella rhodiensis - epifaunal

Abundant mostly at depth less than 300 m, but found also much deeper (Jorissen, 1988). Scherbacher (1994) records only *D. berthelothi* living down to 5cm depth and only in the shallow cores, thus indicating this species is infaunal. This record refers probably to the same species as our *D. rhodiensis*.

Elphidium - epifaunal

Usually abundant close to the seashore, mostly 0-75 m (Jorissen, 1988; Van der Zwaan and Jorissen, 1991), apparently transported in our material.

Fursenkoina - infaunal

Highly indicative of increased organic content and low levels of oxygen (Van der Zwaan and Jorissen, 1991). This genus is a dysoxic indicator (Kaiho, 1994).

Globocassidulina

Found at 1-5 cm in the central Red Sea sediments (Scherbacher, 1994).

Glomospira charoides - infaunal

Occurs in maximum abundance in the top 2 cm, but found living up to 3.5 cm deep (Mackensen and Douglas, 1989). Found living at 1-4 cm in the central Red Sea (Scherbacher, 1994). A deep water species, found in surface sediment samples in the southern ocean at 1000-2300 m depth (Lindenberg and Auras, 1984) and down to 6000m in the Pacific (Berggren and Kaminski, 1990).

Gyroidinoides cf. soldanii - epifaunal (Corliss and Chen, 1988).

A suboxic indicator (Kaiho, 1994). Found living in the central Red Sea at depth up to 2 cm, thus indicating that this species is shallow infaunal (Scherbacher, 1994). Appears at depths of 200m in the northern Red Sea (Said, 1950).

Hanzawaia - epi to shallow infaunal

A deep water species (Keller Grünig et al., in prep.). Found living at 0-2 cm in the central Red Sea (Scherbacher, 1994).

Haplophragmoides bradyi - infaunal

Live specimens occur in maximum abundance in the uppermost 2 cm (Mackensen and Douglas, 1989).

Heterolepa - epi to infaunal (probably = *C. pseudoungerianus* in Scherbacher, 1994).

Abundant in sediment depth of 1.5 cm, occuring at bathyal depth (Corliss, 1985, 1991; Corliss and Chen, 1988). Found living in the central Red Sea at sediment depth up to 5 cm, thus indicating that this species is infaunal (Scherbacher, 1994).

Lagena - epifaunal

A suboxic indicator (Kaiho, 1994). Found living in the central Red Sea at depth of 0-0.5cm (Scherbacher, 1994).

Lenticulina - epifaunal

A suboxic indicator (Kaiho, 1994) and found in organic rich sediments (Hermelin, 1992).

Miliolidae

Widely distributed, but usually abundant in high salinity environments (Reiss et al., 1984; Corliss, 1985, 1991; McCorkle et al., 1990). Large thick-walled *miliolids* are oxic indicators (Kaiho, 1994), others may be infaunal.

Neouvigerina ampullacea

Neouvigerina ampullacea (= U*vigerina auberiana* in Sjoerdsma and Van der Zwaan, 1992).

Abundant in high oxygen levels and moderate total organic carbon levels. *Neouvigerina ampullacea* is found living at 0-4 cm in the central Red Sea, thus indicating it is infaunal. *N. porrecta* was found down to 5 cm in the sediment (Scherbacher, 1994). In the Gulf of Aqaba, found at depth of 125m (Hottinger et al., 1993) and in the northern Red Sea, between 300-700m (Said, 1950).

Nodosaridae - (*Pyramidulina*)

Prefer well oxygenated bottom conditions (Reiss et al., 1984).

Nonion - shallow to deep infaunal

An omnivore, mud-dwelling genus (Corliss and Chen, 1988; Jorissen, 1988; McCorkle et al., 1990; Corliss, 1991; Keller Grünig et al., in prep.) and a suboxic indicator (Kaiho, 1994).

Paracassidulina neocarinata - epi to infaunal

Identified with *Cassidulina*, which is considered an opportunistic genus (Jorissen, 1988).

Porosononion - infaunal

Associated with mud-facies in deeper waters of 40-150 m (Corliss and Chen, 1988). In the Gulf of Aqaba, found at depth of 75m (Hottingr et al., 1993).

Pseudoeponides falsobeccarii - epifaunal

Observed exclusively in the topmost cm with a high percent of organic carbon (Keller Grünig et al., in prep.). Found living in the central Red Sea at 0-1 cm and identified as *Ammonia sp.1* (Scherbacher, 1994).

Rosalina? suezensis - epi to shallow infaunal

Lives in the topmost cm (Keller Grünig et al., in prep.). Characterizes moderately low oxygen and organic carbon levels (Sjoerdsma and Van der Zwaan, 1992).

Textularia - infaunal

Found living at 0-5 cm in the central Red Sea (Scherbacher, 1994). It is recorded up to depths of more than 1100m (Said, 1950).

Trochammina

Widely distributed (Mackensen and Douglas, 1989). Found in core samples from the northern Red Sea at depth of 80-433m (Said, 1949).

The distribution of the benthic foraminifera in the cores is shown according to major taxa and their ecological significance as shown in Table 3.

Table 3 Benthic foraminifera:

#1 = *Bulimina marginata, B. elongata.*

#2 = *Bolivina persiensis, B. variabilis, Bolivinellina* cf. *pescicula, Brizalina subspathulata, B. striatula.*

#3a = *Gyroidinoides* cf. *soldanii.*

#3b = *Heterolepa, Heterolepa* sp. A, *Eponides pusillus, Vonkleinsmidoides.*

#4 = *Neouvigerina ampullacea, N. interrupta, N. porrecta.*

#5 = *Rosalina? suezensis.*

#6 = *Fursenkoina* sp. A.

#7 = *Tretomphaloid* spp.

#8 = *Discorbinella rhodiensis.*

#9 = *Cibicides tabaensis, C. mabahethi, Cibicides* sp. A, *Caribeanella elatensis.*

#10 = *Cancris auriculus.*

#11 = *Miliolidae* (*Quinqueloculina*, *Triloculina*, *Pyrgo*), *Miliolina sp.* *Spirophthalmidium* spp., *Siphonaperta horrida*, *Vertebralina striata.*

#12m = Transported specimens (*Assilina ammonoides*, *Asterorotalia* sp., *Challengerella bradyi*, *Elphidium sp.*).

#13 = *Hanzawaia* sp. A.

#14 = *Spirillina* sp.

#15 = *Globocassidulina* spp., *Paracassidulina neocarinata.*

#16 = *Astrononion* sp. A, *Nonion* spp., *Porosononion* sp. B.

#17a = *Plotnikovina* cf. *aequa*, *Sahulia kerimbaensis.*

#17b = *Textularia cushmani.*

#18a = *Robertinoides bradyi.*

#18b = *Lamarckina ventricosa*, *Alliatinella panayensis.*

#19 = *Lagena* spp., group of *G. laevigata*, *Lenticulina* spp.

#20 = *Pseudoeponides falsobeccarii.*

 # * = *Glomospira* sp., "*Psammosphaera*".

Others = all the species that each constitute less than 1% of the assemblage.

4.3 Ecological significance of pteropods

Cavolinia longirostris

An epipelagic warm-water, cosmopolitan species with a herbivorous diet (Bè and Gilmer, 1977; Almogi-Labin, 1984).

Cavolinia uncinata

Generally an epipelagic, herbivorous tropical species, at times with a diel migration pattern (Bè and Gilmer, 1977; Almogi-Labin, 1984).

Clio convexa

A mesopelagic, herbivorous species was found in sediments from the Indo-Pacific region and found in the Red Sea and Gulf of Aden. Found living down to 600 m in the Gulf of Elat and down to 700 m in the Red Sea with highest abundance during the winter (Bè and Gilmer, 1977; Almogi-Labin, 1982, 1984; Ivanova, 1985; Weikert, 1987).

Creseis acicula

A shallow epipelagic species. *C. acicula* has a herbivorous diet and is known to occur in seasonal dense swarms associated with high zooplankton productivity. It is a cosmopolitan species which withstands the highest salinities of all the pteropod species (Bè and Gilmer, 1977; Almogi-Labin, 1982, 1984).

Creseis chierchiae

An epipelagic species, one of the shallowest, morphologically similar (in juvenile stages) to *C. virgula virgula.* (Almogi-Labin, 1982).

Creseis virgula virgula

An epipelagic tropical-subtropical species with a herbivorous diet. Abundant during summer time in the Gulf of Elat (Bè and Gilmer, 1977; Almogi-Labin, 1984)

Diacria quadridentata

An epipelagic, herbivorous species at times with a diel migration pattern. Abundant during the fall season in the Gulf of Elat (Bè and Gilmer, 1977; Almogi-Labin, 1984).

Hyalocylis striata

A tropical-subtropical species which reaches its greater abundance in areas of cooler and presumably richer waters. In the Gulf of Elat and northern most Red Sea it was found to be an epipelagic species (Bè and Gilmer, 1977; Almogi-Labin, 1982).

Limacina bulimoides

A mesopelagic herbivorous, deep water, subtropical species with highest concentrations in the central water-masses of all oceans. Has a pronounced diel migration and is absent in the present-day Gulf of Elat. Represents intermediate fertility of the waters (Bè and Gilmer, 1977; Almogi-Labin, 1982, 1984).

Limacina inflata

A mesopelagic mostly gyre center type, with a strong diel migration. A most common warm-water cosmopolitan species with a herbivorous diet. Represents a lowering of water fertility (compared to *L. bulimoides*) and dominates during the spring and summer time, during the southwest monsoon in the Red Sea region. Found living down to 400 m in the Red Sea (Bè and Gilmer, 1977; Almogi-Labin, 1982, 1984; Weikert, 1987).

Limacina trochiformis

An epipelagic, herbivorous species. Prefers upwelling regions, thus being an indicator of fertile waters. Exceptionally abundant during the fall season in the Gulf of Elat in the upper 100 m (Bè and Gilmer, 1977; Almogi-Labin, 1982, 1984).

Peraclis reticulata

A mesopelagic, possibly carnivorous species with a strong diel migration most abundant during summer (Almogi-Labin, 1984).

5 - Assemblage distribution in the cores

5.1 Core MC 88 (366m)

The lithology consists of alternating yellow-grey and green-brown calcareous mud. These sediments contain relatively high total organic carbon (TOC) of 0.7% (Fig. 3) and 50% carbonates (Fig. 4).

Ten species of pteropods were identified in this core. The relative abundance of the six major taxa (Fig. 5a) shows that the continuous occurrence of the common species, *Limacina inflata* (~70%) followed by *C. virgula virgula* (~15%) and *C. chierchiae* (~10%) are the main constituents of the assemblage. *Limacina inflata* is by far the most abundant species (up to 270 specimens/g sediment) followed by about 35 specimens each of *C. virgula virgula* and *C. chierchiae* (Fig. 5b). The high percentage of *L. inflata* in the assemblage is emphasized in Fig. 5c where the high percentage of mesopelagic (~70%) pteropods is due to it alone, the percent of *Clio convexa* being negligible (~2%). The number of specimens/g dry sediment in different core samples ranged between 100 to 400.

Twelve species of planktic foraminifera were identified in this core. The relative and total abundance of the seven major taxa (Figs. 6a,b) shows the continuous occurrence of the major species, *Globigerinoides ruber* (~35%) and *G. sacculifer* (~25%) followed by ~15% of *Globigerinita glutinata* and *Turborotalita clarkei* each. The number of specimens/g dry sediment (Fig. 6b) was ~80 for *G. ruber*, ~60 for *G. sacculifer* and ~30 for *G. glutinata* and *T. clarkei* each. The results summarized in Fig. 6b show a prominent shift of most of the species, with a large number of specimens/g dry sediment at 5-6 cm depth. Note the large percentage (~15%) of *T. clarkei* in this shallow core as opposed to the other deeper cores (2-3%). The data in Fig. 6c shows a relatively low plankton/benthos (P/B) ratio (~60%) and a relatively low number of specimens/g dry sediment (~250).

Sixty nine benthic foraminifera species were identified in this core, the highest assemblage diversity of the four cores. The relative and total abundance of the twenty-four major taxa (Figs. 7a,b,c,8a,b) shows the continuous occurrence of the major genera, *Bolivina*-#2 (up to 32%), *Miliolidae*-#11 (up to 15%) and *Astrononion*-#16 (up to 12%) (Fig. 7a,b). The total abundance of the main species decreases, from up to 340 specimens of *Bolivina*-#2 and up to 140 of *Miliolidae*-#11, to up to 120 specimens of *Gyroidinoides*-#3a (Fig. 8a,b). At the depth of 17cm, there is an increase in the relative and total abundance of *Cibicides*-#9. It should be noted that the relative abundance of *Plotnikovina*-#17a decreases from 7% in the upper part of the core (0-5cm) to less than 1% downcore (Fig. 7c).

Fig. 8c shows the total abundance of ~130 benthic foraminiferal specimens/g dry sediment.

5.2 Core MC 98 (579m)

The lithology consists of alternating yellow-grey and green-brown calcareous mud. These sediments contain a relatively high TOC of ~0.35% (Fig. 3) and ~55% carbonate (Fig. 4).

Ten species of pteropods were identified in this core. The relative abundance of the seven major taxa (Fig. 9a) show the continuous occurrence of the common species, *Limacina inflata* (~60%), followed by *L. bulimoides* (up to 25%), *Clio convexa* (~10%) and *L. trochiformis* (~8%) as the main constituents of the assemblage. *Limacina inflata* is by far the most abundant species (up to 880 specimens/g dry sediment) followed by 280 specimens/g of *L. bulimoides* at its peak, ~120 specimens/g of *C. convexa* and ~80 specimens/g of *L. trochiformis* (Fig. 9b). It should be noted that in the lower part of the core there is an increase of *Creseis acicula* and a parallel decrease of *C. chierchiae*. The important addition to the assemblage is the appearance of *L. bulimoides* (as well as *Peraclis reticulata*) which reaches its highest relative and total abundance at 23cm downcore. An opposing trend between *L. trochiformis* and *L. bulimoides* is observed, as well as opposing peaks between the latter and *L. inflata* (Figs. 9a,b). The abundance of the mesopelagic pteropods follows almost completely the trend of total number of specimens/g (~900). The increase (from 70-90%) of the mesopelagic pteropods is parallel to the increase of *L. bulimoides* (Fig. 9c).

Twelve species of planktic foraminifera were identified in this core. The relative and total abundance of the seven major taxa (Figs. 10a,b) show the continuous occurrence of the major species, *G. sacculifer* (10-42%) and *G. ruber* (22-40%), followed by ~20% of *G. glutinata* and ~15% of *Globigerinella siphonifera*. There is generally an opposite trend between *G. ruber* and *G. sacculifer* characterizing three cycles (Fig. 10a). The total number of specimens/g dry sediment (Fig. 10b) show 260-840 specimens/g dry sediment of *G. ruber*, 145-815 of *G. siphonifera*, and 135-470 of *G. glutinata* and 80-460 of *G. sacculifer*. A relatively high P/B ratio (>90%) and a relatively high number of specimens/g dry sediment (~1800) is shown in Fig. 10c.

Sixty three benthic foraminifera species were identified, a slightly lower-diversity assemblage compared to MC 88. The relative and total abundance of the twenty-two major taxa (Figs. 11a,b,c,12a,b,c) shows the continuous occurrence of the major genera, *Cibicides*-#9 (4-25%), *Neouvigerina*-#4 (5-22%), *Bolivina*-#2 (5-20%) and *Miliolidae*-#11(7-17%). In general, *Cibicides*-#9 and *Neouvigerina*-#4 show an increase downcore (Fig. 11a,b). The total abundance of the major groups show a downcore decrease in number of specimens/g dry sediment, from 150 of *Cibicides*-#9 and *Neouvigerina*-#4 each, to 45 and 70 specimens respectively, and from 110 and 100 of *Bolivina*-#2 and *Miliolidae*-#11, to 30 and 50 specimens respectively (Fig. 12a,b).

This core is distinguished by the largest (400-900) number of benthic foraminiferal specimens/g dry sediment (Fig. 8c). The large number is seen in the data of the top five cm of the core as well (Scherbacher, 1994).

5.3 Core MC 93 (929m)

The lithology consists of alternating light yellow-grey and yellow-grey calcareous mud. These sediments have a relatively low TOC of ~0.1% (Fig. 3) and ~70% carbonates (Fig. 4).

Twelve species of pteropods were identified in this core. The relative abundance of the seven major taxa (Fig. 13a) show the continuous occurrence of the major species, *L. inflata*, the dominant species (~62%), followed by *L. bulimoides* (up to 25%), *C. convexa* (~10%) and *L. trochiformis* (~8%). *L. inflata* is by far the most abundant species (455-1150 specimens/g dry sediment) followed by 400 specimens/g of *L. bulimoides* at its peak, ~150 of *C. convexa* and ~100 of *L. trochiformis* (Fig. 13b). *L. bulimoides* reaches its highest relative abundance 19cm downcore and its total abundance 21cm downcore. In general, an opposite trend between *L. trochiformis* and *L. bulimoides* is observed, as well as between the latter and *L. inflata* in the lower part of the core (Fig. 13a). The trend of the total mesopelagic assemblage follows almost completely that of the total number of specimens/g dry sediment (700-1900). The change in relative abundance (80% to 92% and a decrease to 80%) of the mesopelagic pteropods follows variations in the abundance of *L. bulimoides* (compare Figs. 13a and 13c).

Eleven species of planktic foraminifera were identified in this core. The relative and total abundance of the seven major taxa (Figs. 14a,b) shows the continuous occurrence of the major species, *G. sacculifer* (17-47%) and *G. ruber* (~23%), followed by ~22% of *G. siphonifera* and ~17% of *G. glutinata*. There is generally an opposite trend between *G. ruber* and *G. sacculifer* (Fig. 14a). The number of total specimens/g dry sediment (Fig. 14b) show a decrease from 520-1700 specimens/g of *G. sacculifer* and 500-900 of *G. ruber* to *G. siphonifera* (500-1100) and *G. glutinata* (190-600). A high P/B ratio (>95%), as well as a decrease in the total number of specimens downcore from 4500 to 2000, is observed in Fig. 14c.

Fifty seven benthic foraminifera species were identified, a relatively low-diversity benthic assemblage as compared to MC 88. The relative and total abundance of the twenty-three major taxa (Figs. 15a,b,16a,b) show the continuous occurrence of the major genera, *Neouvigerina*-#4

(10-25%), *Miliolidae*-#11 (8-22%), *Astrononion*-#16 (12-20%) and *Cibicides*-#9 and *Gyroidinoides*-#3a (5-17% each). The total abundance of the major groups show a number of specimens/g dry sediment, of 30-60 specimens/g of *Neouvigerina*-#4, 22-50 specimens/g of *Miliolidae*-#11, 22-45 specimens of *Astrononion*-#16, 20-40 of *Cibicides*-#9 and 4-20 of *Bolivina*-#2 (Fig. 16a,b).

Fig. 8c shows a total abundance of ~250 benthic foraminiferal specimens/g dry sediment.

5.4 Core MC 91 (1782m)

The lithology consists of alternating brown and reddish-brown calcareous mud. The sediments contain iron-oxides, especially below 13 cm. These sediments have a relatively low TOC of ~0.1% (Fig. 3) and 60% carbonates (Fig. 4).

Twelve species of pteropods were identified in this core. The relative abundance of the seven major taxa (Fig. 17a) show the continuous occurrence of the major species: *L. inflata*, the dominant species (decreases downcore from ~70 to 40%), followed by *L. bulimoides* (up to 50%), *L. trochiformis* (~10%) and *C. convexa* (~7%) constitute the main part of the assemblage. *L. bulimoides* reaches its highest relative and total abundance 27cm downcore. *L. inflata* is by far the most abundant species (decreasing from ~2400 to ~800 specimens/g dry sediment) followed by 2000 specimens/g of *L. bulimoides* at its peak, ~400 specimens/g of *L. trochiformis* and ~250 specimens of *C. convexa* (Fig. 17b). In general an opposite trend between *L. bulimoides* and *L. inflata* is observed (Fig. 17a). The trend of the total mesopelagic assemblage follows almost completely that of the total number of specimens/g dry sediment (~3300). The increase (75-95%) of the mesopelagic pteropods is parallel to the increase of *L. bulimoides* (compare Figs. 17a and 17c).

Twelve species of planktic foraminifera were identified in this core. The relative and total abundance of the seven major taxa (Figs. 18a,b) show the continuous occurrence of the major species; *G. ruber* (16-40%) followed by *G. sacculifer* (3-35%), *G. glutinata* (~25%) and up to 30% of *G. siphonifera*. There is generally an opposite trend between *G. ruber* and *G. sacculifer* (Fig. 18a). The number of total specimens/g dry sediment (Fig. 18b) decreases from 90-2000 specimens/g of *G. sacculifer*, 550-1600 of *G. ruber* and 390-1600 of *G. glutinata*, to 190-1200 specimens/g of *G. siphonifera*. The highest P/B ratio (>96%), as well as the highest total number of specimens/g dry sediment for any core (2200-6000) is shown in Fig. 18c.

Fourty seven benthic foraminifera species were identified, the lowest assemblage diversity as compared with MC 88. The relative and total abundance of the twenty major taxa (Figs. 19a,b,c,20a,b) show the continuous occurrence of the major genera; *Astrononion*-#16 (14-30%), *Miliolidae*-#11 (2-27%), *Hanzawaia*-#13 (2-19%) and *Neouvigerina*-#4 (0-12%). *Miliolidae*-#11 and *Neouvigerina*-#4 show a decrease in the top cm (Fig. 19a,b). The total abundance of the major groups shows in the same order a decrease in number of specimens/g dry sediment, from 9-37 specimens/g of *Astrononion*-#16 and 5-30 specimens/g of *Miliolidae*-#11, to 3-16 specimens/g of *Hanzawaia*-#13 and 1-15 of *Neouvigerina*-#4 (Fig. 20a,b).

Fig. 8c shows a total abundance of ~75 specimens/g dry sediment.

6 - Stratigraphy

The detailed planktic foraminifera and pteropoda records make it possible to recognize several intervals in the cores, denoting ecostratigraphic zones numbered EC1-EC6 (Fig. 21). Since changes in ecological conditions did not effect the two groups synchronously and to the same extent, a detailed ecostratigraphic framework was obtained by combining the four zones characterized by planktic foraminifera and the two by pteropods.

The peak of *L. bulimoides* was used as a datum line for correlation between the cores. The shallowest core (MC88) was taken close to the shore and was diluted by terrigenous sediments (Fig. 4), the *L. bulimoides* peak was not recorded in this core because of the very high rate of sedimentation compared with the rest of the cores, therefore it cannot be used for correlation with the others. MC88 is lacking any useful correlative information of foraminifera as well.

In the absence of radiometric dates no direct age determination is possible.

Almogi-Labin and others (1991 and personal communication) worked on cores KL11 and KL13 from the central Red Sea and found, by extrapolation, an age of ~4200 years ago for the *L. bulimoides* peak (Fig. 22). This age was used in relation to the cores of this present study. The correlation between the cores is seen in Fig. 21.

Based on this stratigraphy, the sedimentation rate calculated for the cores MC88, MC98, MC93 and MC91 are: at least 11 cm/1000 years, 5.75 cm/1000 years, 4.75 cm/1000 years and 6.75 cm/1000 years, respectively. Assuming a constant rate of sedimentation, it was possible to estimate the age of the bottom of core MC98 to be 4.8 Kyr, that of MC93 as 6.4 Kyr and MC98 as 5.3 Kyr.

6.1 Description of ecostratigraphic zones (EC1-EC6) (Fig. 21)

EC1: Characterized by a relatively low abundance of *G. sacculifer* and a high one of *G. ruber*. *L. bulimoides* is absent or of very low abundance, while *L. trochiformis* (as well as *L. inflata*) is of a relatively high abundance (compare Figs. 9a, 10a, 13a, 14a, 17a, 18a).

EC2: This zone is characterized by a high total and relative abundance of *G. sacculifer* along with a decrease in the relative abundance of *G. ruber*. *L. bulimoides* is absent or of very low abundance while *L. inflata* is of high abundance.

EC3: This zone shows a decrease in the total and relative abundance of *G. sacculifer* as opposed to *G. ruber* and is important as a marker of the last appearance, or beginning of the large decrease, of *L.* bulimoides (Figs. 21, 23).

EC4: This zone is characterized by a low total and relative abundance of *G. sacculifer* along with a decrease in the relative abundance of *G. ruber*. *L. bulimoides* is present and its relative and total abundance increases downcore (*L. inflata* is of high abundance).

EC5: Like EC2, it is characterized by a high total and relative abundance of *G. sacculifer* along with a decrease in the relative abundance of *G. ruber*. *L. bulimoides* reaches its highest total and relative abundance.

EC6: Recorded only in MC93 (929m), it shows a low total and relative abundance of *L. bulimoides* and high relative abundance of *G. sacculifer* (Figs. 21, 23).

7 - Major benthic foraminifera groups:

The response of benthic foraminifera is not synchronous with the changes in planktic foraminifera and pteropods. For this reason the distribution of the major benthic foraminiferal groups is briefly summarized below.

The cores were arranged according to stratigraphic correlation represented above. The changes of the main species are described from the shallowest to the deepest core (a lateral W-E transect). Vertical downcore changes were detected in some of the studied cores.

Group 1- generally decreases from shallow to deeper cores (W-E):

Bulimina - #1: A clear lateral decrease in the relative abundance, from ~8% decreasing to ~2%, is seen in Fig. 24.

Bolivina - #2: The relative abundance shows a clear lateral decrease from 25% to 5% (Fig. 25). A slight decrease in the relative abundance downcore is observed.

Globocassidulina - #15: The relative abundance shows a lateral decrease from ~7% to ~3% (Fig. 26).

Group 2 - consists of species more frequent in the intermediate depths:

Neouvigerina - #4: The relative abundance shows an increase of up to 20% in the two middle cores compared to the shallowest and deepest ones, (~5%) as seen in Fig. 27.

Cibicides - #9: The relative abundance shows an increase of up to 20% in the two middle cores compared to the shallowest and deepest ones (~5%) as seen in Fig. 28. A slight increase in the relative abundance downcore is observed in the two middle cores.

Group 3 - generally increase from shallow to deeper cores (W-E):

Miliolidae - #11: The relative abundance shows a lateral increase from ~10% to ~25% in the deepest core (Fig. 29).

Astrononion - #16: The relative abundance shows a lateral increase from ~8% to ~23% in the deepest core (Fig. 30).

Hanzawaia sp. A - #13: The relative abundance shows a lateral increase from ~2% to ~10% in the deepest core (Fig. 31).

Glomospira charoides - #*: The relative abundance shows a lateral increase from ~1% in the shallowest core, to ~5% in the deepest one (Fig. 32).

8 - Discussion

The qualitative composition of the planktic and benthic foraminiferal assemblages does not change significantly throughout the cores, although the relative and total abundance of individual species does change considerably. With the notable exception of *L. bulimoides*, the same holds true for the pteropod assemblage. The main changes in both groups do not concern the presence/absence of species, but the relative abundance (up to 30%), which is significant in *G. sacculifer* and to a lesser degree, in *G. ruber*. As a result, division into six ecostratigraphic zones was made mainly on the basis of the cyclical changes of *G. sacculifer*. Since this species is a shallow to intermediate water one (Almogi-Labin, 1984; Erez et al., 1991; Bijma and Hemleben, 1994), most of the changes reported in this study reflect the intermediate water mass (50m-300m deep) during the past 5000-6000 years.

8.1 Planktic foraminifera

The planktic foraminiferal assemblage recorded in this study is generally similar to the living assemblage as seen by Auras-Schudnagies et al. (1989) and Ivanova (1985) in surface sediment samples. The detection of *Turborotalita clarkei* in the present study is of no ecological significance since the size fraction analysis, >149µm, is not representative for this species, which is smaller (Hottinger et al., 1993).

The relative and total abundance of *G. sacculifer* generally dominates over that of *G. ruber* (not withstanding the bi-weekly reproduction of *G. ruber* vs. the lunar reproduction of *G. sacculifer*) (Figs. 10a, 14a, 18a), except in the shallow core MC88 (366m), where the total abundance of *G. ruber* is twice that of *G. sacculifer* (Fig. 6a) (Almogi-Labin, 1984; Hemleben et al., 1989; Bijma et al., 1990; Erez et al., 1991). This may be due to the fact that the core taken at this site represents only a part of the full water column as compared to the others. The distance from the shore may also play a role. The opposite dominance of *G. sacculifer* and *G. ruber* has been observed in the different oceans and this anticyclicity in Quaternary sediments has been reviewed (among others) by Luz and Reiss (1994, unpublished). Reasons given for this phenomenon by various authors are :

1. Temperature: Minimum winter temperatures during the glacial periods (below 17°C) are thought to have prevented *G. sacculifer* from surviving in the Gulf of Elat and northern Red Sea sediments, while *G. ruber* withstood temperatures down to 13°C (Reiss et al., 1980; Reiss and Hottinger, 1984). However, Bijma et al. (1990), working on living specimens under laboratory conditions, found identical lower temperature (14°C) limits for the two species. Thus, this factor is probably not the cause for the differences in abundance between the two species.

2. Salinity: Anticyclicity between *G. sacculifer* and *G. ruber* in the Pleistocene Red Sea sediments has been explained by lowered temperatures superimposed on the species-specific upper salinity limits, with *G. ruber* having a wider salinity range (above 36‰ or below 34.5‰) than *G. sacculifer* (Berggren and Boersma, 1969). On the other hand, shifts in dominance in present day oceans seem to have a different explanation. *G. sacculifer* is dominant in the north Red Sea and Gulf of Elat (Almogi-Labin, 1984; Auras-Schudnagies et al., 1989), where salinities at present reach 41‰, and is absent in the southeast Levantine Basin, where salinities are 39.5‰. Since 49‰ is the upper salinity tolerance for both *G. sacculifer* and *G. ruber*, it is unlikely that present day salinity differences are the sole factor for the dominance pattern. In addition, Bijma et al. (1990) found in laboratory conditions that the opposite dominance in present oceans is not controlled by salinity, as the two species in question have the same salinity optimum.

3. Water fertility: *G. sacculifer* dominates over *G. ruber* in the nutrient-poor waters of the north Red Sea, whereas *G. ruber* is abundant in the southern part of the Red Sea, which is more fertile (Zobel, 1971; Weikert, 1987; Kroon, 1988; Auras-Schudnagies, 1989; Bijma et al., 1990). In the northeastern Atlantic, Ottens (1992) showed the main controlling factor for foraminiferal distribution to be nutrient availability. On the other hand, *G. sacculifer* is absent

today in the southeastern, nutrient-poor, Levantine Basin, whereas *G. ruber* is present (Luz and Reiss, 1994, unpublished). Most probably, water fertility only partially controls the changes in relative abundance of *G. sacculifer* and *G. ruber* (although no definite understanding of this correlation has yet been reached).

Auras-Schudnagies et al. (1989) showed the connection between the intensity and duration of the inflowing fertile waters from the southern Red Sea (during the summer monsoon) and their control over the distribution pattern of the different species examined. North of 20°N, the Red Sea is depleted in nutrients and has an oligotrophic character, while south of 20°N there is an entrance of relatively fertile waters from the Arabian Sea through the Gulf of Aden. The shift in the convergence zone changes the water masses nutrient level and the dominant species of the assemblages. I suggest that migration of the convergence zone, north or south of its present border (20°N) might have led to the downcore changes observed in this study in the relative abundance of *G. sacculifer* (one of the most dominant species in the Gulf of Elat and northern Red Sea) (Almogi-Labin, 1984; Kroon, 1988; Auras-Schudnagies, 1989). These changes were apparently greater in the intermediate water mass (50-300m deep) than in the upper or deep waters. Thus, the distinct changes in relative abundance of *G. sacculifer*, a good representative for changes in the intermediate water mass, are not seen as clearly for the shallow (upper 50m) epipelagic *G. ruber*, nor for the benthic foraminiferal species, which represent the bottom water mass (Reiss et al., 1974; Almogi-Labin, 1984; Bijma et al., 1990; Erez et al., 1991).

4. <u>Food requirements:</u> *G. ruber* feeds mostly on phytoplankton while *G. sacculifer* is a carnivore, feeding on copepods and, in juvenile stages, algae (Hemleben et al., 1989). Thus, the distribution of copepods might strongly affect the distribution of *G. sacculifer* and, consequently, the ratio of the two species. Bijma and others (1990) suggest that *G. ruber* relies more on symbionts (more autotrophic) than the carnivorous (more heterotrophic) *G. sacculifer*, thus reflecting availability of nutrients. However, information concerning use of symbionts as food and the connection between feeding habits and distribution is very scarce and conclusions in this regard relating directly to presence/absence of the two species cannot be made at present.

5. <u>Water stratification:</u> Transition from the photic zone to complete darkness may trigger gametogenesis in *G. sacculifer*. The gametes concentrate in a narrow depth zone of given density and, by that, increase their chances of fusion (Erez et al., 1991 with ref.). The distance between the photic zone and the gametogenesis depth zone is dependent upon water-mass characteristics and should be relatively small to enable the juvenile *G. sacculifer* to regain the photic zone and feed on the abundant phytoplankton there, as well as to acquire symbionts (Luz and Reiss, 1994, unpublished; see also Bijma et al., 1994). The pycnocline south of 20°N intensifies and rises, compared to its less strong and deeper structure north of 20°N (Maillard and Soliman, 1986). Therefore, the depth and intensity of the pycnocline can be of great importance as a partial mechanism explaining the changes in the relative abundance seen in *G. sacculifer* in the present study.

The mechanism which causes stratification is the difference in water density (Patzert, 1972; Cember, 1988). There are no large rivers flowing into the central Red Sea bringing fresh water which could trigger stratification in the water column (Edwards, 1987). The Khor Baraka river reaches the Red Sea about 100 km south of Port Sudan and therefore only slightly influences the cores studied in this paper (Rossignol-Strick, 1987). In this area of the sea, such differences are probably caused by small changes in climatic conditions, from semi-arid to more arid ones, and vice versa. These climatic changes apparently had the largest effect on the intermediate water mass, where *G. sacculifer* is abundant (this is also shown by the mesopelagic pteropod *L. bulimoides* as explained further on).

A more arid climate with frequent strong cold-winds in the winter, could have caused increased evaporation in the Gulf of Suez and northern Red Sea (including the Gulf of Elat) forming, as a result, the deep and intermediate water masses, respectively (Patzert, 1972; Cember, 1988). Eshel et al. (1994) assumes wind forcing is secondary to thermohaline forcing, but agrees on the source of the deeper waters. Ventilation of the deeper water masses are therefore controlled by the formation of deep waters in the Gulf of Suez and the northern Red Sea itself, which in turn, control the dominance of mesopelagic fauna in these deeper water masses. These waters produce a more oxygenated deep and intermediate southern inflow and cause the weakening of the oxygen minimum zone (OMZ), thus allowing fauna to live and migrate to deeper waters (Patzert, 1972; Weikert, 1987; Cember, 1988). Differences in this inflow from the north can trigger or weaken the water stratification and increase the pycnocline gradient. The changes in the intensity of this inflow can also cause changes in the relationship between the depth of the pycnocline and that of the photic zone and, as a result, can lead to changes in the relative abundance of *G. sacculifer* (Erez et al., 1991).

6. A combination of factors: The most probable scenario is a combination of the different parameters: changes in position of the convergance zone changed water mass inflow (north or south of the convergence zone). This in turn changed the nutrient levels and faunal assemblage in the convergence zone area. Along with changes in the stratification of the water column (weakening of the OMZ), the relationship between the depth of the pycnocline and that of the photic zone was altered and may have led to the changes detected in *G. sacculifer*.

The mesopelagic pteropod, *L. bulimoides*, reaches high total and relative abundance during times of a less stratified water column. The latter enables a full diurnal migration (Bè and Gilmer, 1977; Almogi-Labin, 1982, 1984). Therefore, the climatic settings at the time of its strongest peak (~4200 years BP) were apparently more arid, with a deeper water column habitat for the mesopelagic species. This deeper and less stratified water column is, as expected, correlative to the episodes of higher relative abundance of *G. sacculifer*. *Globigerina sacculifer* can overcome the density barrier of migrating from the gametogenesis depth of water to the photic zone more easily in a relatively mixed water column than in an intensely-stratified water column. The correlation between the higher relative abundance of *L. bulimoides* and of *G. sacculifer* is seen in Fig. 23. This parallel correlation stops at ~2400 years before present (yrBP) where *L. bulimoides* and *G. sacculifer* decrease in abundance, while *L. bulimoides* disappears altogether. *G. sacculifer* on the other hand, continues to show a cyclical increase-decrease pattern. The ecological changes are not exactly synchronous between the two due to the species-specific differences between these separate groups.

The problem remains that with current data we are not able to give a full explanation for the *G. ruber* - *G. sacculifer* anticyclicity seen here and in other oceans.

The pteropod assemblage is very well preserved, indicating that no dissolution has occurred and therefore cannot be the cause for the assemblage changes seen in any of the cores.

8.2 Reconstruction of the water column - paleohydrography

The changes observed in the different species can help reconstruct the paleo-water column properties in the central Red Sea during the past ~6000 years.

The sedimentation rate calculated for the cores MC98, MC93 and MC91 are; 5.75cm, 4.75cm and 6.75cm/1000 years, respectively. Assuming a constant rate of sedimentation, it was possible to estimate the age of the bottom of core MC98 to be 4.8 Kyr, that of MC93 as 6.4 Kyr and MC98 as 5.3 Kyr.

6400-5300 - MC93 (929m) represents the longest record spanning 6400 years. The period of 6400-5300 yrBP is represented by the very low abundance of the pteropod *L. bulimoides* and the high abundance of the planktic foraminifera *G. sacculifer* (Fig. 23). This may be due to a slightly low oxygen level at the OMZ because of decreased ventilation of the intermediate water column which affects only the deeper, mesopelagic *L.bulimoides.* A relative increases of *L. trochiformis* at this time, indicates a slightly stratified water column which did not affect the shallow mesopelagic species (see Fig. 13a). This stratification caused a relatively high nutrient level, as indicated by the increase of *L. trochiformis* which reflects slightly higher nutrient levels in the water (Bè and Gilmer, 1977).

5300-3000 - The zone between 5300 and 3500-3000 yrBP, in the three deepest cores, was characterized by a relatively less stratified water column. Therefore a probable scenario is a slight climatic change at 5300 yrBP from less arid to slightly more arid, and therefore a slightly less stratified water column. This is seen by the relatively high abundance of the shallow mesopelagic species, *G. sacculifer*, *G. glutinata*, *G. siphonifera* (Figs. 10a, 14a, 18a) and the very high abundance of the mesopelagic pteropods, *L. bulimoides* followed by *L. inflata* (Figs. 9a, 13a, 17a). *Limacina bulimoides*, a deep mesopelagic species (Bè and Gilmer, 1977; Almogi-Labin, 1982, 1984), reaches its highest abundance at this time (~4200 yrBP) and is seen clearly in all the three cores (Fig. 23). This period represents the most aerated water column and therefore the most arid climate in the past 6400 years. This is seen in the terrestrial record as well. Wasson (1995) showed extremely low lake levels in Lake Didwana, India, 4000 years ago and Weiss and others (1993) found a marked increase in aridity and wind circulation, subsequent to a volcanic eruption at ~4200 years ago in northern Mesopotamian, Syria.

3500-2000 - The zone between 3500-2000 yrBP represents a new change in the climatic settings, from the slightly arid period to a less arid and more humid one. These conditions lead to less ventilation of the water column and, therefore, a more stratified one. The increase in stratification increases the nutrient level as seen by the increase in the pteropod *L. trochiformis* (Figs. 9a, 13a, 17a). This is followed by a slight increase in *C. convexa* and almost a total decrease in *L. bulimoides*, a dominant mesopelagic species in the previous zone, which decreases probably as a result of limitation in oxygen levels and strengthening of the stratification (Fig. 23). In the Red Sea *L. bulimoides* migrates to depth of ~200m hence, deeper than those of *G. sacculifer* (~100m) and therefore diasppears at this stage, while the latter continues to live (Bijma and Hemleben, 1994). The higher abundance of the epipelagic species (both foraminifera and pteropods), especially after the large decrease in *L. bulimoides*, is seen by the high abundance of *G. ruber* (followed by *G. siphonifera* and *G. glutinata*) in Figs. 10a, 14a and 18a.

2000-600 - Another change in the climatic settings is seen between 2000-600 yrBP. The conditions are very similar to those between 6400-5300 yrBP seen in MC93 (929m). An increase in the relative abundance of *G. sacculifer* together with a decrease in the rest of the planktic foraminiferal assemblage represents a broadening of the mixed water layer and a weakening of the stratification, due to a slightly more arid period (Figs. 10a, 14a, 18a). A very low lake level in Lake Didwana, India was detected at 1000 yrBP, showing this increased aridity as well (Wasson, 1995). The ventilation and weakening of water stratification is seen by the high relative abundance of the mesopelagic *L. inflata* which migrates to depth of 400m (Weikert, 1987). The weakening of the stratification was not to the same degree seen during the period 5000-3000 yrBP, as detected by the abundance of the epipelagic pteropods (*L. trochiformis*, *C. acicula* and *C. virgula virgula*) seen in Figs. 9a, 13a and 17a.

600-present - The final change in the climatic settings is seen between 600 yrBP to present. The last ~600 years were less arid and therefore less mixing of the waters occurred. The stronger stratification of the water column is seen through the dominant species of the assemblage. An increase in the epipelagic *G. ruber* (followed by a slight increase of *G. glutinata* and *O. universa*) (Figs. 10a, 14a, 18a) and the highest relative abundance of the epipelagic *L. trochiformis* (followed by a slight increase in the mesopelagic *L. inflata*) as seen in Figs. 9a, 13a and 17a.

8.3 Reconstruction of the water column - possible mechanisms

In examining the different agents which could influence the climatic and/or the hydrographic settings, the reasons below are suggested:

1. Changes in the El-Niño Southern Oscillation (ENSO): The Southern Oscillation is caused by the interannual sea surface temperature variations of the tropical Pacific. The periodicity of the oscillation is estimated to be approximately 4 years (Anderson et al., 1992). Geological records are capable of recording long-term changes associated with the ENSO system and evidence exists that such changes in the frequency and amplitude of ENSO do occur. Longer cycles that exhibit periodicity between 80-100 years are preserved in marine sediments. These changes bring to faunal and physical changes in the waters (Anderson et al., 1992). The reason and forcing mechanism for the changes seen in the ENSO system are not completely understood at present and more research is in line. The core samples examined in the present study, show a resolution of 150-200 year interval for each cm, thus hampering the recognition of the short period cycles of ENSO.

2. Monsoonal changes: Changes in the intensification of the monsoon are recorded on an astronomical cycle scale (Rossignol-Strick, 1983). The duration and global timing of sub-cycles in the monsoon system is at present unknown (Wasson, 1995). The controlling factors of these changes are mainly atmospheric. A weather system, like the monsoon, develops at times with reference to the trade wind convergence designation, the intertropical convergence zone (ITCZ). A possible explanation for changes in the monsoonal regime, involve a change in the inclination of the intertropical convergence and the compression of the zone (Rognon and Williams, 1977; Barry and Chorley, 1992; Shulmeister and Lees, 1995). Variations in the monsoon intensity on a sub-cycle level might be connected to the Late Holocene climate fluctuations, which were observed in the Red Sea records. However, the timing of the sub-cycles are not established so far.

3. The presence of small gyre centers: The large scale circulation of the Red Sea is dominated by thermohaline forces, winds, evaporation and the monsoonal system (Patzert, 1972; Quadfasel and Baudner, 1993). Quadfasel and Baudner (1993) showed that the local rotation of the wind field was apparently able to generate gyre-scale circulation cells. Their location is thought to be linked to the major topographic basins of the sea. These eddies were observed in the area of 20°N and could be the reason for changes in the fertility of the water. In the margins of a clockwise eddy the nutrient levels are slightly higher than in the center (Ring group, 1981). Therefore the position of the cores in relation to these eddies could have played a certain role in the character of the waters surrounding the cores.

   The highest abundance of *L. bulimoides* in the three cores, along with the largest difference in the relative abundance of *G. sacculifer*, is detected in the core MC91 (1782m). The position of this core is probably at the gyre-center, meaning that the nutrient levels of the surrounding waters might be relatively low. This apparently had an influence on the abundance of the species as compaired with core MC93 (929m). This core is probably positioned at the gyre-margin, where nutrient levels are slightly higher, and the differences described above are not as sharp.

8.4 Benthic foraminifera

The deep water body has a stable and constant temperature and salinity of 21.5°C and 40.6‰, respectively (Patzert, 1972). On the other hand, the total organic carbon content and oxygen levels (see Figs. 3 and 33) change significantly. The surface waters of the Red Sea are close to oxygen saturation levels. At a depth of 200-650 meters there is an oxygen minimum zone of 1.5 ml O_2/l in the north, decreasing towards 20°N and southwards to the level of 0.5 ml O_2/l. The bottom waters below 700m depth are well ventilated with oxygen levels of 2 ml O_2/l (Newmann and McGill, 1962). Renewal of the intermediate and deep water masses is controlled by the rate of formation of deep waters in the Gulf of Suez, Gulf of Elat and the northern Red Sea itself. The oxygen content of the intermediate waters is controlled also by the increasing consumption southwards, because of higher fertility of the waters (Patzert, 1972; Cember, 1988 and ref. within).

As mentioned previously, the shallowest of the four multi-cores examined was taken within the OMZ, another at the margin of the OMZ and two cores in the deeper and more oxygenated deep water mass. Three major benthic foraminiferal assemblages were distinguished based on their composition. Each assemblage is composed of a number of characteristic species, and additional ubiquitous species.

Group 1 - OMZ assemblage

The assemblage found in core MC88 is characterized by a low number of ~100 specimens/g dry sediment (Fig. 8c), along with the highest diversity of species (Fig.34), altogether 69 species. The low abundance is partially related to the higher sedimentation rate of this core (366m), minimum of 11 cm/1000 years.

The dominant species in this assemblage are all infaunal; *Bulimina* (#1), *Bolivina* (#2) and *Globocassidulina* (#15), comprising together ~40% of the assemblage. The species *Discorbinella rhodiensis* (#8), *Cancris auriculus* (#10) and *Fursenkoina sp.A* (#6) are part of the characteristic species comprising this assemblage and are absent in the other cores. These latter species comprise ~8% of the assemblage which brings all the characteristic species to comprise 48% of this assemblage. The three dominant taxa (#1, #2 and #15) show a clear lateral decrease in relative abundance, from the shallowest, ~8%, 25% and 7%, respectively to the deepest core, ~2%, 5% and 3%, respectively (see Figs. 24, 25 and 26). The increase in total abundance is generally parallel to the increase in number of total benthos (compare Figs. 8a, b with Fig. 8c).

Bulimina is an opportunistic species, following high food levels (Corliss and Chen, 1988; Jorissen, 1988; Corliss, 1991; McCorkle et al., 1990; Van der Zwaan and Jorissen, 1991; Keller Grünig et al., in prep.). *Bolivina* is abundant in areas of high TOC levels (Sjoerdsma and Van der Zwaan, 1992; Gupta, 1994). *Globocassidulina* is an infaunal species found living at 1-5 cm in the central Red Sea (Scherbacher, 1994).

The OMZ assemblage, is associated with a low oxygen content of <0.5 ml O_2/l (Fig. 33) and a high TOC content of ~0.7% wt (Fig. 3).

The supply of food (organic matter inputs) has a major influence on the distribution and abundance of deep-sea benthic foraminifera. An associated factor influencing the diversity and abundance of benthic fauna is the dissolved oxygen level in the bottom water and sediment pore water (Sjoerdsma and Van der Zwaan, 1992; Sen Gupta and Machain-Castillo, 1993; Gooday, 1994). Foraminiferal species have different oxygen and food (TOC levels) requirements.

Therefore different foraminiferal assemblages can reflect regions with specific TOC levels (Gooday, 1994). These species can be used as indicators of paleo-oxygen or paleo-TOC levels.

Tolerance to low oxygen levels and preference of high organic carbon content in the sediment, both play an important role for the dominating species in these areas, which are usually opportunistic species (Van der Zwaan and Jorrisen, 1991). A high dominance and low diversity of these species are typical of oxygen-poor environments (Sen Gupta and Machain-Castillo, 1993). Different studies in oxygen minimum zones support the low diversity and high dominance of the foraminiferal population, which constitute up to 80% of the assemblage. Quinterno and Gardner (1987) observed that at the Russian River, California at the depth of 500-1000m, the O_2 levels are 0.5 ml O_2/l and the dominant species were *Epistominella*, *Bolivina*, *Bulimina* and *Globobulimina spp.* Douglas and Heitman (1979) worked on the California Borderland (at depth of 400-950m) with O_2 levels of 0.1-0.3 ml O_2/l, and found frequent species of *Bolivina*. At the depth of 1200-1900m with O_2 levels of 0.3-0.5 ml O_2/l, the dominant species observed were the infaunal *Fursenkoina*, *Cassidulina* and Buliminids. In the eastern Pacific OMZ the dominant genera are *Bolivina* and *Bulimina* like in the present study (Sen Gupta and Machain-Castillo, 1993).

In the Red Sea the oxygen minimum is well developed (<0.5 ml O_2/l) but the conditions do not reach anoxia in the sediment surface (Weikert, 1987). The two factors controlling the dominance of the benthic species in the Red Sea OMZ are the dissolved O_2 level and the food availability, or in other words, the TOC level. The limitation of each factor plays a dominant role in the diversity. In this case the high diversity of species is probably to a large degree, due to the high TOC level (0.7% wt.) which allow favorable conditions, along with very low oxygen levels which cause the presence of the infaunal, buliminid species. Thus the high TOC preservation and low, but present, dissolved O_2 allow for the development of a heterogeneous diverse, although oxygen-limited, benthic population.

Group 2 - Transitional assemblage (OMZ margin)

The assemblage is characterized by the highest number of up to 900 specimens/g, (Fig. 8c) and by the high diversity of species (57-63 species) (Fig. 34).

The epifaunal to shallow infaunal benthic foraminifera most abundant in this assemblage are; *Neouvigerina* (#4) mostly *N. ampullacea* and *N. porrecta* and *Cibicides* (#9) mostly *C. mabahethi*, comprising together ~60% of the assemblage. The species *Lamarckina ventricosa* (#18b) and *Gyroidinoides cf. soldanii* (#3a) are part of the species comprising this assemblage and are scarce in the other cores. The latter comprise 8-13% of the assemblage which brings all the characteristic species to comprise ~70% of this assemblage. The abundance of the dominant species (#4 and #9) decreases laterally towards the OMZ as well as towards the more aerated deeper water mass (Figs. 27, 28). The total abundance of the two, is highest in core MC98 (579m) and follows the trend of number of benthos in this core (compare Figs. 12a,b, 16a,b and Fig. 8c).

Neouvigerina is abundant under moderate oxygen and TOC levels and is food dependent (Sjoerdsma and Van der Zwaan, 1992). Scherbacher (1994) records *C. mabahethi* living mainly at the surface and down to 3cm depth, thus indicating this species is epifaunal to shallow infaunal. *Cibicides spp.* (excluding *C. mabahethi*) were found living between oxygen levels of 1.3-6.0 ml O_2/l hence, are oxic indicators (Kaiho, 1994).

The relatively most abundant species of the transitional assemblage, are associated with moderate oxygen levels of 0.5-1.5 ml O_2/l (Fig. 33) and TOC levels of 0.3-0.1% wt (Fig. 3). The high abundance and diversity reflects the large food supply which along with the presence of moderate oxygen levels allow the development of a diverse, food-dependent benthic population. This assemblage is combined of ~40% epibenthic species (mainly *Cibicides spp.* and *Rosalina ? suezensis*) and ~60% shallow to deep infaunal ones (mainly *Bolivina spp.*, *Neouvigerina spp.* and *Astrononion sp.*) reflecting conditions similar to those of moderately low oxygen levels (compare with Sen Gupta and Machain-Castillo, 1993).

Group 3 - Well aerated assemblage

The assemblage is characterized by the lowest number (about 70) of specimens/g dry sediment, (Fig. 8c), along with the lowest diversity of species (Fig. 34), altogether 47 species.

Most dominant in the deepest water mass are epi- to infaunal foraminifera; *Miliolidae* (#11), *Astrononion* (#16), *Hanzawaia sp.A* (#13) and *Glomospira charoides* (#*), comprising together ~55% of the assemblage. Their relative abundance is highest in the aerated water mass and decreases towards the OMZ (Figs. 29, 30, 31, 32).

Hanzawaia is a deep water species (Keller Grünig et al., in prep.). Found living at 0-2 cm in the central Red Sea (Scherbacher, 1994). *Glomospira charoides* is a deep water species (Lindenberg and Auras, 1984; Berggren and Kaminski, 1990). Moderate organic matter fluxes and moderately low levels of O_2 (suboxic indicators, 0.3-1.5 ml O_2/l) are indicated by the common occurrence of *Astrononion* assemblages (Sjoerdsma and Van der Zwaan, 1992; Gooday, 1994; Kaiho, 1994). In the central Red Sea in the deep aerated region, *Astrononion* is found living between 2-5 cm sediment depth (Scherbacher, 1994). In this infaunal habitat, the oxygen level probably decrease to suboxic levels which are favored by *Astrononion* species. *Miliolidae* is a widely distributed group (Corliss, 1985, 1991). Different species of *Miliolidae* were grouped together in the present study, making it difficult to significantly characterize the different species ecologically.

The relatively most abundant species of the aerated water mass are associated with the highest oxygen levels of >2 ml O_2/l (Fig. 33) and lowest TOC levels of ~0.1% wt (Fig. 3). The low abundance and diversity reflects to a certain degree, the scarce food which present difficult conditions for the benthic population (Sjoerdsma and Van der Zwaan, 1992).

The three groups are presented in Fig. 35 with relation to the differing oxygen and TOC levels.

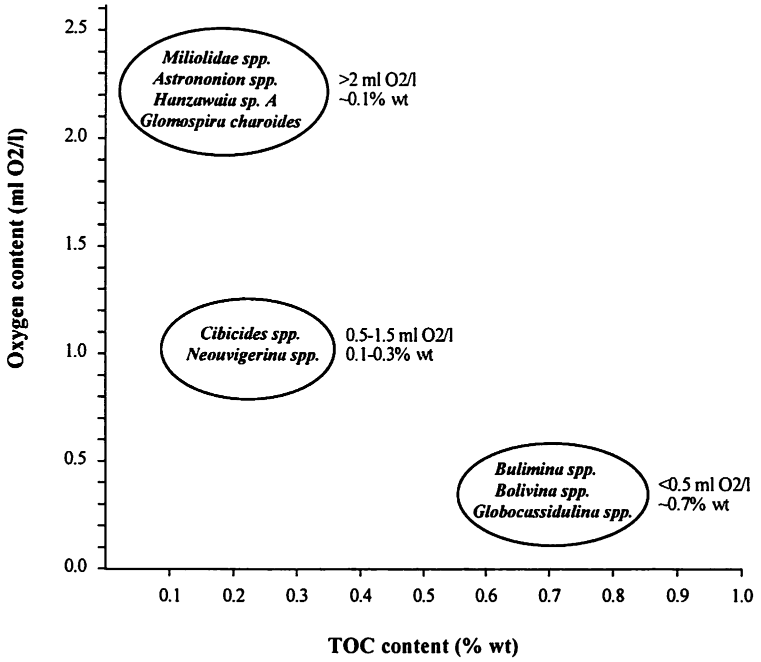


Fig. 35. Benthic foraminifera groups according to oxygen and total organic carbon (TOC) levels.

Agglutinated species

Most of the agglutinated have been combined with rare species (others) which together show no definite quantitative trend in the different cores. This is not the case in the top 5 cm (studied by M. Scherbacher). The relative abundance of the agglutinated species was considerably higher, reaching 35% in MC91 (1782m). The agglutinated species examined by M. Scherbacher (1994) were mainly organically cemented species (*Ammoscalaria spp.*, *Labrospira spp.*, *Hormosina guttifera* and others).

Fig. 36 shows the relative abundance of the "others" as well as the group of organic cemented species, as a function of core depth.

Soft bodied agglutinated foraminifera have no fossilization potential due to their fast decomposition after death (Gooday, 1994). Organically cemented species seem to decompose as they reach the sea floor and undergo oxygenation, thus their relative abundance decreases tremendously after burial. The results in Fig. 36 are in agreement with this phenomenon.

Present day foraminiferal assemblages

The benthic foraminiferal assemblage is unique to the Red Sea and is different from benthic assemblages of the modern oceans. The important species in well oxygenated environments of the oceans are the epifaunal species: *Cibicides spp.*, *Cibicidoides spp.*, *Gyroidina spp.*, *Globocassidulina spp.* and thick-walled miliolids (Gooday, 1994; Kaiho, 1994). The high dominance of buliminids (mostly *Bolivina* and *Bulimina* species) is common in the low oxygen zones, for both the Arabian Sea and the Red Sea.

The Arabian Sea on the other hand, is characterized by a benthic foraminiferal assemblage which is controlled by oxygen and TOC levels, similar to the central Red Sea (present study fauna). One of the main differences between the components controlling the assemblages in the two seas is the presence of an active upwelling system, and therefore enlarged biological activity, in the Arabian Sea. The large consumption of organic matter, promotes the creation of an intense oxygen minimum zone with <0.2 ml O_2/l (Hermelin and Shimmield, 1990; Hermelin, 1992).

The major benthic foraminifera which comprise the OMZ assemblage associated with high organic content of the sediments, are mostly *Bolivina* and *Bulmina* species. In the Arabian Sea, below the OMZ the dominant species are *Bulimina aculeata* and *Uvigerina hispida*. The sediments deposited closer to the continent are characterized by the agglutinated *Reophax spp.* (Hermelin and Shimmield, 1990).

The circulation pattern which leads to the prominent and permanent OMZ in the Red Sea (Weikert, 1987) and high fertility of the water in the Arabian Sea (Hermelin, 1992 and ref. within) are not present in the well-oxygenated Gulf of Elat. The arid climate, high evaporation rates and presence of a 252m barrier separating the Gulf of Elat from the Red Sea, cause the absence of a significant thermocline, halocline and pycnocline and lead to a mixed water column (Reiss and Hottinger, 1984). The benthic foraminiferal assemblages characteristic to the Gulf of Elat are therefore different from those of the Red Sea and Arabian Sea (compare Hottinger et al., 1993).

8.5 Paleoceanography of the deep water mass

The downcore record of this study represents the past 5000-6000 years of the Late Holocene, and the paleoceanographic changes during this time interval.

Many authors rely on TOC as an indicator of bottom oxygenation levels (Van der Zwaan and Jorrisen, 1991; Sen Gupta and Machain-Castillo, 1993). The TOC does not change significantly downcore in each of the different cores (Fig. 3), indicating that no major shifts in the oxygenation levels occurred in the past ~6000 years. Changes in TOC levels were detected only in MC88 (366m) which represents the past ~2000 years. The lowest total abundance of the OMZ assemblage was observed 7cm and 15cm downcore together with the lowest TOC levels of 0.55% wt (compare to highest value 0.78% wt) recorded for this water mass (compare Figs. 8a,b and Fig. 3). This probably reflects periods of a less intense OMZ and less consumption of organic matter, or on the other hand, a lower supply of organic matter (decrease in productivity).

The $CaCO_3$ content (Fig. 4) does not change significantly downcore, indicating that like the TOC, no major shifts in the flux of planktic organisms occurred in the past ~6000 years. The same is observed for the size fraction >63µm (Fig. 37) which does not show significant shifts downcore, indicating that no major changes occurred in the biogenic particle flux (mainly foraminifera and pteropods) to the seafloor or calcium carbonate dissolution, during this time period. The slight relative changes in the size fraction >63µm detected in the deepest water mass (MC91 - 1782m) may reflect a lateral displacement contribution. Thus, as stated above, it seems that in general the deep water body did not change significantly during the last 6000 years. Therefore, the current deep water structure remained stable and similar to the recent deep water configuration, this, in contrast to the more significant changes detected in the mixed layer and the upper part of the intermediate water as reflected by the changes seen in the planktic foraminifera and pteropods.

At the margin of the OMZ at 579m (MC98) some changes with time were detected. These changes are mainly expressed by distinct fluctuations in the abundance of benthic foraminifera/g dry sediment. The largest number of specimens/g dry sediment (400-900) were observed at this water depth as well as the largest shifts in their total number (Fig. 8c). These shifts are probably due to the fact that the core is located at the margin of the OMZ. Changes are detected more easily at OMZ margins, even if they are small, whereas MC93 (929m) which is located in the deeper water mass, does not reflect these extreme shifts in numbers. Peaks in number of specimens/g dry sediment are observed 9cm and 17cm downcore, ~2000 yrBP and ~3800 yrBP respectively, and coincide with periods of relatively high TOC levels (~0.33% wt). A decrease in number of benthos occurred 2400 yrBP contemporaneously to times of somewhat lower TOC levels of 0.28% wt (11cm downcore) and 5500 yrBP (25 cm downcore) where it does not coincide with low TOC (~0.35) (compare Figs. 3 and 8c). The periods of relatively high numbers of benthos are thought to coincide with a relatively higher water fertility at these times (see Gooday, 1994).

The four cores were taken at the OMZ or at the deeper and more aerated water masses. The long term (during the last ~6000 years) changes in the benthic fauna were not found to be synchronous with those of the planktic species which in turn reflect changes occurring in the mixed layer and intermediate waters.

By observing the shifts in abundance of the three assemblages a reconstruction of the bottom water mass, represented by the benthic foraminifera, can be made. At times of higher number of specimens and higher diversity of species, the food availability was probably higher. This is reflected by higher TOC and relatively lower O_2 levels.

9 - Summary and Conclusions

1) Three of the four multicores analyzed were correlated by using the dated (~4200 years before present) maximum abundance of *L. bulimoides* observed earlier at other Red Sea locations. This datum was not recognized in the shallowest core. Using this datum, an age of ~6400 yrBP can be estimated for the bottom of the deepest core sequence. Furthermore, an average rate of accumulation of ~5 cm/1000 years in the three correlated cores can be estimated.

2) Using planktic foraminifera and pteropoda, six ecostratigraphic zones were established and recognized in the three correlated deeper cores. The thickness of these zones does not change appreciably from core to core. This indicates that the foraminiferal and pteropod assemblages are not disturbed by either displacement or dissolution.

3) The number of planktic foraminifera >149μm varies from ~400 specimens/g dry sediment in the shallowest core to ~4000/g in the deepest one, reflecting on one hand the thickness of the water column and the composition of the assemblage, richer in deeper dwelling species in the deeper core. This is generally correlative with the bulk calcium carbonate content of the sediment.

4) The most prominent downcore changes in the planktic foraminiferal assemblage, pertain to the relative abundance of the epipelagic *G. ruber* to that of the epi-shallow mesopelagic *G. sacculifer*. These changes are probably due to periodic fluctuations in stratification and position of the OMZ or of the pycnocline vs. the photic zone, influencing conditions required for optimal reproduction of *G. sacculifer*. The periodicity of these changes is approximately 3000 years.

5) There is a clear correlation from ~5300 to ~2400 yrBP between the *G. ruber* vs. *G. sacculifer* cycle and the frequency and presence/absence of *L. bulimoides*. This correlation strongly supports the interpretation of a slightly stronger stratification of the water column in the past 3000 years (as compared to the period between ~5300-3000 yrBP), especially between ~3000-2700 yrBP.

6) The paleoceanographic changes mentioned above and represented by proxy indicators reflect climatic fluctuations in particular in the northern Red Sea area. Thus, drier and harsher winter regime in the north produced denser waters sinking to intermediate depth between ~5300-3000 yrBP.

7) As far as benthic foraminifera are concerned, three lateral assemblages were distinguished: the OMZ assemblage, the transitional (OMZ margin) assemblage and the deeper more aerated water assemblage. The organic matter input and its preservation, together with the dissolved O_2 levels in the bottom water and sediment pore-water, both play a major role in determining the specific assemblage composition. The infaunal species of *Bolivina*, *Bulimina* and *Globocassidulina* are the dominant ones of the OMZ assemblage. The transitional (OMZ margin) assemblage is comprised mainly of the epifaunal to shallow infaunal *Neouvigerina spp.* and *Cibicides spp.* and the deep more aerated assemblage is comprised mainly of the epifaunal to shallow infaunal species of *Miliolidae*, *Hanzawaia*, *Astrononion* and *Glomospira*.

The benthic foraminiferal assemblage composition, TOC content and the $CaCO_3$ content do not change significantly downcore in each of the cores, indicating that in general, the deep water body did not change much during the past 6000 years. This in contrast to the changes detected in the planktic assemblages, representing the mixed layer and intermediate waters.

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Appendix

List of benthic foraminifera describing the distribution data:

MC88

Bulimina marginata (B.marginat)

Bolivinellina cf. pescicula (B.pescicul)

Brizalina subspathulata (B.subspat)

Heterolepa cf. subhaidingerii (Heterolep)

Tretomphalus spp. (Tretom. sp)

Cancris auriculus (C.auriculu)

Spirophthalmidium sp. (Spiroph.s)

Miliolidae div. (Miliolid.div)

Rosalina? suezensis + *Rosalina spp.* (R.suezensi)

Gyroidinoides cf. soldanii (G.cf.solda)

Bolivina persiensis (B.persiens)

Fursenkoina sp. A (Furse.sp A)

Spirillina spp. (Spirilli.spp)

Neouvigerina ampullacea (N.ampulla)

Neouvigerina porrecta (N.porrecta)

Discorbinella rhodiensis (D.rhodiens)

Cibicides tabaensis (C.tabaensi)

Nonion sp. + *Astrononion sp. A* (Nonion sp)

Globocassidulina sp. (Globoca.s)

Sahulia kerimbaensis (S.kerimba)

Plotnikovina cf. aequa (P.cf.aequa)

Reophax spp. (Reopha.sp)

Heterolepa? sp. A (Heter.sp A)

Pseudoeponides falsobeccarii (P.falsobec)

Paracassidulina neocarinata (P.neocarin)

Siphonaperta horrida (S.horrida)

Porosononion sp. B (Poros.sp)

Lagenammina sp. (Lagena.sp)

Reussella sp. (Reussella)

Neouvigerina interrupta (N.interrupta)

Cibicides spp. (Cibicid.sp)

Lamarckina ventricosa (L.ventricos)

Textularia cushmani (Textula.sp)

Robertinoides bradyi (R.bradyi)

Amphistegina radiata (A.radiata)

Svratkina acuta (Svra.acuta)

Hanzawaia sp. A (Hanz.sp A)

Eponides pusillus + *Vonkleinsmidoides* (Discorbino)

Ehrenbergina compressa (E.compres)

Ammobaculites? sp. (Ammo.?sp)

Hyalinea balthica (H.balthica)

Pyrgo spp. (P.phlegeri)

Lenticulina spp. (Lenticulina)

Milliolidae div. (S.milliolid)

Neocorbina marginata (Neocorbin)

Bulimina striata (Bul.striata)

Articulina pacifica (Ar.pacifica)

Vertebralina striata (Vert.striata)

Valvobifarina mackinnonii (Valvobif.s)

Discorbinella bertheloti (D.berthelo)

Bolivina variabilis (B.variabilis)

Brizalina striatula (B.striatula)

Spirotextularia floridana (Spir.florid)

Nodophthalmidium antillarum (N.antillaru)

Alliatinella panayensis (A.panayen)

Caribeanella elatensis (C.elatensi)

Floresina sp. A (Flores.spA)

Abditodentrix rhomboidalis (Arhomboi)

Discorbinella? sp. (Disscorbi?)

Cassidelina spinescens (C.spinesc)

Elphidium sp. (Elophidiu.s)

Rotorbinella cf. lepida (R.cf.lepida)

Globocassidelina oriangulata (G.oriangu)

Patellinella sp. (Patellinell)

Loxostomina limbata costulata (Loxostom)

Fissurina sp. (Fissurina)
Neouvigerina porrecta subsp. A (Neouvi.sp)
Rotorbinella ? sp. (Rotorb?s)

MC98

Bulimina marginata (B.marginat)
Bolivinellina cf. pescicula (B.pescicul)
Brizalina subspathulata (B.subspath)
Eponides pusillus + Vonkleinsmidoides (Discorbino)
Heterolepa cf. subhaidingerii (Heterolepa)
Tretomphalus spp. (Tretom. sp)
Cancris auriculus (C.auriculus)
Spirophthalmidium sp. (Spiroph.sp)
Miliolidae div. (Miliolid.div)
Rosalina? suezensis (R.suezensi)
Gyroidinoides cf. soldanii (G.cf.solda)
Bolivina persiensis (B.persiensu)
Brizalina striatula (B.striatula)
Spirillina spp. (Spirilli.spp)
Neouvigerina ampullacea (N.ampulla)
Neouvigerina porrecta (N.porrecta)
Discorbinella rhodiensis (D.rhodiens)
Cibicides tabaensis (C.tabaensi)
Neouvigerina interrupta (N.interrupt)
Globocassidulina sp. (Globoca.s)
Loxostomina spp. (Loxostomi)
Lamarckina ventricosa (Lamarckin)
Pyrgo spp. (Pyrgo spp)
Siphonaperta horrida (S.horrida)
Textularia cushmani (S.cushman)
Plotnikovina cf. aequa (P.cf.aequa)
Cibicides mabahethi (C.mabahet)
Sahulia kerimbaensis (S.kerimba)
Cassidelina spinescens (C.spinesce)
Pseudoeponides falsobeccarii (P.falsobec)
Cibicides spp. (Cibicid.spp)

Nonion sp. + Astrononion sp. A (Nonion sp)

Porosononion sp. B (Poros.sp B)

Heterolepa? sp. A (Heter.spA)

Hanzawaia sp. A (Hanzawaia)

Svratkina acuta (Svra.acuta)

Siphonina tubulosa (Siphonina)

Cibicides sp. A (Cibicid.s.A)

Alliatinella panayensis (A.panayen)

Glandulina group of G. laevigata (group laevi)

Lagena spp. (Lagena sp)

Glomospira charoides (Glomospir)

"Psammosphaera" spp. ("Psammo")

Paracassidulina neocarinata (Para.neo)

Rotorbinella cf. lepida (R.cf.lepida)

Caribeanella elatensis (Carib.elate)

Cassidelina? makiyama (C.makiyam)

Lenticulina spp. (Lenticulina)

Challengerella bradyi (Ch.bradyi)

Assilina ammonoides (Assilina.a)

Pyramidulina catesbyi (pyramiduli)

Reussella sp. (Reussella)

Loxostomina limbata costulata (Limbata.co)

Vertebralina striata (Vert.striata)

Astacolus sp. A (Astaculus)

Anomalinulla glabra (Anom.glab)

Siphotextularia heterostoma (Sipho.hete)

Angulogerina angulosa (Trifarina)

Neoeponides bradyi (Neo.bradyi)

Haplophragmoides bradyi (Haplophr)

Asterorotalia sp. (Asterorot)

Epistominella sp. (Epistomin)

Neorotalia sp. (Neorotalia)

MC93

Bulimina marginata (B.margina)

Bolivinellina cf. pescicula (B.pescicu)

Brizalina subspathulata (B.subspat)

Heterolepa cf. subhaidingerii (Heterolop)

Cancris auriculus (C.auriculu)

Tretomphalus spp. (Tretomph)

Spirophthalmidium sp. (Spiroph.s)

Miliolidae div. (Miliolid.di)

Rosalina? suezensis (R.suezen)

Gyroidinoides cf. soldanii (G.cf.solda)

Bolivina persiensis (B.persien)

Spirillina spp. (Spirilli.sp)

Neouvigerina ampullacea (N.ampulla)

Neouvigerina porrecta (N.porrect)

Discorbinella rhodiensis (D.rhodien)

Cibicides tabaensis (C.tabaens)

Nonion sp. + *Astrononion sp. A* (Nonion sp)

Globocassidulina sp. (Globoca.s)

Sahulia kerimbaensis (S.kerimba)

Plotnikovina cf. aequa (P.cf.aequ)

Eponides pusillus + *Vonkleinsmidoides* (Discorbin)

Heterolepa? sp. A (Heter.sp)

Pseudoeponides falsobeccarii (P.falsobe)

Hanzawaia sp. A (Hanz.sp.A)

Siphonaperta horrida (S.horrida)

Porosononion sp. B (Poros.sp)

Neouvigerina interrupta (N.interrup)

Cibicides spp. (Cibicid.sp)

Cibicides sp. A (Cibic.s.A)

Alliatinella panayensis (A.panaye)

Lagena spp. (Lagena s)

Glandulina group of G. laevigata (g-laevigat)

Lenticulina spp. (Lenticulin)

Pyramidulina catesbyi (pyramidul)

Neoeponides bradyi (Neoeponi)
Textularia sp. (Textularid)
Evolvocassidulina sp. (Evalvocas)
Caribeanella elatensis (C.elatensi)
Rotorbinella cf. lepida (R.cf.lepid)
Pyrgo spp. (Pyrgo spp)
Lamarckina ventricosa (L.ventrico)
Textularia cushmani (T.cushm)
Assilina ammonoides (Assilina.a)
Cibicides mabahethi (C.mabah)
Brizalina striatula (B.striatula)
Loxostomina limbata costulata (Loxostom)
Cassidelina spinescens (C.spinesc)
Glomospira charoides (Glomospi)
Angulogerina angulosa (Trifarina)
Svratkina acuta (Svra.acut)
Siphonina tubulosa (S.tubulos)
"Psammosphaera" spp. (Pseammo)
Bolivina sp. (Bolivina s)
Bulimina elongata (Bul.elong)
Haplophragmoides bradyi (Haplophrag)
Discorbinella? sp. (Disscorbin)
Abditodentrix rhomboidalis (A.rhombo)

MC91
Bulimina marginata (B.margina)
Brizalina subspathulata (B.subspat)
Tretomphalus spp. (Tretomph)
Spirophthalmidium sp. (Spiroph.s)
Miliolidae div. (Miliolid.di)
Rosalina? suezensis (R.suezen)
Gyroidinoides cf. soldanii (G.cf.solda)
Bolivina persiensis (B.persien)
Spirillina spp. (Spirilli.sp)
Neouvigerina ampullacea (N.ampulla)
Neouvigerina porrecta (N.porrect)

Neouvigerina interrupta (N.interrup)

Nonion sp. + Astrononion sp. A (Nonion sp)

Globocassidulina sp. (Globoca.s)

Plotnikovina cf. aequa (P.cf.aequ)

Vonkleinsmidoides (Vonkleins)

Eponides pusillus (E.pusillus)

Pseudoeponides falsobeccarii (P.falsobe)

Hanzawaia sp. A (Hanz.sp.A)

Siphonaperta horrida (S.horrida)

Porosononion sp. B (Poros.sp)

Cibicides spp. (Cibicid.sp)

Textularia cushmani (T.cushm)

Cibicides mabahethi (C.mabah)

Cibicides sp. A (Cibic.s.A)

Alliatinella panayensis (A.panaye)

Lagena spp. (Lagena s)

Glandulina group of G. laevigata (g-leavigat)

Lenticulina spp. (Lenticulin)

Loxostomina limbata costulata (Loxostom)

Cassidelina spinescens (C.spinesc)

Glomospira charoides (Glomospi)

Angulogerina angulosa (Trifarina)

"Psammosphaera" spp. (Pseammo)

Bolivina sp. (Bolivina s)

Bulimina elongata (Bul.elong)

Haplophragmoides bradyi (Haplophrag)

Abditodentrix rhomboidalis (A.rhombo)

Trochammina sp. (Trocham)

Ammodiscus flavians (Ammodis)

Reussella sp. (Reussella)

Pattelina corrugata (Patellinell)

Paracassidulina neocarinata (P.neocari)

Ehrenbergina compressa (E.compre)

Pseudononion grateloupi (Pseudono)

Reophax spp. (Reophax)

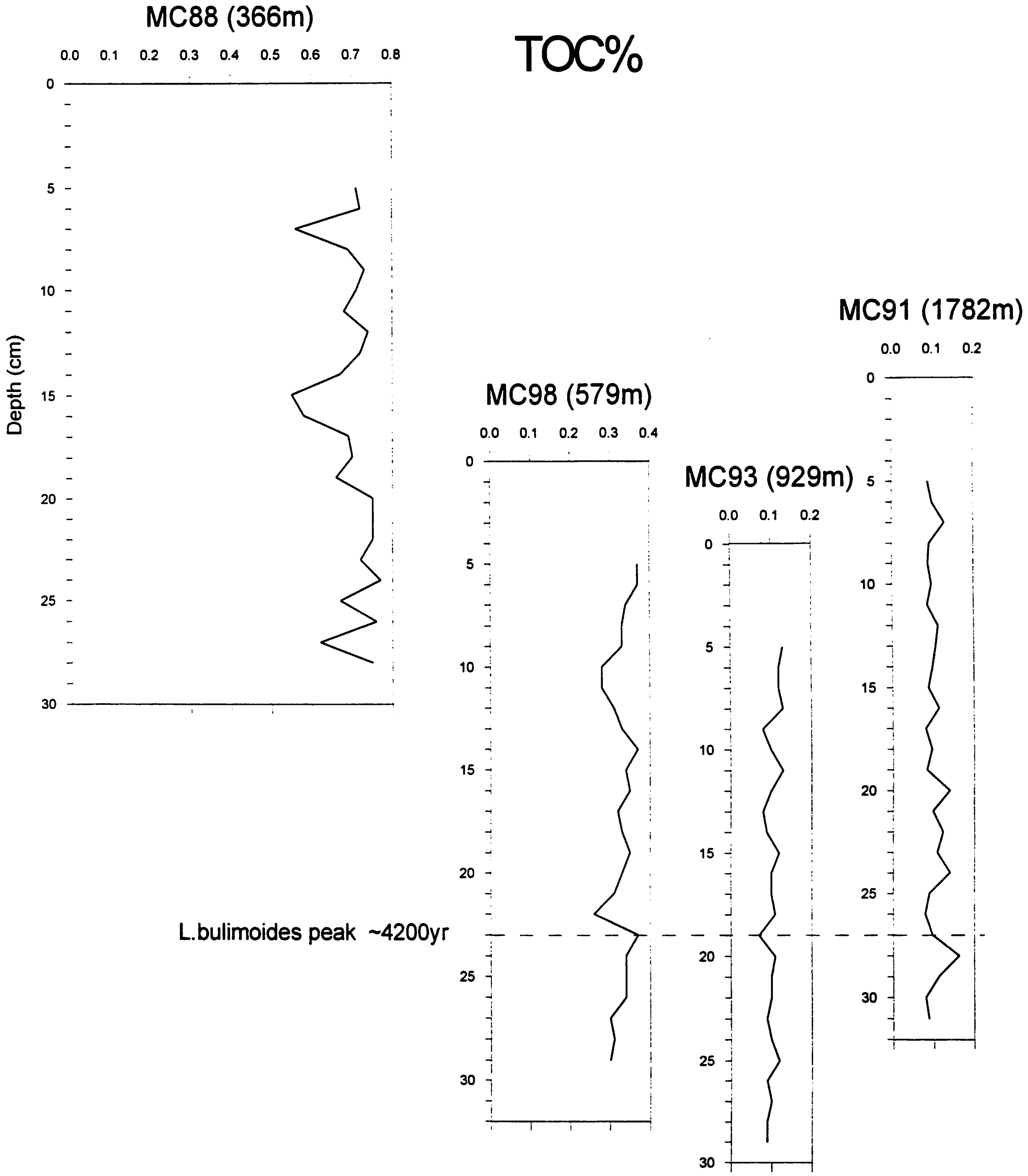


Fig. 3. Total organic carbon content (%wt.), datum line = L.bulimoides peak, as explained later on in the text.

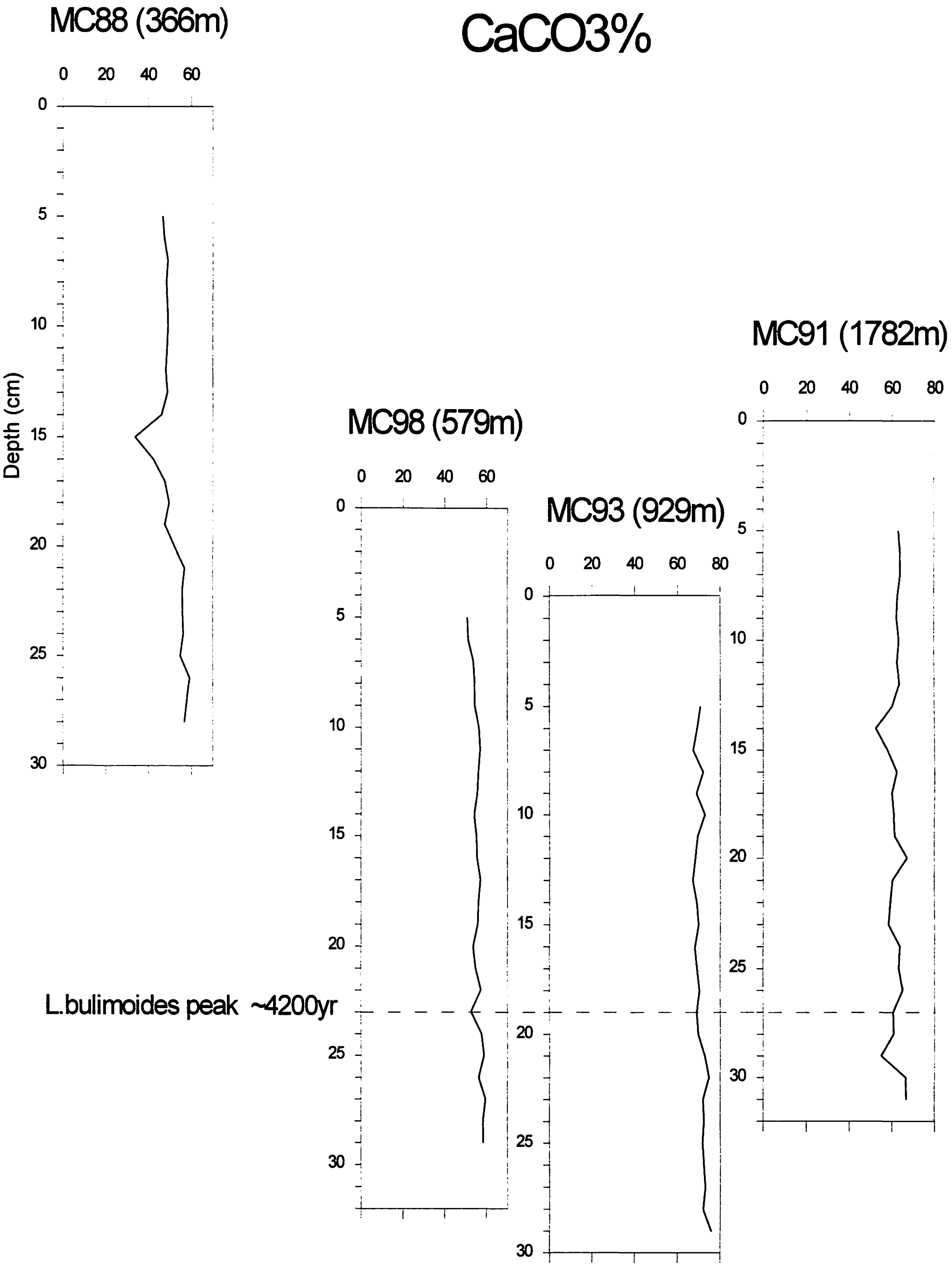


Fig. 4. Carbonate content (%wt.), datum line = L.bulimoides peak, as explained later on in the text.

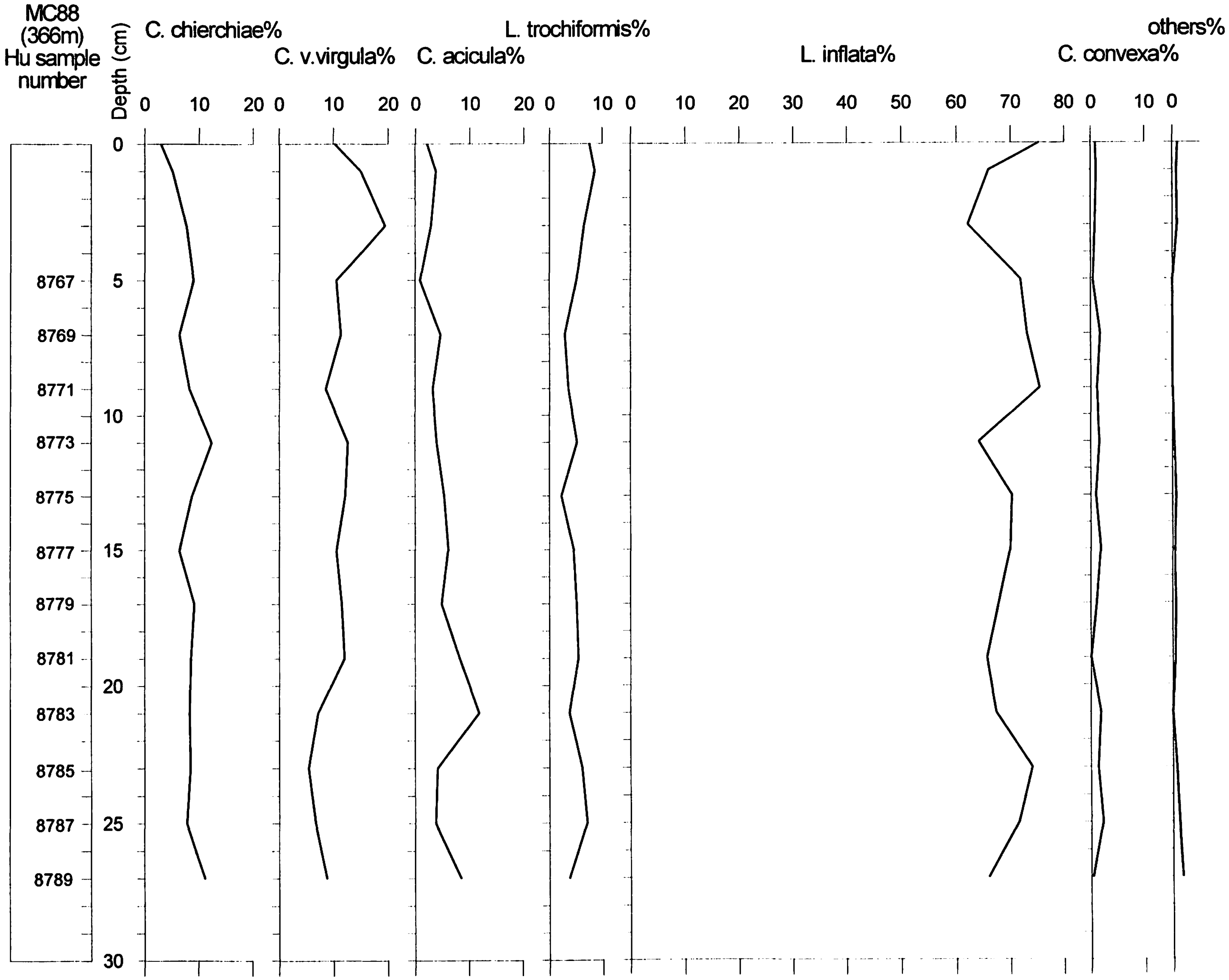


Fig. 5a. Relative abundance of pteropods in MC88 (366 m depth)

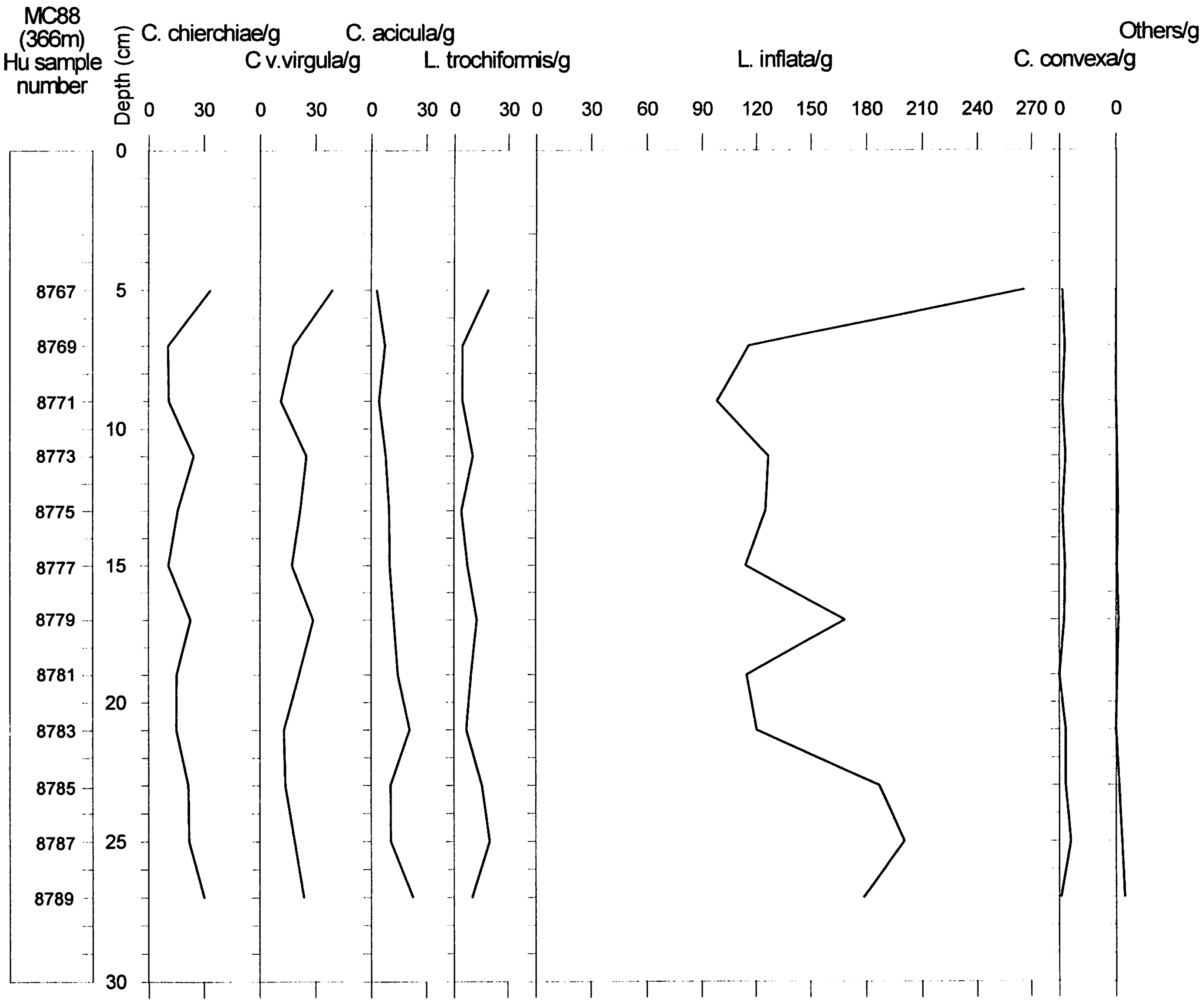


Fig. 5b. Total abundance of pteropods (specimens/g dry sediment) in MC88 (366 m depth)

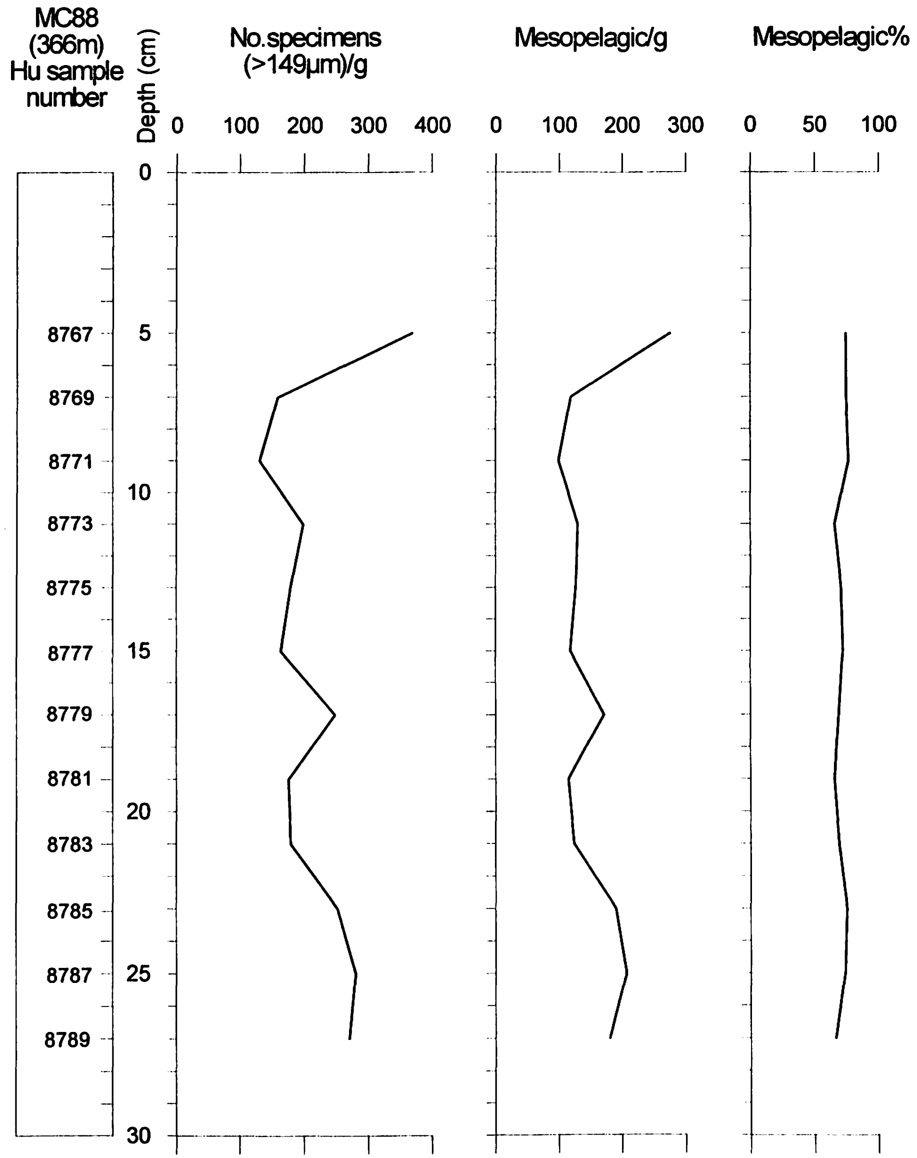


Fig. 5c. Total abundance of pteropods and the mesopelagic taxa in MC88 (366 m depth)

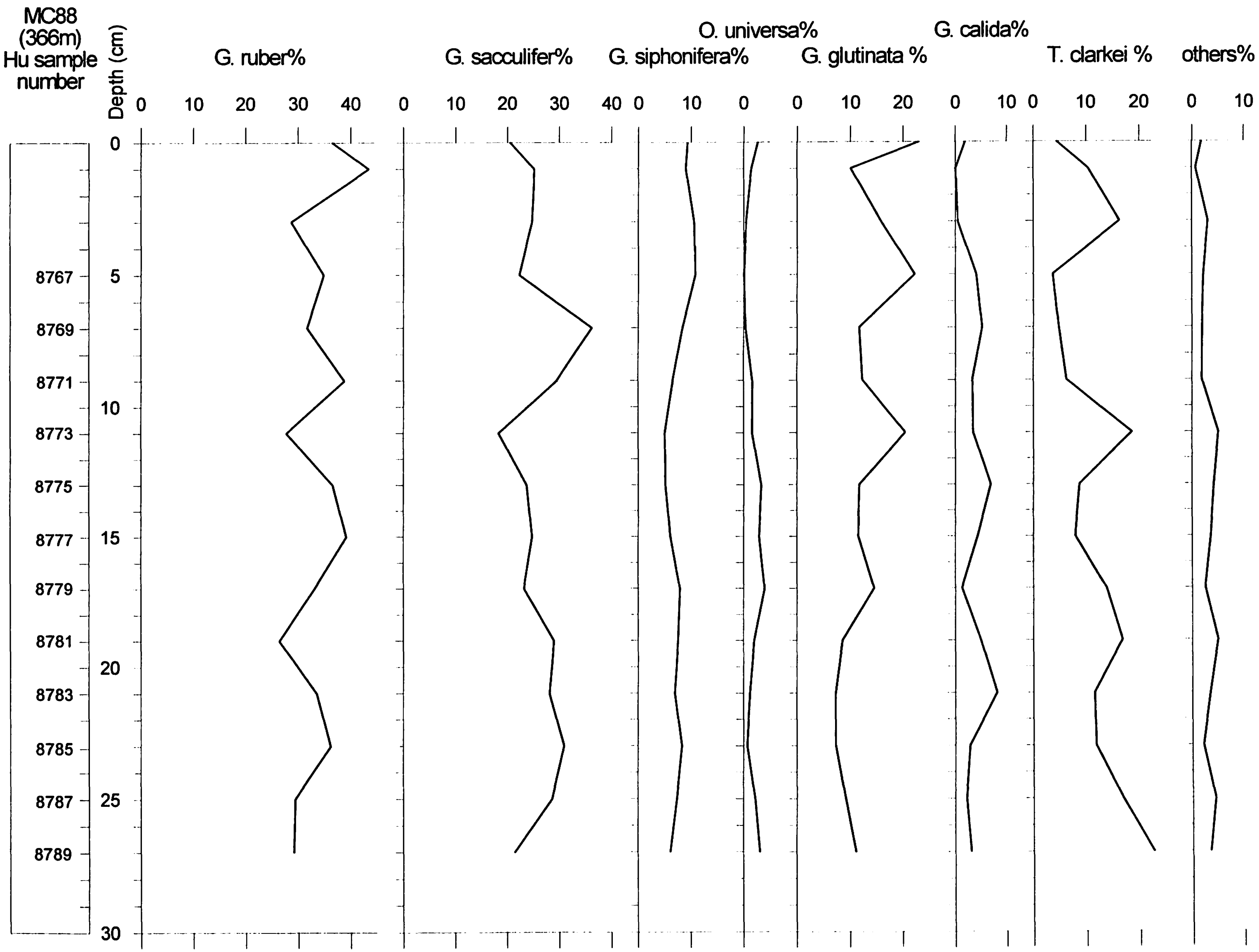


Fig. 6a. Relative abundance of planktic foraminifera in MC88 (366 m depth)

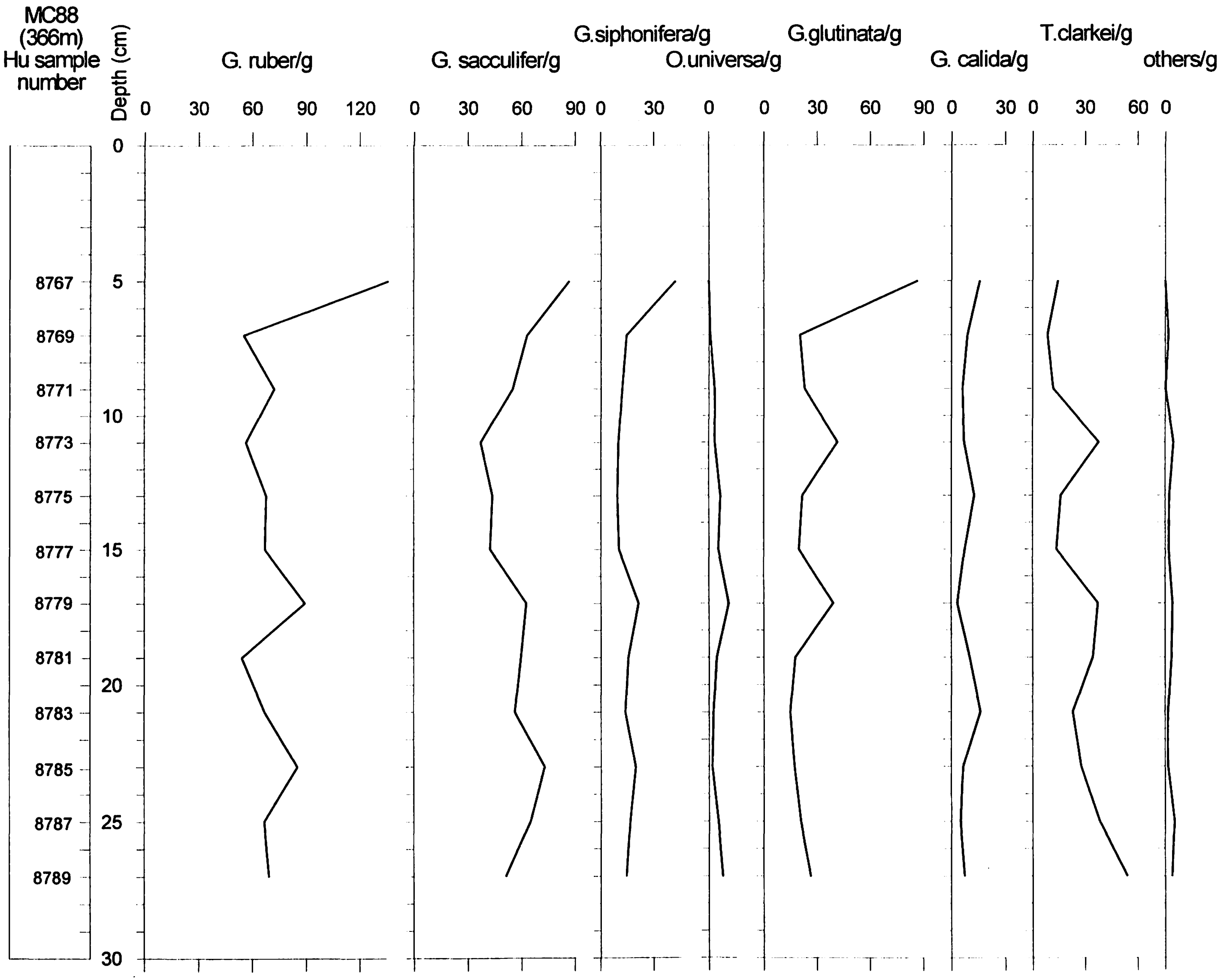


Fig. 6b. Total abundance of planktic foraminifera (specimens/g dry sediment) in MC88 (366 m depth)

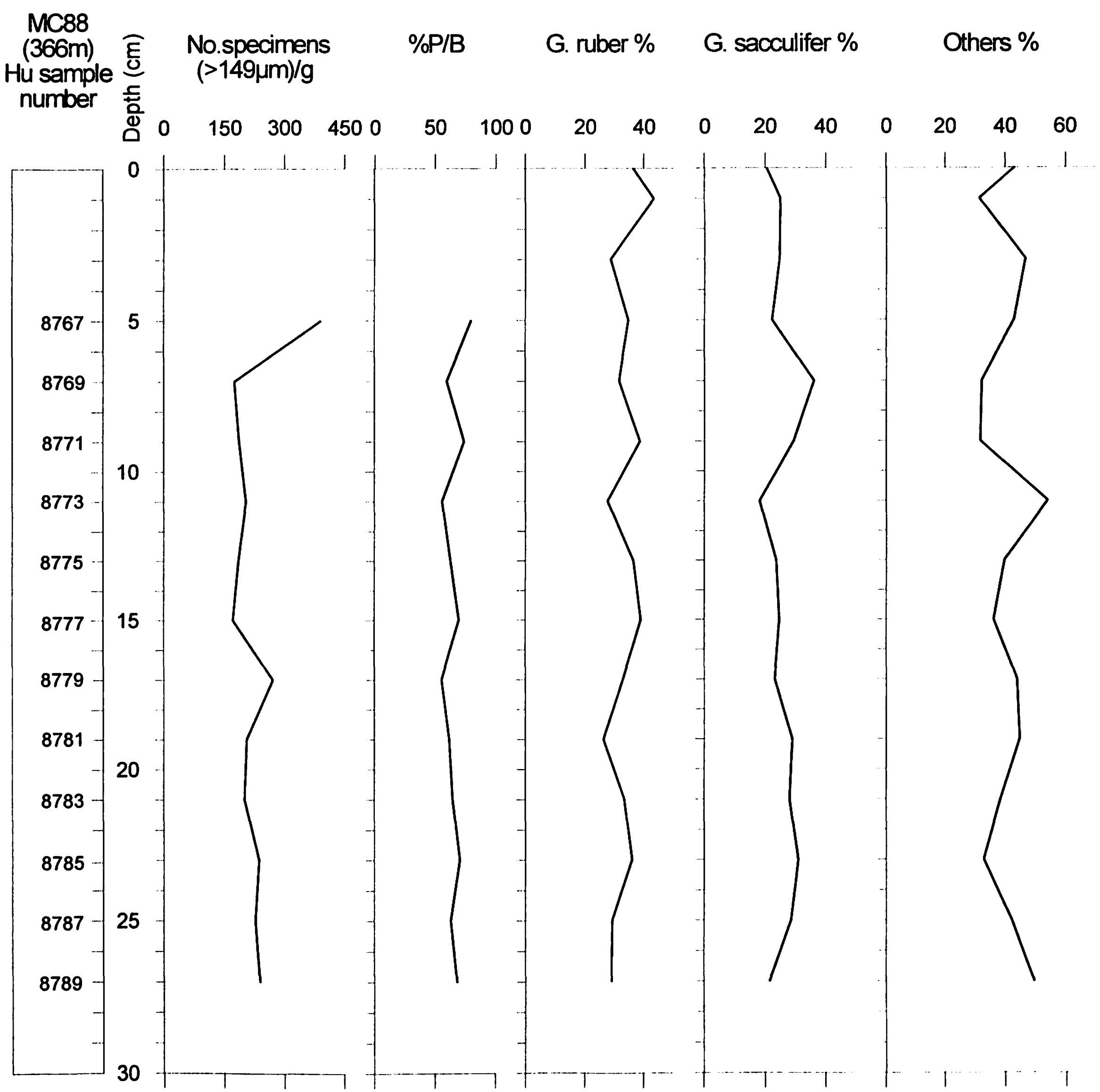


Fig. 6c. Total and relative abundance of the main planktic foraminifera taxa and the P/B ratio in MC88 (366 m depth)

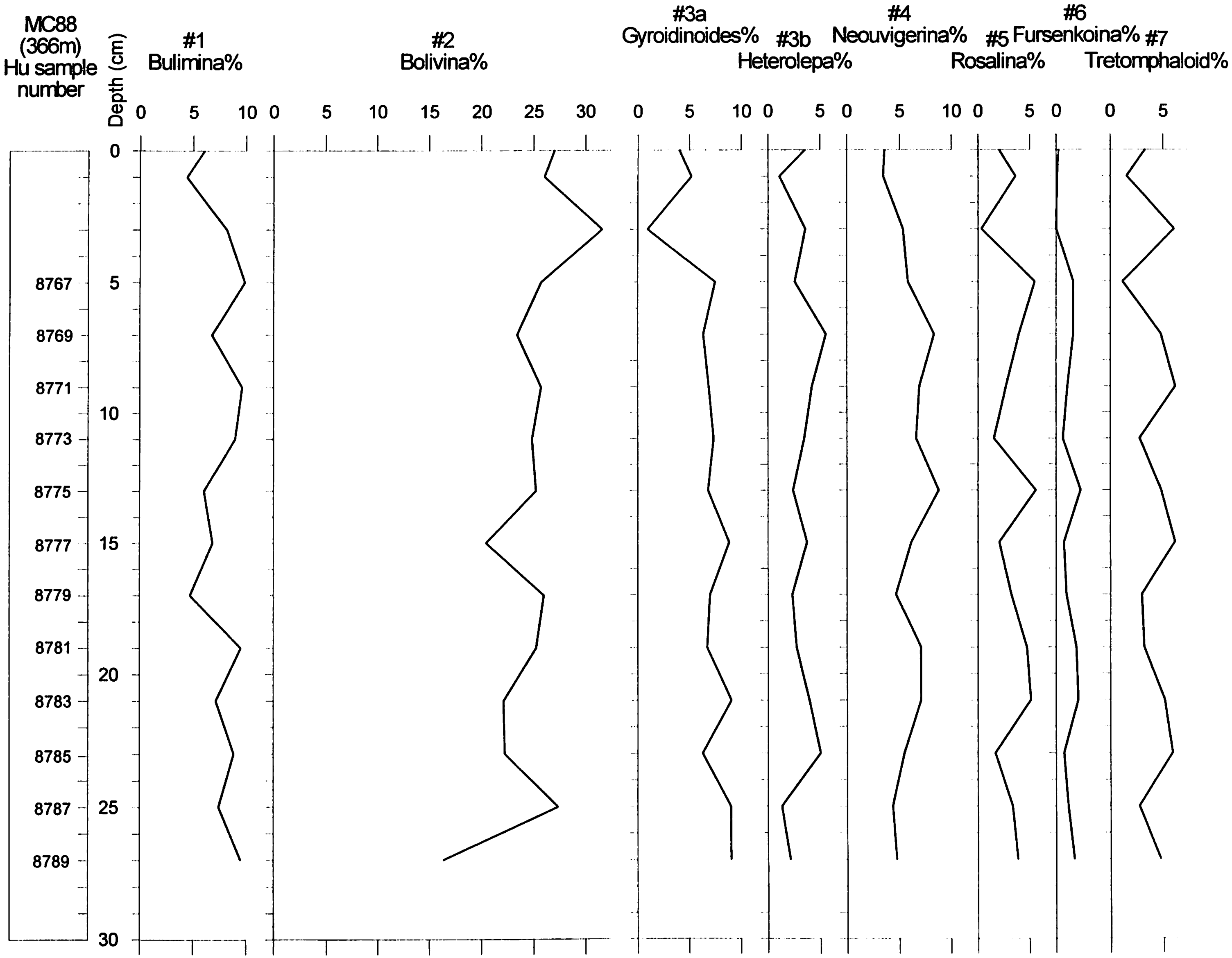


Fig. 7a. Relative abundance of benthic foraminifera in MC88 (366 m depth)

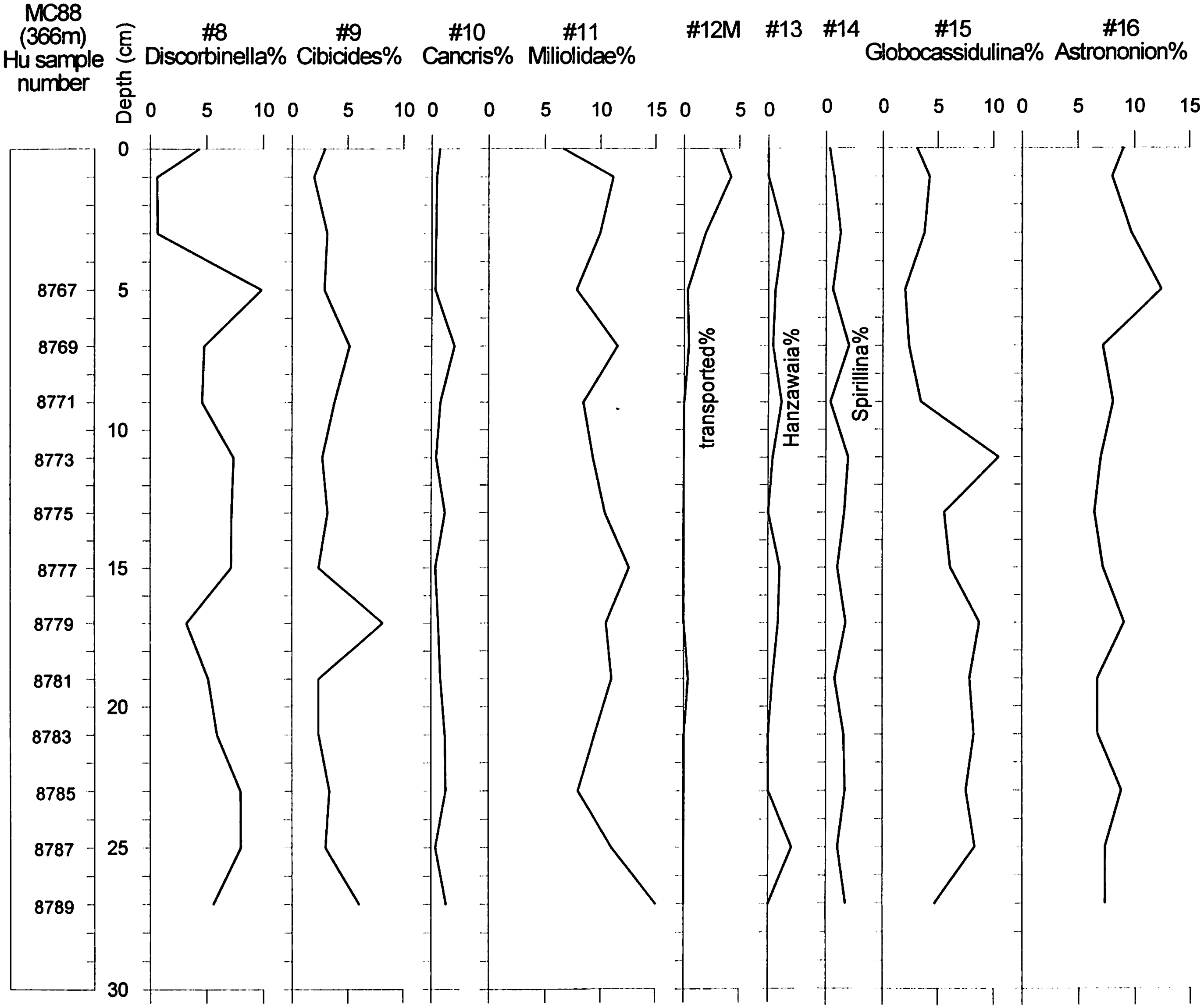


Fig. 7b. Relative abundance of benthic foraminifera in MC88 (366 m depth)

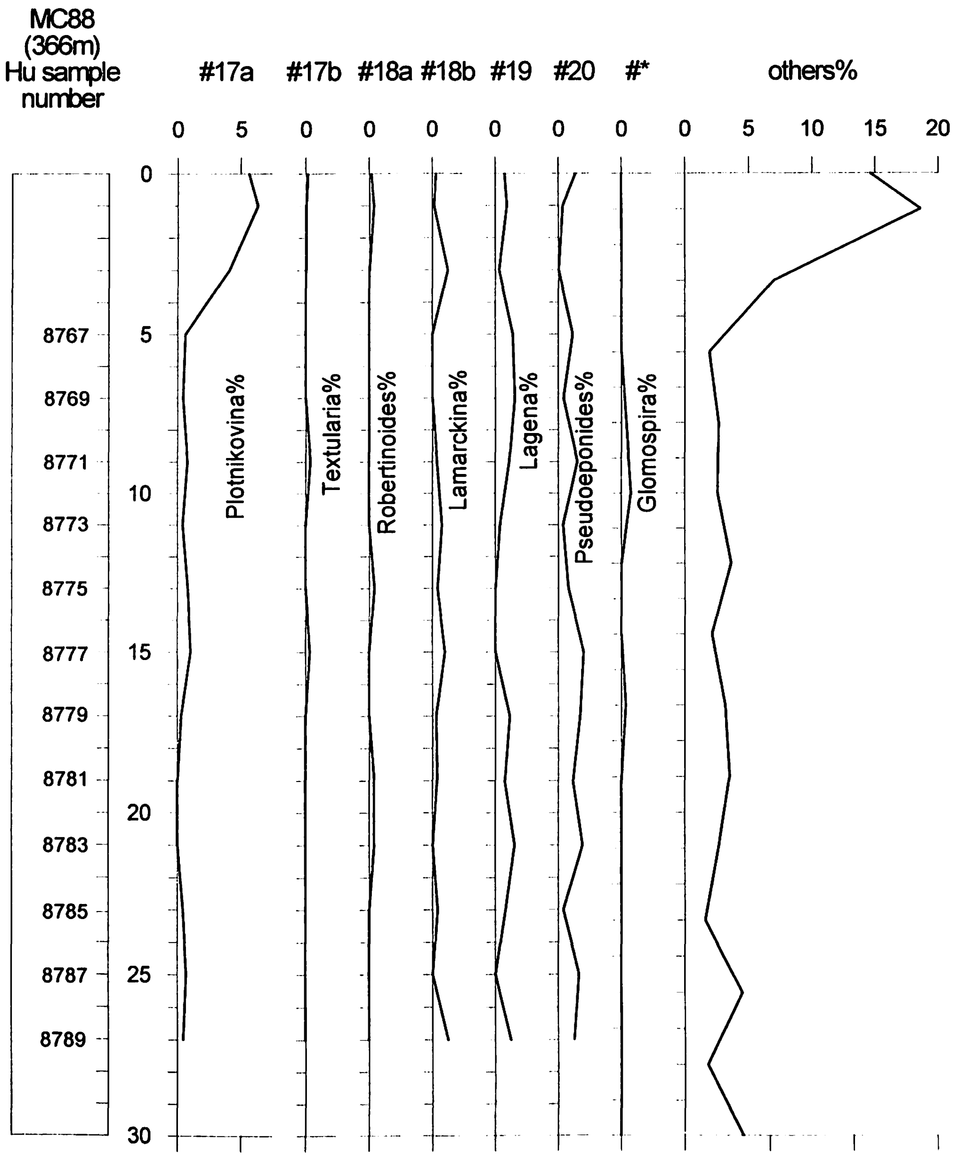


Fig. 7c. Relative abundance of benthic foraminifera in MC88 (366 m depth)

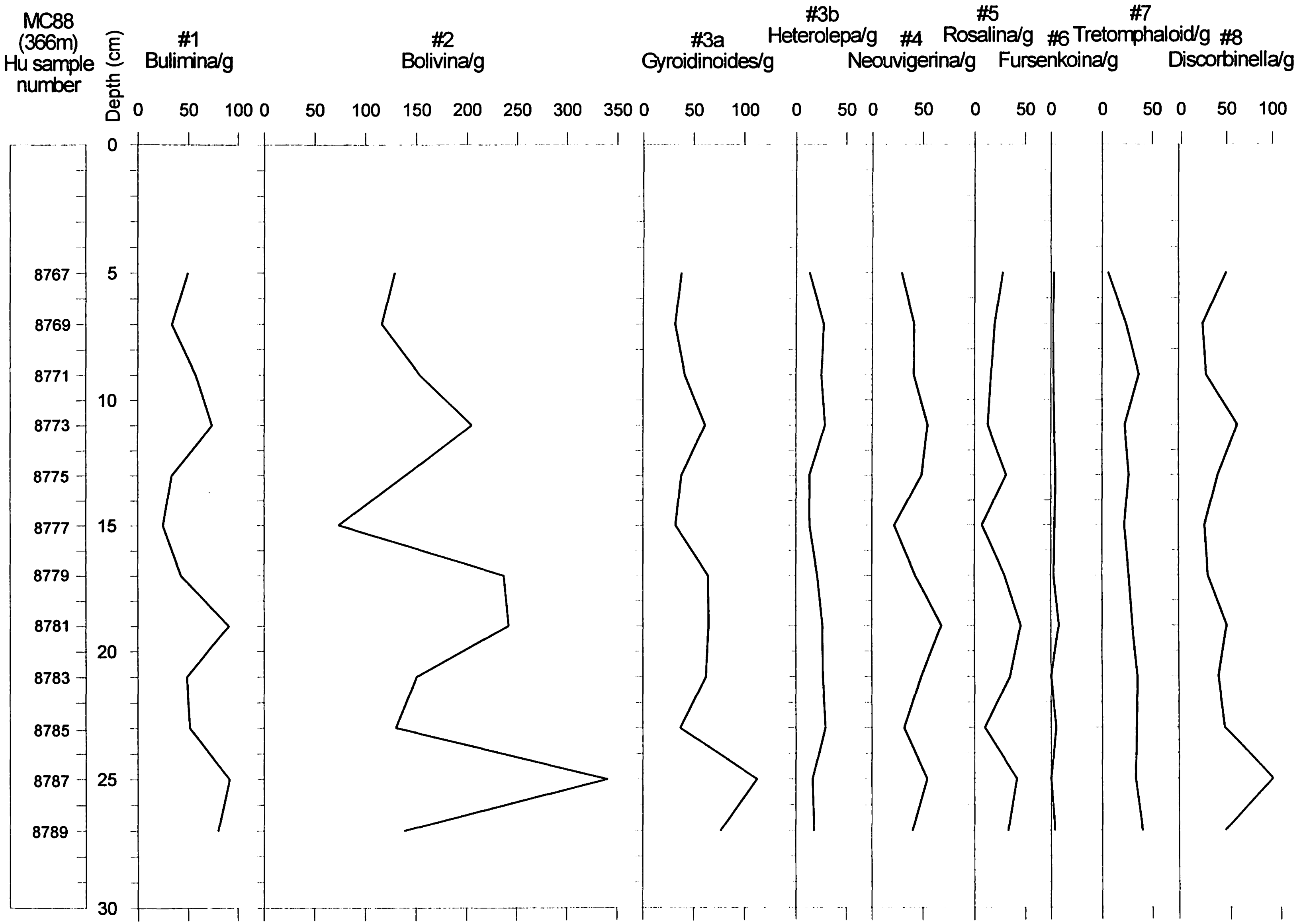


Fig. 8a. Total abundance of benthic foraminifera (specimens/g dry sediment) in MC88 (366 m depth)

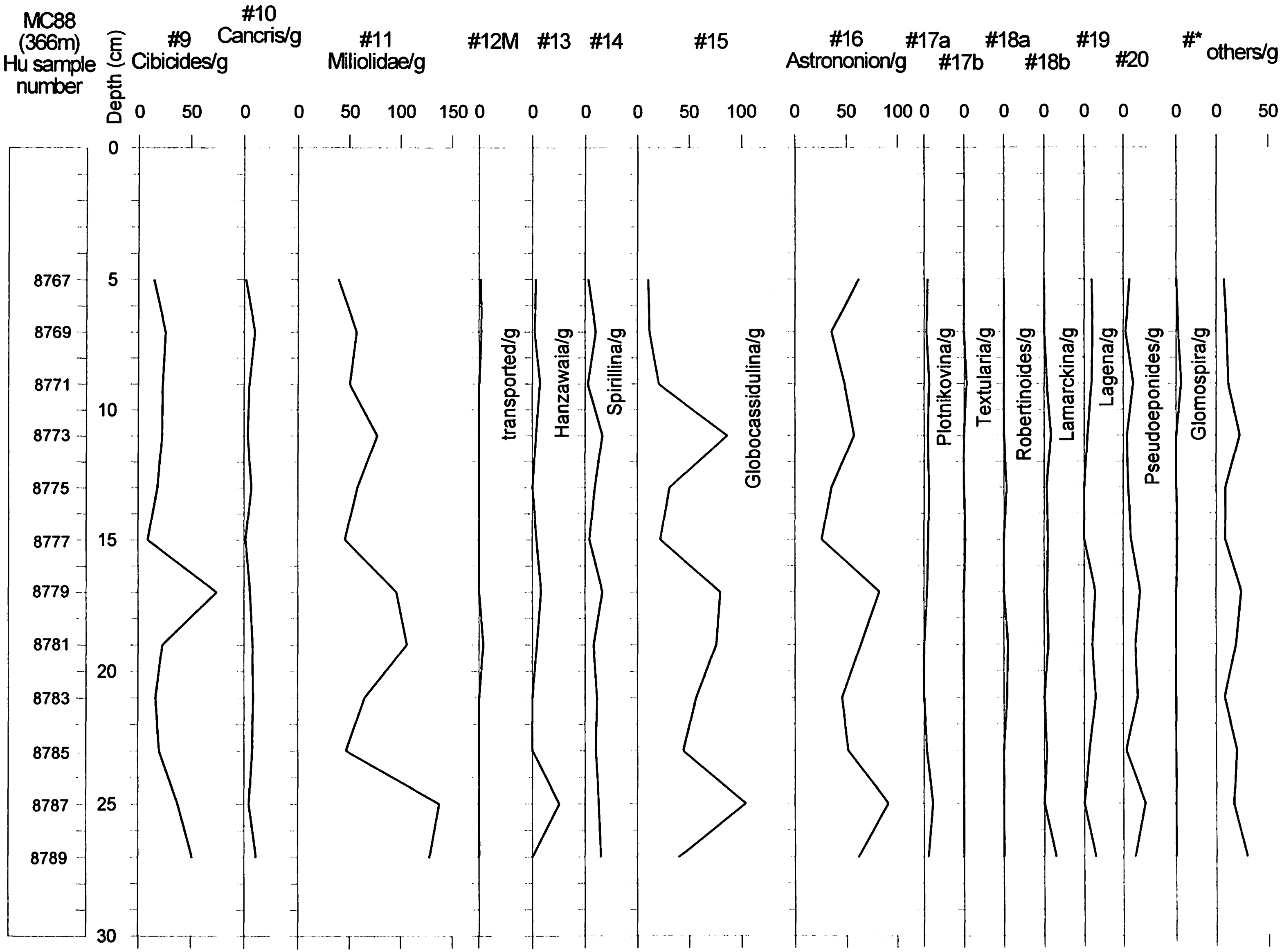


Fig. 8b. Total abundance of benthic foraminifera (specimens/g dry sediment) in MC88 (366 m depth)

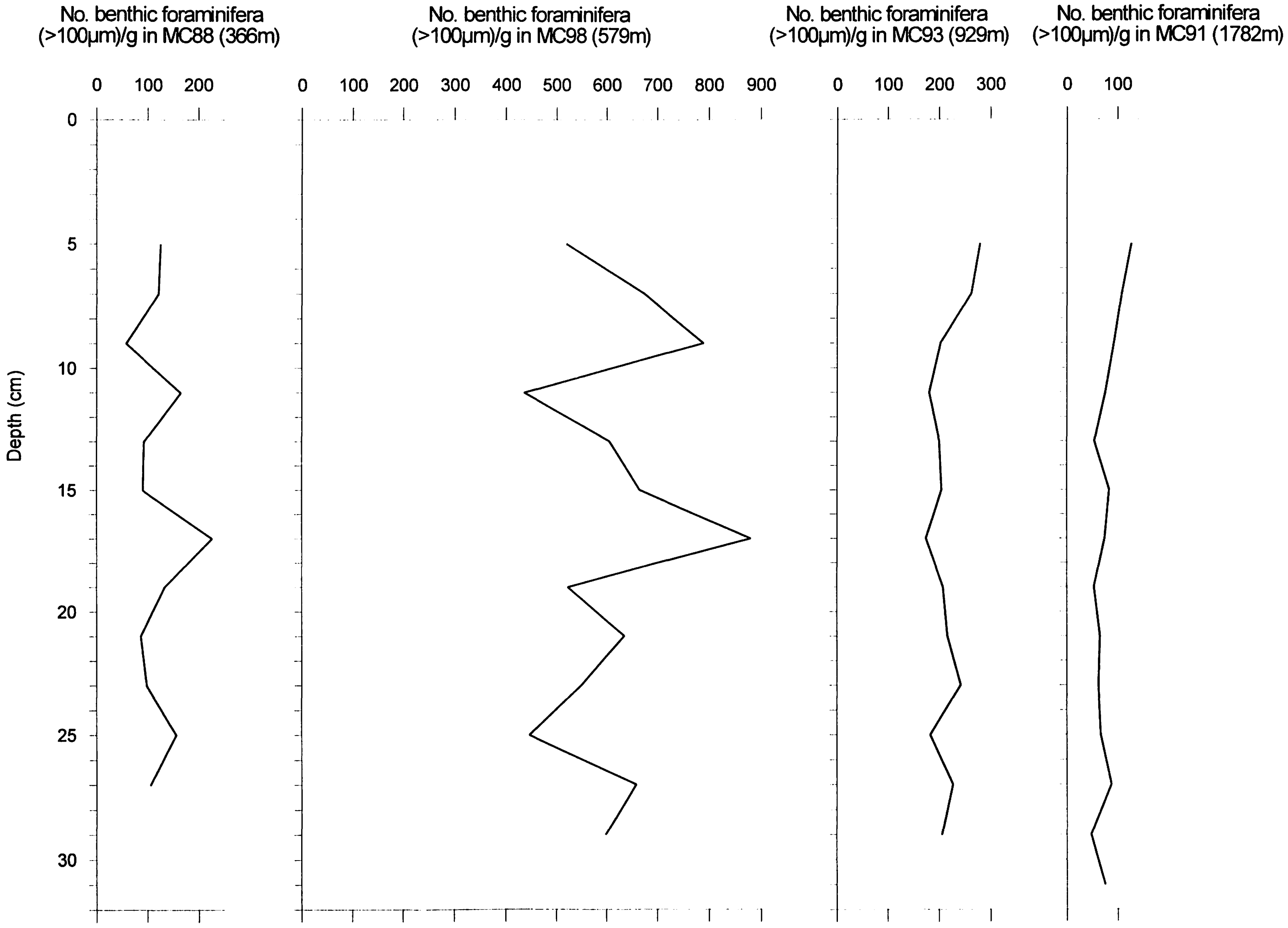


Fig. 8c. Total abundance of the benthic foraminifera in MC88, MC98, MC93 and MC91

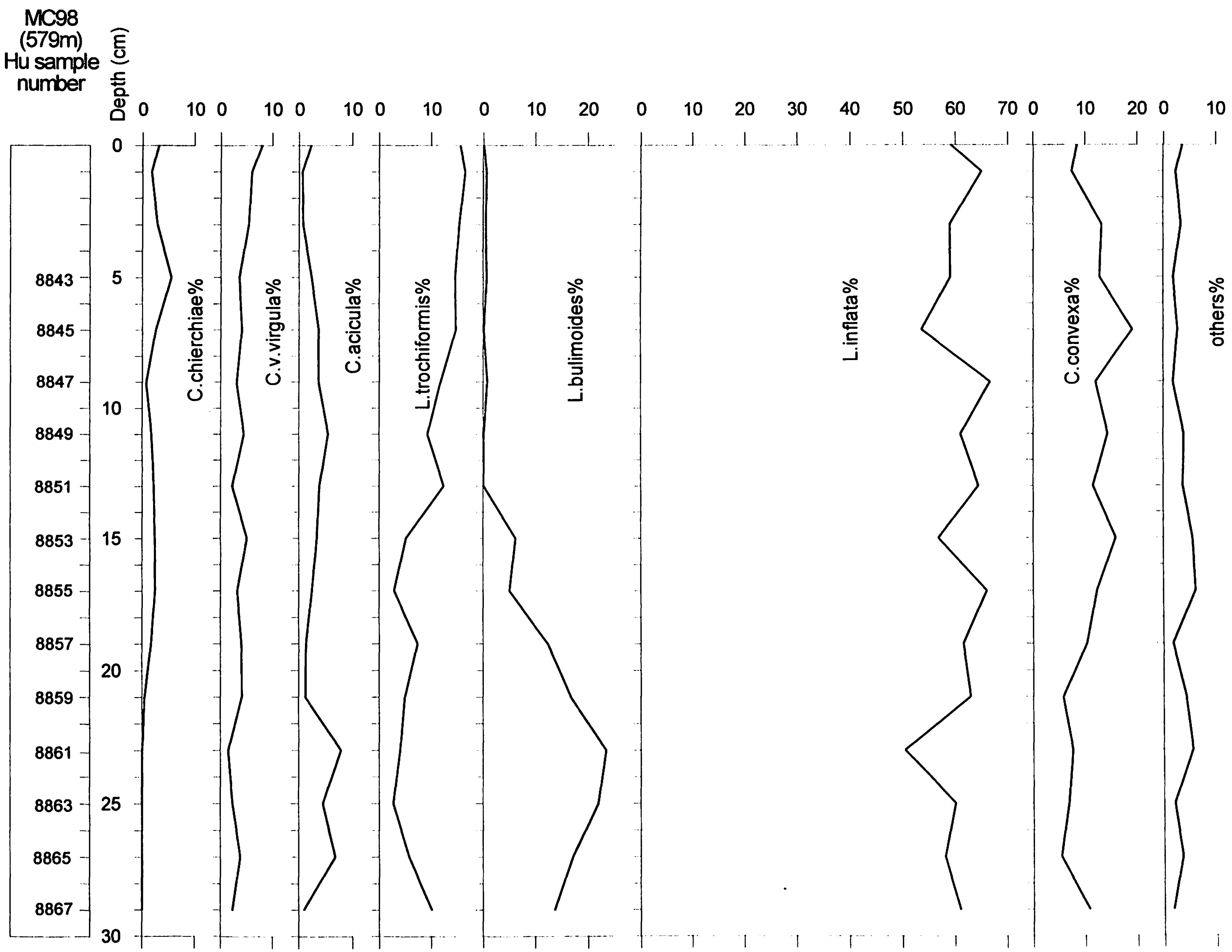


Fig. 9a. Relative abundance of pteropods in MC98 (579 m depth)

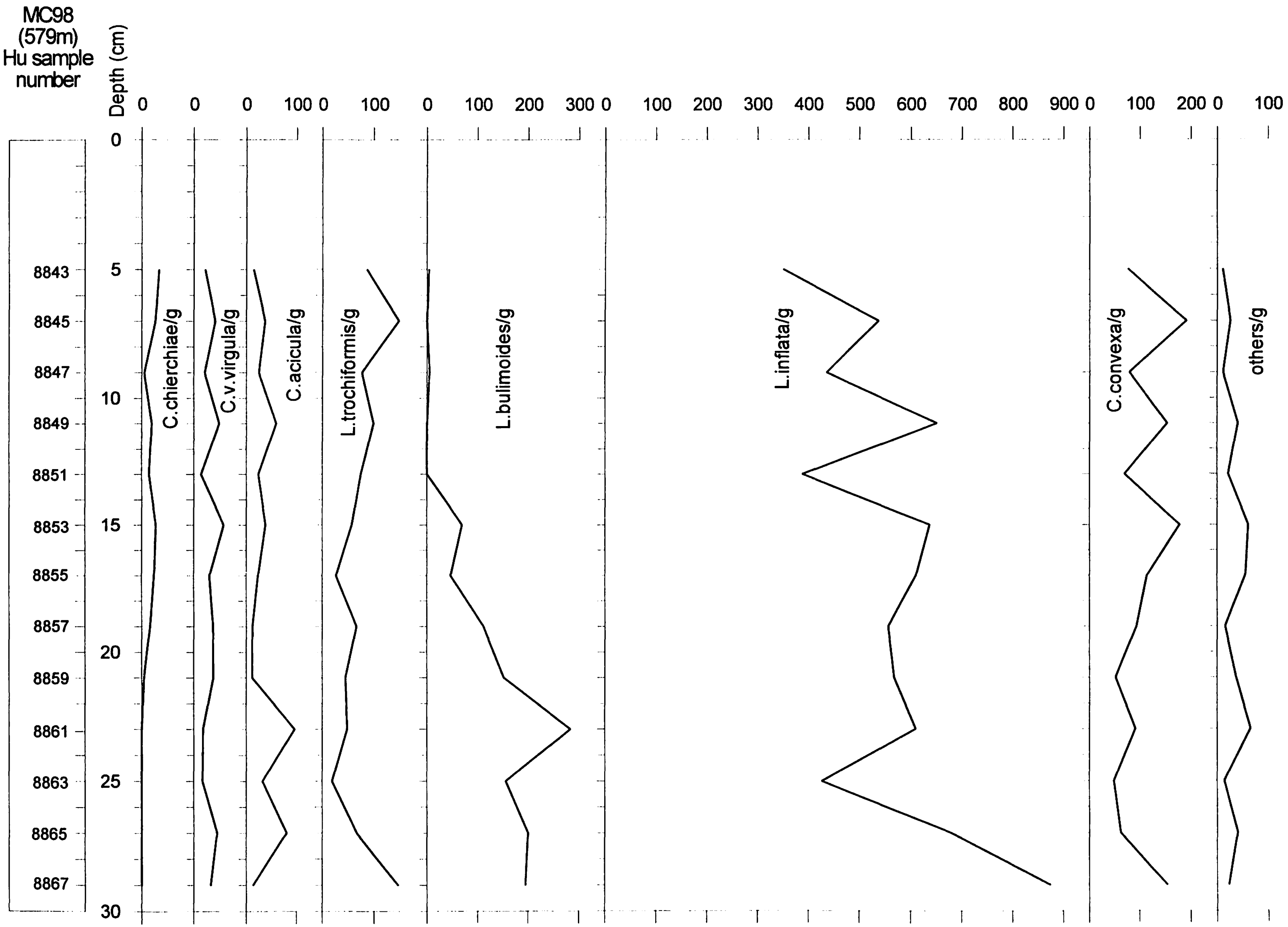


Fig. 9b. Total abundance of pteropods (specimens/g dry sediment) in MC98 (579 m depth)

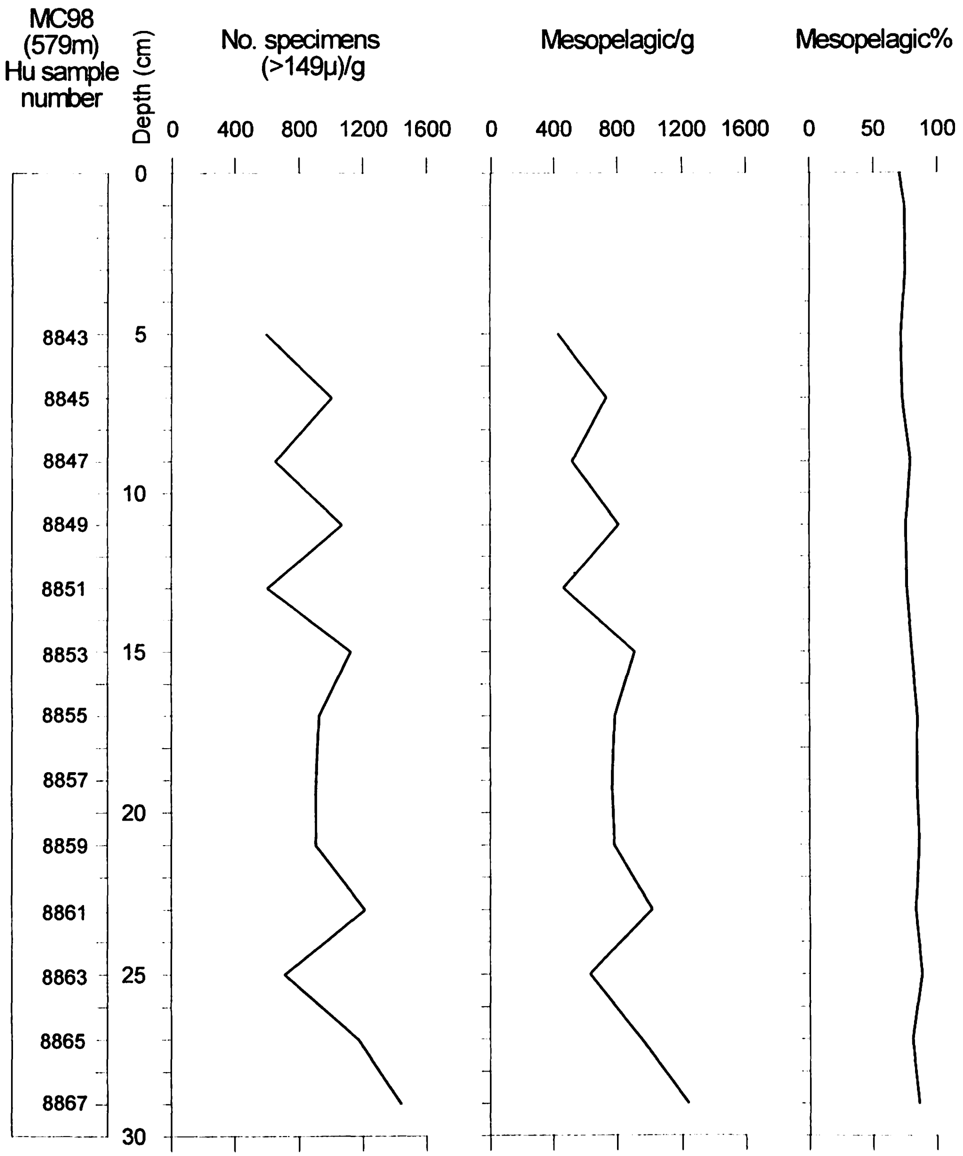


Fig. 9c. Total abundance of pteropods and mesopelagic taxa in MC98 (579 m depth)

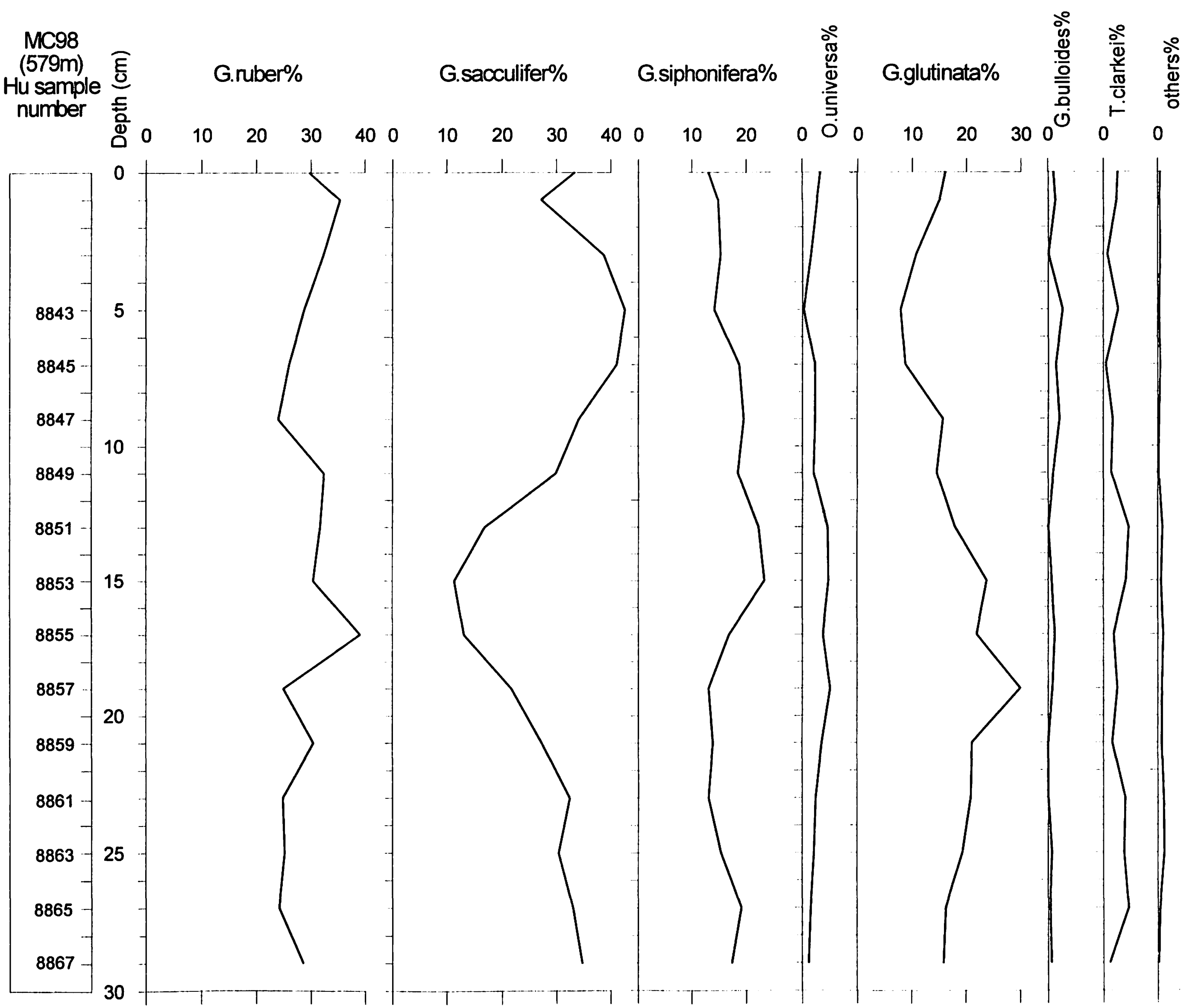


Fig. 10a. Relative abundance of planktic foraminifera in MC98 (579 m depth)

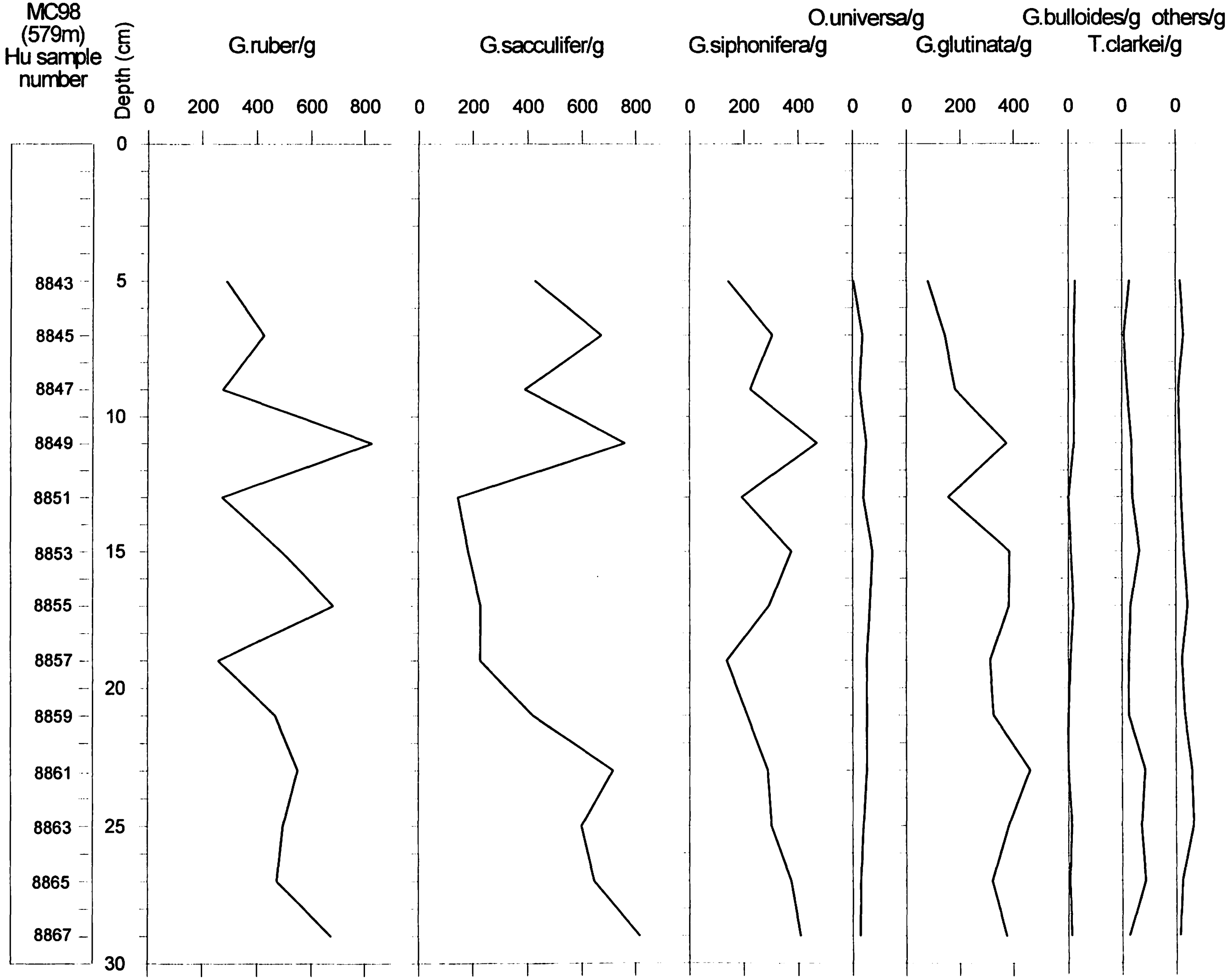


Fig. 10b. Total abundance of planktic foraminifera (specimens/g dry sediment) in MC98 (579 m depth)

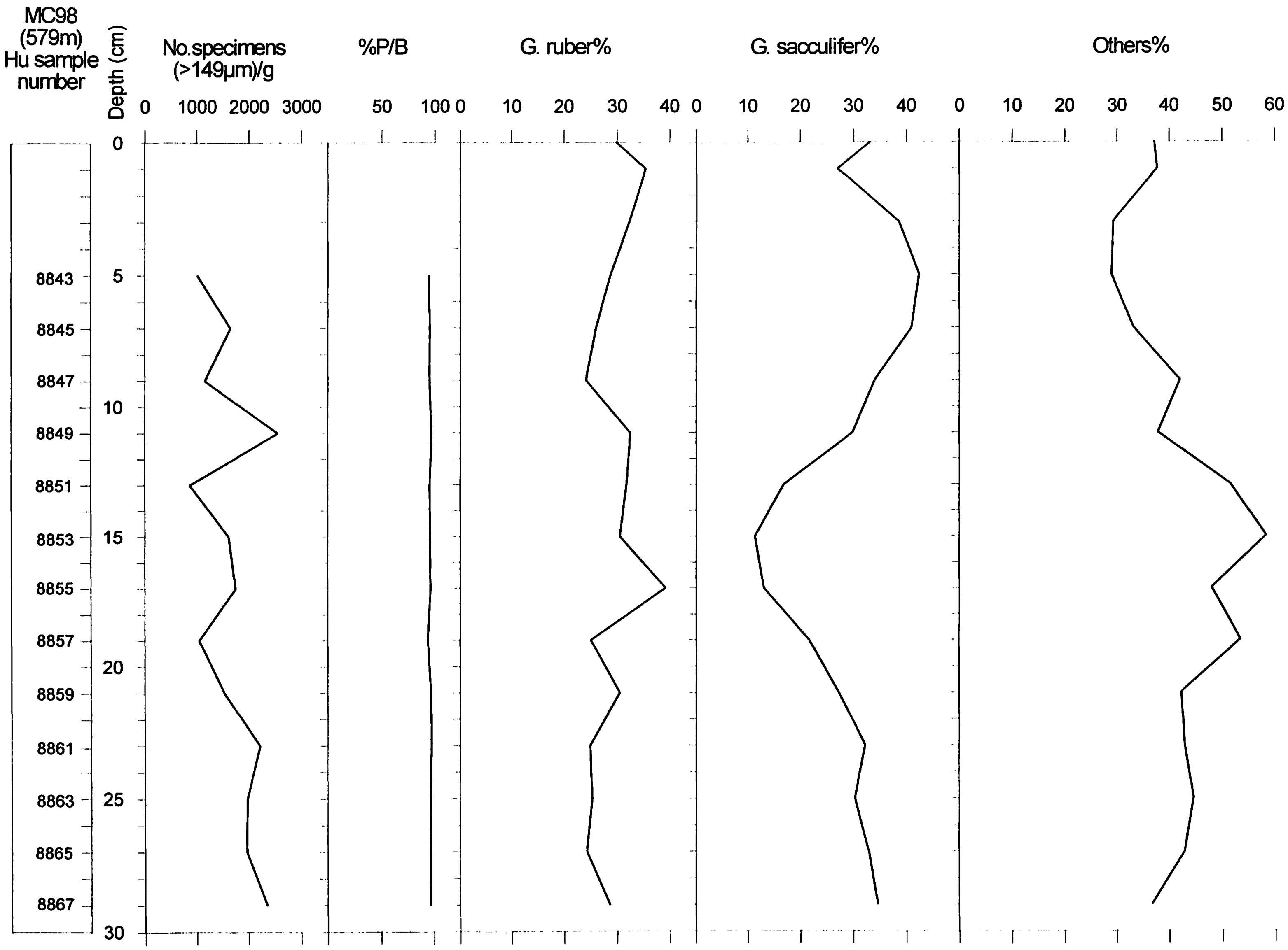


Fig. 10c. Total and relative abundance of the main planktic foraminifera taxa and the P/B ratio in MC98 (579 m depth)

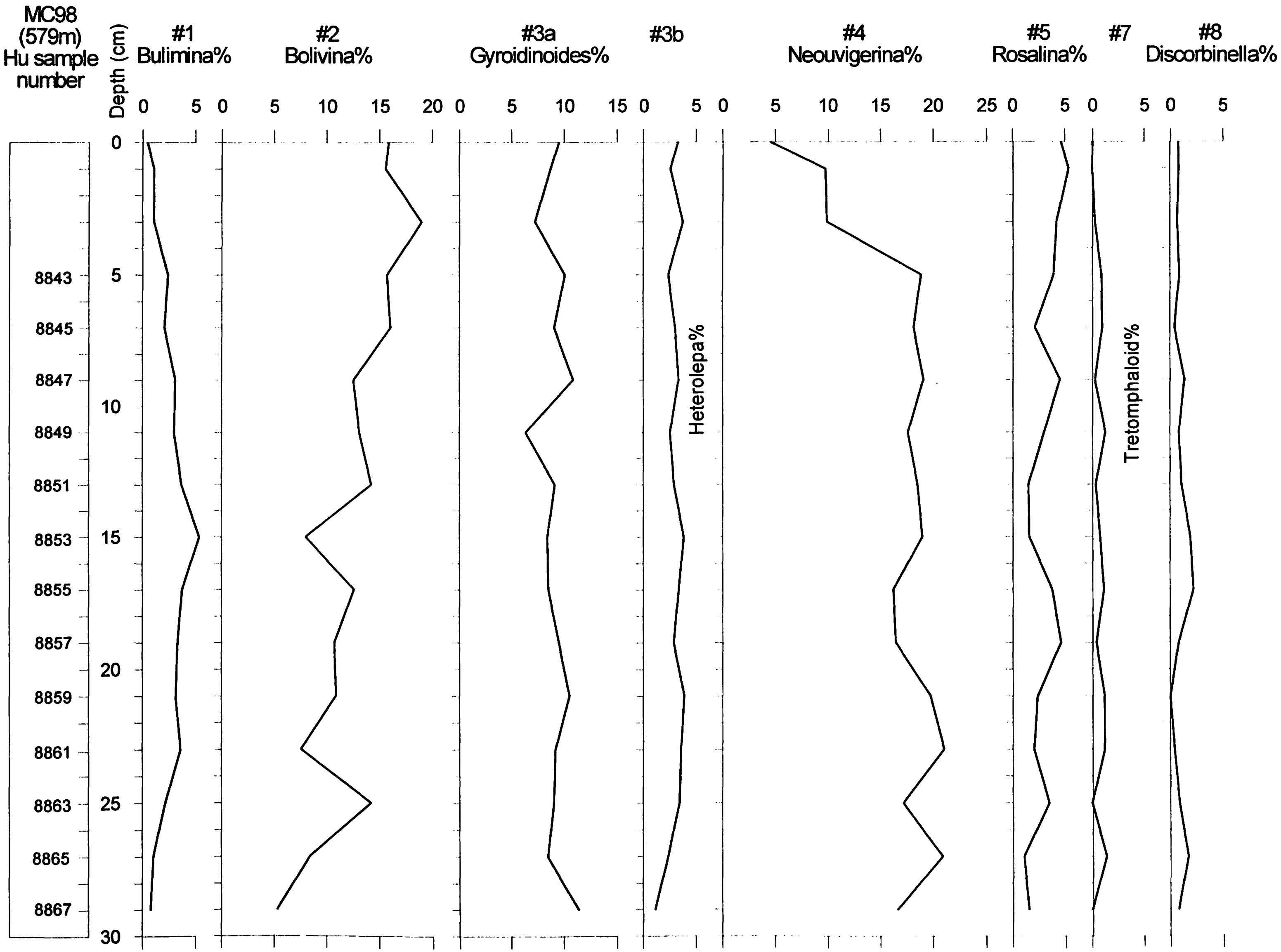


Fig. 11a. Relative abundance of benthic foraminifera in MC98 (579 m depth)

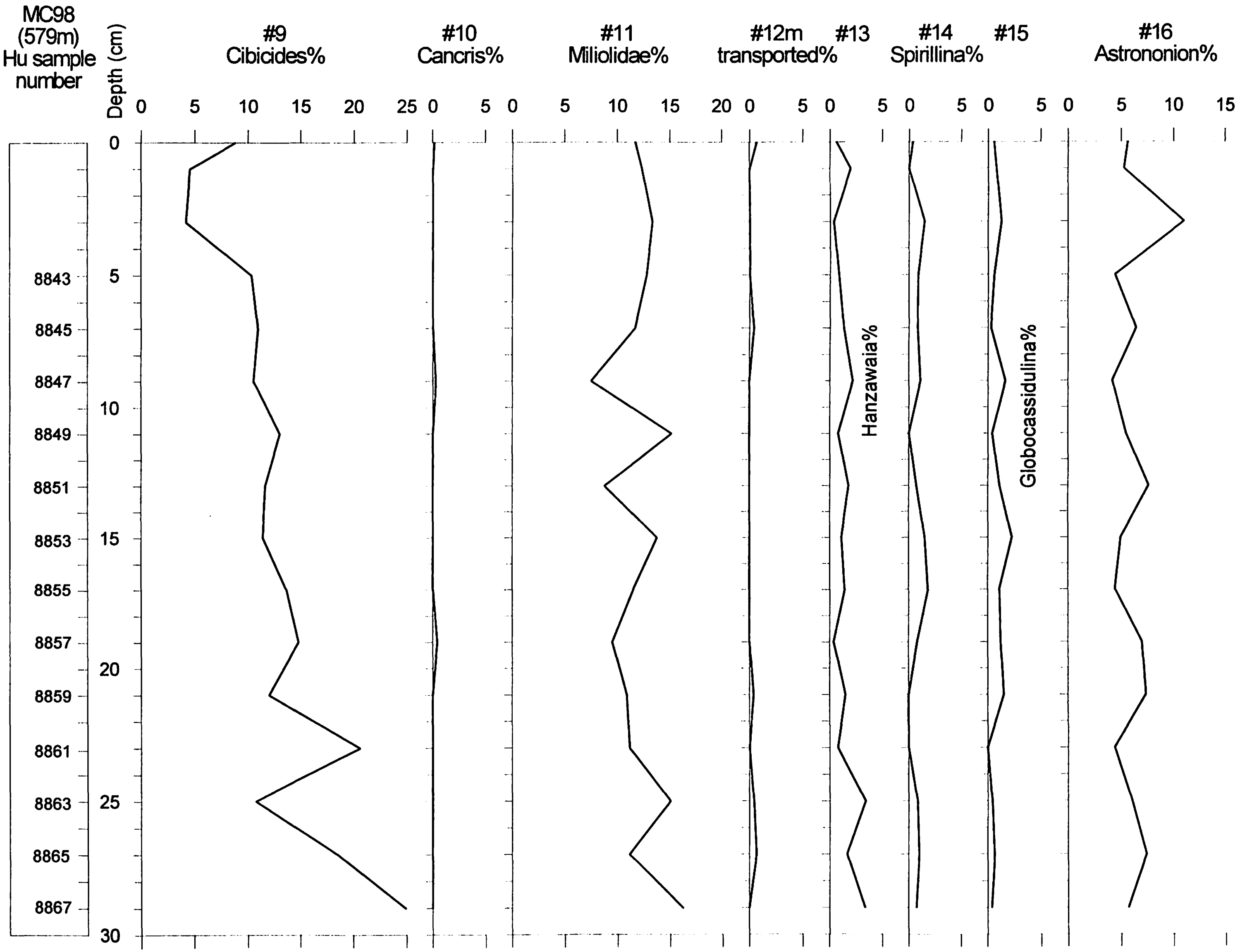


Fig. 11b. Relative abundance of benthic foraminifera in MC98 (579 m depth)

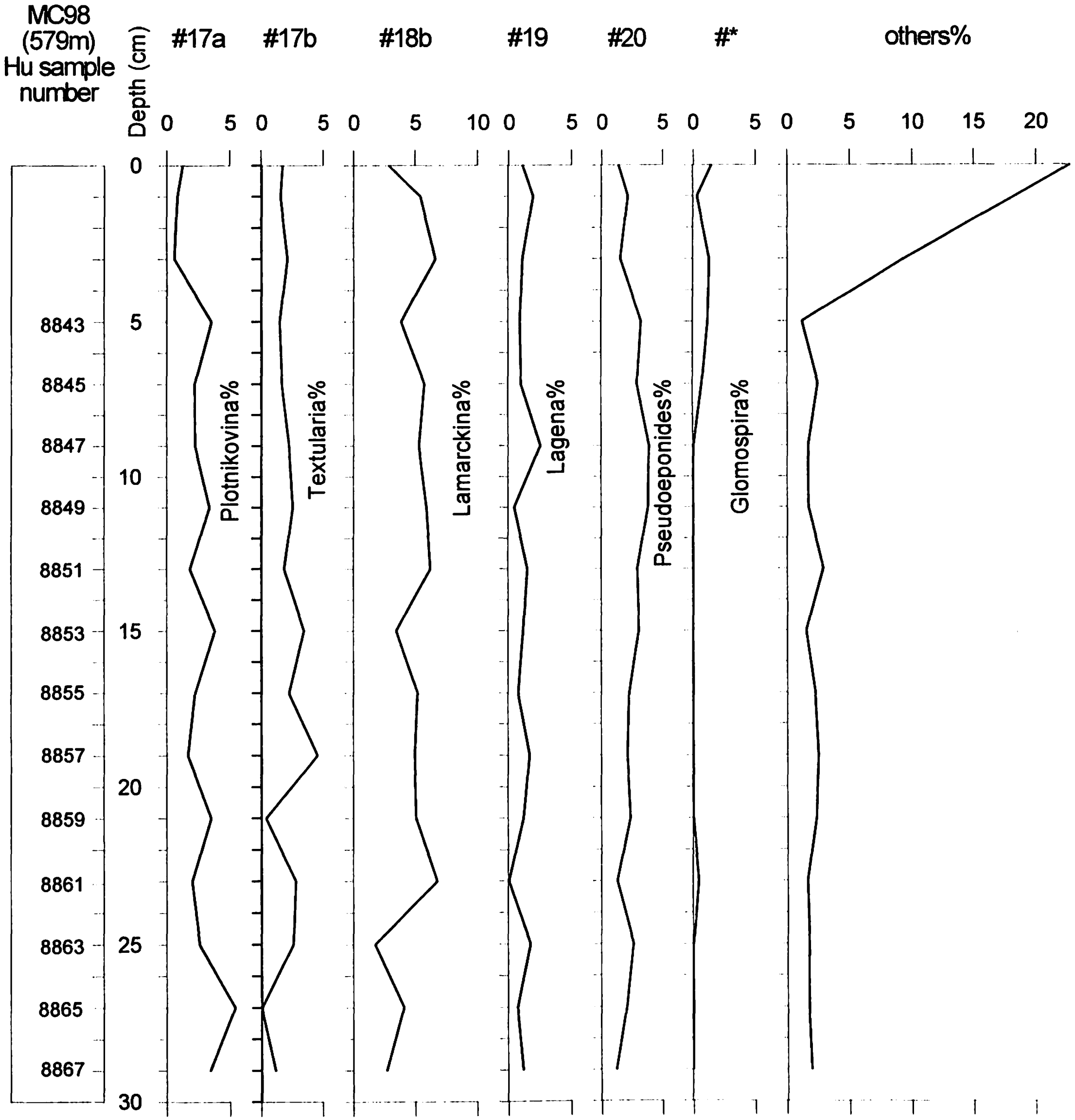


Fig. 11c. Relative abundance of benthic foraminifera in MC98 (579 m depth)

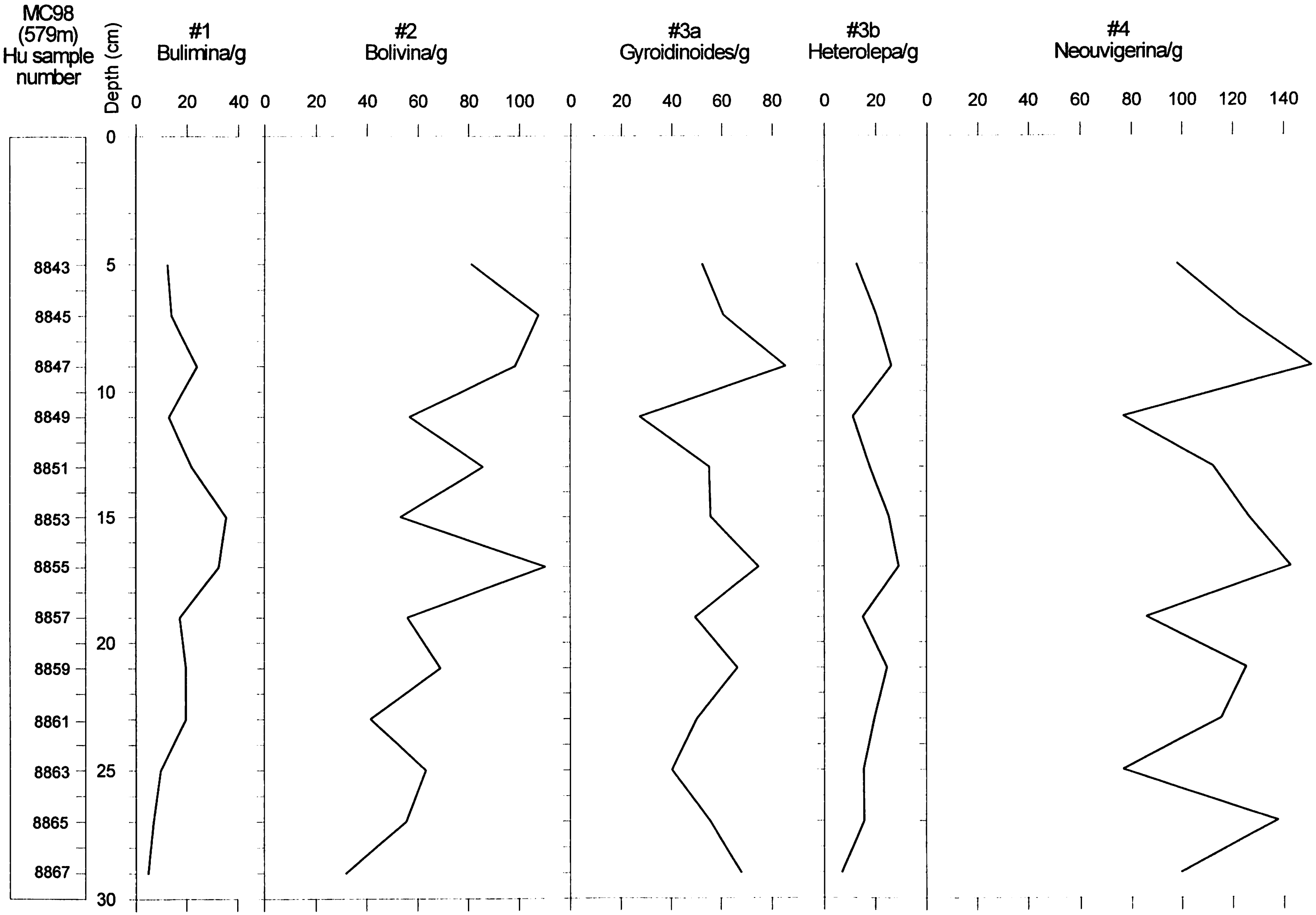


Fig. 12a. Total abundance of benthic foraminifera (specimens/g dry sediment)in MC98 (579 m depth)

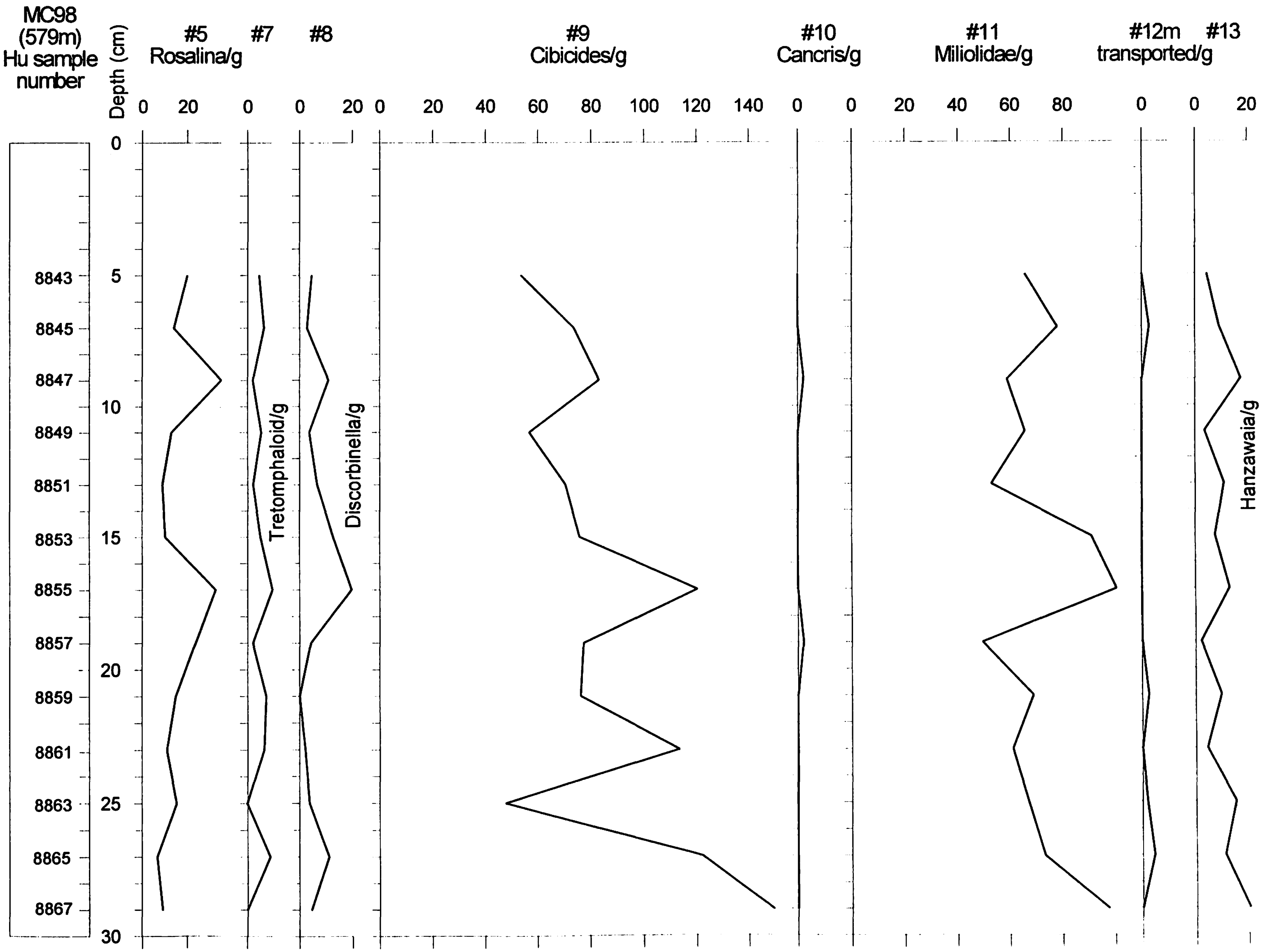


Fig. 12b. Total abundance of benthic foraminifera (specimens/g dry sediment) in MC98 (579 m depth)

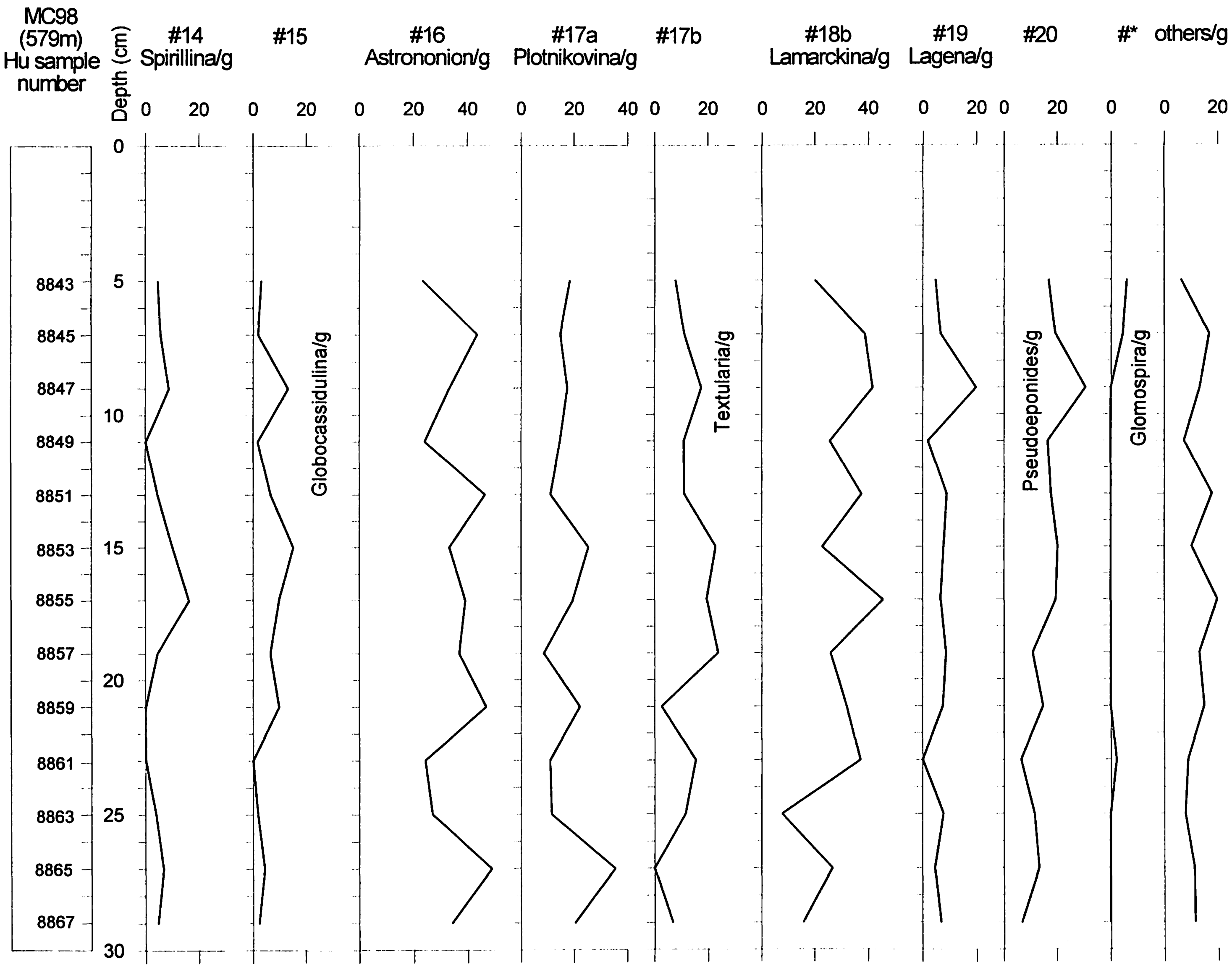


Fig. 12c. Total abundance of benthic foraminifera (specimens/g dry sediment) in MC98 (579 m depth)

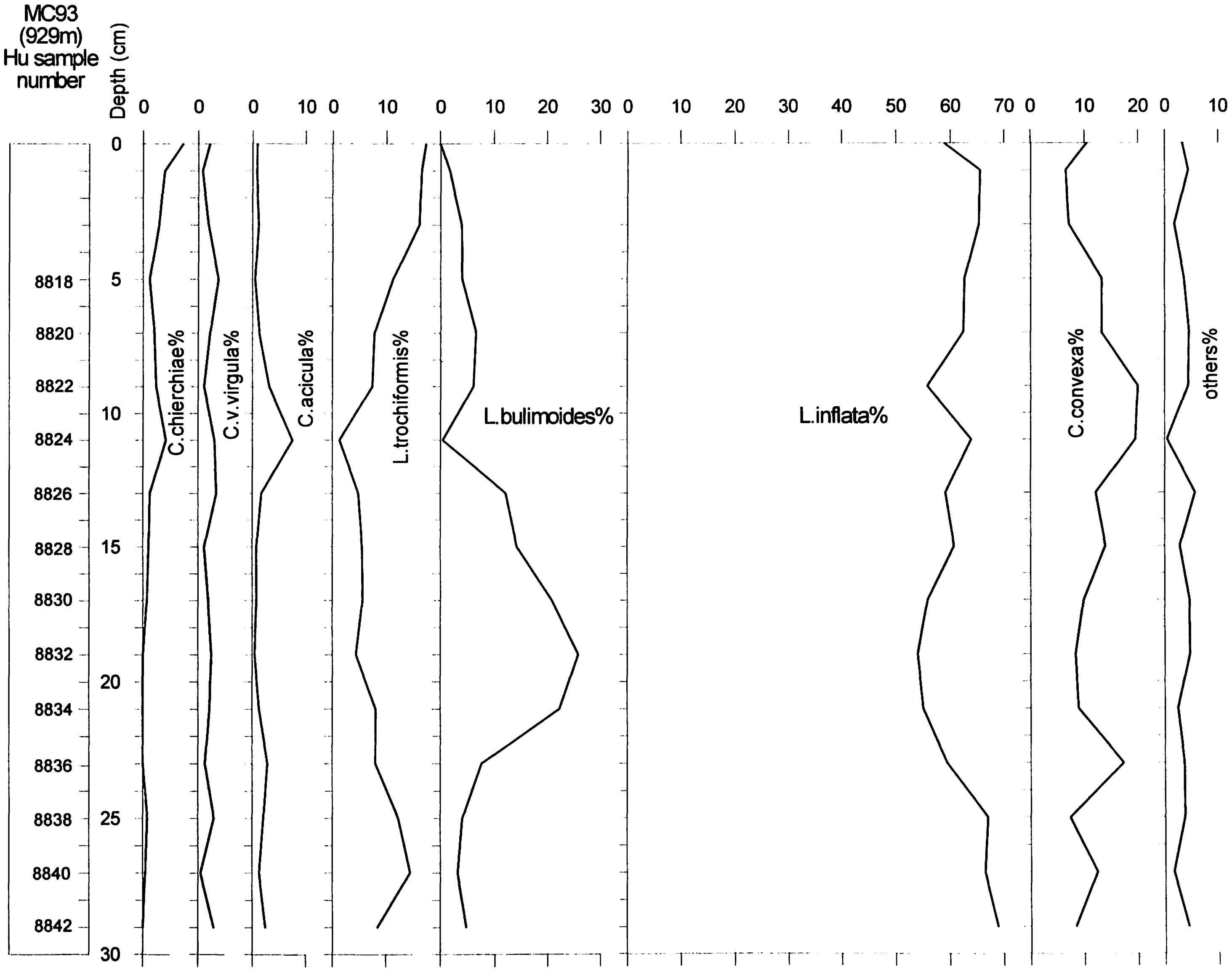


Fig. 13a. Relative abundance of pteropods in MC93 (929 m depth)

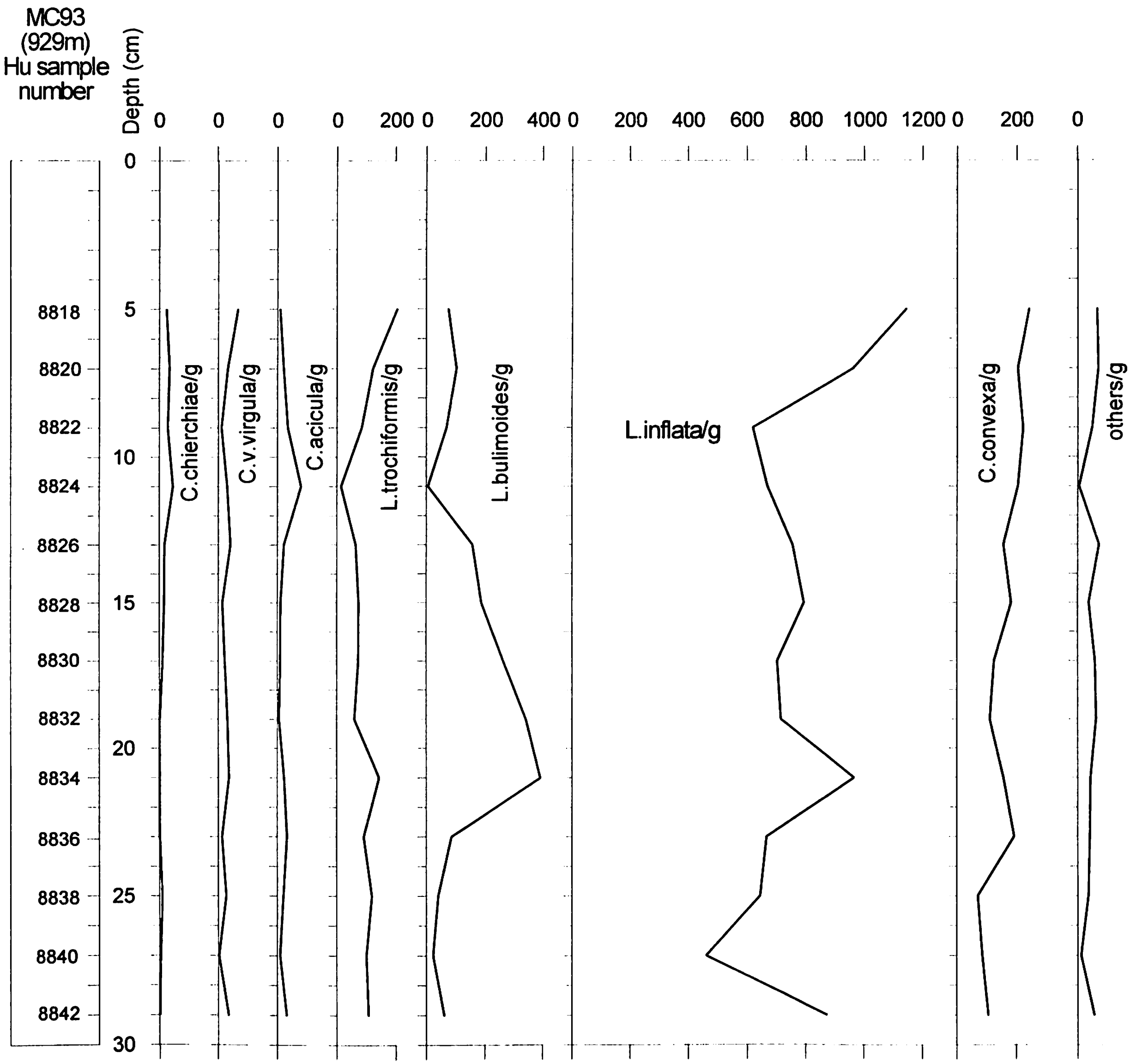


Fig. 13b. Total abundance of pteropods (specimens/g dry sediment) in MC93 (929 m depth)

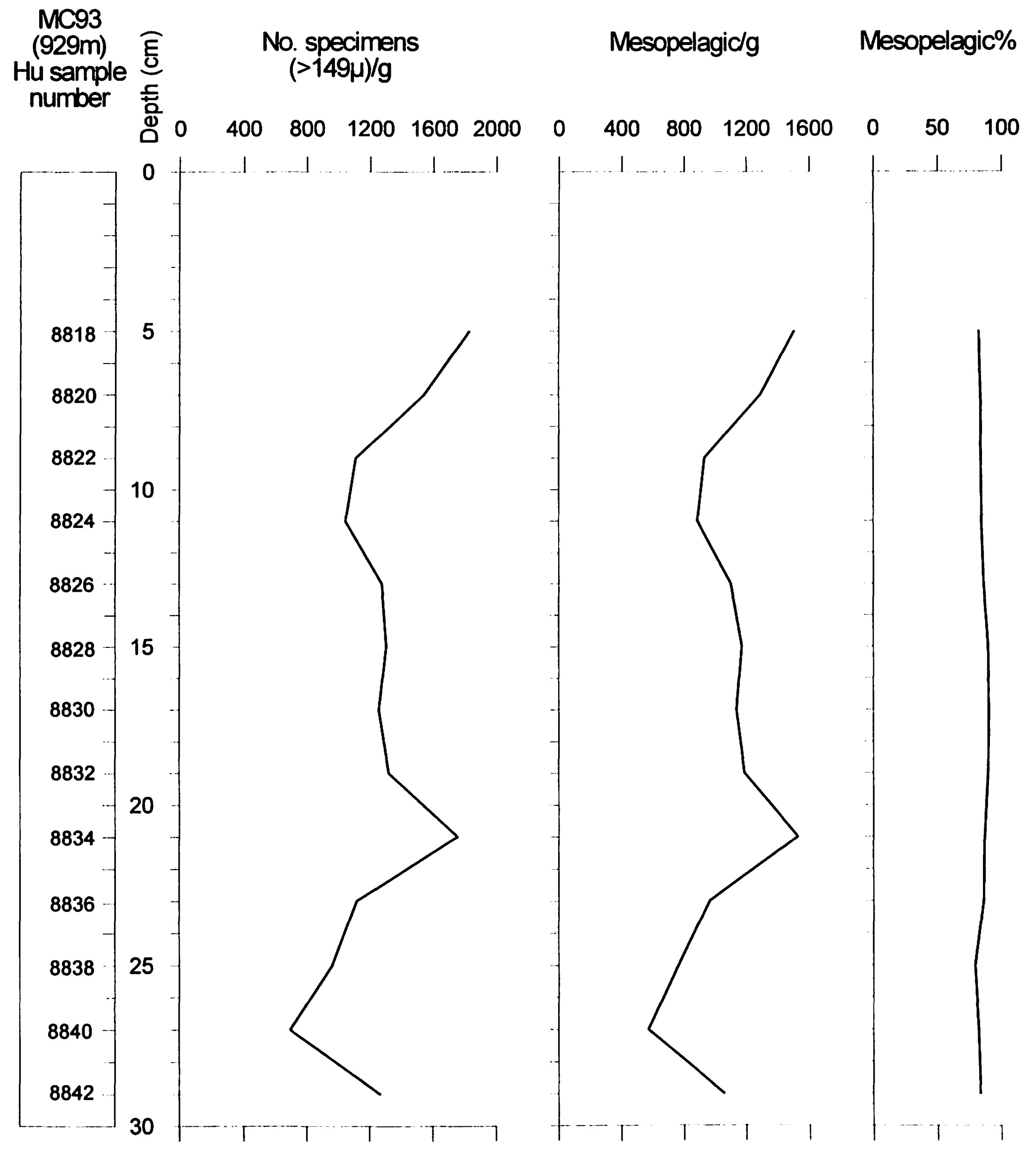


Fig. 13c. Total abundance of pteropods and mesopelagic taxa in MC93 (929 m depth)

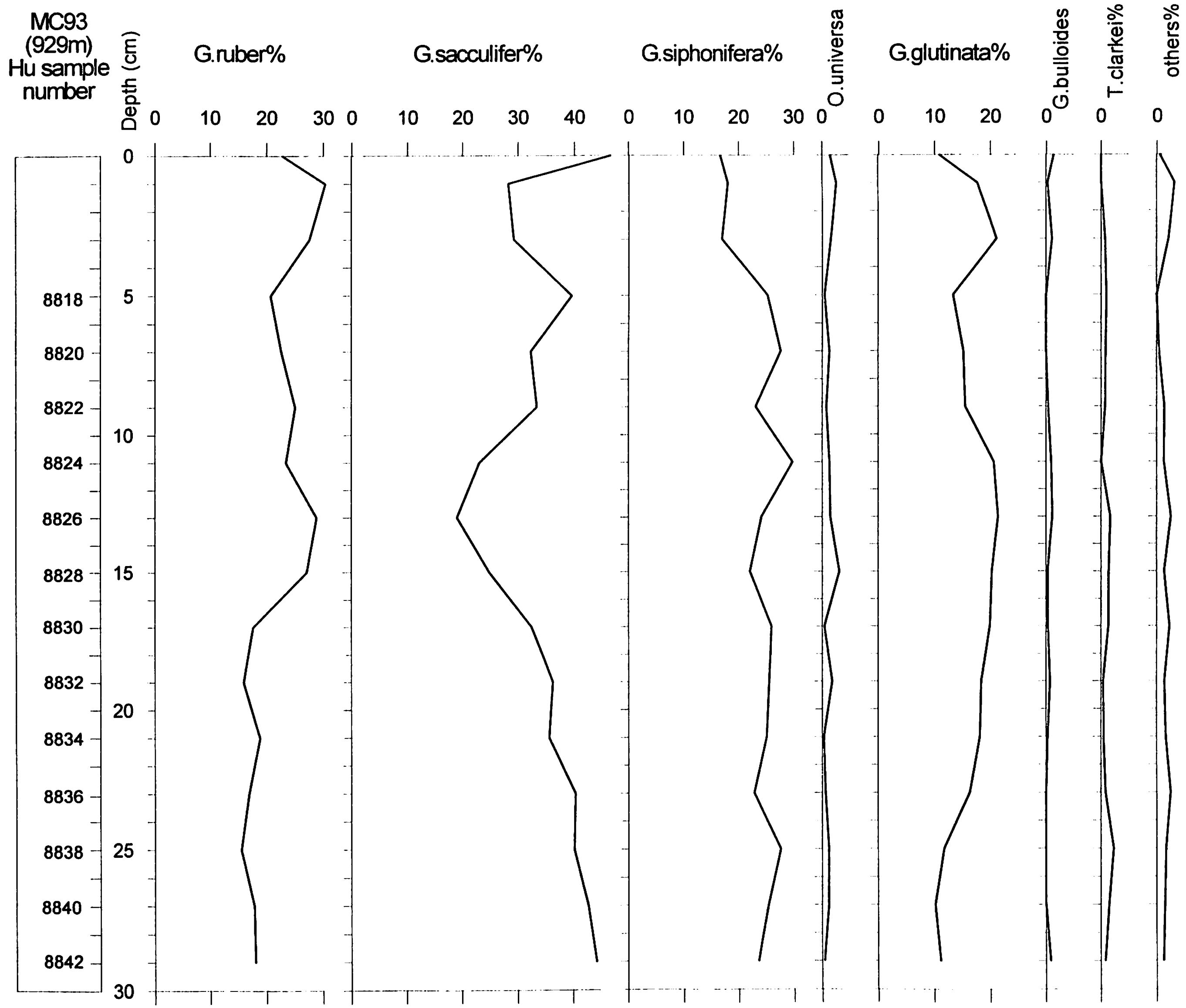


Fig. 14a. Relative abundance of planktic foraminifera in MC93 (929 m depth)

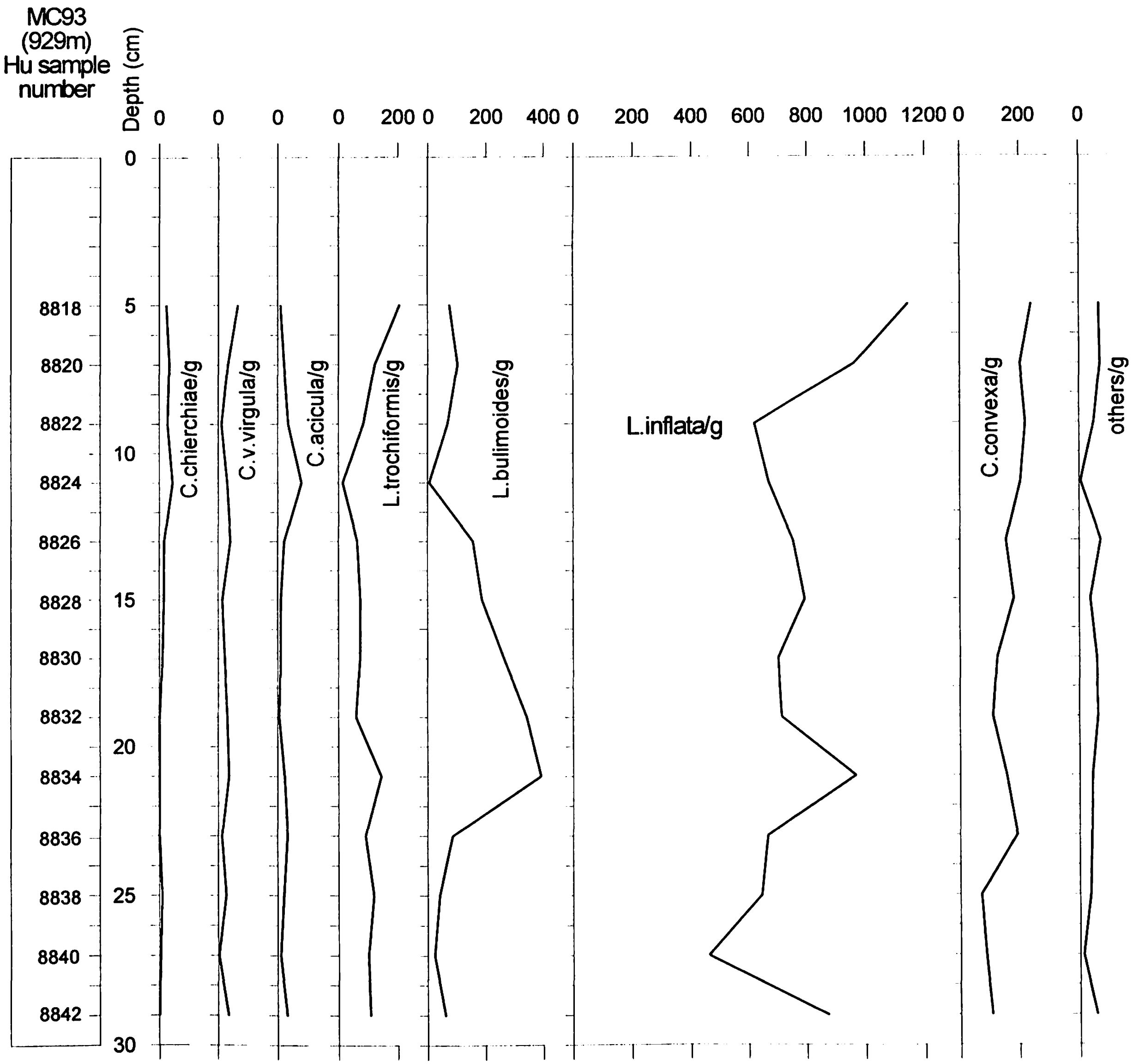


Fig. 14b. Total abundance of pteropods (specimens/g dry sediment) in MC93 (929 m depth)

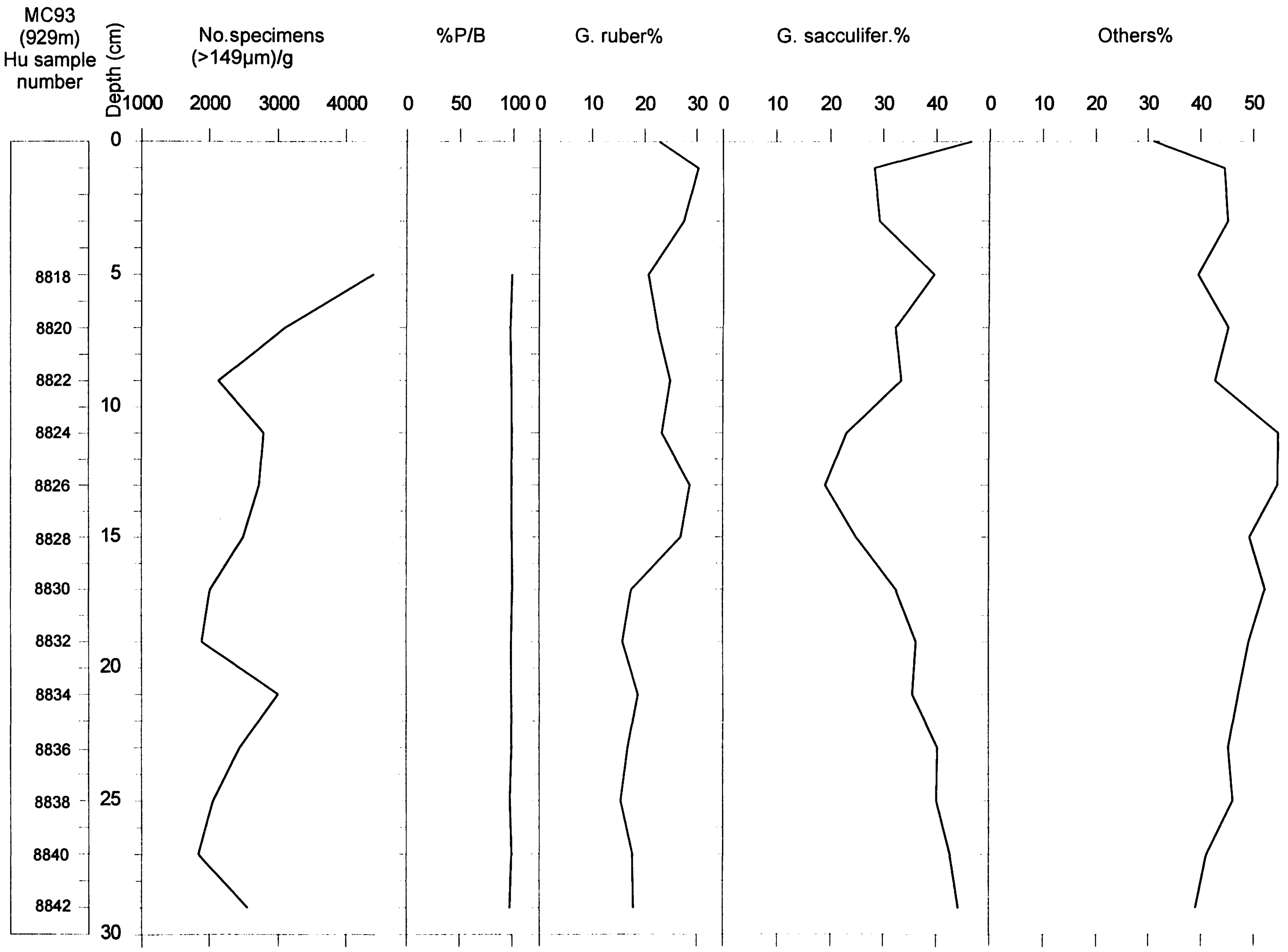


Fig. 14c. Total and relative abundance of the main planktic foraminifera taxa and P/B ratio in MC93 (929 m depth)

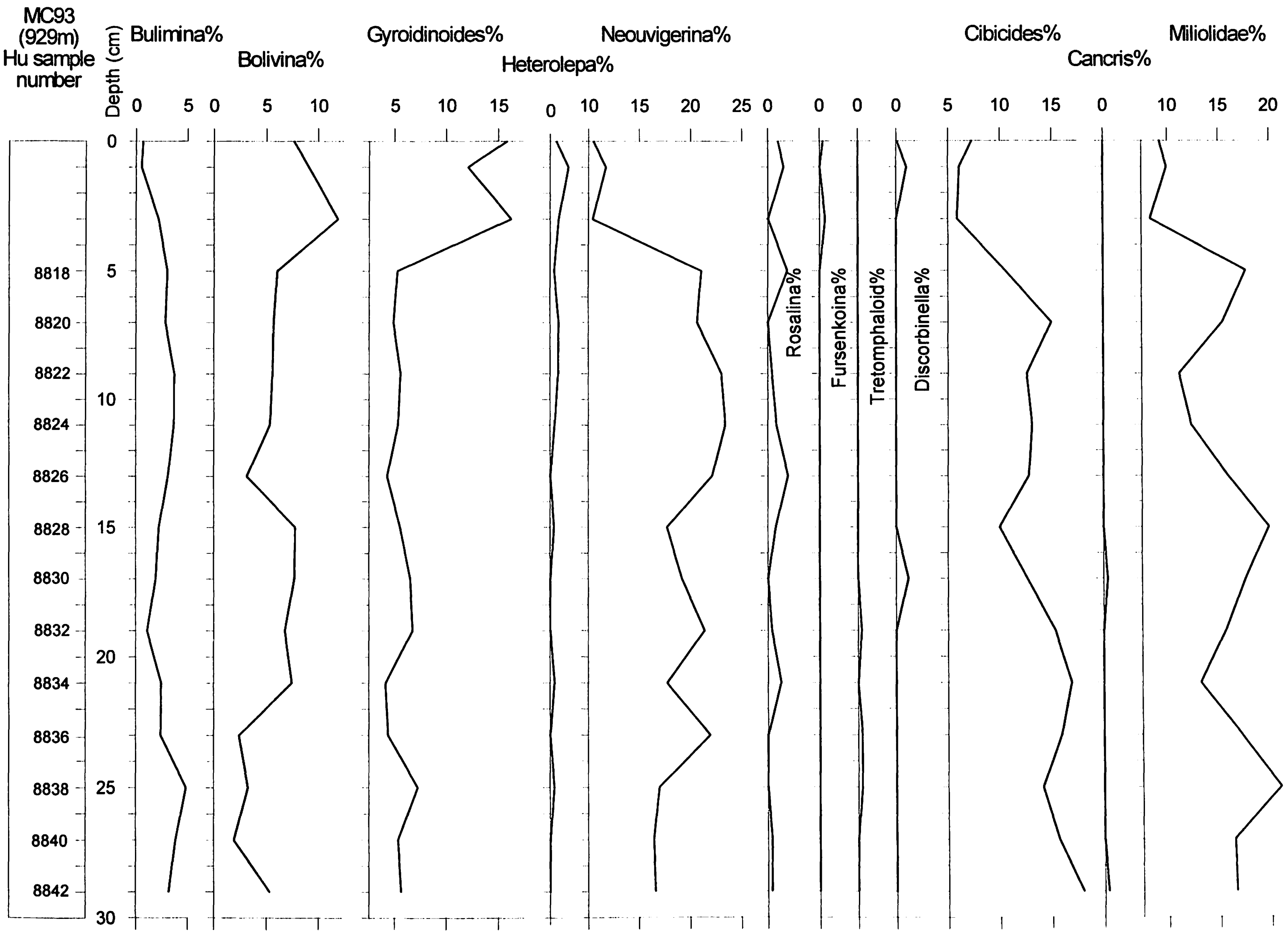


Fig. 15a. Relative abundance of benthic foraminifera in MC93 (929 m depth)

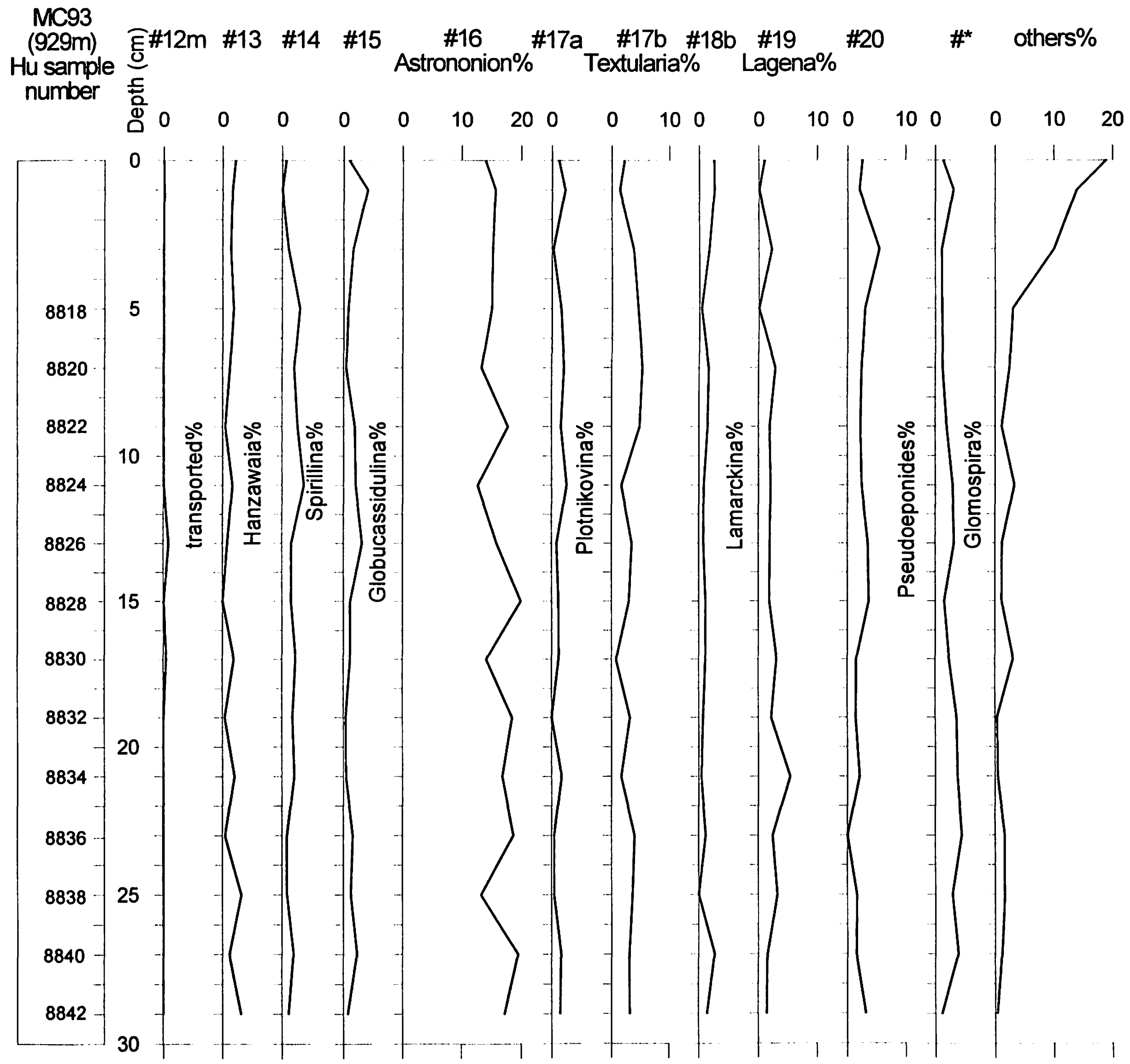


Fig. 15b. Relative abundance of benthic foraminifera in MC93 (929 m depth)

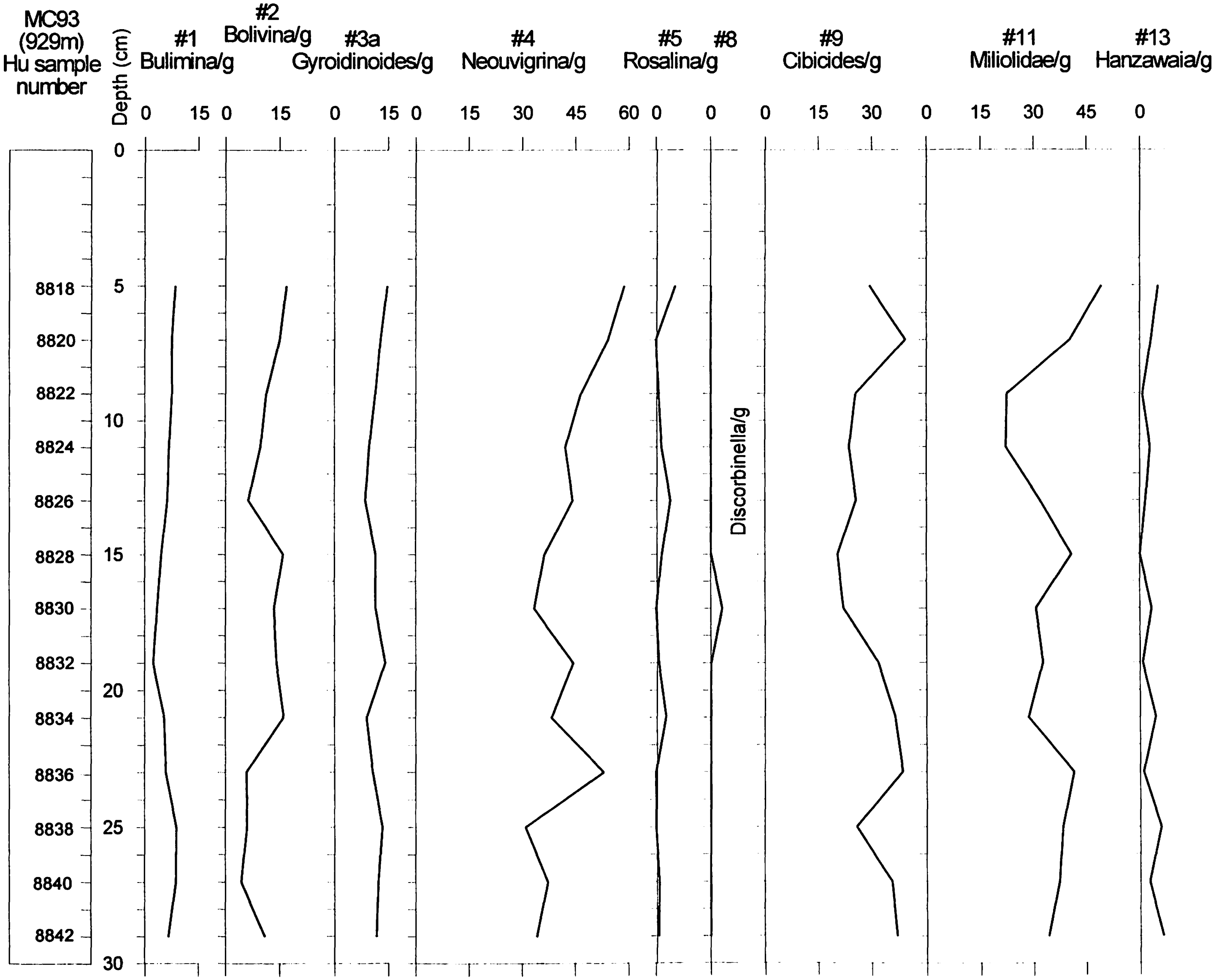


Fig. 16a. Total abundance of benthic foraminifera (specimens/g dry sediment) in MC93 (929 m depth)

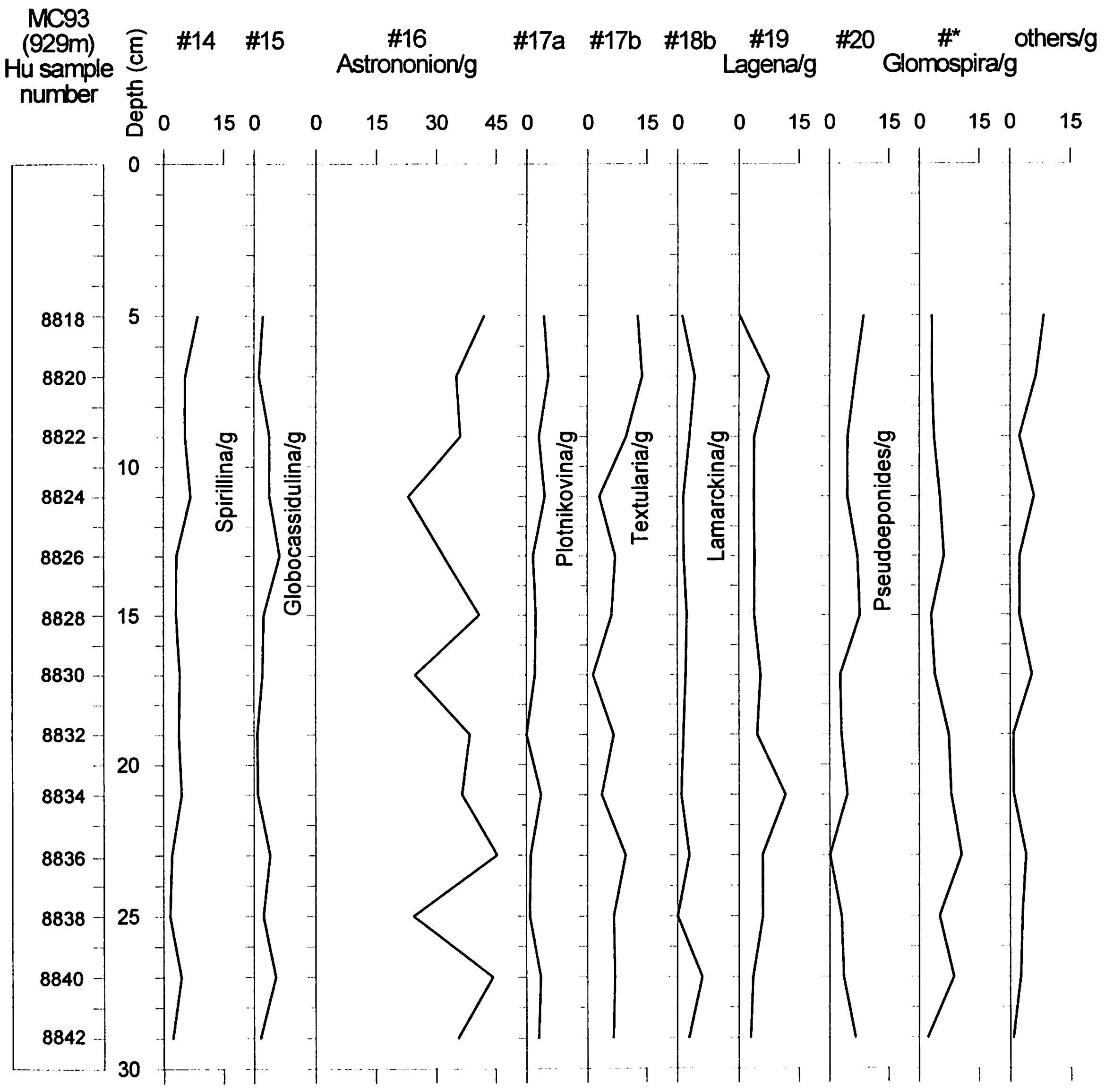


Fig. 16b. Total abundance of benthic foraminifera (specimens/g dry sediment) in MC93 (929 m depth)

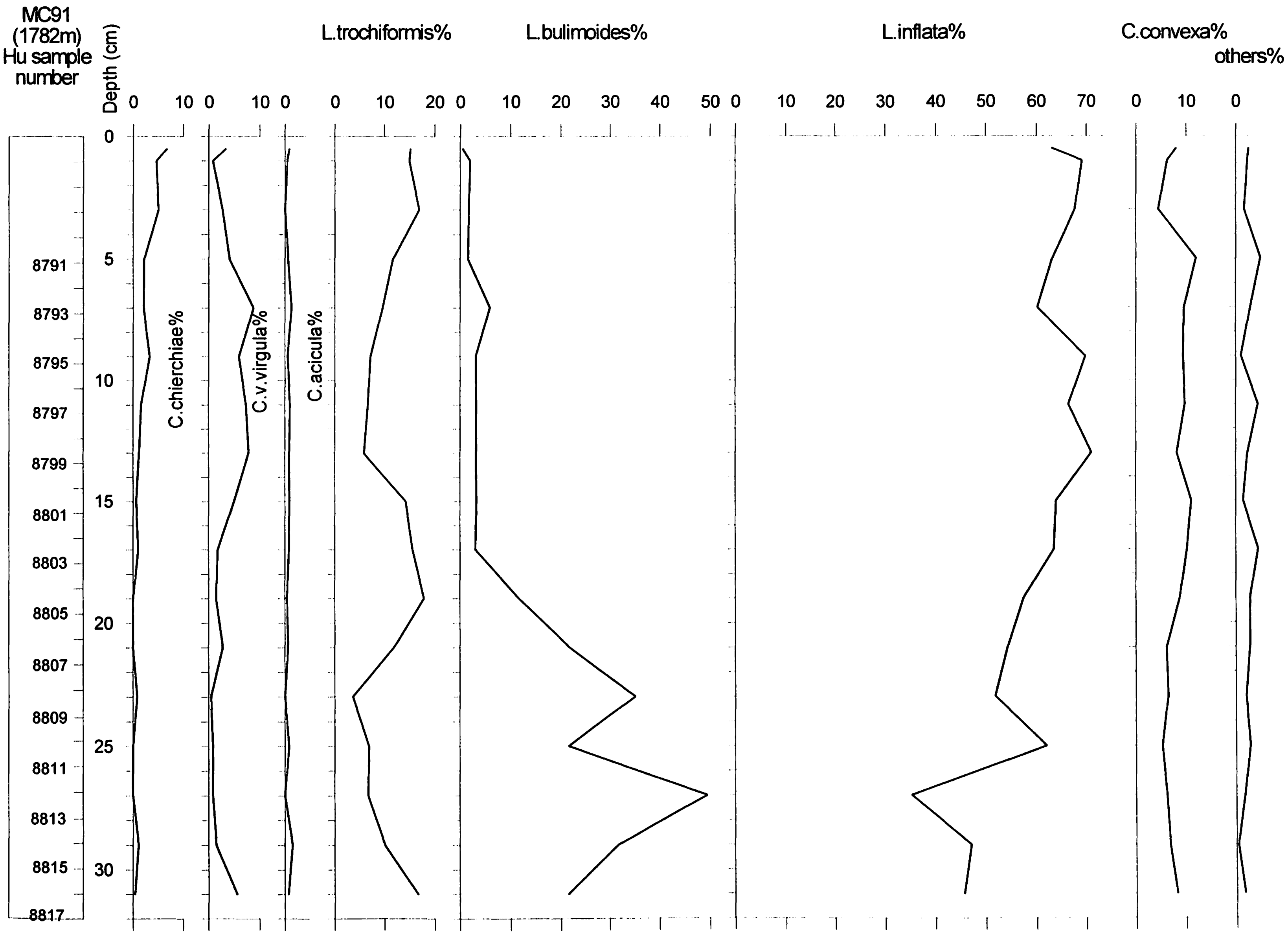


Fig. 17a. Relative abundance of pteropods in MC91 (1782 m depth)

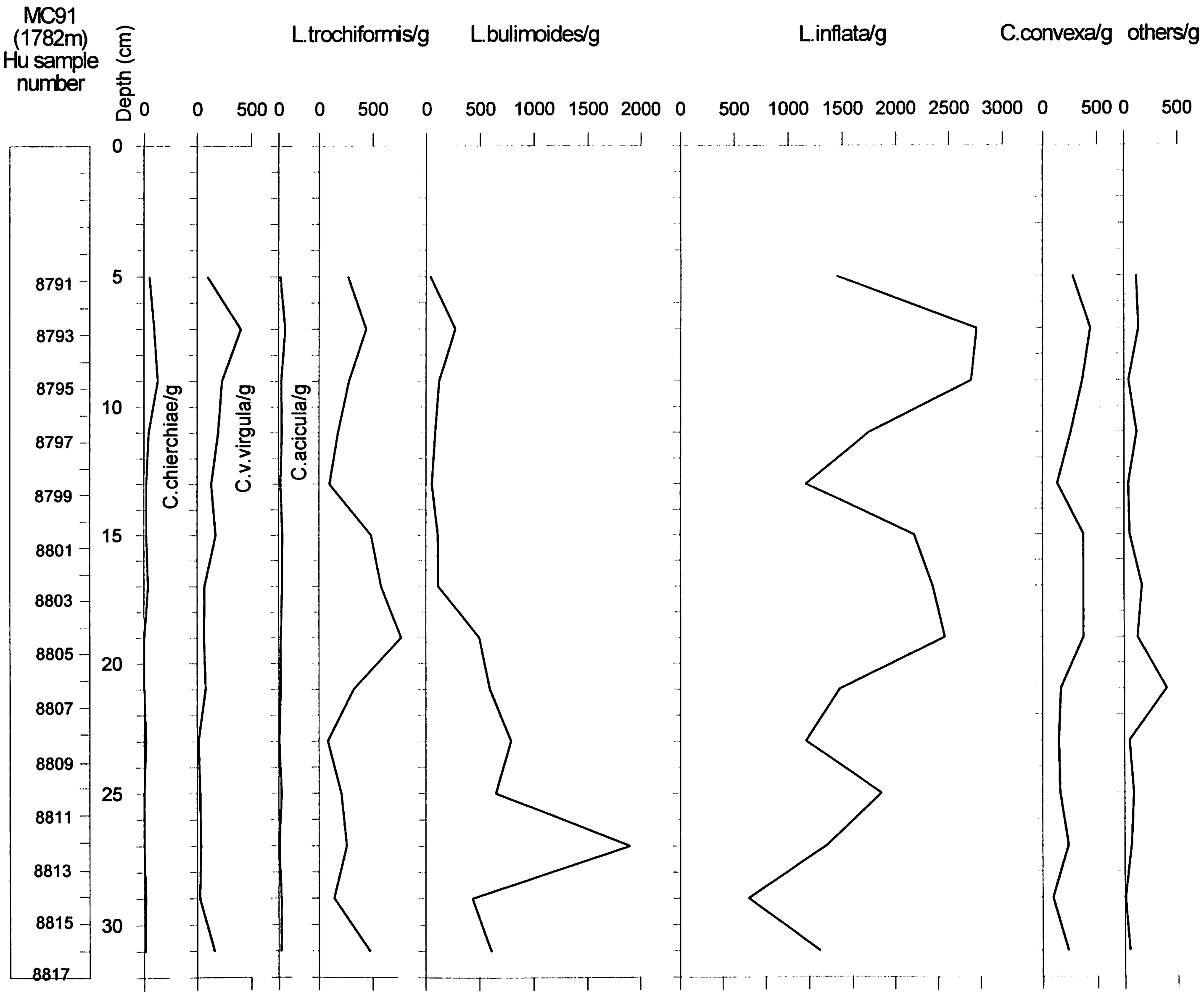


Fig. 17b. Total abundance of pteropods (specimens/g dry sediment) in MC91 (1782 m depth)

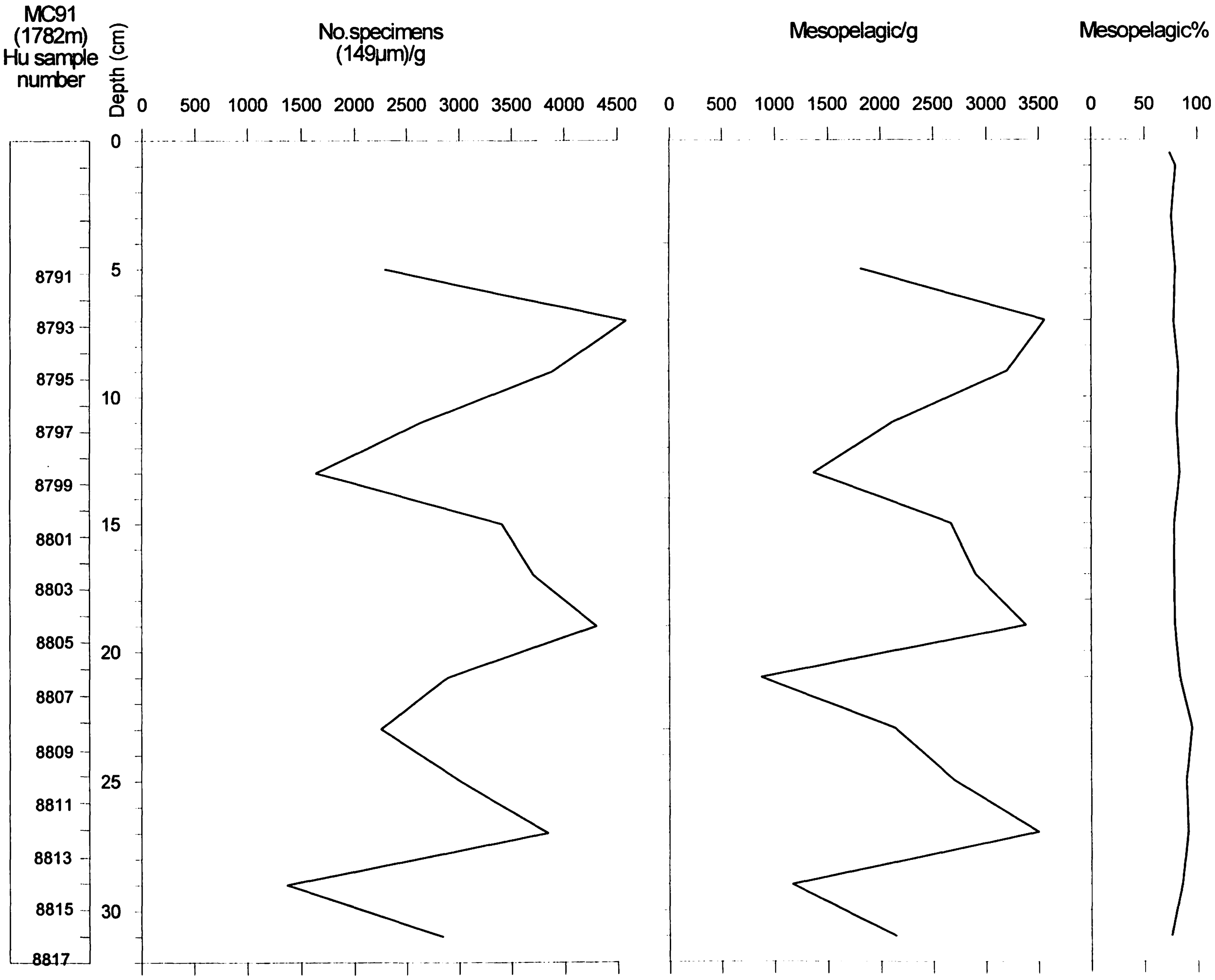


Fig. 17c. Total abundance of pteropods and mesopelagic taxa in MC91 (1782 m depth)

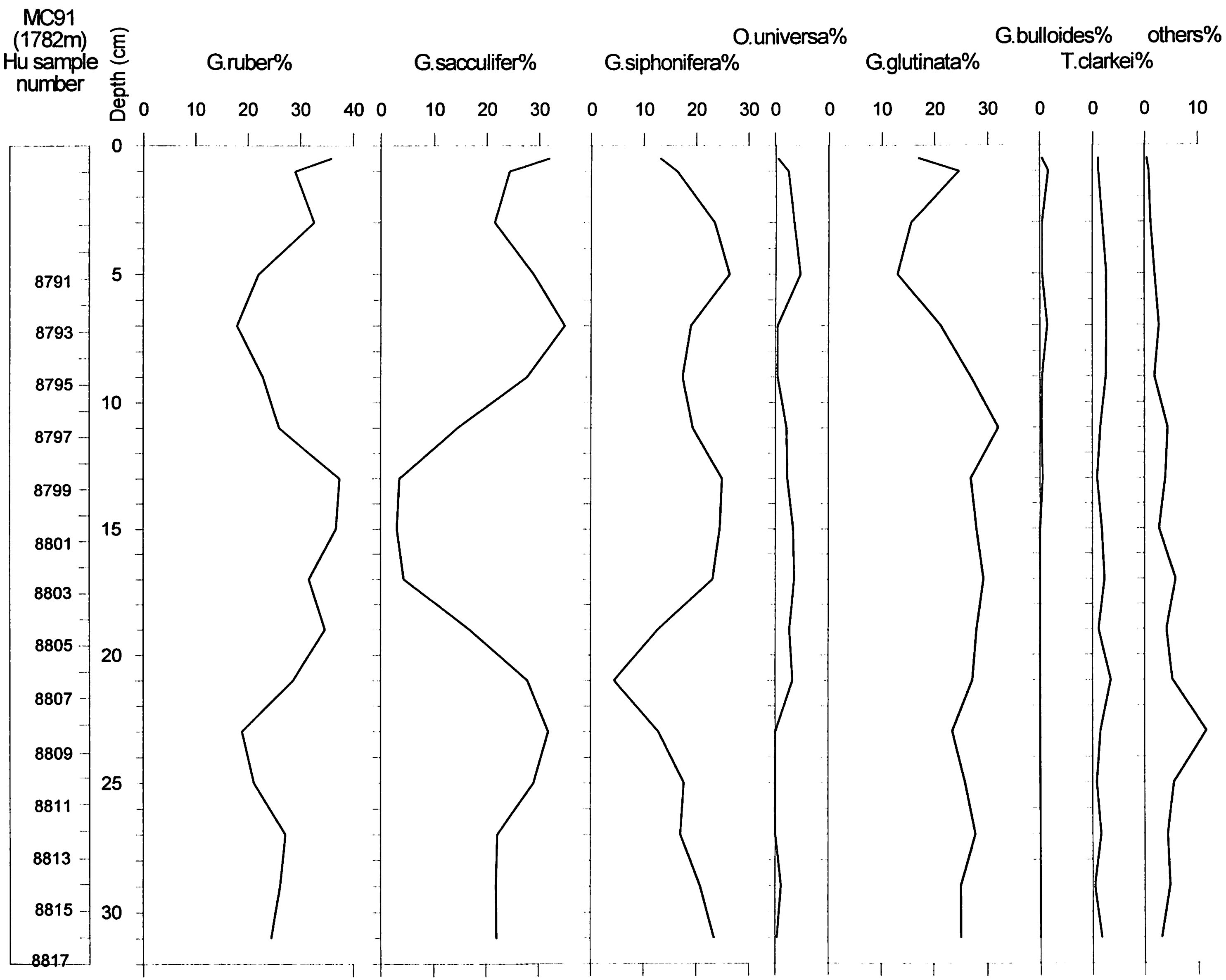


Fig. 18a. Relative abundance of planktic foraminifera in MC91 (1782 m depth)

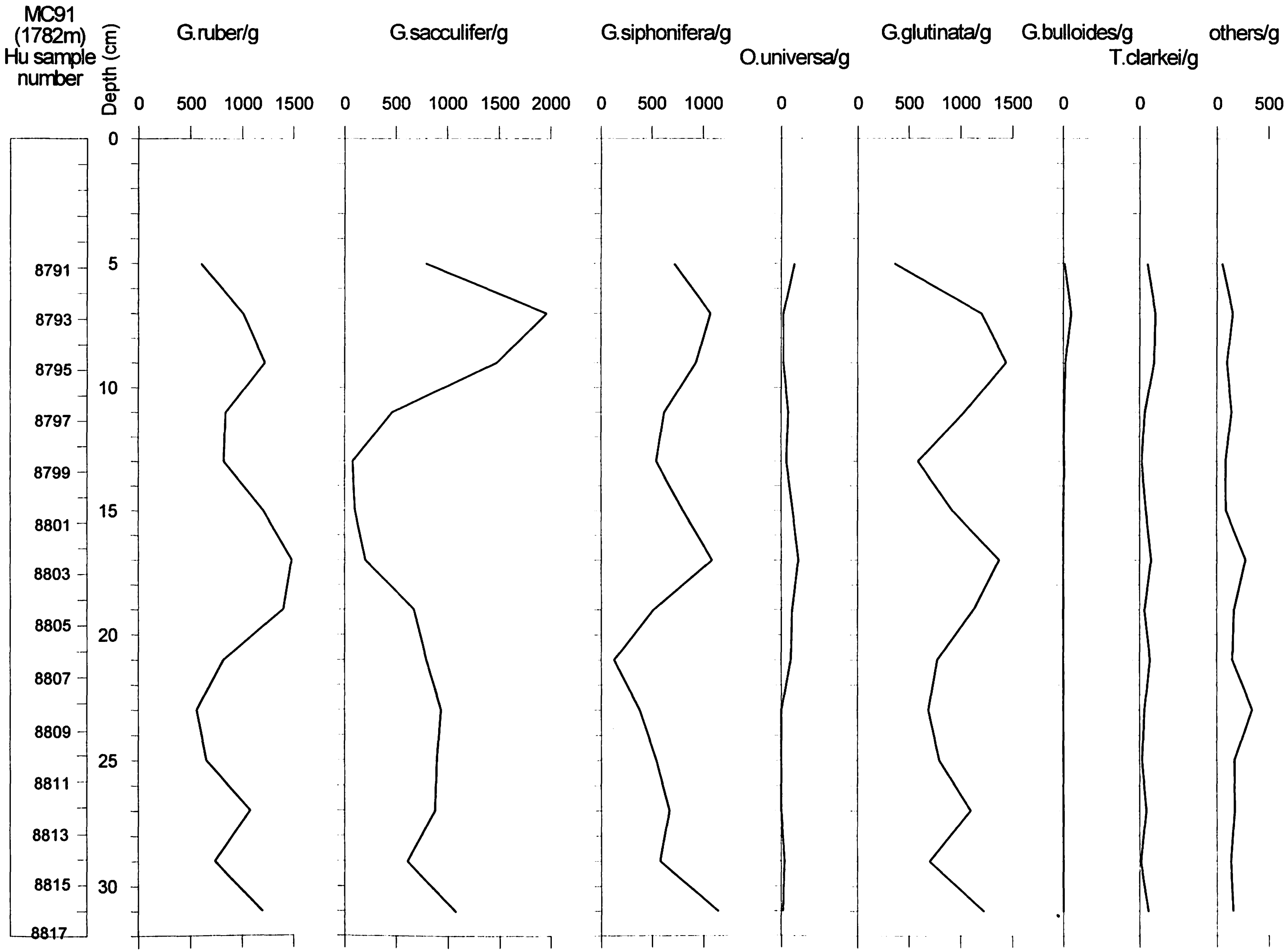


Fig. 18b. Total abundance of planktic foraminifera (specimens/g dry sediment) in MC91 (1782 m depth)

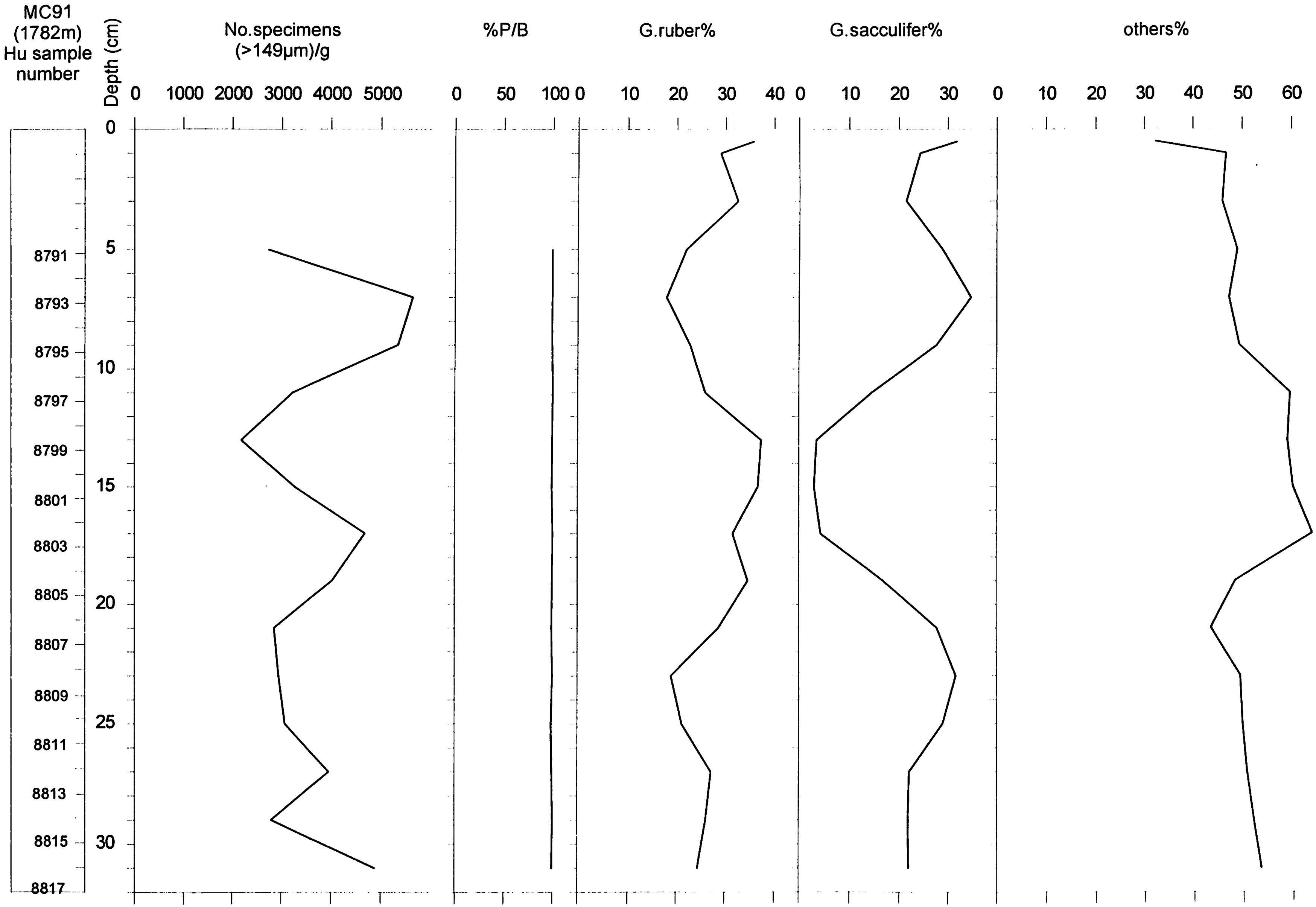


Fig. 18c. Total and relative abundance of the main planktic foraminifera taxa and P/B ratio in MC91 (1782 m depth)

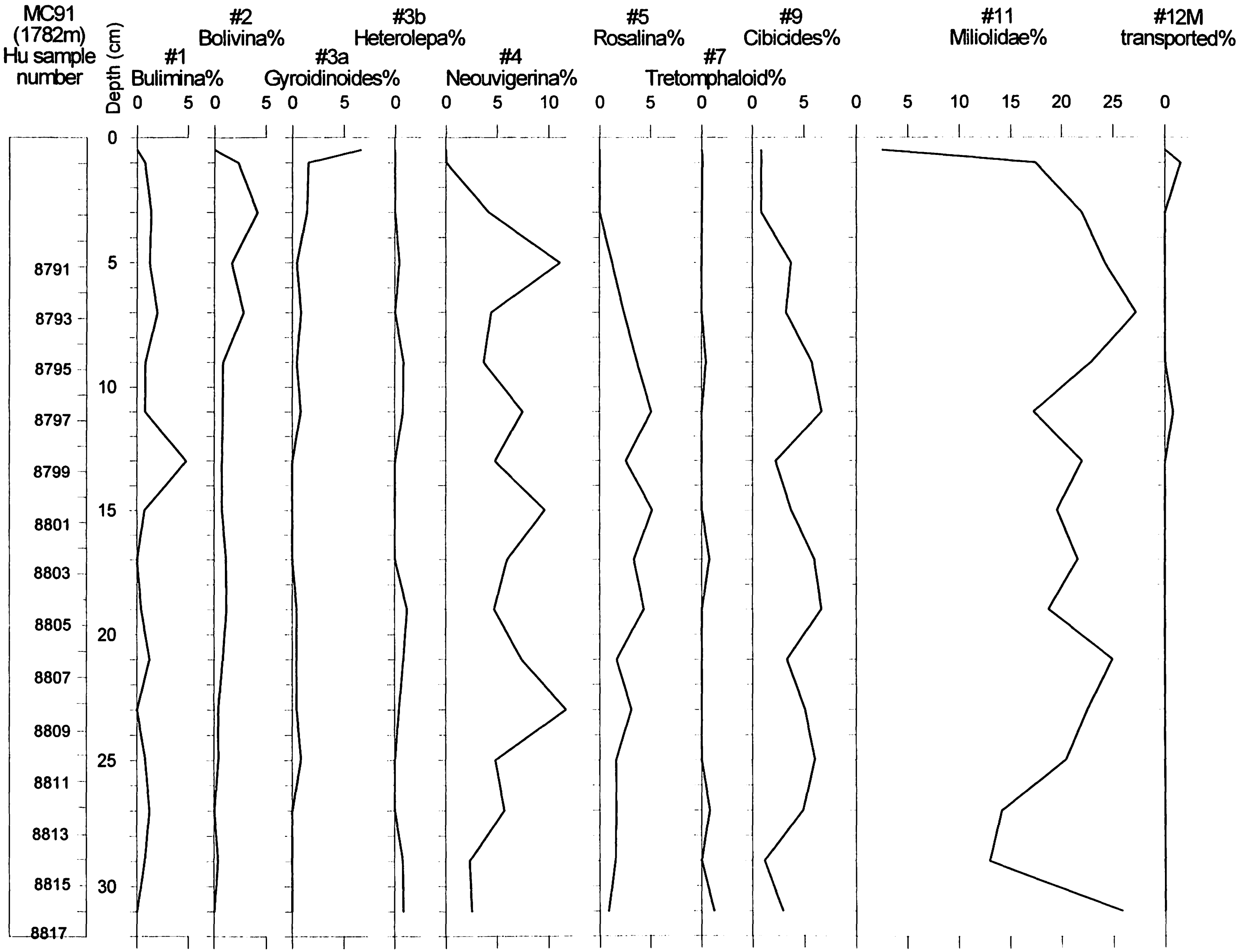


Fig. 19a. Relative abundance of benthic foraminifera in MC91 (1782 m depth)

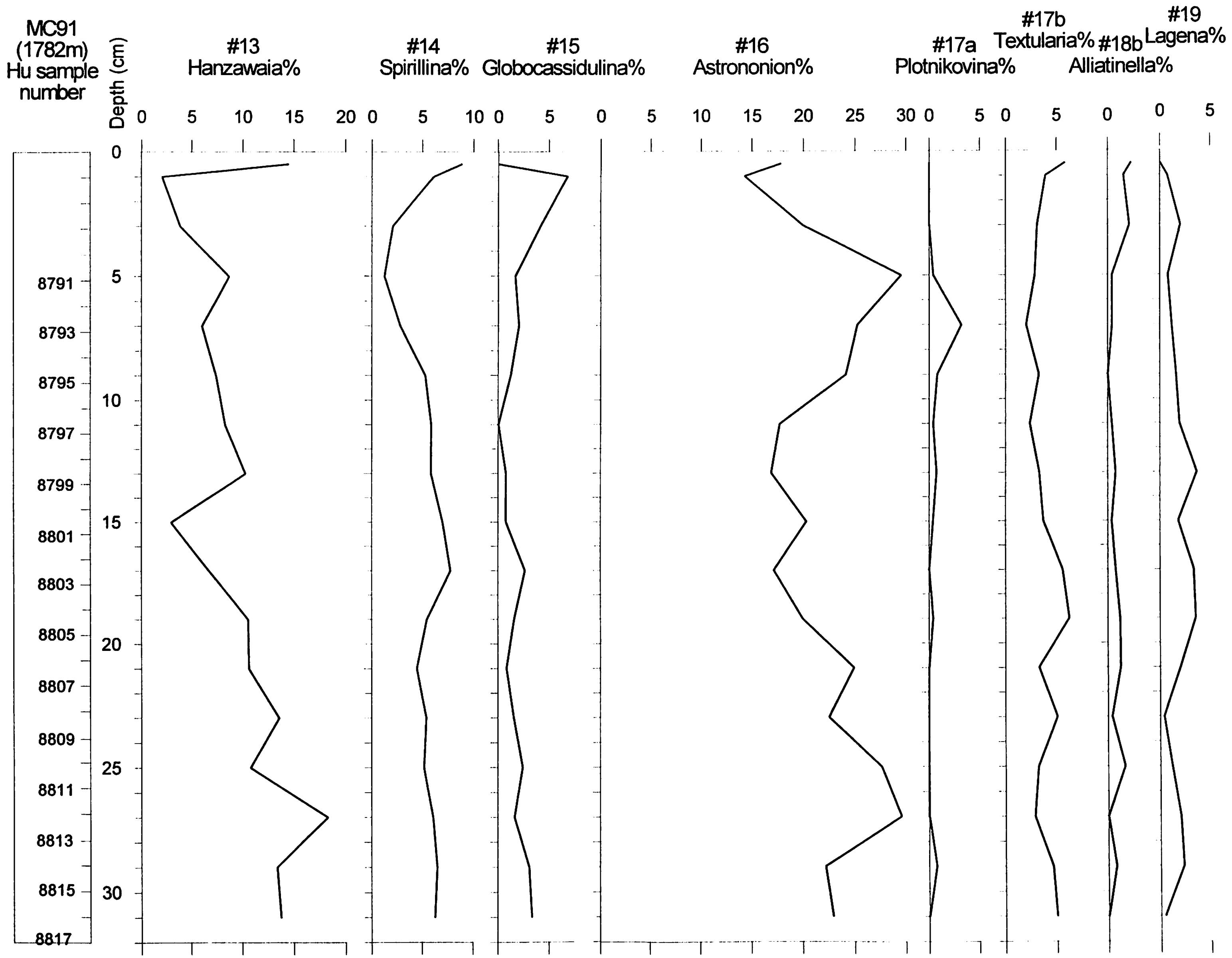


Fig. 19b. Relative abundance of benthic foraminifera in MC91 (1782 m depth)

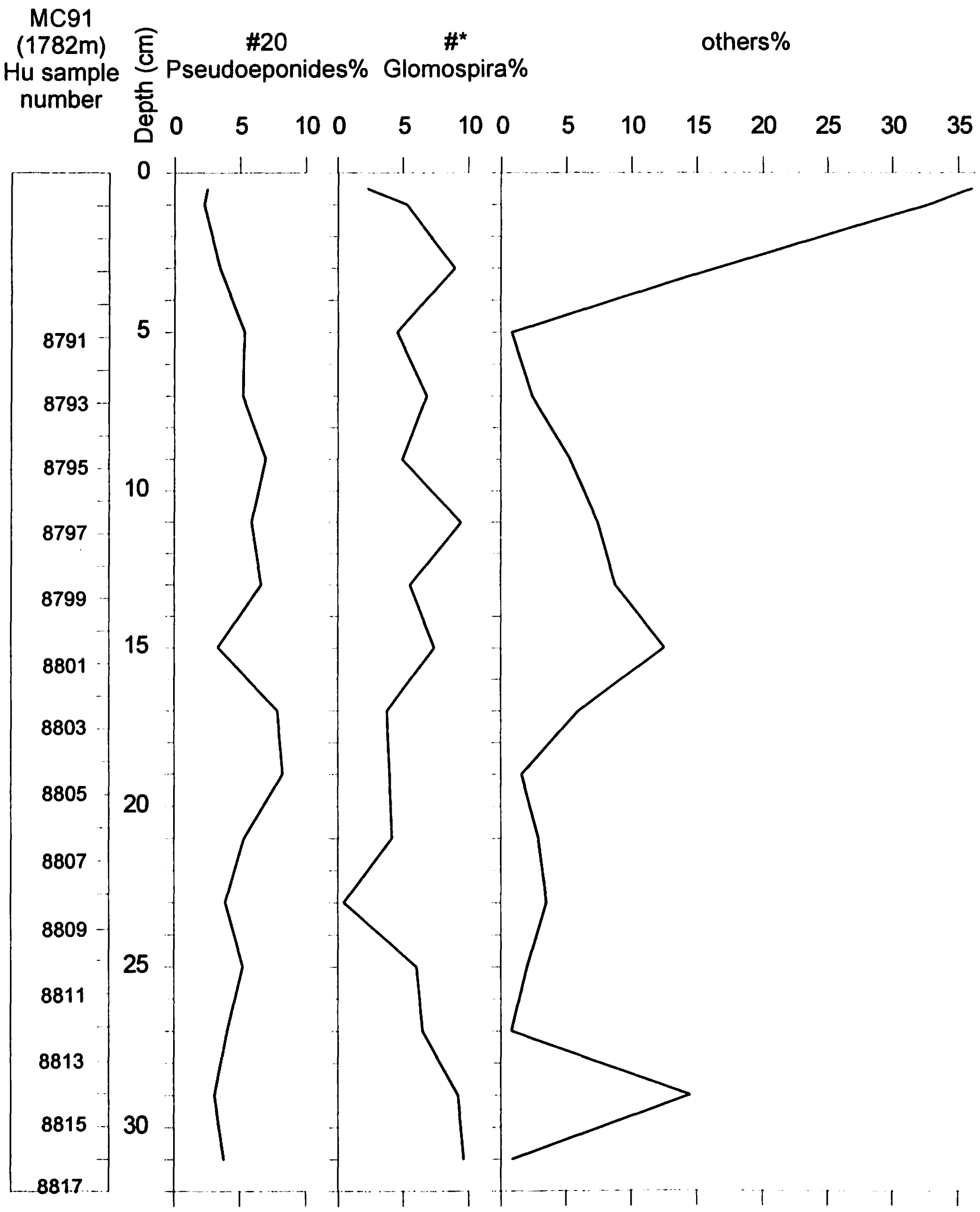


Fig. 19c. Relative abundance of benthic foraminifera in MC91 (1782 m depth)

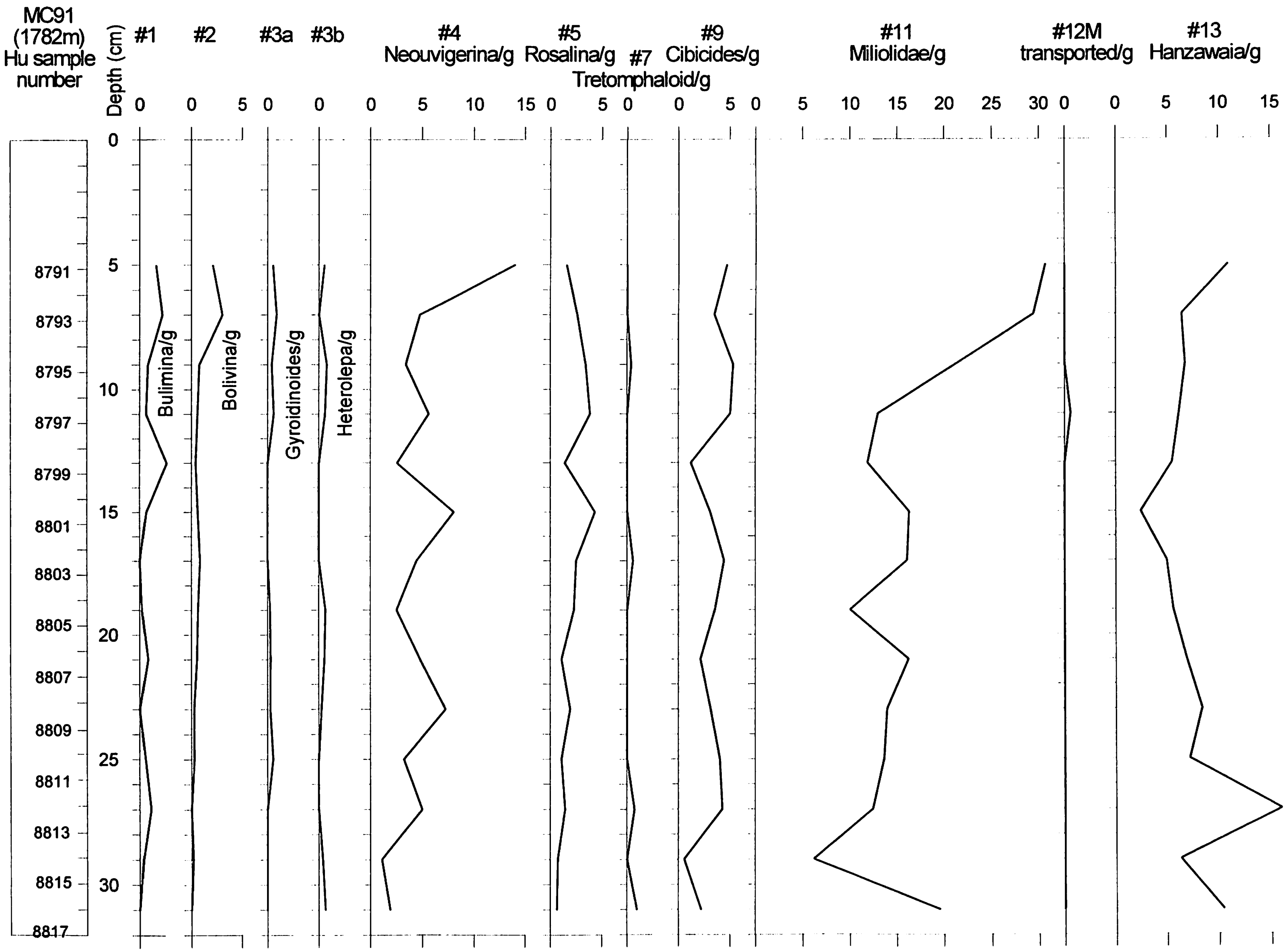


Fig. 20a. Total abundance of benthic foraminifera (specimens/g dry sediment) in MC91 (1782 m depth)

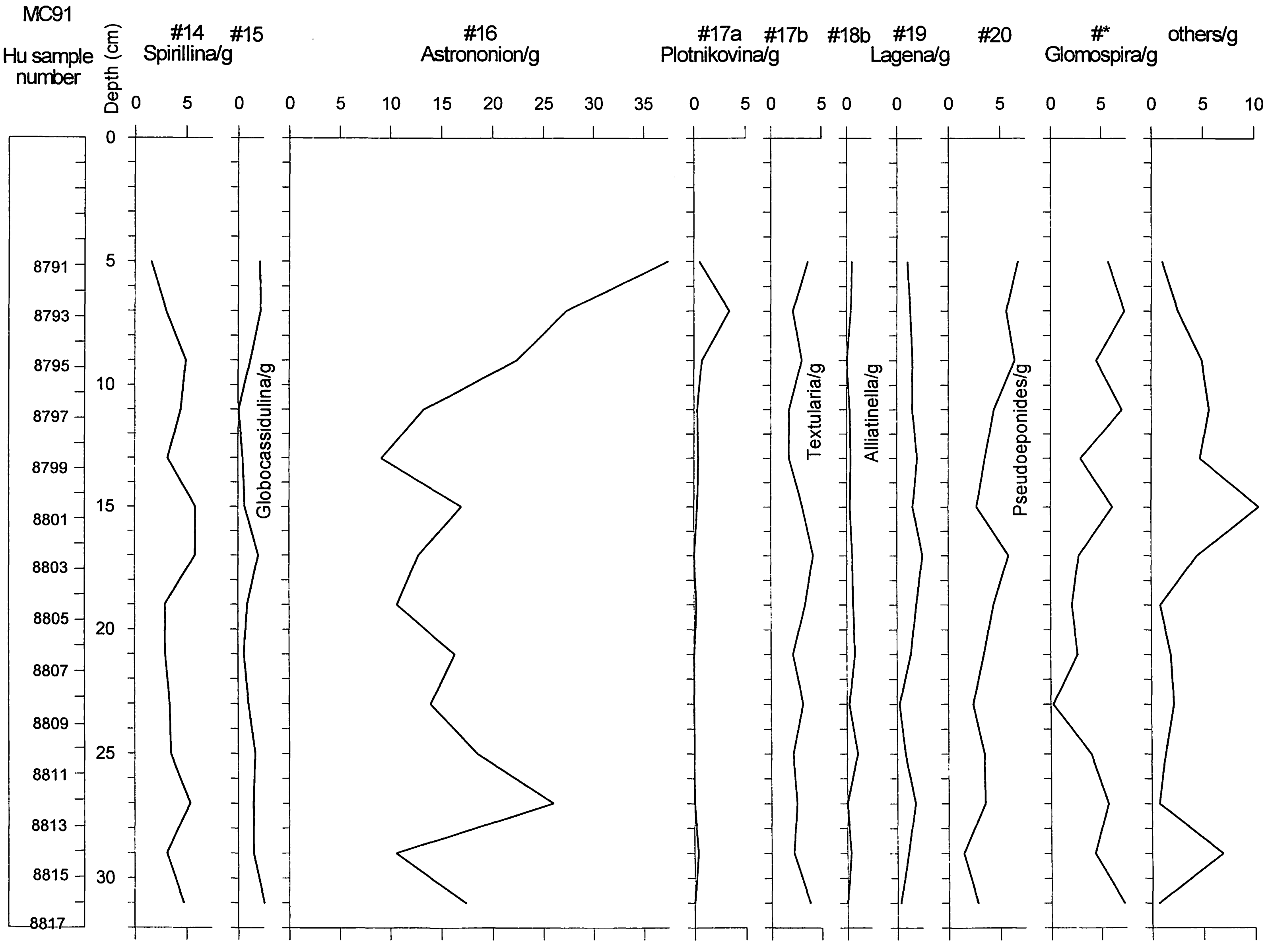


Fig. 20b. Total abundance of benthic foraminifera (specimens/g dry sediment) in MC91 (1782 m depth)

Correlation of the cores

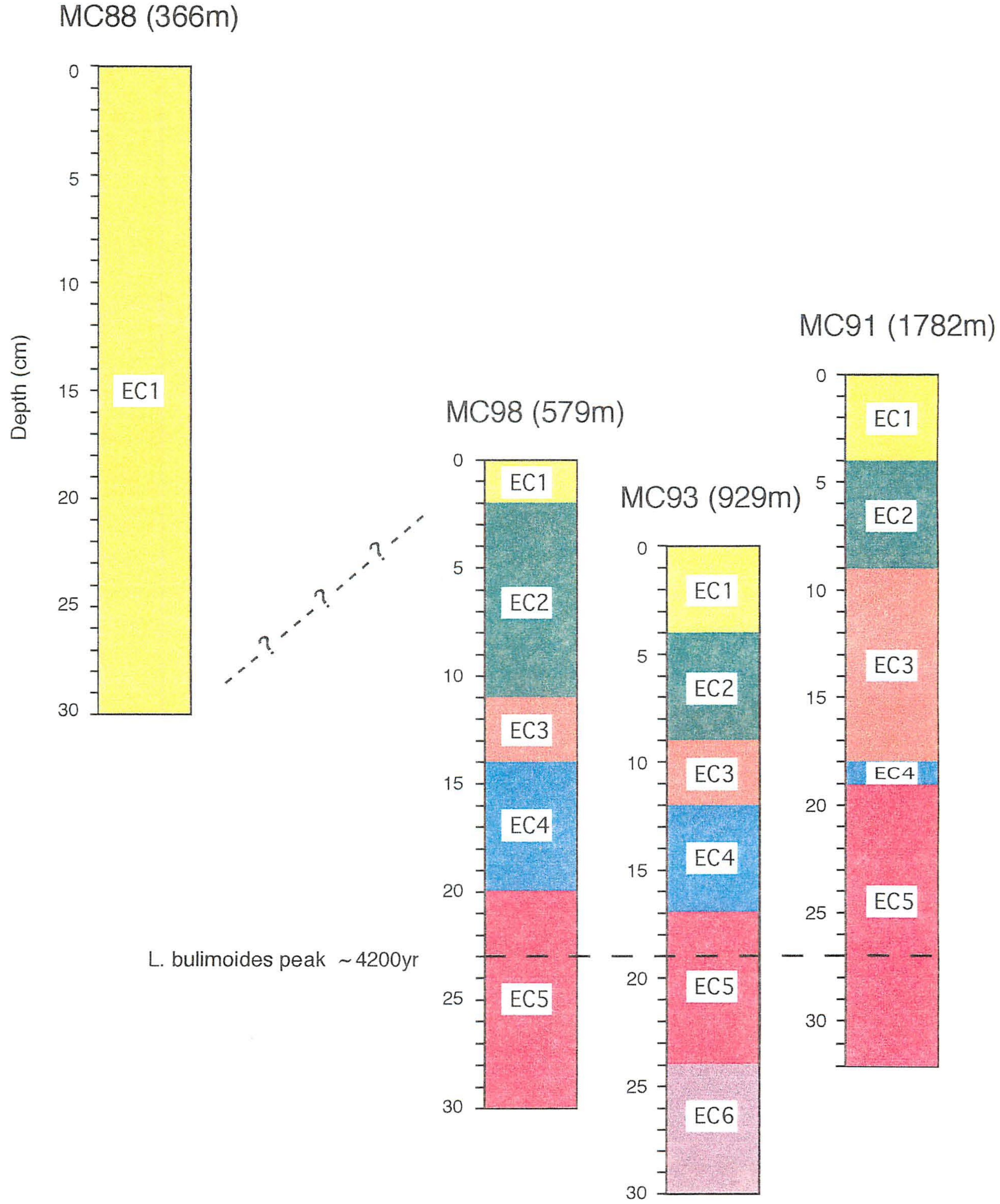


Fig. 21. Correlation of the cores: combined planktic foraminifera and Pteropoda zonation (datum line = L. bulimoides peak)

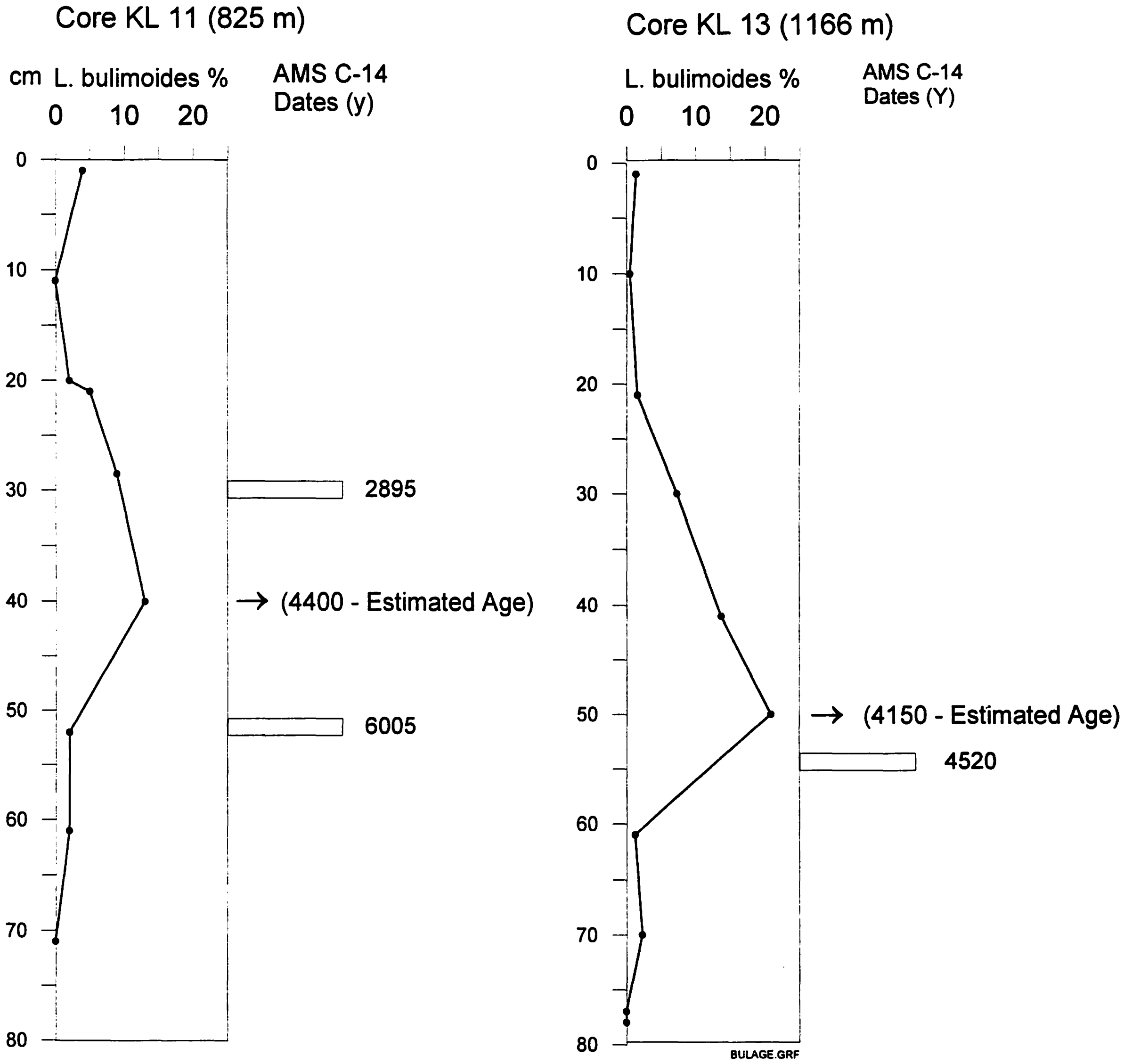


Fig. 22. L. bulimoides maximum abundance age estimation based upon AMS ^{14}C dates in cores KL11 and KL13, central Red Sea

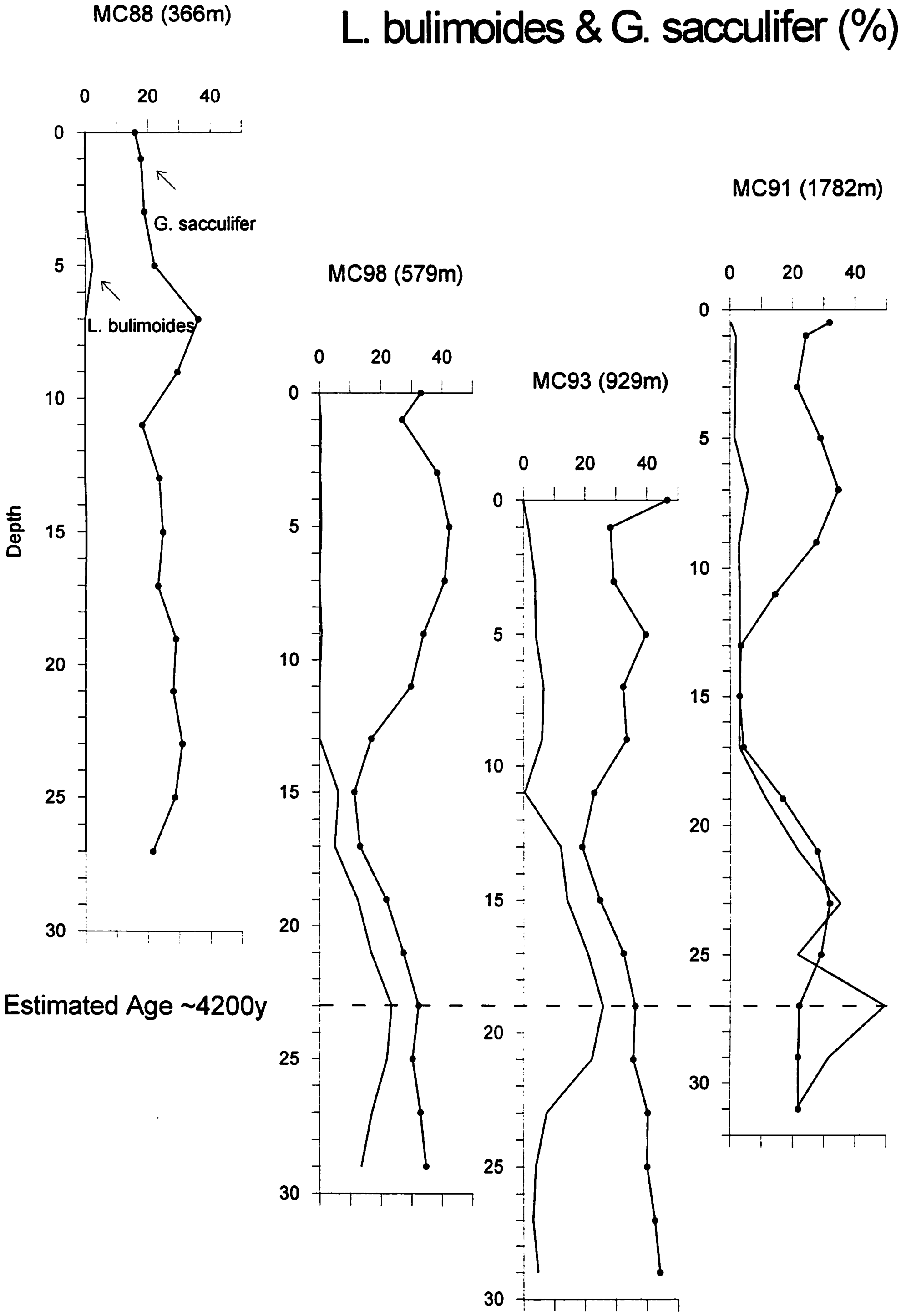


Fig. 23. Correlation between the relative abundance of both L. bulimoides and G. sacculifer in the four cores.

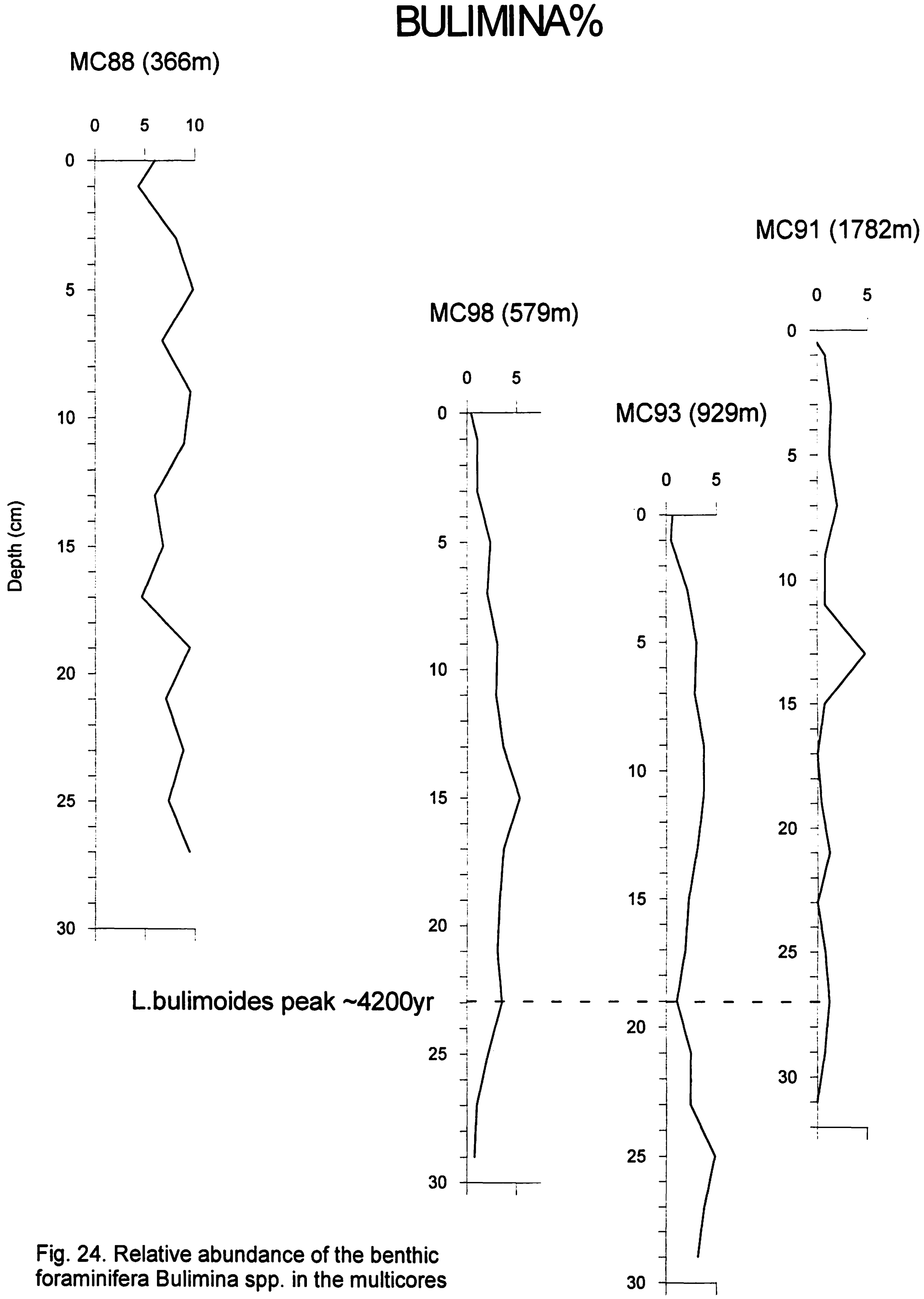


Fig. 24. Relative abundance of the benthic foraminifera Bulimina spp. in the multicores

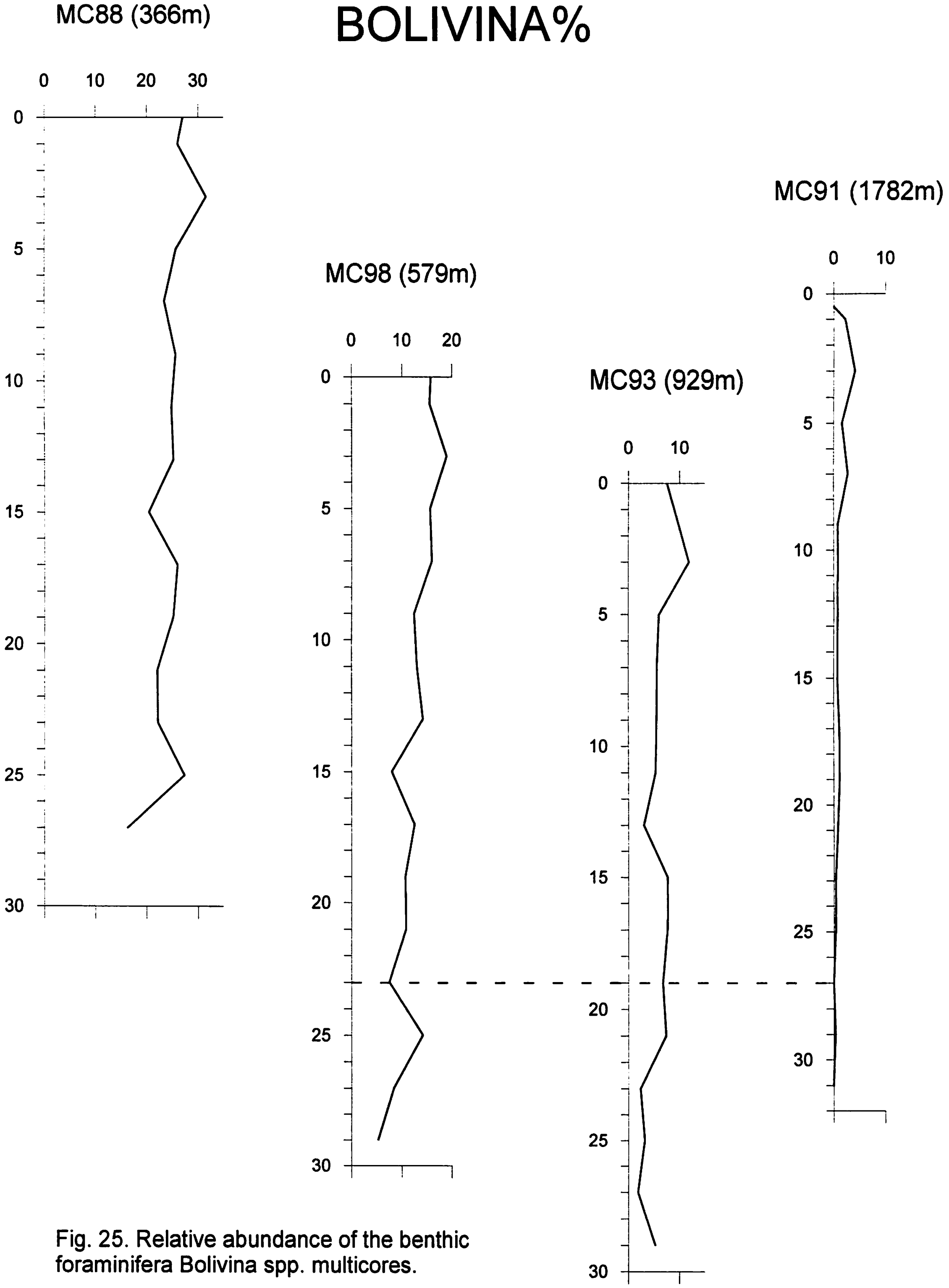


Fig. 25. Relative abundance of the benthic foraminifera Bolivina spp. multicores.

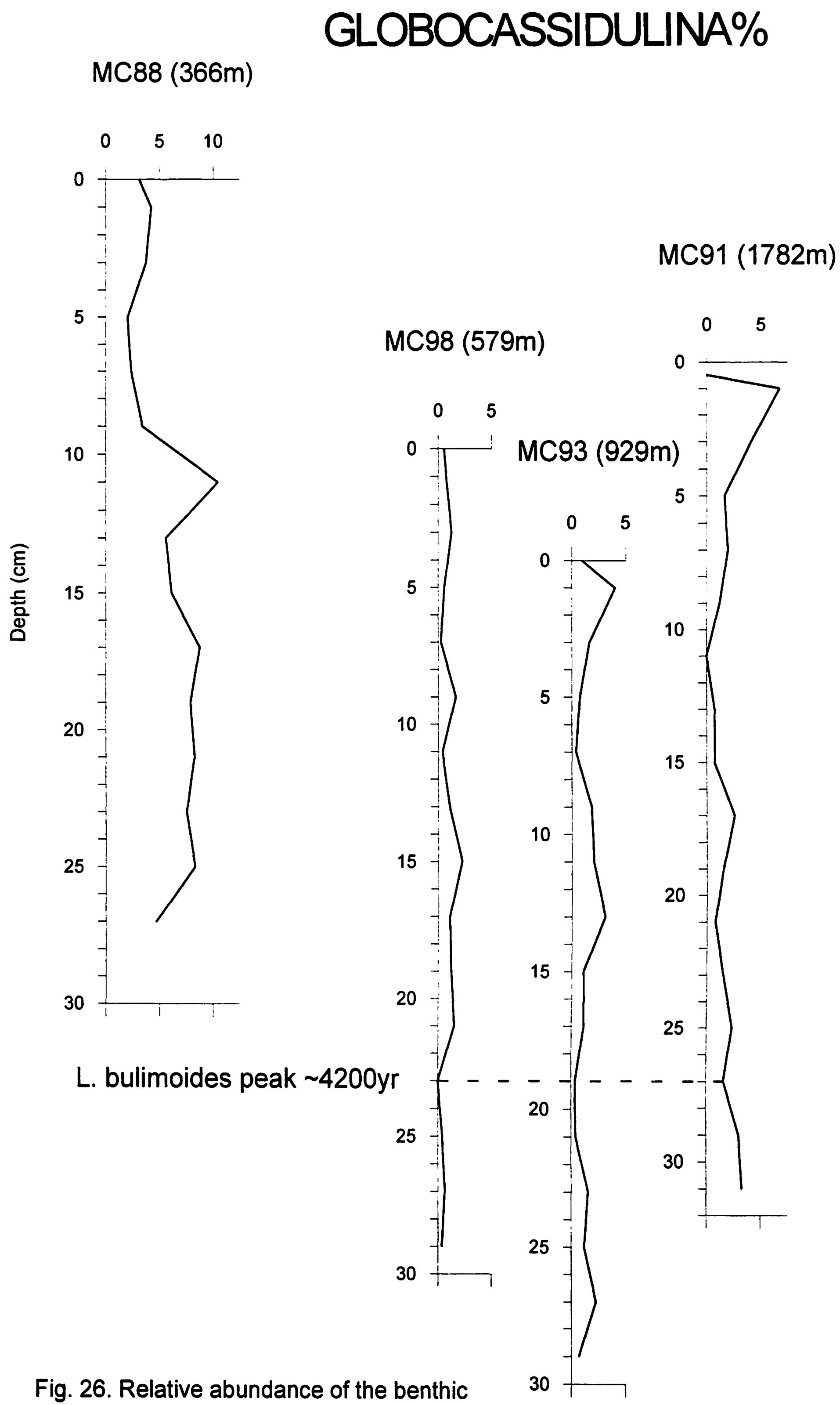


Fig. 26. Relative abundance of the benthic foraminifera Globocassidulina spp. in the multicores

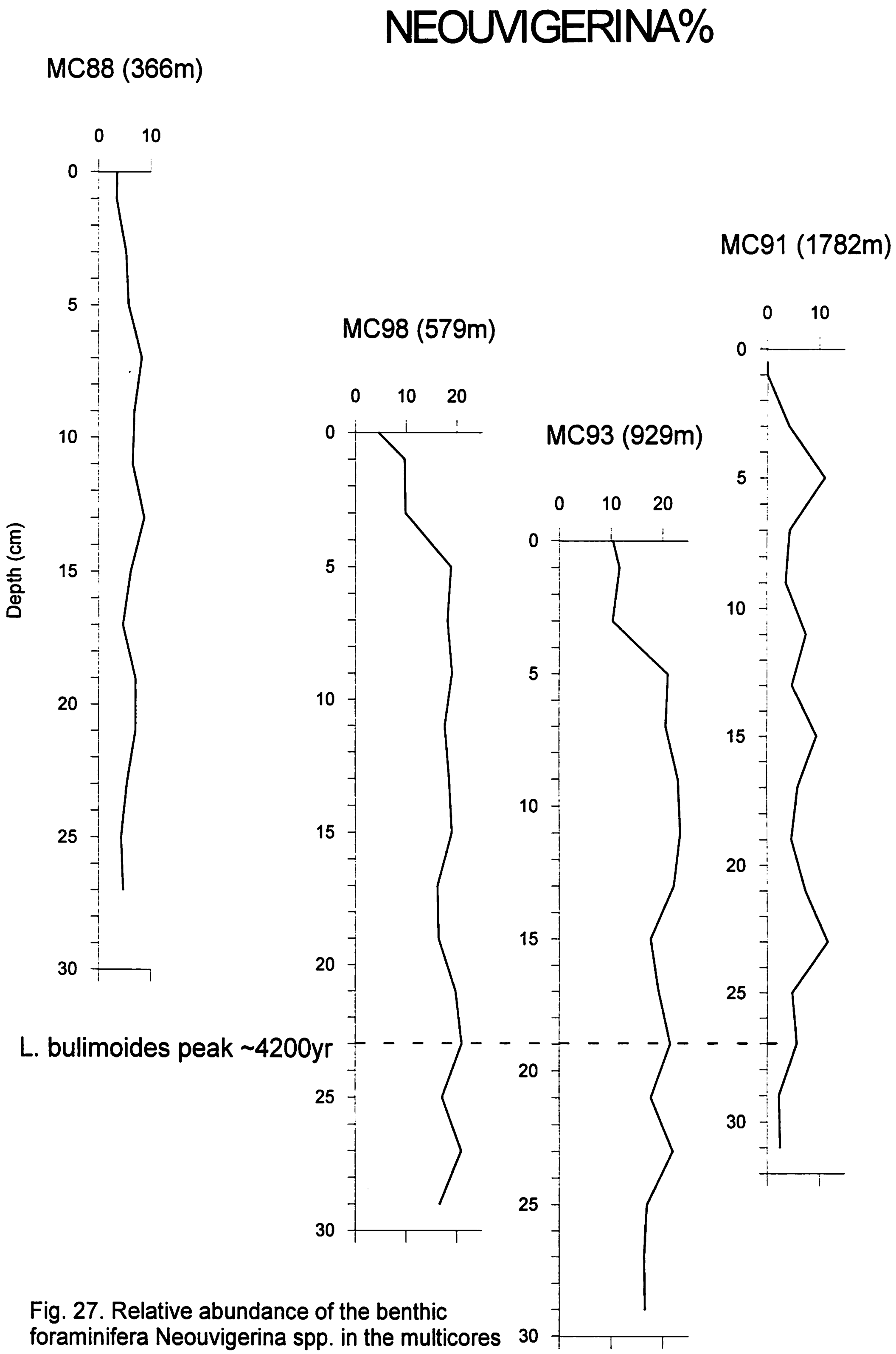


Fig. 27. Relative abundance of the benthic foraminifera Neouvigerina spp. in the multicores

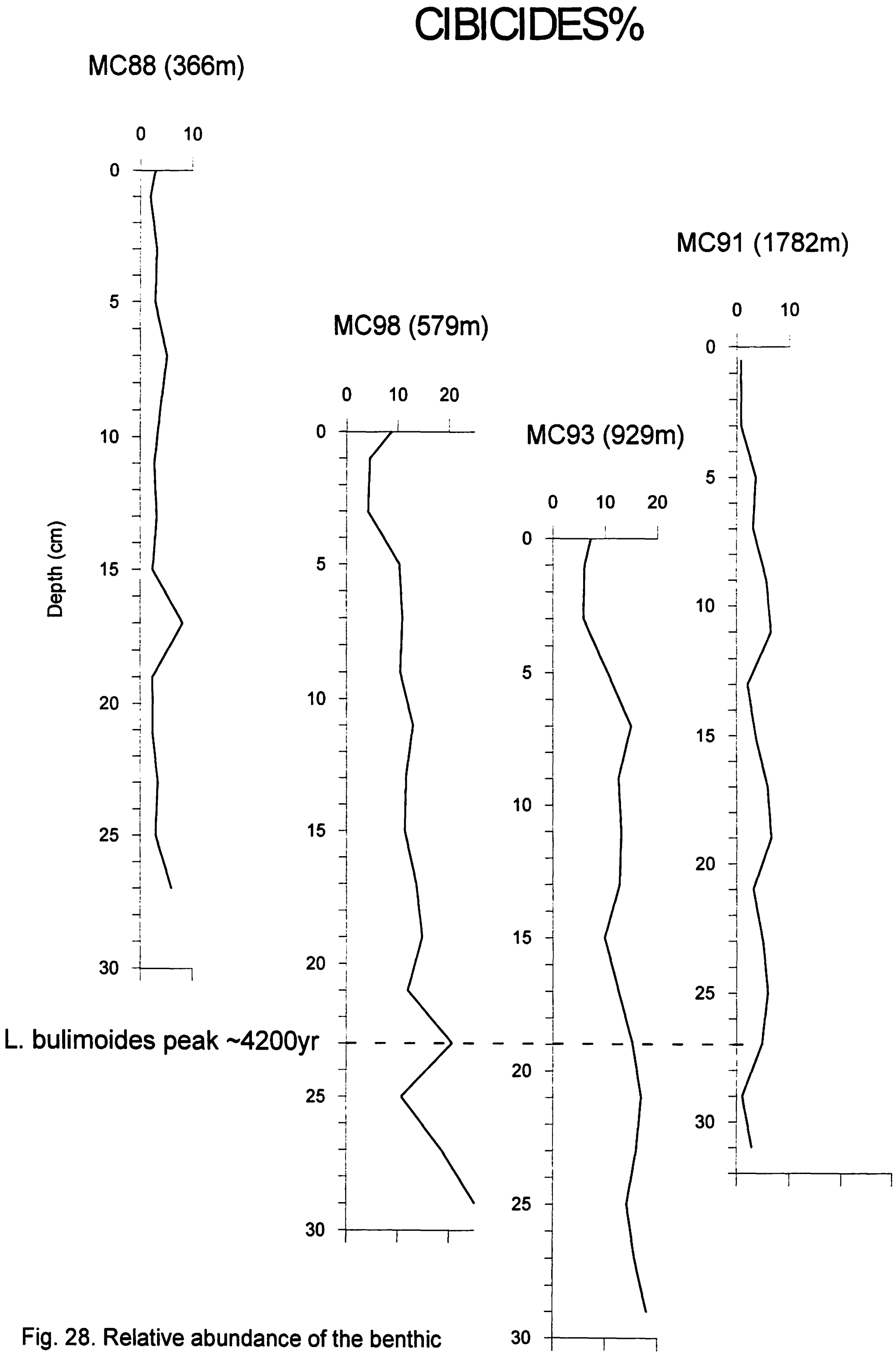


Fig. 28. Relative abundance of the benthic foraminifera Cibicides spp. in the multicores

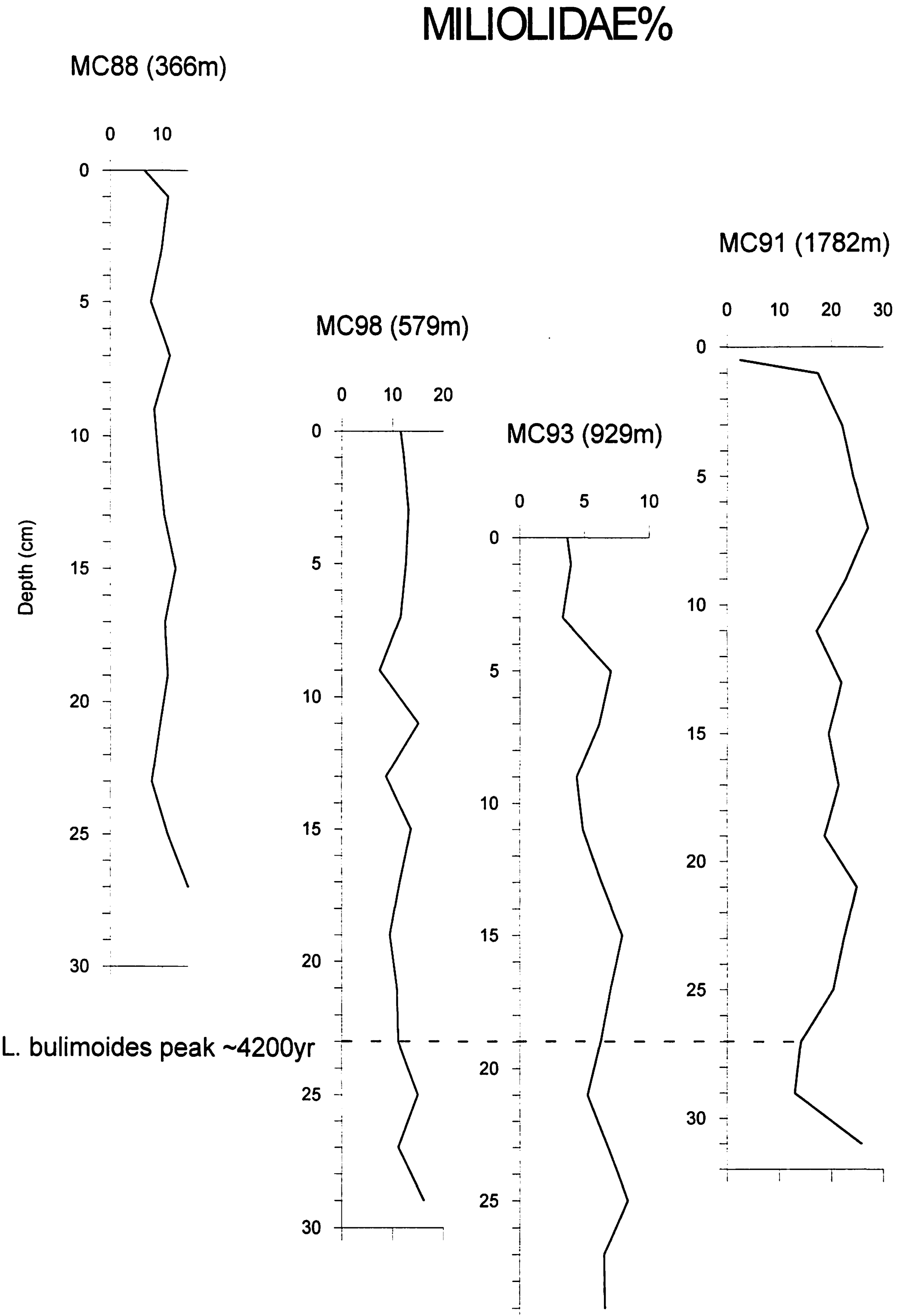


Fig. 29. Relative abundance of the benthic foraminifera Miliolidae spp. in the multicores

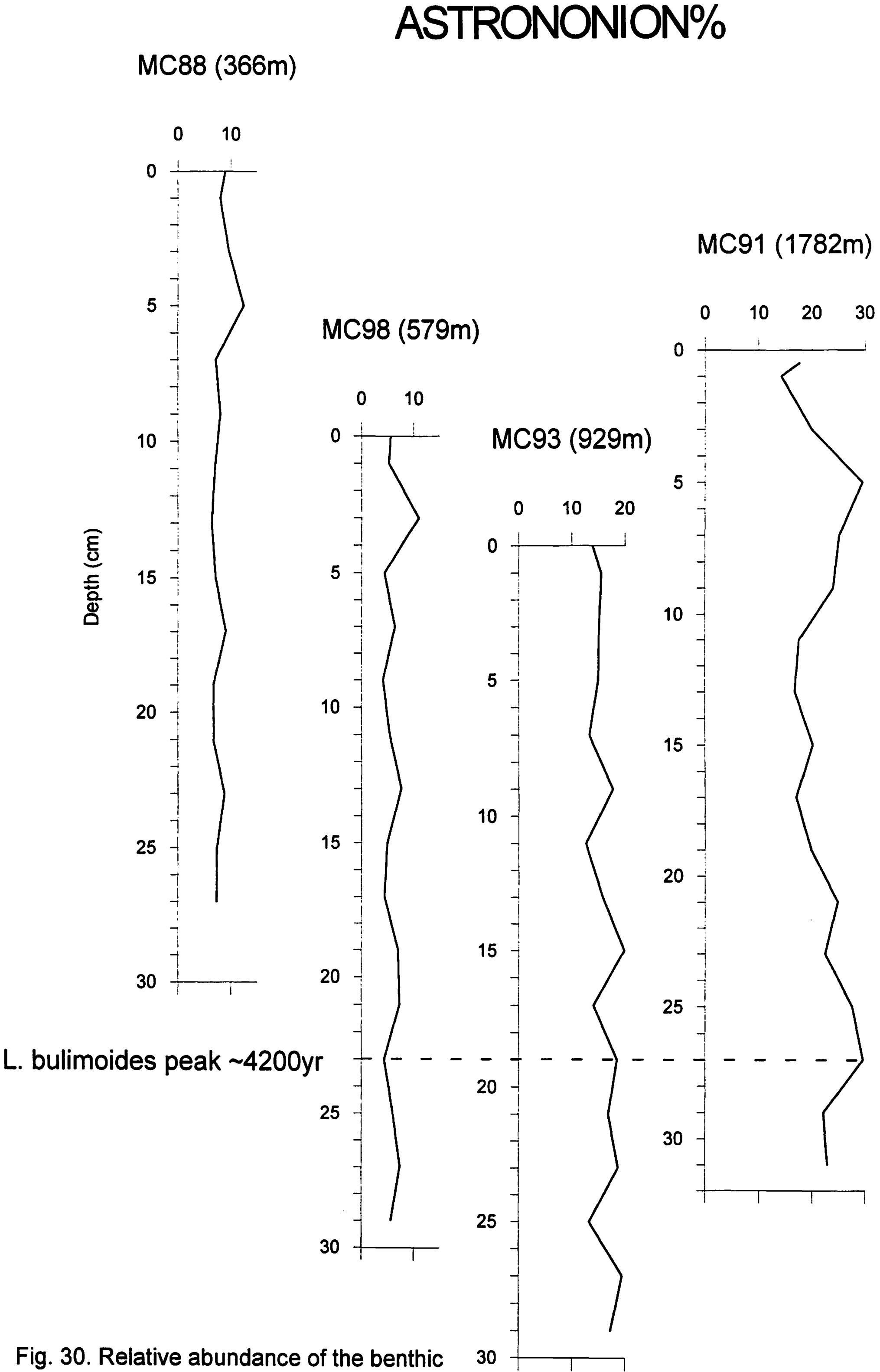


Fig. 30. Relative abundance of the benthic foraminifera Astrononion in the multicores

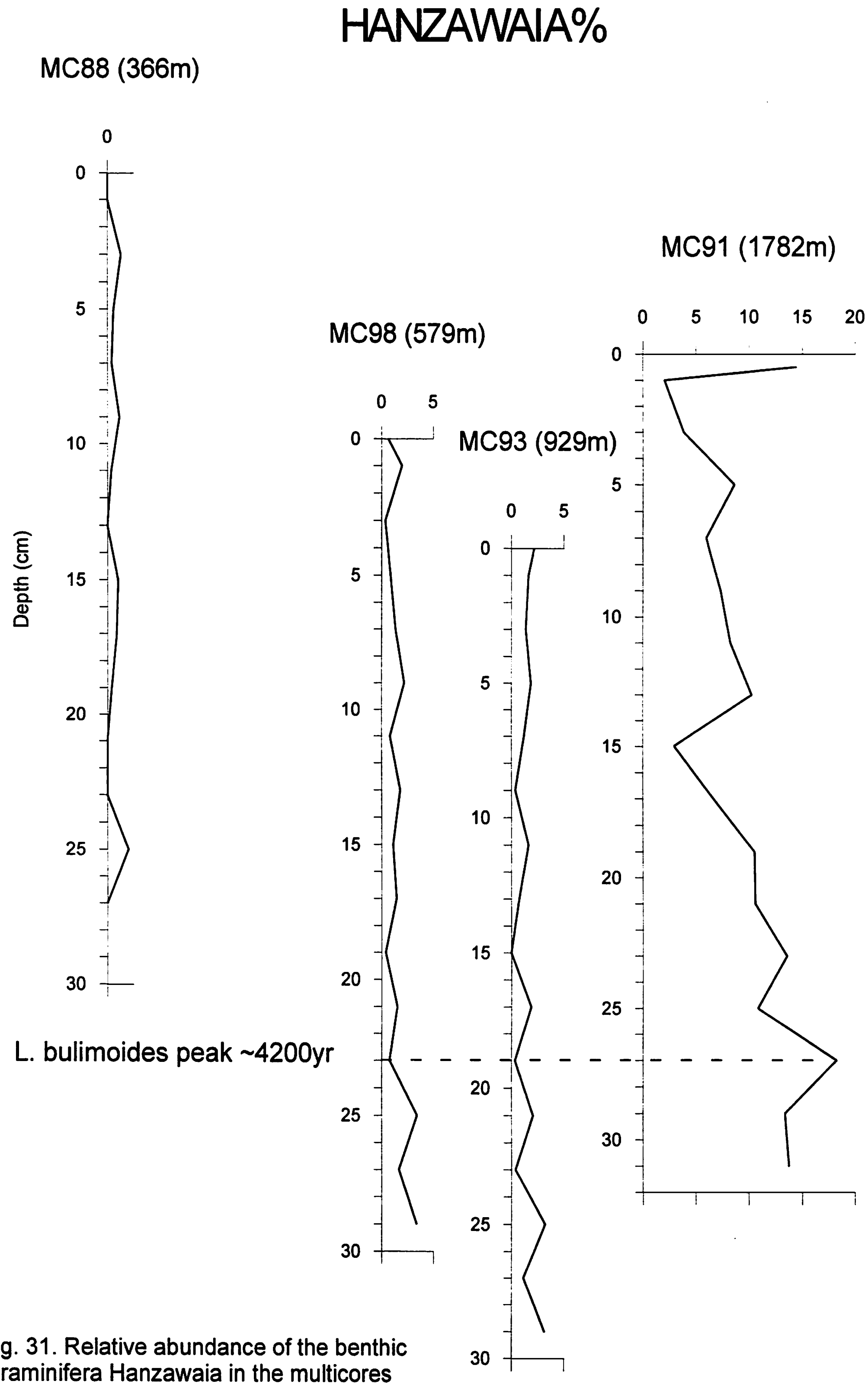


Fig. 31. Relative abundance of the benthic foraminifera Hanzawaia in the multicores

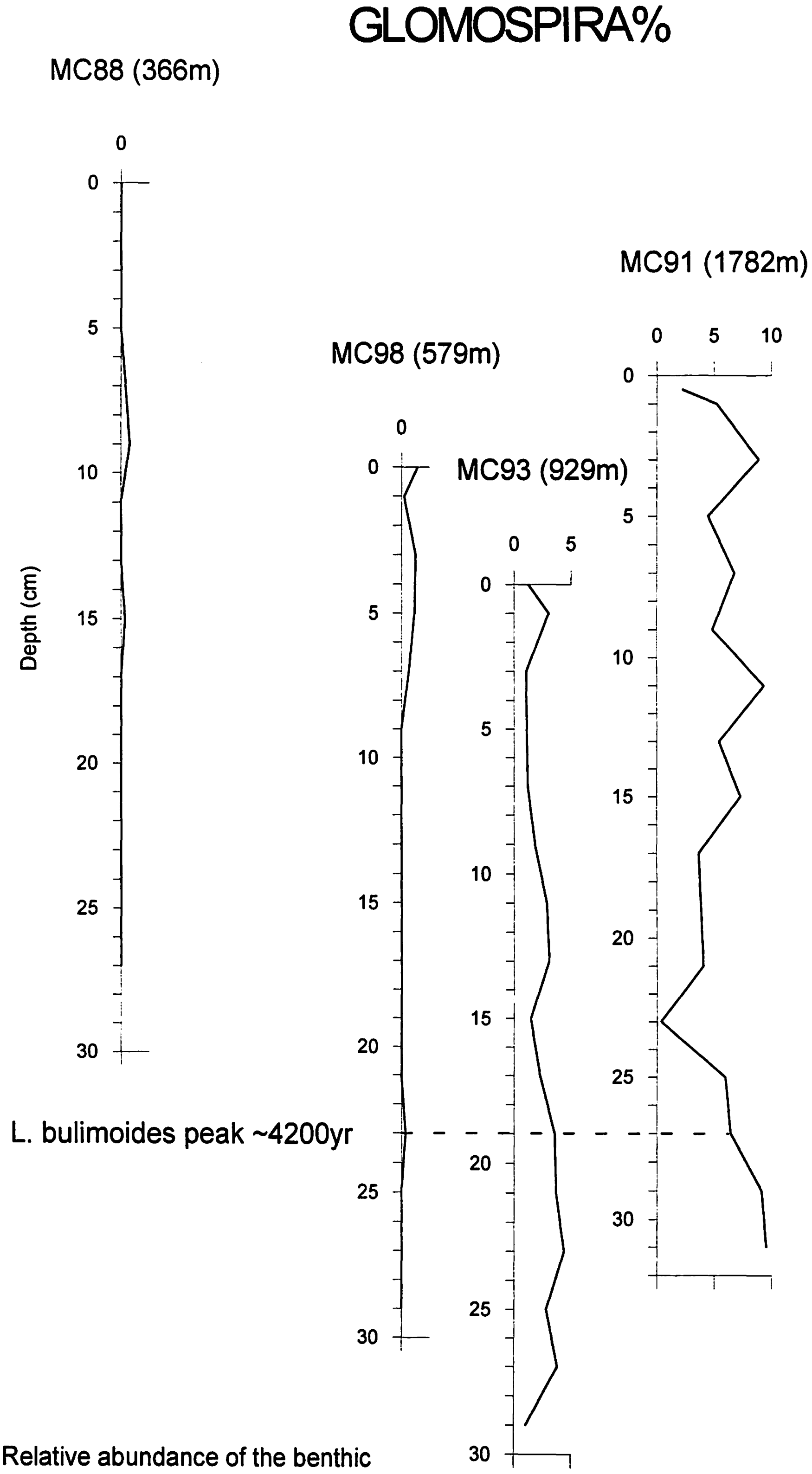


Fig. 32. Relative abundance of the benthic foraminifera Glomospira charoides in the multicores

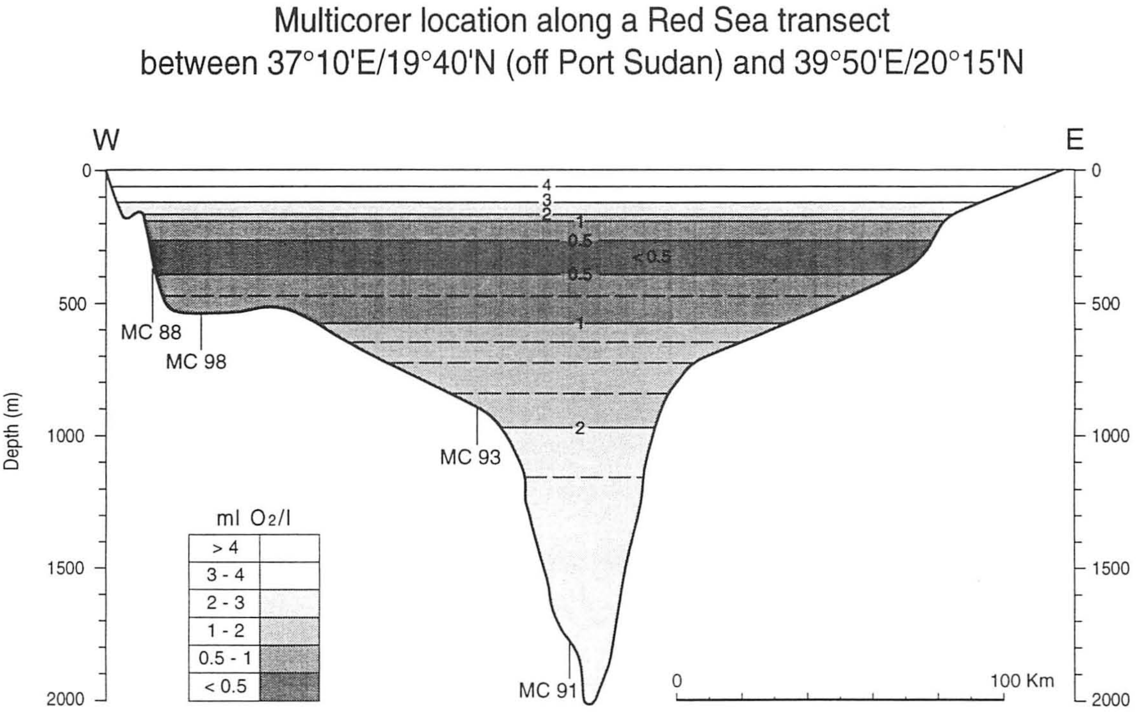
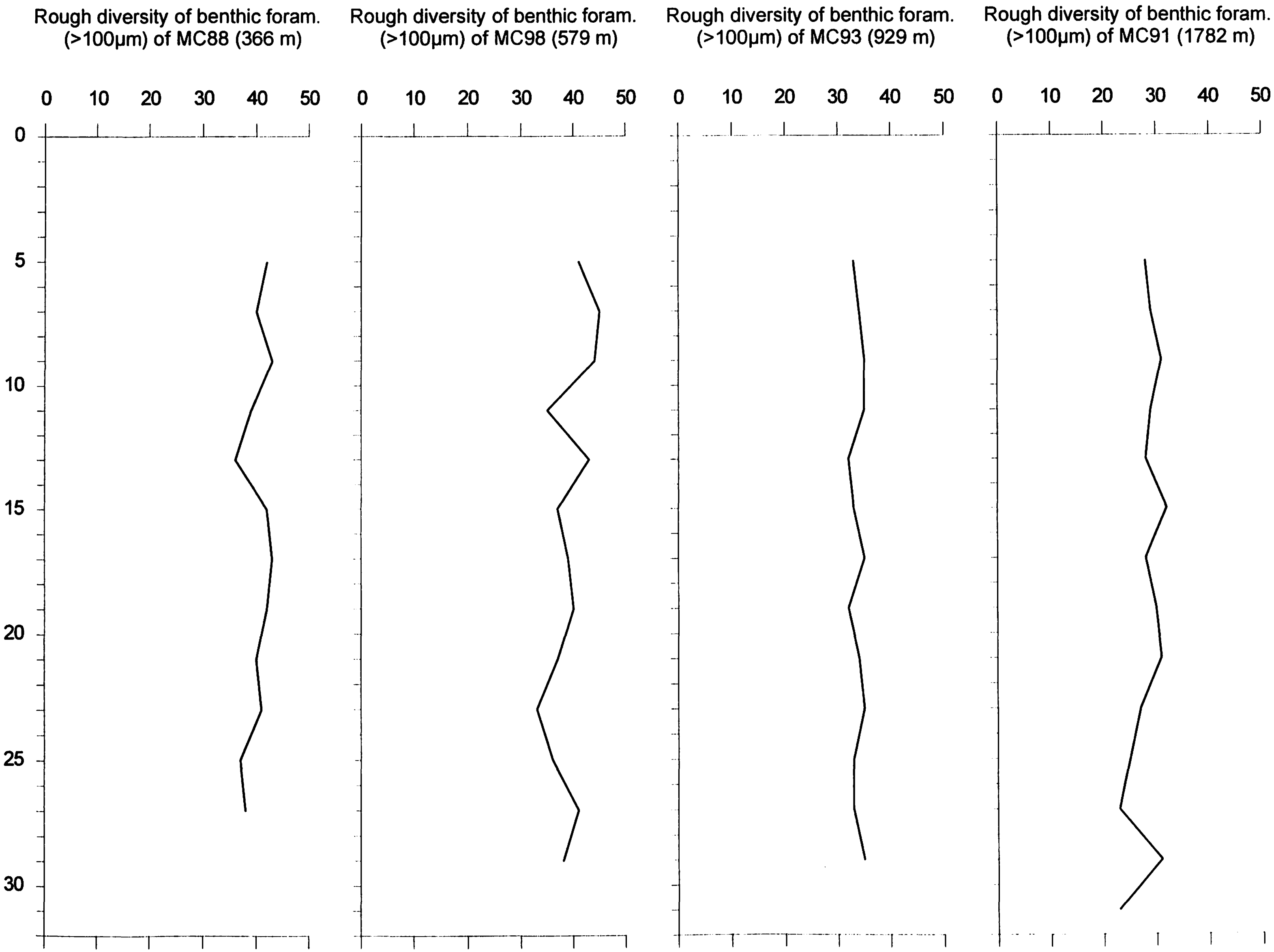


Fig. 33. Bathymetry is based on Coleman, 1972;
Schematic oxygen content is based on data from Newmann and Mcgill, 1962.


Rough diversity of benthic foram. (>100µm) of MC88 (366 m)

Rough diversity of benthic foram. (>100µm) of MC98 (579 m)

Rough diversity of benthic foram. (>100µm) of MC93 (929 m)

Rough diversity of benthic foram. (>100µm) of MC91 (1782 m)

Fig 34. Rough diversity calculated for the benthic foraminifera (benthic foram.) in the four cores.

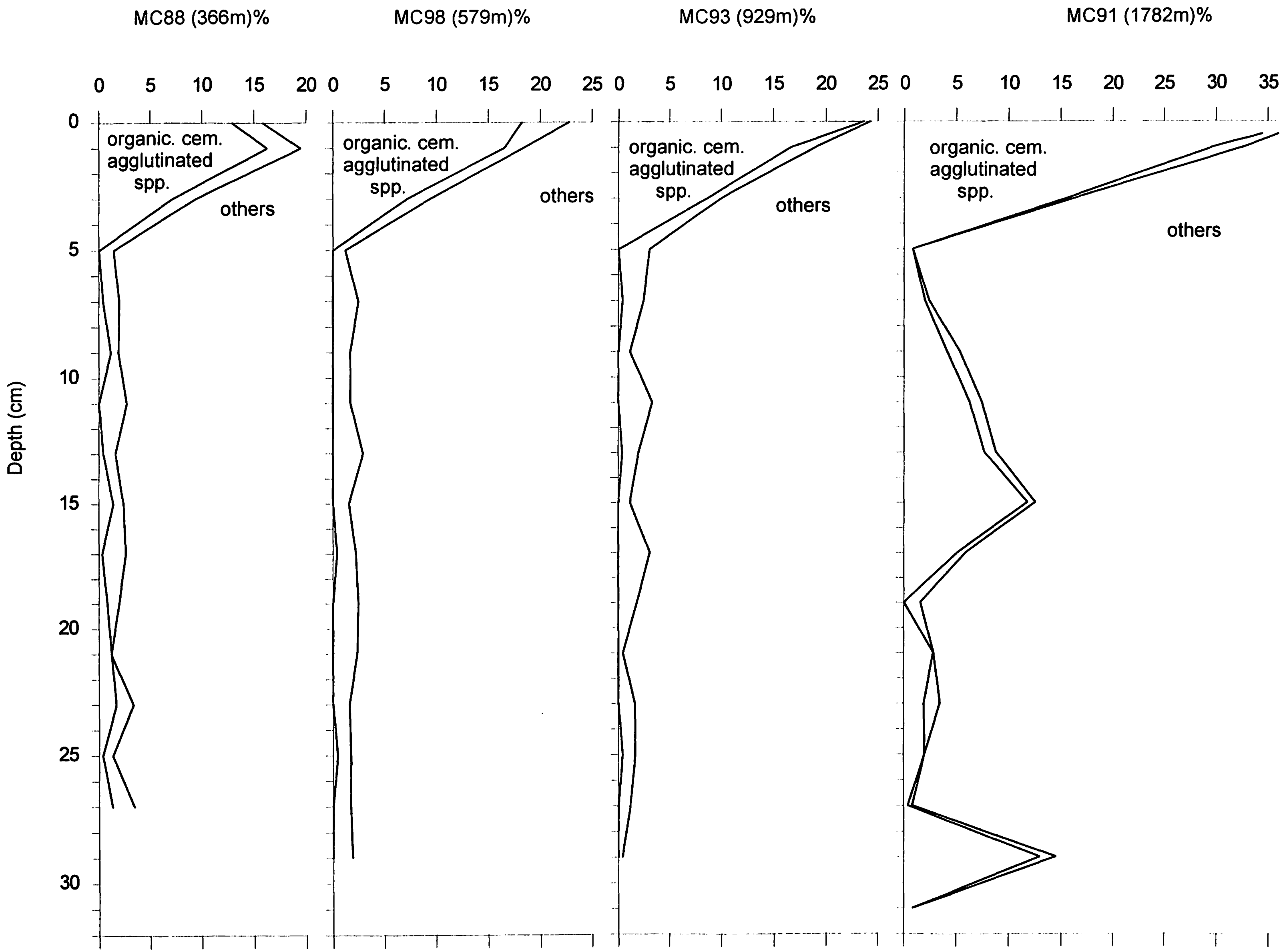


Fig. 36. The relative abundance of the organically (organic.) agglutinated cemented (cem.) foraminifera species as compared to "others".

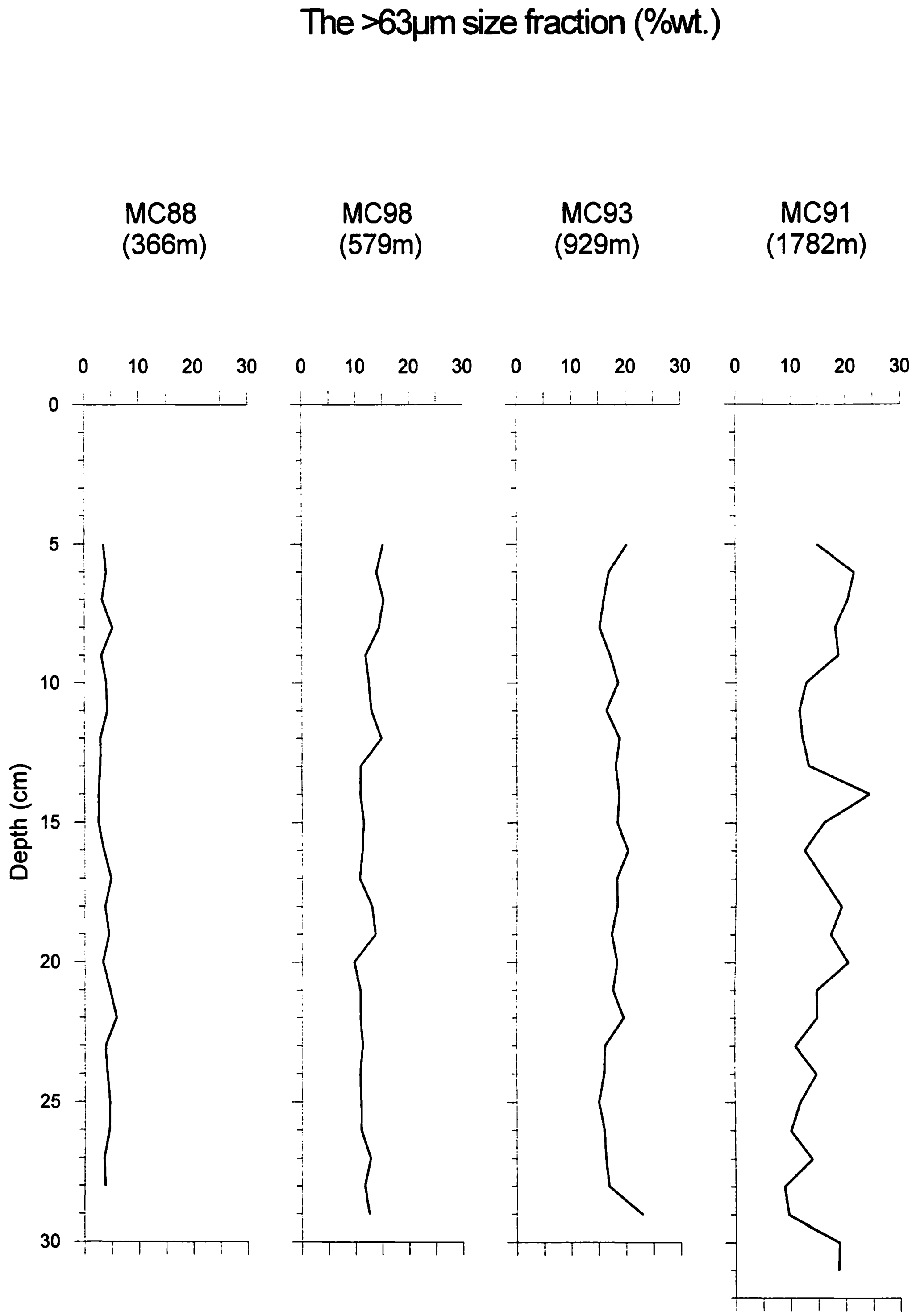


Fig. 37. The >63μm size fraction (%wt.).

תקציר

שינויים במאסף פטרופודה ופורמיניפרה פלנקטוניים ובנתוניים אפשרו זיהוי שינויים במבנה ותכונות עמודת המים האמצעית והעמוקה של ים סוף, ובהמשך הביאו לשחזור מפורט יותר של התנאים הפלאואוקינוגרפיים בהולוקן המאוחר. לשם כך נבדקו ארבעה גלעינים קצרים (multicores) שנדגמו ע״י פרופ. Ch. Hemleben מאוניברסיטת Tübingen, מעל סיפון אוניית המחקר ״מטאור״. הגלעינים נלקחו ממרכז ים סוף לאורך חתך מערב-מזרח, בעומקי מים של 366, 579, 929 ו- 1782 מטרים. הגלעינים ממוקמים בין קווי רוחב 19-20°N, דרומית לגבול המונסון הנוכחי (איזור ההתכנסות), ומאפיינים מסות מים שונות. קידוח אחד נלקח ממסת המים האמצעית המאופיינת בריכוז חמצן מינימלי (איזור ה- OMZ). קידוח נוסף נלקח ממסת המים האמצעית משולי ה- OMZ, ושני גלעינים הוצאו ממסת המים התחתונה, ממים עמוקים ומאווררים יותר.

לשם השגת רקורד בעל רזולוציה גבוהה, נלקחו דגימות בטווחים קרובים (כל 2 ס״מ). הדוגמאות נשטפו, נופו, יובשו, וחולקו בצורה אקראית לשם איסוף של כ- 300 פרטים של כל אחת מהקבוצות הבאות: פורמיניפרה פלנקטוניים, פורמיניפרה בנתוניים ופטרופודים. כל פרט הוגדר ונספר. קורלציה של שלושה מתוך ארבעת הקידוחים נעשתה ע״י שימוש בשיא הנפיצות של הפטרופוד *Limacina bulimoides*. שיא זה נצפה בעבר באיזורים נוספים של ים סוף, ותוארך לתקופה של ~4200 שנה לפני ההווה (yrBP). בקידוח הרדוד ביותר (MC88 - 366 מ׳) לא אובחן השיא הזה ולכן לא ניתן היה לקשור קידוח זה לשאר שלושת הקידוחים. בהסתמך על תיארוך שיא הנפיצות הזה, הוארך קצב השקעה של ~5/1000 ס״מ לשנה בשלושת הקידוחים ברי-ההשוואה, ולקצב של לפחות 11/1000 ס״מ לשנה בקידוח הרדוד. מכאן נקבע גיל של ~6400 yrBP לבסיס הקדום ביותר בקידוחים.

שינויים שנמצאו בהרכב ונפיצות המאסף הפלנקטוני בשלושת הקידוחים העמוקים, משקפים שינויים בתכונות עמודת המים של השכבה העליונה (mixed layer) ומסת המים האמצעית. שינויים אלה אפשרו את חלוקת הרקורד לשישה אופקים אקוסטרטיגרפיים יחודיים, וכן אפשרו שחזור פלאואוקינוגרפי של ה- ~6000 שנה האחרונות. עובי האופקים אינו משתנה באופן משמעותי מקידוח לקידוח ומצביע על כך שמאספי הפורמיניפרה ופטרופודה לא הופרעו ולא עברו המסה משמעותית.

מספר הפורמיניפרה הפלנקטוניים >149µm נע בין ~400 פרטים\גרם סדימנט בקידוח הרדוד, ל- ~4000 פרטים\גרם סדימנט בקידוח העמוק. גידול זה משקף מצד אחד את עובייה של עמודת המים, ומצד שני את הרכב המאסף העשיר במינים מזופלגיים בקידוח העמוק. השינויים בתכולת הקרבונט בסדימנט משתנים בהתאמה לשינוי במספרי הפורמיניפרים. השינויים הבולטים ביותר במאסף של הפורמיניפרה הפלנקטוניים מתייחסים לנפיצות היחסית של הפורמיניפר האפיפלגי *Globigerinoides ruber*, ושל המין המזופלגי *G. sacculifer*. נראה ששינויים אלה באים בעקבות השינויים המחזוריים בשיכוב ובמיקום ה- OMZ והפיקנוקלינה בעמודת המים, לעומת עומק האיזור הפוטי. אלו השפיעו גם כן על תנאי הרבייה האופטימליים הדרושים ל- *G. sacculifer*. מחזוריות שינויים אלה, היא בסביבות 3000 שנה.

ישנה התאמה טובה, בתקופה בין 5300-2400 yrBP, בין המחזוריות של *G. ruber* לעומת *G. sacculifer* לבין דגם ההופעה/העלמות של *L. bulimoides*. יחס זה תומך בהשערה ששיכוב עמודת המים היה חזק יותר ב- 3000 שנה האחרונות לעומת התקופה שבין 5300-3000 yrBP, ובעיקר בין 3000-2700 yrBP. שינויים פלאואוקינוגרפיים אלה משקפים שינויים אקלימיים, בייחוד באיזור הצפוני של ים סוף. מכאן, שמערכת חורפים יבשים וקשים יותר בצפון, גרמו לשקיעתם של מים צפופים לעומקי ביניים, בין 5300-3000 yrBP.

המידע המתייחס לפורמיניפרה הבנתוניים מאפשר חלוקה לשלושה מאספים בתימטריים: מאסף ה- OMZ (~350 מ׳), מאסף איזור הביניים של שולי ה- OMZ (~600-900 מ׳) והמאסף העמוק והמאוורר יותר (~1800 מ׳). שטפי החומר האורגני ומצב שימורו, ביחד עם רמות החמצן המומס במים התחתונים ובמי הנקבים של הסדימנט, משפיעים על הרכב המאספים הבנתוניים הספציפיים. המינים הדומיננטיים המרכיבים את מאסף ה- OMZ הם המינים האינפאונליים *Bolivina, Bulimina* ו- *Globocassidulina*. מאסף הביניים של שולי ה- OMZ מורכב מהמינים האפיפאונליים עד אינפאונליים רדודים *Neouvigerina* ו- *Cibicides*, והמאסף העמוק והמאוורר יותר, מורכב מהמינים האפיפאונליים עד אינפאונליים רדודים *Hanzawaia*, *Miliolidae*, *Astrononion* ו- *Glomospira*.

תכולת החומר האורגני, הקלציום קרבונט, הפרקציה >63 µm כמו גם הפורמיניפרה הבנתוניים, לא משתנים באופן מובהק לאורך כל אחד מהקידוחים ובכך מעידים שבאופן כללי גוף המים העמוק לא השתנה מהותית במשך ה- ~6000 שנה האחרונות. זאת בניגוד לשינויים שנמצאו במאספים הפלנקטוניים, המייצגים את שכבת המים העליונה והאמצעית.

משרד התשתיות הלאומיות
המכון הגיאולוגי

שחזור הארועים הפלאואוקינוגרפיים בהולוקן המאוחר של ים סוף

יעל אדלמן

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דו"ח מס' GSI / 5 / 98
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