PLIOCENE-PLEISTOCENE RADIOLARIAN INVESTIGATIONS OF THE EQUATORIAL OCEANS.

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SEC = North and South Equatorial Currents; NECC = North Equatorial Counter

Current; EUC = Equatorial Under Current; CC = California Current; PC = Peru

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ABSTRACT

This study explores and develops the application of Polycystine

radiolarian microfossils to the investigation of Late Cenozoic deep-sea

sediments recovered by the Deep Sea Drilling Program (DSDP) and

Ocean Drilling Program (ODP), and utilizes these advances in

undertaking a detailed palaeoenvironmental study of the Plio-Pleistocene

Olduvai magnetosubchron (1.95-1.79Ma) of the equatorial Indo-Pacific

Oceans. A number of radiolarian tools are used as palaeoceanographic

proxies, including the recognition of distinct glacial and interglacial

assemblages, which form the basis of a new Radiolarian Temperature

Index (RTI), and the further development and refinement of the Upwelling

Radiolarian Index (URI), shown here for the first time to be applicable to

upwelling regions throughout the Plio-Pleistocene equatorial Oceans.

Radiolarian biostratigraphy is also investigated, confirming that a

recently devised Plio-Pleistocene biozonation scheme for the Indian

Ocean is also largely applicable in the Atlantic, and also provides the

first astronomically calibrated radiolarian biodatums for the Indian Ocean

Plio-Pleistocene. Stratigraphy based on synchronous abundance

variations of *Cycladophora davisiana*, previously only used in high-

latitude regions, is assessed in low-latitudes with encouraging results,

including a significant abundance peak coincident with the Plio-

Pleistocene boundary in both the Indian and Pacific Oceans. The

potential of this dating technique for intra- and inter-oceanic correlation at all latitudes is demonstrated.

The palaeoceanographic reconstruction of the Indo-Pacific Olduvai subchron indicates a tripartite palaeoceanographic division of the subchron, with conditions analagous to the modern El Niño prevalent during the middle part of the Olduvai. In the eastern equatorial Pacific at this time, trade wind intensity, upwelling, and bioproductivity is reduced, with a concomitant rise in sea-surface temperatures. A comparison with land sequences indicate palaeoenvironmental changes consistent with known El Niño phenomena, although these conditions are likely to lay beyond the present-day natural limits of interannual El Niño variability.

1. INTRODUCTION TO OVERVIEW

This report is an overview of 15 research papers published between 1992 and 1998 concerning the taxonomy of Pliocene-Pleistocene Radiolaria and their biostratigraphic and palaeoceanographic applications. This overview reviews the field of radiolarian research in terms of biostratigraphy and palaeoceanography and demonstrates the original contribution made by the author to the development of these fields through the publication of the submitted papers. It also outlines the results of the study into the palaeoceanography of the Equatorial Oceans during the Olduvai magnetosubchron (1.95-1.79Ma), and for the first time compares these results with other studies of Olduvai palaeoenvironments from around the world.

The papers included in this overview are listed below, and wherever they are cited within the text of the overview they are marked with an asterisc (*e.g.* *Haslett, 1992).

1. *Funnell, B. M., Haslett, S. K., Kennington, K., Swallow, J. E., & Kersley, C. L., 1996. Strangeness of the equatorial Ocean during the Olduvai magnetosubchron (1.95 to 1.79 Ma). In: A. Moguilevsky & R. Whatley (eds.) *Microfossils and Oceanic Environments*. University of Wales, Aberystwyth Press, 93-109.

2. *Haslett, S. K., 1992. Early Pleistocene glacial-interglacial radiolarian assemblages from the eastern equatorial Pacific. *Journal of Plankton Research*, **14**, 1553-1563.

3. *Haslett, S. K., 1994a. High-resolution radiolarian abundance data through the Late Pliocene Olduvai subchron of ODP Hole 677A (Panama Basin, eastern equatorial Pacific). *Revista Española de Micropaleontologia*, **26**, 127-162.

4. *Haslett, S. K., 1994b. Plio-Pleistocene radiolarian biostratigraphy and palaeoceanography of the mid-latitude North Atlantic (DSDP Site 609). *Geological Magazine*, **131**, 57-66.

5. *Haslett, S. K., 1995a. Modern and palaeoecological significance of the radiolarian *Spongaster tetras tetras* Ehrenberg in the eastern equatorial Pacific. *P. S. Z. N. I: Marine Ecology*, **16**, 273-281.

6. *Haslett, S. K., 1995b. Mapping Holocene upwelling in the eastern equatorial Pacific using Radiolaria. *The Holocene*, **5**, 470-478.

7. *Haslett, S. K., 1995c. Pliocene-Pleistocene radiolarian biostratigraphy and palaeoceanography of the North Atlantic. In: R. A. Scrutton, M. S. Stoker, G. B. Shimmield, & A. W. Tudhope (eds.) *The Tectonics, Sedimentation and Palaeoceanography of the North Atlantic Region*. Geological Society Special Publication No. 90, 217-225.

8. *Haslett, S. K., 1996. Radiolarian faunal data through the Plio-Pleistocene Olduvai magnetosubchron of ODP Leg 138 sites 847, 850, and 851 (eastern equatorial Pacific). *Revista Española de Micropaleontologia*, **28**, 225-256.

9. *Haslett, S. K., & Funnell, B. M., 1996. Sea-surface temperature variation and palaeo-upwelling throughout the Plio-Pleistocene Olduvai subchron of the eastern equatorial Pacific: an analysis of radiolarian data from ODP sites 677, 847, 850 and 851. In: A. Moguilevsky & R. Whatley (eds.) *Microfossils and Oceanic Environments*. University of Wales, Aberystwyth Press, 155-164.

10. *Haslett, S. K., & Funnell, B. M., 1998. Low-latitude Plio-Pleistocene temporal abundance variations in the radiolarian *Cycladophora davisiana* Ehrenberg: stratigraphic and palaeoceanographic significance. In: A. Cramp, C. J. McLeod, S. V. Lee, & E. J. W. Jones (eds.) *Geological Evolution of Ocean Basins: Results from the Ocean Drilling Program*. Geological Society Special Publication, No. 131, 83-89.

11. *Haslett, S. K., Funnell, B. M., & Dunn, C. L., 1994a. Calcite preservation, palaeoproductivity and the radiolarian *Lamprocyrtis neoheteroporos* Kling in Plio-Pleistocene sediments from the eastern equatorial Pacific. *Neues Jahrbuch für Geologie und Paläontologie, Monatschefte*, **1994**, 82-94.

12. *Haslett, S. K., Funnell, B. M., Bloxham, K. S., & Dunn, C. L., 1994b. Plio-Pleistocene palaeoceanography of the tropical Indian Ocean (ODP Hole 709C): radiolarian and $CaCO_3$ evidence. *Journal of Quaternary Science*, **9**, 199-208.

13. *Haslett, S. K., Kennington, K., Funnell, B. M.. & Kersley, C. L., 1995. Pliocene-Pleistocene radiolarian and diatom biostratigraphy of ODP

Hole 709C (equatorial Indian Ocean). *Journal of Micropalaeontology*, **14**, 135-143.

14. *Kennington, K., Haslett, S. K., & Funnell, B. M., in press. Offshore transport of neritic diatoms as indicators of surface current and trade wind strength in the Plio-Pleistocene eastern equatorial Pacific. *Palaeogeography, Palaeoclimatology, Palaeoecology.*

15. *Zhao, M., Haslett, S. K., Jordan, R. W., Knaack, J. J., Sarnthein, M., Teece, M., & Eglinton, G., in press. Muli-proxy sedimentary records of upwelling and wind systems off NW Africa over the last 35,000 years. *Earth & Planetary Science Letters.*

2. APPLICATION OF RADIOLARIA TO PLIOCENE-PLEISTOCENE PALAEOCEANOGRAPHY AND BIOSTRATIGRAPHY.

Polycystine Radiolaria are planktonic marine Sarcodine protozoa that secrete a siliceous opaline test. The Superorder Polycystina is divided into two Orders of Radiolaria, the Spumellaria (skeleton in the form of a sphere, or derived from a sphere, e.g. ellipsoidal, discoidal, lenticular, spiral), and the Nassellaria (skeleton bipolar and usually bilaterally symmetrical). Although Radiolaria can be studied using both reflected light and scanning electron microscopy, traditionally they have been mounted in Canada balsam and viewed in transmitted light. This allows for examination of internal spicules and skeletal structure, features that are important for identification (Anderson, 1983; Brasier, 1980; Casey, 1993; De Wever et al., 1994; Haslett, 1993; Kling, 1978).

The purpose of this review is to outline the application of Radiolaria to Late Neogene-Quaternary studies, which is principally two-fold; 1) their use in reconstructing past oceanographic environments; and 2) their use in dating deep-sea sediments.

2.1 Radiolaria and Palaeoceanography

Radiolaria are holoplanktonic marine organisms mainly found living in the open ocean, rather than in neritic environments, inhabiting the water column from the surface to depths of many hundreds of meters (Renz, 1976; Kling,

1979; Dworetzky & Morley, 1987). There are in excess of 500 extant

species. Such species diversity is attributable to the niche-specific ecology

of many species, and indeed Casey *et al.* (1990) state that expanding

ocean niche-diversity through the Cenozoic is matched by a concomitant

increase in radiolarian allopatric speciation and diversity. Therefore,

Radiolaria are invaluable in the late Cenozoic as proxy indicators of ocean

water masses, water depth, water temperature, nutrient availability, and

physical processes, such as upwelling.

Riedel (1958), comparing differences between low-latitude Pacific

and Antarctic radiolarian faunas, was the first to suggest that Radiolaria may

be useful as palaeoecological indicators. This observation stimulated studies

of radiolarian biogeography in surface sediments of Antarctica (Hays, 1965),

the Indian Ocean (Nigrini, 1967), eastern equatorial Pacific (Nigrini, 1968),

North Pacific (Nigrini, 1970), North and South Atlantic (Goll & Björklund,

1971, 1974), in order to establish the distribution of extant species and their

relationship to overlying water masses (Casey, 1971).

In comparison with other microfossil groups, planktonic

foraminiferal ecology is relatively well-known, and their use in

reconstructing palaeo-sea surface temperatures (SST's) is now almost

universally accepted. Their popularity may be because there are

relatively few species of planktonic Foraminifera compared to Radiolaria,

and that they are well preserved in Atlantic sediments where Radiolaria

are often poorly preserved (Sanfilippo, 1987), and where many of the

pioneering deep-sea micropalaeontological studies were undertaken.

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However, in ocean basins where the sea-floor is deeper than the lysocline and carbonate compensation depth (CCD), generally c. 4 km depth, calcareous microfossils such as Foraminifera are not preserved and the sediment often comprises 100% siliceous ooze. Also, some oceans, such as the Southern Ocean, are dominated by siliceous plankton. It is in these oceanic and sedimentary environments that the usefulness of Radiolaria is apparent, although their inclusion in all multi-proxy studies of deep-sea sediments should be regarded as standard.

2.1.1 Radiolaria as Water Temperature Indicators

Nigrini (1970) in her study of North Pacific surface sediments statistically identified radiolarian assemblages using recurrent group analysis. This information was applied to a palaeotemperature study of Quaternary sediments of Core V20-130 where Nigrini (1970) constructed a radiolarian temperature number (Tr) for each downcore sample. The Tr was based on an equation developed for diatoms (Td) by Kanaya & Koizumi (1966):-

$$Tr = (Xw / (Xt + Xc) + Xw) \times 100$$

where Xw is the combined abundance of the tropical (warm) assemblage species, Xt is the abundance of the transitional assemblage species, and Xc is the abundance of the subartic (cold) assemblage species. The resultant Tr-record for V20-130 was not entirely successful and did not correspond

well with Td for the same core, although they did correspond at some important levels (e.g. last glacial maximum) indicating the potential of the technique. The problem was attributed by Nigrini (1970) to the position of the core-site, in that it occupies a transitional oceanographic setting. However, the use of recurrent group analysis in identifying assemblages may have been misleading, in that the method considers only the presence or absence of a species, which ignores the ecological importance of species abundance. In this way, 17 and 13 species were included in Xw and (Xt + Xc) respectively. Also, the inclusion of transitional assemblage species as a component in Xc of Kanaya & Koizumi's (1966) original equation may have reduced the signal from the cold water subarctic assemblage. Johnson & Knoll (1974) later applied a Tr, which they called the "radiolarian climatic index", to Pleistocene cores from the equatorial Pacific with some success. Nigrini's (1970) study was the first to employ Radiolaria as a palaeoceanographic proxy, however, the Tr was not widely used again until quite recently. Recurrent group analysis also has not been employed widely since the early 1970's, although it was used by Johnson & Nigrini (1980, 1982) in a study of radiolarian biogeography of the Indian Ocean.

In 1971, Imbrie & Kipp published their seminal paper on a transfer function technique, which revolutionised the application of microfossils to palaeoceanographic research, and in particular to the study of sea-surface temperature (SST). It involves analysing surface sediment (Holocene) microfossil faunas (or floras) from the study area and defining

the ecological parameters (*e.g.* SST) for each sample. The number of variables (species) per sample is reduced to a few ecologically meaningful assemblages using factor analysis (Klovan & Imbrie, 1971). A species score matrix is produced indicating the importance of each species to a factor assemblage, and a factor loading value indicates the contribution made by factor assemblages to each sample, which may be a positive or negative contribution. Factor analysis is then performed on a downcore dataset. The transfer function of Imbrie & Kipp (1971) estimates the SST for each sample based on their statistical similarity with the Holocene dataset for which SST is known. Factor analysis and the transfer function quickly became standard micropalaeontological techniques and widely used by Quaternary radiolarian workers (Moore, 1973, 1978; Sachs, 1973a, b; Hays *et al.*, 1976b; Lozano & Hays, 1976; Dow, 1978; Molina-Cruz, 1977a, b, 1984, 1988; Pisias, 1978, 1979, 1986; Moore *et al.*, 1980; Romine & Moore, 1981; Schramm, 1985; Molina-Cruz & Martinez-López, 1994). Many of these studies were contributions to CLIMAP (CLIMAP Project Members, 1976), and used a common taxonomic framework (Nigrini & Moore, 1979).

Factor assemblages are mathematical constructions and as such are objective groupings of species. A wealth of radiolarian ecological information has been derived from the studies cited above, with many of them reaching consistent conclusions concerning particular species. Table 1 lists the dominant species that characterise factor assemblages from the main studies of the modern Pacific and its regions. From this

Table 1. Radiolaria included in factor assemblages (various authors).

Species	Pan-Pacific (Moore, 1978)							Tropical Pacific (Moore, 1978)				Eastern Pacific (Romine & Moore, 1981)				Eastern Pacific (Schramm, 1985)			
	Tropical	Western Pacific	Subarctic	Transitional	Antarctic	East Central	Temperate	Tropical	Western Pacific	Australian	New Guinea	Tropical	Equatorial (divergence)	Peru Current (upwelling)	Subtropical	Upwelling	East Tropical	West Tropical	Subpolar
Tetrapyle octacantha	✓								✓			✓	✓					✓	
Stylodictya validispina				✓															
Stylochlamydium asteriscus	✓							✓		✓			✓						
Stylatractus spp.															✓				
Spongurus sp.																			
Spongaster tetras										✓	✓	✓							
Pylospira octopyle																			
Pterocorys zancleus					✓														
Pterocorys minythorax													✓	✓		✓			
Pterocanium auritum																			
Octopyle stenozona	✓							✓				✓	✓	✓			✓		
Lithelius minor					✓	✓	✓						✓	✓					
Lirospyris (?) *toxarium*													✓	✓				✓	
Larcopyle buetschlii																			
Heliodiscus asteriscus													✓	✓					
Giraffospyris angulata														✓					
Euchitonium hexagonatum																			
Euchitonia elegans/furcata		✓						✓					✓						
Didymocyrtis tetrathalamus	✓	✓						✓	✓		✓	✓	✓		✓				
Dictyocoryne profunda		✓						✓	✓										
Cycladophora davisiana			✓									✓		✓					
Cenosphaera cristata			✓										✓						
Botryostrobus auritus				✓								✓		✓					
Botryostrobus aquilonaris	✓	✓																	
Antarcissa strelkovi				✓															
Antarcissa denticulata				✓															
Actinomma sp.	✓	✓																	
Actinomma medianum	✓					✓													
Acrosphaera spinosa										✓	✓								
Acrosphaera murrayana										✓	✓								

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Table 1. Radiolaria included in factor assemblages (various authors).

Species	*Subtropical southeast Pacific (Molina-Cruz, 1977a)*				
	Subtropical Factor	Equatorial Factor (divergence)	Peru Factor (coastal upwelling)	Chile Factor (temperate waters)	Backwater Factor
Tetrapyle octacantha	✓		✓		
Stylodictya validispina					
Stylochlamydium asteriscus		✓			
Stylatractus spp.					
Spongurus sp.		✓			✓
Spongaster tetras					
Plyospira octopyle		✓			
Pterocorys zancleus					
Pterocorys minythorax		✓			
Pterocanium auritum			✓		
Octopyle stenozona	✓		✓		
Lithelius minor				✓	
Liriospyris (?) toxarium	✓				
Larcopyle butschlii	✓				
Heliodiscus asteriscus					
Giraffospyris angulata					
Eucyrtidium hexagonatum		✓			
Euchitonia elegans/furcata					
Didymocyrtis tetrathalamus	✓				
Dictyocoryne profunda					
Cycladophora davisiana	✓	✓		✓	
Cenosphaera cristata					
Botryostrobus auritum	✓				
Botryostrobus aquilonaris					
Antarctissa strelkovi					
Antarctissa denticulata					
Actinomma sp.					
Actinomma medianum					
Acrosphaera spinosa					
Acrosphaera murrayana	✓				

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summary it is clear that certain species have definite ecological preferences. For example, the occurrence of *Acrosphaera murrayana* is principally related to coastal upwelling, *Antarctissa denticulata* and *A. strelkovi* are confined to the Southern Ocean around Antarctica, *Botryostrobus aquilionaris* characterises subpolar waters, *Botryostrobus auritus* is dominant along zones of equatorial divergence-driven upwelling, *Cycladophora davisiana* is an important component in cool water and upwelling assemblages, *Didymocyrtis tetrathalamus* is a characteristic species in tropical/subtropical assemblages, *Pterocorys minythorax* is dominant in both equatorial divergence and coastal upwelling areas, *Spongaster tetras* is dominant only in the western tropical Pacific, and *Octopyle stenozona* and *Tetrapyle octacantha* (often combined) are consistently the dominant species in tropical assemblages. In addition to these important species, the distribution of most radiolarian species counted by CLIMAP Project Members (1976) in the course of their investigations are shown in maps compiled by Lombari & Boden (1985).

The use of factor analysis and transfer functions allows large species datasets to be processed, relating modern to fossil assemblages, yet until the early 1990's there was little independent information available to verify the accuracy of the palaeoenvironmental records being produced using Radiolaria. *Haslett (1992, 1995a) explored the palaeoecology of a number of these species to establish whether their modern ecology is consistent with their occurrence in the fossil record.

*Haslett (1992) analysed Early Pleistocene radiolarian faunas from climatic extremes; glacial maxima and minima identified in the $\delta^{18}O$ record of Ocean Drilling Program (ODP) Site 677 in the eastern equatorial Pacific (Shackleton & Hall, 1989). Faunal counts from glacial maximas were combined to produce a composite glacial assemblage, and counts from glacial minimas were combined to produce a composite interglacial assemblage. The composite assemblages were ranked and described according to their dominant taxa (dominant taxa comprise ≥5% of a composite assemblage). The interglacial assemblage is characterised by *Tetrapyle octacantha*, *Octopyle stenozona*, and *Theocorythium vetulum*, and the glacial assemblage by *Cycladophora davisiana*, *Botryostrobus auritus*, *Anthocyrtidium zanguebaricum*, and *Hexacontium enthacanthum*. It is inferred that the abundance of these species is influenced by water temperature, and that the assemblages represent warm and cold water conditions respectively. This palaeoecological information corresponds closely to the modern distribution of those species listed in Table 1, and of the additional species, *T. vetulum* is now extinct, and *A. zanguebaricum* and *H. enthacanthum* possess modern distributions related to the occurrence of cold SST's (Lombari & Boden, 1985).

*Haslett (1995a) investigated the case of *Spongaster tetras* which is reported by some authors to be indicative of warm tropical conditions (Moore, 1978; Nigrini & Moore, 1979). Yet doubts about this view are expressed by Anderson *et al.* (1989a, b, c) who conducted laboratory

experiments on living cultures of *Spongaster tetras*. *Haslett (1995a)

compares the Plio-Pleistocene record of this species in the eastern

equatorial Pacific with other palaeoenvironmental indicators ($CaCO_3$,

$\delta^{18}O$, and $\delta^{13}C$) revealing that *Spongaster tetras* is most commonly

present during periods of upwelling, often at isotopically defined glacial

maxima, when surface productivity and salinity is high, and SST is

expected to be relatively low. Therefore, the palaeoecological

significance of *Spongaster tetras* cannot be viewed simply as indicating

tropical warm water conditions, particularly in complex oceanographic

settings such as the eastern equatorial Pacific.

In their study of Plio-Pleistocene palaeoceanography of ODP Site

709 in the tropical Indian Ocean, *Haslett *et al.* (1994b) constructed

'glacial' and interglacial' indices based on the summed percentage

abundance of the component species of the glacial and interglacial

assemblages of *Haslett (1992). These indices were compared to an

independently derived Radiolarian Temperature Index (RTI) calculated

using the equation of Kanaya & Koizumi (1966). However, the species

included in the RTI as warm (Xw) and cold (Xc) water indicators, are

selected through factor analysis. Notably , Xw includes *Tetrapyle*

octacantha and *Octopyle stenozona*, and Xc *Botryostrobus auritus* and

Anthocyrtidium zanguebaricum; thus, very similar in composition to

*Haslett's (1992) assemblages from the Pacific. These indices produce a

consistent relative SST record which corresponds well to other available

palaeoenvironmental proxies ($\delta^{18}O$, $CaCO_3$) for Site 709.

In the Plio-Pleistocene sequence of ODP Site 677 in the eastern equatorial Pacific, factor analysis again groups *Tetrapyle octancantha* and *Octopyle stenozona* into Xw, whilst *Cycladophora davisiana* is singled out as the principal Xc species. *Haslett & Funnell (1996) confirm the relationship of these species in Holocene surface sediments of the eastern equatorial Pacific (see Haslett & Funnell, 1993), and use this core-top dataset to convert RTI values to SST (°C), allowing construction of SST records for the Plio-Pleistocene of ODP Sites 677, 847 and 851. *Kennington *et al.* (in press) erect independent SST records for these sites based on a diatom transfer function, however, although there is excellent agreement between the records, the RTI derived SST's are consistently cooler, yet more reconcilable with the present SST regime in the region (Wyrtki, 1967; Levitus, 1984; Fiedler *et al.*, 1991).

In summary, two methods of employing Radiolaria as SST indicators have had proven success. The Radiolarian Temperature Index based on Kanaya & Koizumi (1966) essentially provides relative SST records, whilst the transfer function method of Imbrie & Kipp (1971) is capable of assigning absolute SST's (°C) to fossil assemblages. The ecology of the relatively small number of individual radiolarian species that have been studied has largely been derived from surveys of their distribution in surface (Holocene) sediments of the modern ocean (Lombari & Boden, 1985), and grouped into assemblages, aiding downcore comparisons, using a range of statistical techniques such as

recurrent group analysis (*e.g.* Nigrini, 1970) and factor analysis (*e.g.* Molina-Cruz, 1977a).

2.1.2 Radiolaria as Upwelling Indicators

Nigrini & Caulet (1992) brought together a number of studies investigating the relationship of Late Neogene-Quaternary Radiolaria to upwelling. To accomplish this they examined the stratigraphic distribution of species in cores from the Peru Current (De Wever *et al.,* 1990), the Oman Margin (Nigrini, 1991), and the Somalian Gyre (Caulet *et al.,* 1992), all coastal upwelling centres. They conclude that of the species listed in Table 1, as dominant in upwelling factor assemblages, *Cycladophora davisiana* ,*Tetrapyle octacantha/Octopyle stenozona*, *Botryostrobus auritus, Spongurus* sp., *Stylochlamydium asteriscus*, and *Lithelius minor*, their occurrence is not directly related to upwelling. However, they go on to describe an assemblage which characterises Indo-Pacific upwelling (Table 2), although not all the 22 component species occur in all areas. They were also able to group species of the upwelling assemblage into three catergories, based on the nature of their occurrence in tropical upwelling areas. The first category consists of *endemic upwelling species*, which includes species only found commonly in sediments from upwelling areas; the second category comprises *displaced temperate species*, those species which are common in temperate waters, but not usually found in tropical areas, and the third

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Table 2. Category, distribution, and biostratigraphy of upwelling radiolarian species.

Category	Species	Biogeography[1]	Stratigraphic Range[2]
Endemic Upwelling Species	Actinomma spp. group	Peru & Oman	Miocene-Pleistocene
	Anthocyrtidium rectidentatum	Oman	Pliocene
	Collosphaera sp. aff. C. huxleyi	Peru, Oman, & Somalia	Miocene-Recent
	Cypassis irregularis	Peru, Oman, & Somalia	Pleistocene-Recent
	Dictyophimus infabricatus	NW Africa, Peru, Oman, & Somalia	Pliocene-Recent
	Eucyrtidium aderces	Oman	Pliocene
	Eucyrtidium erythromystax	NW Africa, Peru, & Oman	Pleistocene-Recent
	Inversumbella macroceras	Peru, Oman, & Somalia	Miocene-Recent
	Lamprocyclas hadros	NW Africa, Peru & Oman	Miocene-Recent
	Lamprocyclas maritalis ventricosa	NW Africa, Peru, & Oman	Pleistocene-Recent
	Phormostichoartus schneideri	Peru & Oman	Pliocene-Pleistocene
	Plectacantha cremastoplegma	Peru	Pleistocene-Recent
	Pseudocubus warreni	Peru	Miocene-Recent
	Pterocanium grandiporus	NW Africa, Peru, & Oman	Miocene-Recent
Displaced Temperate Species	Acrosphaera murrayana group	NW Africa, Peru, Oman, & Somalia	Miocene-Recent
	Pentapylonium implicatum	Peru, Oman, & Somalia	Miocene-Recent
	Pterocanium auritum	NW Africa, Peru, Oman, & Somalia	Miocene-Recent
Enhanced Tropical Species	Lamprocyrtis nigriniae	Peru, Oman, & Somalia	Pleistocene-Recent
	Lithostrobus cf. L. hexagonalis	NW Africa, Peru, Oman, & Somalia	Miocene-Recent
	Phormostichoartus caryoforma	NW Africa, Peru, Oman, & Somalia	Pliocene-Recent
	Phormostichoartus crustula	NW Africa, Peru, Oman, & Somalia	Miocene-Recent
	Pterocorys minythorax	NW Africa, Peru, Oman, & Somalia	Miocene-Recent

[1]from Nigrini & Caulet (1992), *Haslett (1995c), *Zhao et al. (in press);
[2]from Nigrini & Caulet (1992), *Haslett (1994, 1996)

category consists of *enhanced tropical species*, which are species common in the tropics, but are more abundant and/or more robust in upwelling areas.

Using the upwelling assemblage, Caulet *et al.* (1992) constructed an Upwelling Radiolarian Index (URI) by summing the percentage abundance of component species of the upwelling assemblage. They studied the last 160 ka from core MD85674 from the south Somalian Gyre, and comparing the URI with Foraminifera, $CaCO_3$, $\delta^{18}O$, and $\delta^{13}C$, were able to recognise some important trends of the glacial/interglacial patterns of upwelling and productivity. Generally, peak URI values were found to be virtually synchronous with $CaCO_3$ maxima and with low $\delta^{13}C$ values in the Foraminifera *Neogloboquadrina dutertrei*. For the eastern equatorial Pacific, Archer (1991a, b) postulated that $CaCO_3$ deposition in pelagic sediments, in the form of calcareous nannofossils and planktonic Foraminifera, is controlled by surface water productivity which, as the URI indicates, is enhanced by upwelling. Also, low $\delta^{13}C$ values from planktonic Foraminifera in the northern Indian Ocean are recorded during intense upwelling episodes (Kroon & Ganssen, 1988). Thus, the correlation between peak URI and low $\delta^{13}C$ values, in conjunction with $CaCO_3$ maxima, in core MD85674, suggest that the upwelling radiolarian species described by Nigrini & Caulet (1992) are indeed characteristic of upwelling.

Nearly half the species considered by Nigrini & Caulet (1992) to be characteristic of upwelling were newly described by them, and

therefore had not been available for inclusion in previous biogeographic

investigations of surface sediments. Thus, for many of these species,

there was no modern distributional information with which to verify the

upwelling connection. *Haslett (1995b) examined 44 Holocene sediment

surface samples from the eastern equatorial Pacific upwelling system

and constructed a URI for each site. URI spatial variation is mapped and

compared to thermocline depth in the region (Fig. 1). The depth of the

thermocline is an indication of the degree of upwelling that occurs within

the water column. In areas of strong upwelling the thermocline lies at a

shallow depth. Where upwelling is weak or absent the thermocline

extends to greater depths. *Haslett (1995b) shows good correlation

between the Holocene URI and the present day thermocline depth in the

eastern equatorial Pacific, indicating that the component species of the

URI may be regarded as reliable upwelling proxies. *Haslett's (1995b)

study also demonstrates the potential of the URI for reconstructing

upwelling systems over wide geographical areas in the geological record,

with its application limited only by the availability of well-dated cores, and

by the stratigraphic ranges of the URI component species.

The general stratigraphic range of these upwelling species is

given in Table 2. Most of the species are extant, with two becoming

extinct in the Pleistocene. The Pleistocene is the only epoch in which the

upwelling species co-exist, with fewer species in existence further back

in geological time, and with the species that are present displaying

increasingly sporadic occurrences and impersistent ranges. Therefore,

Figure 1. Comparison of a) Upwelling Radiolarian Index (URI %) applied to Holocene surface sediments of the eastern equatorial Pacific (from *Haslett, 1995c); and b) thermocline depth (m) in the region (after Fiedler *et al.*, 1991).
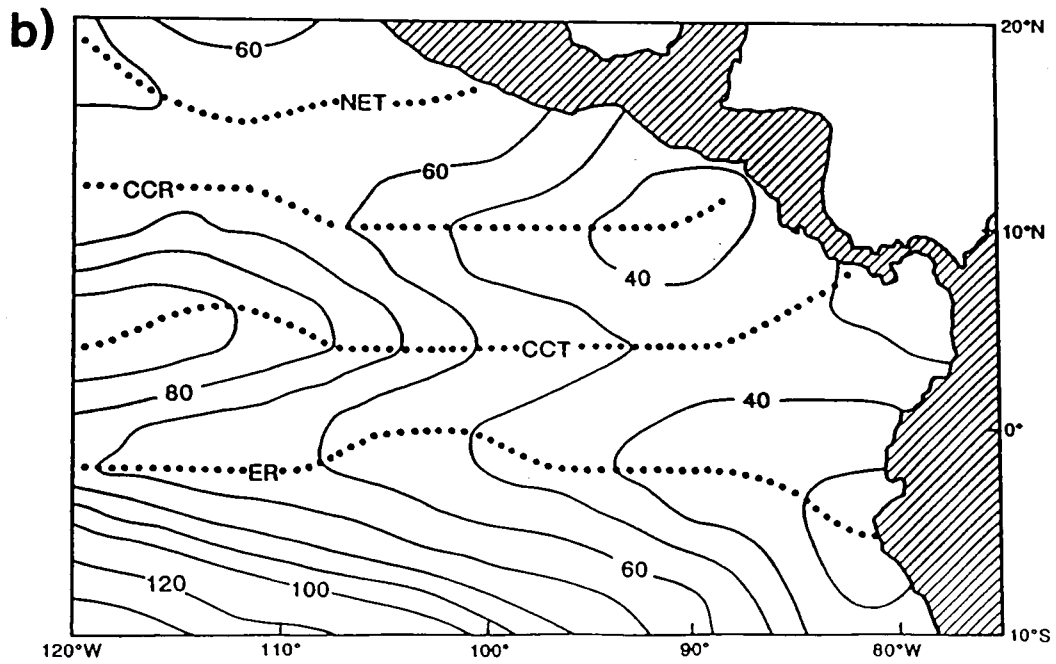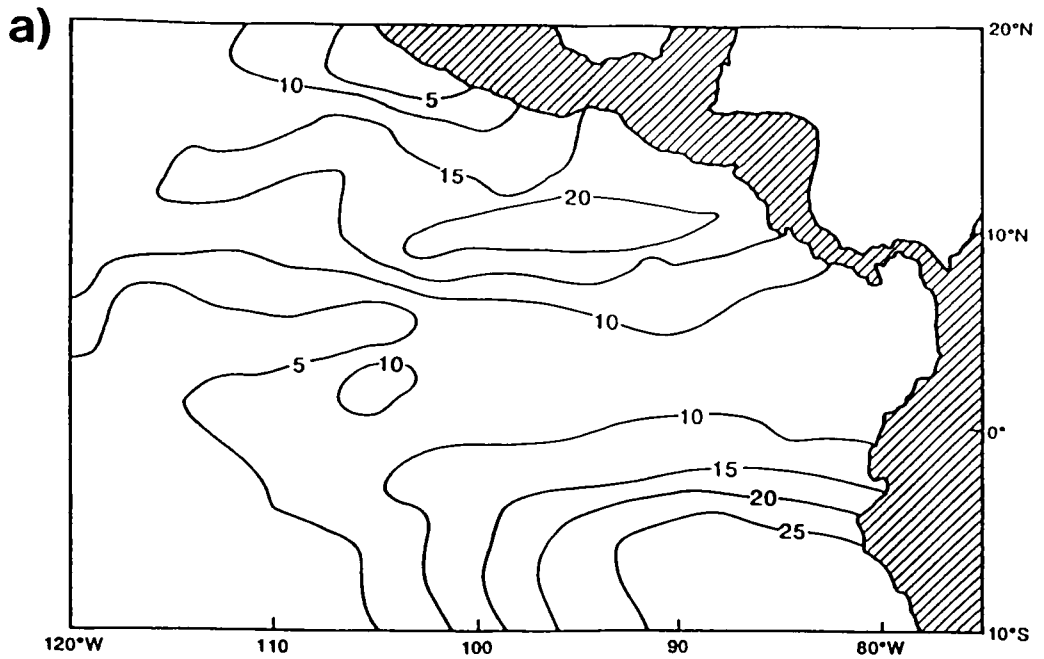
the Quaternary may be the optimum time period to which the URI can be

applied with success (e.g. Caulet et al., 1992; *Haslett, 1995b; Vénec-

Peyré et al., 1995; *Zhao et al., in press). In the latest Pliocene and

earliest Pleistocene, *Haslett et al. (1994a, b) construct upwelling

records using the ancestor (Lamprocyrtis neoheteroporos) of a common

Quaternary upwelling species (Lamprocyrtis nigriniae) identified by

Nigrini & Caulet (1992). *Haslett et al. (1994a) found that the percentage

abundance of L. neoheteroporos correlated reasonably well with $CaCO_3$

preservation (Fig. 2), an accepted palaeoproductivity proxy (Archer,

1991a, b), concluding that L. neoheteroporos, as direct ancestor of L.

nigriniae, could be considered a species indicative of palaeo-upwelling.

This conclusion improves the possibility of extending the successful

application of the URI to the Pliocene.

*Haslett & Funnell (1996) fully explore the application of a URI to

the Pliocene-earliest Pleistocene of the eastern equatorial Pacific. Of the

22 species described by Nigrini & Caulet (1992) only Inversumbella

macroceras, Lamprocyclas hadros, Pseudocubus warreni, Acrosphaera

murrayana, Pterocanium auritum, Lithostrobus hexagonalis, and

Phormostichoartus crustula could be expected to be found during the

time period under investigation. Dictyophimus infabricatus and

Lamprocyrtis neoheteroporos could also be added to this list according

to the findings of *Haslett (1996) and *Haslett et al. (1994a) respectively.

A preliminary survey however, found I. macroceras and P. warreni to be

absent from the material studied, and D. infabricatus, L. hadros and P.

Figure 2. Relationship between the upwelling radiolarian *Lamprocyrtis neoheteroporos* and CaCO₃, a palaeoproductivity proxy, through the Olduvai subchron at ODP Site 677, eastern equatorial Pacific (after *Haslett *et al.*, 1994a).
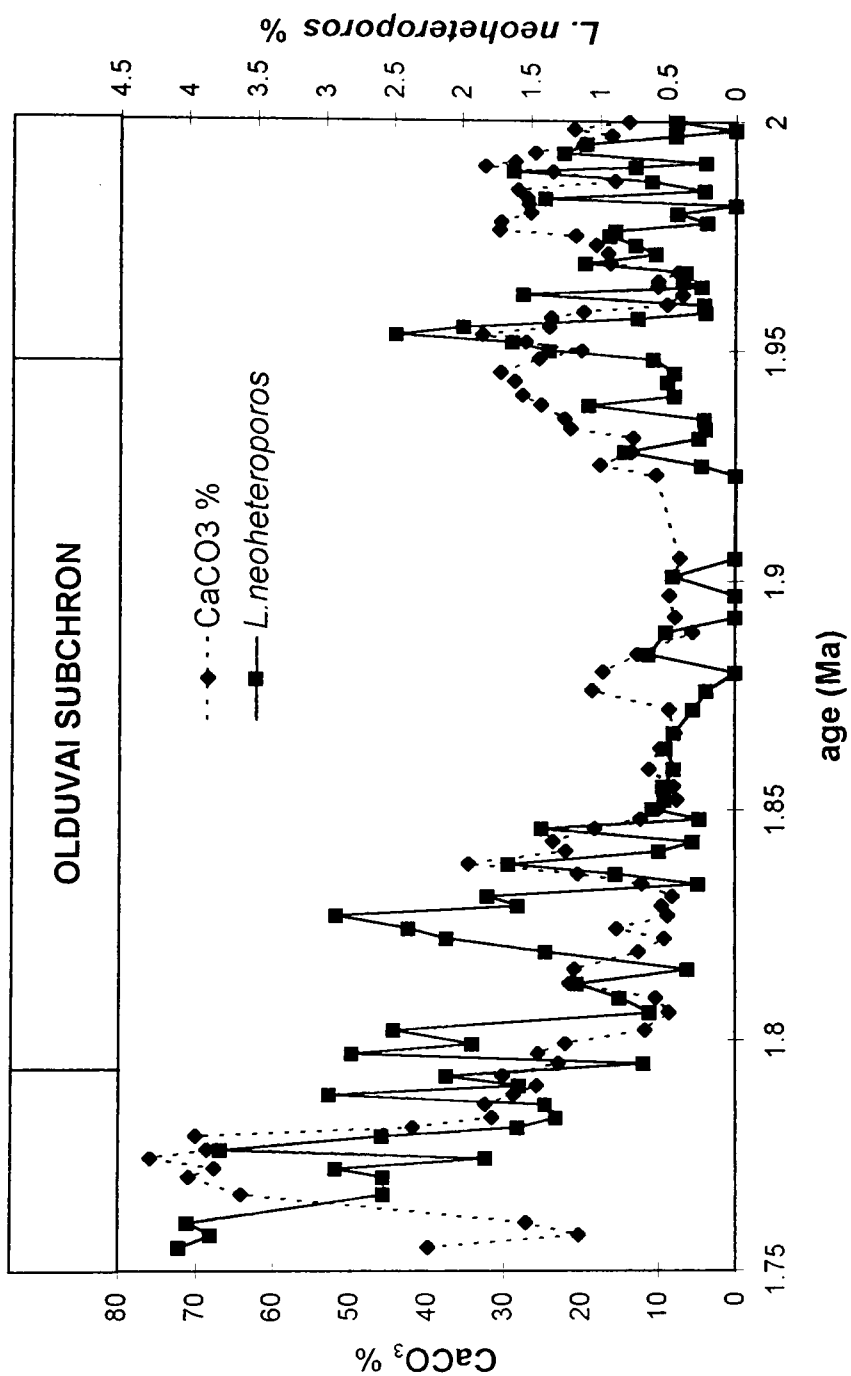
crustula to be extremely rare. Only *A. murrayana*, *L. hexagonalis*, *L. neoheteroporos*, and *P. auritum* were found to be present in significant numbers. These four species were included in the URI and produced upwelling records consistent with other proxy indicators (*Funnell *et al.,* 1996). Based on these URI records *Haslett & Funnell (1996) attempt to construct a palaeothermocline depth record for ODP sites 847 and 850 in the eastern equatorial Pacific by converting URI values to palaeothermocline depths according to the relationship between the spatial variation of Holocene URI values and present-day thermocline depths in the region (*Haslett, 1995b). The results are again consistent with other proxies and do not deviate excessively from the present-day thermocline depth at each site (Fiedler *et al.,* 1991).

Nigrini & Caulet (1992), in describing the upwelling radiolarian assemblage, only investigated sites in the Indo-Pacific region. *Haslett (1995c) makes a preliminary survey of Radiolaria in Late Pleistocene material from ODP site 658 located in a tropical North Atlantic Ocean coastal upwelling cell, offshore Cap Blanc, northwest Africa. A number of elements of Nigrini & Caulet's upwelling assemblage were encountered, representing the first record of the assemblage in the Atlantic Ocean. The species encountered by *Haslett (1995c) include *Acrosphaera murrayana*, *Lamprocyrtis nigriniae*, *Lithostrobus hexagonalis*, *Pterocanium auritum*, and *Pterocorys minythorax*. The recognition of this assemblage in the Atlantic has allowed a URI to be constructed for the Late Quaternary of ODP site 658 (35-0 kyr) (*Zhao *et al.,* in press), which

has been compared successfully with a number of other palaeoceanographic proxies (Fig. 3) (Eglinton *et al.*, 1992; Zhao *et al.*, 1995; Jordan *et al.*, 1996; *Zhao *et al.*, in press). In addition to those species encountered by *Haslett (1995c), *Zhao *et al.* (in press) in their more extensive study, also encountered *Dictyophimus infabricatus*, *Eucyrtidium erythromystax*, *Lamprocyclas hadros*, *Lamprocyclas maritalis ventricosa*, *Phormostichoartus caryoforma*, *Phormostichoartus crustula*, and *Pterocanium grandiporus*.

The recognition of an upwelling radiolarian assemblage and the construction of the URI provides the palaeoceanographic community with a potent tool for reconstructing temporal and spatial aspects of both coastal and oceanic upwelling systems in the Late Neogene and Quaternary. The technique compares well with other micropalaeontological upwelling proxies (see Peterson *et al.*, 1995), such as planktonic Foraminifera $\delta^{18}O$ ratios (*e.g.* Steens *et al.*, 1992), diatoms (*e.g.* *Funnell *et al.*, 1996), coccoliths (*e.g.* Molfino & Macintyre, 1987, 1990a, b), and dinoflagellates (*e.g.* Malmgren & Funnell, 1991). It is particularly well-suited to tropical upwelling systems where opal content is usually high and well-preserved (Lisitzin, 1971; Davies & Gorsline, 1976), and also in areas where deposition occurs below the calcite compensation depth. Radiolaria also have the advantage of being relatively large, compared to diatoms, coccoliths, and dinoflagellates, allowing more rapid faunal analysis.

Figure 3. Upwelling Radiolarian Index (URI %) and other proxies through the Late Quaternary of ODP Site 658, offshore NW Africa (from *Zhao *et al.*, in press).
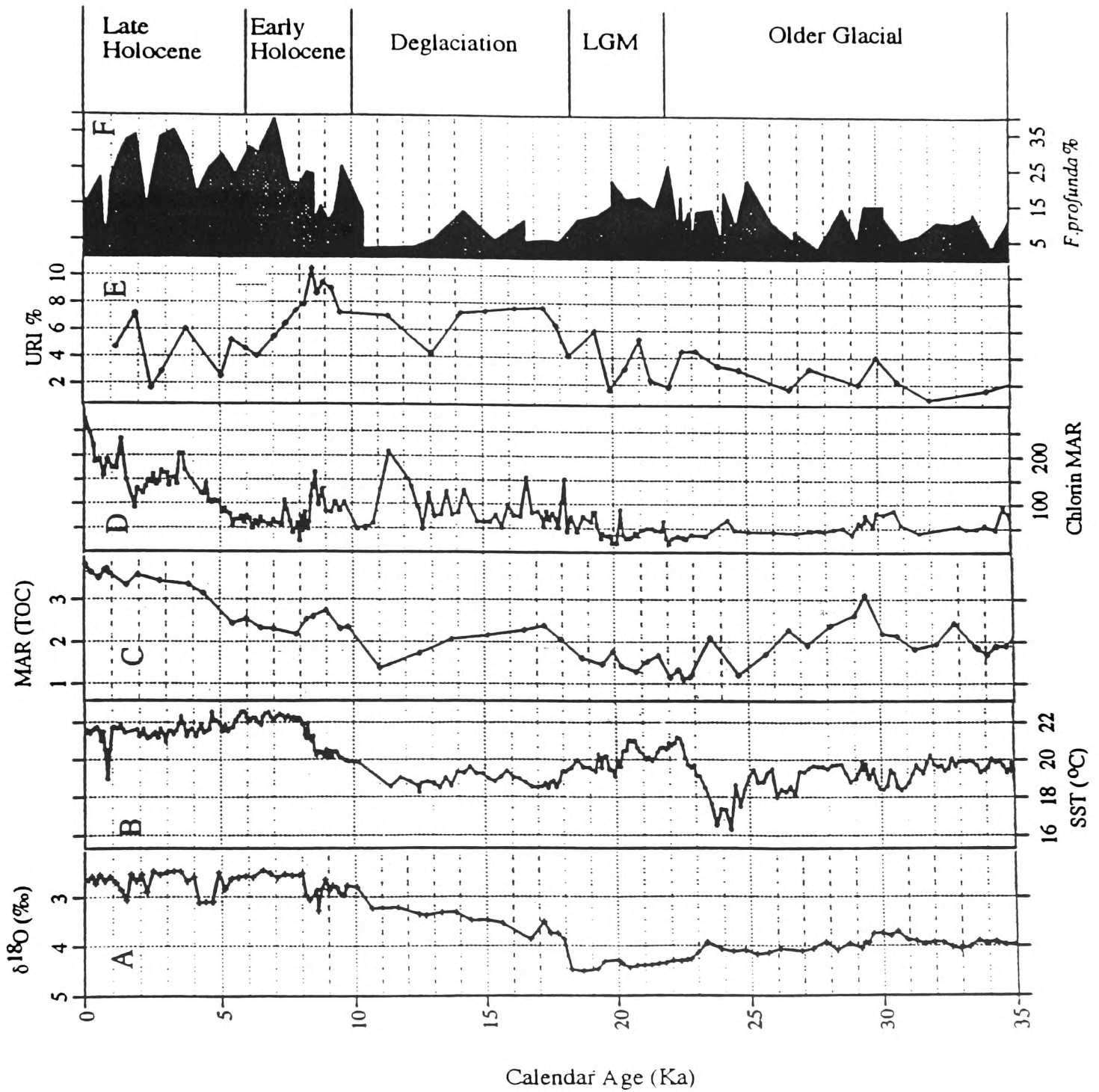
2.2 Pliocene-Pleistocene Radiolarian Biostratigraphy

Radiolaria were first described by F. J. F. Meyen in 1834, but it was the work of the famous microscopists C. G. Ehrenberg and Ernst Haeckel that established a taxonomic framework for radiolarian classification. The system proposed by Haeckel in the reports of the *Challenger* voyages in 1887 was primarily based on the geometry of the radiolarian test, and even at the time Haeckel himself recognised its artificiality. Radiolaria have been found to possess a long geological record, extending back to the Cambrian (*c.* 500 million years ago). A consequence of the artificial Haeckelian classification was that early workers of fossil Radiolaria encountered similar test geometries to living and Holocene specimens described by Haeckel (1887). This gave the impression that Radiolaria were an evolutionary stable group of organisms that had remained unchanged since their origin in the Lower Palaeozoic, and therefore were of little biostratigraphical value. It was not until the work of W. R. Riedel in the 1950s' and 60s' that a more natural classification began to emerge (Riedel, 1953, 1957, 1959, 1967). Riedel and his colleagues concentrated on tracing phylogenetic lineages through time, finding that many species have quite short geological ranges, making them ideal for biostratigraphy (Sanfilippo & Riedel, 1970, 1980, 1982, 1992; Riedel & Sanfilippo, 1978, 1986; Westberg & Riedel, 1978).

2.2.1 Radiolarian Biodatums and Biozonations

Radiolarian evolutionary events are typically used as biodatums, such as the inception or extinction of species, although some acme events have been proposed. Biodatums are generally referred to as First Appearance Datums (FADs) and Last Appearance Datums (LADs), although other denotions are used, such as morphotypic base and top (Bm and Tm). Some biodatums are used to define biozones (intervals of time defined by biological markers) according to standard international procedure (Hedberg, 1976). A biodatum selected for this purpose ideally has a widespread geographic occurrence, with the event occurring synchronously from place to place. Radiolarian biozones are commonly erected as Range Chronozones or Interval Chronozones. A Range Chronozone is defined by the total stratigraphic range of an individual species, from its FAD to its LAD, and is usually named after the nominate species. An Interval Chronozone is defined using biodatums from different species, for example, from the LAD of one species to the FAD of another, and may be named after one of the species, or by some other species which may be common within the time interval represented by the biozone.

The first radiolarian biozonal scheme for the Quaternary of the equatorial Pacific and Indian Oceans was presented by Nigrini (1971) in which she erected four biozones (Fig. 4). This work provided a means of relatively dating tropical Quaternary sediments using Radiolaria.

Figure 4. Radiolarian biostratigraphic zonal schemes for the Pacific, Indian, and Atlantic Oceans (see Table 3 for explanation of zone abbreviations).

Age (Ma)[1]	Polarity	Pacific Ocean[2]	Indian Ocean[3]	Atlantic Ocean[4]
0.2		*Buccinosphaera invaginata* zone	NR1	NR1-2
0.4		*Collosphaera tuberosa* zone	NR2	
0.6			NR3	NR3
0.8			NR4	NR4
1		*Amphirhopalum ypsilon* zone		
1.2				NR5
1.4		*Anthocyrtidium angulare* zone	NR5	
1.6				
1.8				
2			NR6	NR6-7
2.2		*Pterocanium prismatium* zone		
2.4				
2.6			NR7	
2.8		*Spongaster pentas* zone		
3			NR8	NR8
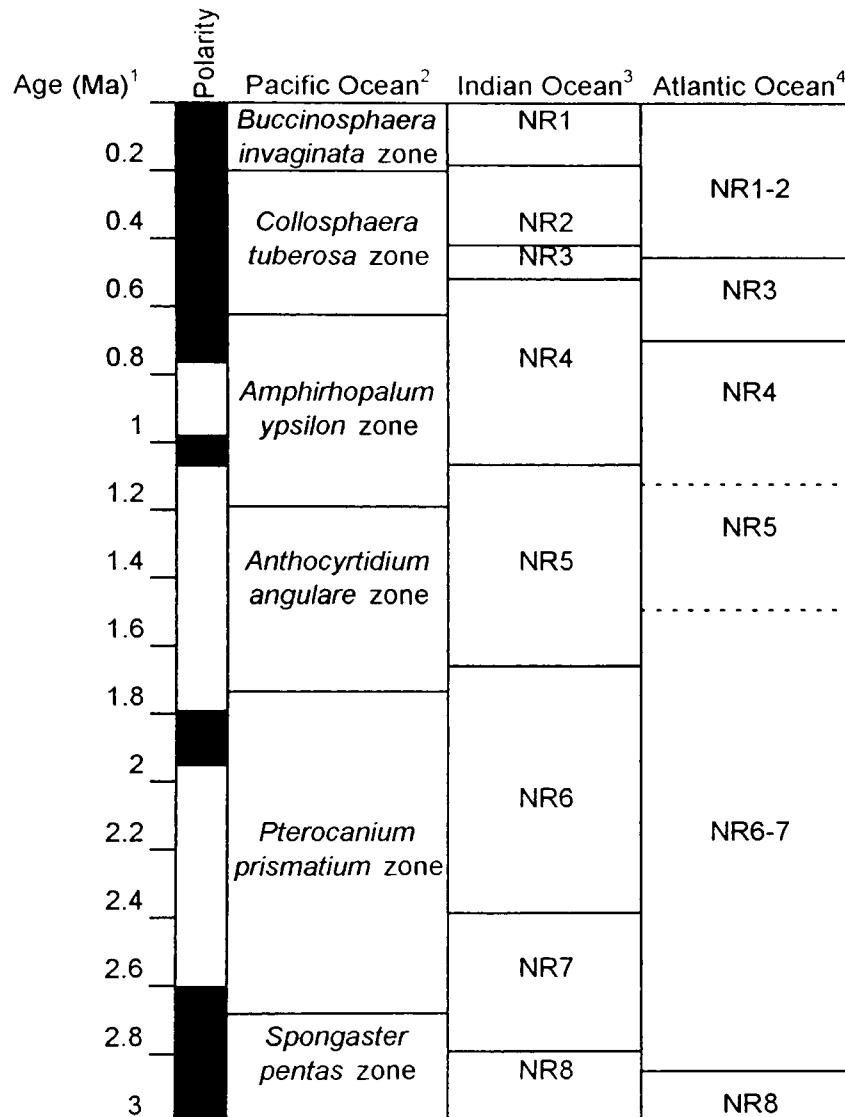
[1]Shackleton *et al.* (1990); Shackleton *et al.* (1995)
[2]Nigrini (1971); Sanfilippo *et al.* (1985); Moore *et al.* (1993)
[3]Johnson *et al.* (1989)
[4]*Haslett (1994b)
(dashed line indicates tentative boundary position)

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Absolute ages for these biodatums were later provided by Johnson & Knoll (1975). The stratigraphic resolution obtainable using Nigrini's (1971) scheme, with only four biozones spanning the entire Quaternary, is inevitably coarse. Yet despite this, this scheme has been widely used, mainly because it is easy to apply, and has been incorporated into the "standard" Cenozoic radiolarian biozonation (e.g. Riedel & Sanfilippo; Sanfilippo et al., 1985). This is not for the lack of alternative schemes, as Goll (1980) for example, erected a more refined biozonation for the tropical Pacific, but included a number of unfamiliar species which probably contributed to the schemes ultimate neglect. Also, other schemes have been erected for other geographic regions, such as the North Pacific (Hays, 1970; Kling, 1973; Foreman, 1975), North Atlantic (see review by *Haslett, 1995c), northeast Atlantic (Björklund, 1976; Goll & Björklund, 1980), and Antarctica (Hays, 1965, 1967, 1970; Hays & Opdyke, 1967; Chen, 1975).

In the late 1980's a concerted attempt was made to provide a new higher resolution Pliocene-Pleistocene radiolarian biozonation. This was initiated by an extensive appraisal of the timing of known Neogene radiolarian biodatums in palaeomagnetically and biostratigraphically dated cores from the equatorial Indian and Pacific Oceans (Johnson & Nigrini, 1985). This study indicated that a number of biodatums previously used as biozonal boundary markers were diachronous and unsuitable for inter-oceanic biostratigraphy. These results contributed further to the lack of suitable radiolarian species available for Pliocene-

Pleistocene biostratigraphy. Largely in response to this situation,

taxonomic studies were undertaken on two potentially useful genera of

Radiolaria, *Pterocorys* (Caulet & Nigrini, 1988) and *Anthocyrtidium*

(Nigrini & Caulet, 1988), which provided a number of new biodatums

based on Indian and Pacific Ocean material, again from

palaeomagnetically and biostratigraphically dated cores. Subsequentally,

Johnson *et al.* (1989) erected a new palaeomagnetically calibrated

Pliocene-Pleistocene radiolarian biozonation for the tropical Indian

Ocean, later refined by Caulet *et al.* (1993) (Fig. 4; Table 3). Johnson *et

al.* (1989) recognised 33 radiolarian biodatums and erected 11 biozones

for the Pliocene-Pleistocene, nearly doubling the number of biozones

reported earlier for the same interval by Sanfilippo *et al.* (1985). This

increase in biozones put Radiolaria on a *par* with other microfossil

biozonations, such as planktonic Foraminifera (Bolli & Saunders, 1985)

and calcareous nannofossils (Martini, 1971), but exceeding diatoms

(Barron, 1985).

All of this work referred to the Indian and Pacific Oceans, and

there was little information concerning the biostratigraphic application of

these species in the Atlantic Ocean until *Haslett (1994b) published an

account of Pliocene-Pleistocene radiolarian biostratigraphy at DSDP Site

609 in the North Atlantic (Fig. 4). *Haslett (1994b) demonstrated that

elements of Johnson *et al.*'s (1989) biozonation could be applied in the

Atlantic Ocean, suggesting that this scheme offered the potential to

become a standard Pliocene-Pleistocene biozonation, enabling

correlation throughout the world's tropical to mid-latitude oceans. This is

Table 3. Radiolarian biozonation scheme erected by Johnson *et al.* (1989) for the equatorial Indian Ocean.

Zone code	Name	Zone type	Duration (Ma)	Lower boundary definition	Other biodatums within the zone
NR1	*Buccinosphaera invaginata*	Range Chronozone	0.17-0	FAD *Buccinosphaera invaginata*	none
NR2	*Collosphaera tuberosa*	Interval Chronozone	0.42-0.17	LAD *Stylatractus universus*	none
NR3	*Stylatractus universus*	Interval Chronozone	0.58-0.42	FAD *Collosphaera tuberosa*	none
NR4	*Amphirhopalum ypsilon*	Interval Chronozone	1-0.58	LAD *Anthocyrtidium angulare*	LAD *Anthocyrtidium nosicaae*; LAD *Pterocorys campanula*; FAD *Pterocorys hertwigii*; FAD *Anthocyrtidium euryclathrum*
NR5	*Anthocyrtidium angulare*	Interval Chronozone	1.55-1	LAD *Pterocanium prismatium*	FAD *Lamprocyrtis nigriniae*; LAD *Lamprocyrtis neoheteroporos*; LAD *Anthocyrtidium michelinae*
NR6	*Pterocanium prismatium*	Interval Chronozone	2.35-1.55	LAD *Anthocyrtidium jenghisi*	FAD *Anthocyrtidium angulare*; FAD *Pterocorys zancleus*; LAD *Theocorythium vetulum*
NR7	*Anthocyrtidium jenghisi*	Interval Chronozone	2.65-2.35	LAD *Stichocorys peregrina*	FAD *Cycladophora davisiana*; FAD *Lamprocyrtis neoheteroporos*; FAD *Theocorythium trachelium*
NR8	*Stichocorys peregrina*	Interval Chronozone	3.25-2.65	LAD *Phormostichoartus fistula*	LAD *Anthocyrtidium ehrenbergi*; LAD *Anthocyrtidium pliocenica*
NR9	*Phormostichoartus fistula*	Interval Chronozone	3.55-3.25	LAD *Phormostichoartus doliolum*	LAD *Lychnodictyum audax*
NR10	*Phormostichoartus doliolum*	Interval Chronozone	3.87-3.55	LAD *Anthocyrtidium prolatum*	LAD *Amphirhopalum ypsilon*; LAD *Spongaster pentas*; FAD *Spongaster tetras*; LAD *Spongodiscus klingi*; LAD *Spongaster berminghami*
NR11	*Anthocyrtidium prolatum*	Range Chronozone	4.7-3.87	FAD *Anthocyrtidium prolatum*	FAD *Spongaster pentas*; FAD *Anthocyrtidium ophirense*

hampered somewhat however, by the apparent diachroneity of some biodatums between the Indian and Atlantic Oceans (Table 4).

The absolute ages for these biodatums were calculated in all cases cited above through interpolation between dated palaeomagnetic reversals using the timescale of Berggren *et al.* (1985a, b). Johnson *et al.* (1989) suggest that the precision of some biodatums is less than 100ka, however, little consideration is given to possible variations in sedimentation between reversals. Ruddiman *et al.* (1986) and Shackleton *et al.* (1990, 1995) provide an alternative method of dating sedimentary cores by tuning $\delta^{18}O$ and GRAPE density records to the periodicity of astronomical cycles: 400ka and 100ka eccentricity cycles, 41ka obliquity cycles, and 23-19ka precessional cycles. This method commonly allows for samples to be dated to within *c.* 20ka (*i.e.* interval between adjacent precessional excursions), and enables very high precision ages to be applied to biodatums. Moore *et al.* (1993) exploited astronomical timescales constructed for ODP Leg 138 cores from the eastern equatorial Pacific to derive ages for the assessment of diachroneity of Neogene-Quaternary radiolarian biodatums in the region (Table 4). They categorised all events occurring throughout the region within 150ka as synchronous, and six of the eleven Quaternary (0-2Ma) biodatums in the eastern equatorial Pacific met this criteria. Of the diachronous events, only one was significantly greater than 300ka. This study is important for the accuracy of the astronomically tuned ages

Table 4. Radiolarian biodatum ages in the Atlantic, Indian, and Pacific Oceans. Ages for Atlantic and Indian Ocean biodatums are recalculated here using astronomically derived ages for palaeomagnetic reversals (Shackleton *et al.,* 1990, 1995).

Biodatums	Atlantic Ocean[1]	Indian Ocean[2]	Pacific Ocean[3]	Age Range	Accuracy
FAD *Buccinosphaera invaginata*		0.13-0.19		0.13-0.19	0.06
LAD *Stylatractus universus*	0.27-0.6	0.4-0.5	0.41-0.5	0.27-0.6	0.33
FAD *Collosphaera tuberosa*		0.43-0.63	0.58-0.65	0.43-0.65	0.22
LAD *Anthocyrtidium nosicaae*	0.6-0.8	0.71-0.82		0.6-0.82	0.22
LAD *Pterocorys campanula*		0.71-0.84		0.71-0.84	0.13
FAD *Pterocorys hertwigii*	0.8-0.94	0.82-0.91		0.8-0.94	0.14
FAD *Anthocyrtidium euryclathrum*		0.91-0.94		0.91-0.94	0.03
LAD *Anthocyrtidium angulare*		1.02-1.13	1.12-1.25	1.02-1.25	0.23
FAD *Lamprocyrtis nigriniae*		1.11-1.17	1.21-1.45	1.11-1.45	0.34
LAD *Lamprocyrtis neoheteroporos*	1.06-1.17	1.19-1.23	1.02-1.12	1.02-1.23	0.21
LAD *Anthocyrtidium michelinae*		1.63-1.67		1.63-1.67	0.04
LAD *Pterocanium prismatium*		1.64-1.68	1.7-1.78	1.64-1.78	0.14
FAD *Anthocyrtidium angulare*		1.64-1.77	1.75-1.79	1.64-1.79	0.15
FAD *Pterocorys zancleus*		1.77-1.79		1.77-1.79	0.02
LAD *Theocorythium vetulum*		1.9-2	1.16-1.26	1.16-2	0.84
LAD *Anthocyrtidium jenghisi*		2.27-2.5	2.27-2.52	2.27-2.52	0.25
FAD *Cycladophora davisiana*	2.24-2.44	2.33-2.67	2.65-2.76	2.24-2.76	0.52
FAD *Lamprocyrtis neoheteroporos*	2.07-2.24	2.4-2.67	3.14-3.36	2.07-3.36	1.29
FAD *Theocorythium trachelium*		2.33-2.69	1.47-1.78	1.47-2.69	1.22
FAD *Pterocorys minythorax*			1.49-1.78	1.49-1.78	0.29
LAD *Lamprocyrtis heteroporos*			1.49-2.09	1.49-2.09	0.6
LAD *Stichocorys peregrina*	2.79-2.94	2.75-2.84	2.49-2.88	2.49-2.94	0.45
FAD *Lamprocyrtis heteroporos*			3.14-3.44	3.14-3.44	0.3
LAD *Anthocyrtidium ehrenbergi*		3-3.07		3-3.07	0.07
LAD *Anthocyrtidium pliocenica*		3.4-3.56	3.13-3.63	3.13-3.63	0.5
LAD *Phormostichoartus fistula*		3.31-3.45	3.48-5.3	3.31-5.3	1.99
LAD *Lychnodictyum audax*		3.39-3.53	3.67-4.04	3.39-4.04	0.65

[1] after *Haslett (1994) & Westberg-Smith *et al.* (1986)
[2] after Johnson *et al.* (1989) & *Haslett *et al.* (1995)
[3] Moore *et al.* (1993) & Moore (1995)

applied to the radiolarian biodatums, which does not involve the same degree of interpolation as palaeomagnetic timescales.

Extending this approach into the Indian Ocean, *Haslett *et al.* (1995) investigated a Pliocene-Early Pleistocene section from ODP Site 709 and identified ten radiolarian biodatums. Oxygen isotope stratigraphy is available for part of the section (Shackleton & Hall, 1990), which was astronomically tuned by correlation with ODP Site 677 (Shackleton *et al.*, 1990; see also *Funnell *et al.*, 1996), allowing dates to be assigned to six biodatums (Table 4). Only one of the biodatums identified in ODP Site 709 (LAD *Anthocyrtidium jenghisi*) appears to be synchronous with the eastern equatorial Pacific, as defined by Moore *et al.* (1993). To date, no attempt has been made to extend this approach of dating radiolarian biodatums through the entire Quaternary of the Indian Ocean, or at all in the Atlantic Ocean. These are pressing objectives which are required for a fully integrated low-latitude radiolarian biozonation of the world's oceans.

2.2.2 Cycladophora davisiana *Abundance Events*

Cycladophora davisiana is generally a cold-water high-latitude species whose relative abundance has been shown to vary synchronously through the Late Pliocene and Quaternary of high-latitude oceans (Hays *et al.*, 1976a; Morley, 1980, 1987; Morley & Hays, 1979, 1983). The abundance variations of this species have been used as a means of

correlating sedimentary sequences in a similar manner to $\delta^{18}O$

stratigraphies (*i.e.* counting peaks and troughs in the continuous record),

and similarly have been variously coded by authors for ease of reference

when cross-correlating different cores; either by letters (*e.g.* Hays *et al.*,

1976a), numbers (*e.g.* *Haslett & Funnell, 1998), or alpha-numerically

(*e.g.* Caulet, 1982, 1986). Although stratigraphies based on *C. davisiana*

are widely used at mid- to high-latitude sites, *Haslett & Funnell (1998)

demonstrate that the same method may also be applied with success to

low-latitude sediments. These authors erect *C. davisiana* stratigraphies

spanning the Olduvai subchron (Plio-Pleistocene) of ODP sites from the

equatorial Indian and Pacific Ocean (sites 677, 709, 847, 850, and 851),

as a means of independently evaluating high-resolution timescales

developed by other methods. The results are encouraging, with a high

degree of consistency in the *C. davisiana* stratigraphies between all

sites. In particular, *Haslett & Funnell (1998) recognise a major peak in

C. davisiana abundance coincident with the Plio-Pleistocene boundary at

1.81Ma (Hilgen, 1991). This peak may represent a useful new biomarker

for the Tertiary-Quaternary boundary, and indicates a major intrusion of

cool high-latitude water into the equatorial Oceans at this time, perhaps

associated with $\delta^{18}O$ stage 64. This new work indicates that *C. davisiana*

stratigraphy may have the potential for correlation not only in high-

latitude regions, but on intra- and inter-oceanic scales covering all

latitudes. However, these promising indications require further research

in the future.

3. GLOBAL ENVIRONMENTAL CHANGE THROUGH THE PLIOCENE-PLEISTOCENE OLDUVAI MAGNETOSUBCHRON (1.95-1.79 Ma).

The Olduvai event is a normal polarity magnetosubchron within the reverse polarity Matuyama chron. The base and top of the Olduvai have been assigned various dates, but is currently taken as 1.95 and 1.79 Ma respectively (Table 5), spanning 160,000 years. Because of its relatively long duration, the Olduvai is the most conspicuous subchron within the Matuyama, and the shorter Jaramillo, Cobb Mountain, and Reunion events are less readily identified. The time interval covered by the Olduvai subchron is significant for a number of reasons: it's upper limit coincides closely with the internationally defined Plio-Pleistocene boundary (Hilgen, 1991), it straddles the base of the LaPlace orbital chron, characterised by the 41 ka obliquity cycle (Berger & Wefer, 1992; Berger *et al.*, 1994), and it coincides with the emergence of *Homo habilis*, the first *Homo* species to evolve (Walker & Leakey, 1978; deMenocal, 1995). Kappelman (1984) realised the potential of the Olduvai for correlating palaeoenvironmental records from geographically widespread locations, encompassing both continental and marine records (Kappelman, 1986).Thus, the Olduvai offers an opportunity to investigate environmental change on a global basis during a period largely ignored by international projects, such as the Late Quaternary CLIMAP (1976)

Table 5. Ages that have been assigned to the lower and upper boundaries of the Olduvai magnetosubchron (Matuyama magnetochron, Plio-Pleistocene).

reversal	age (Ma)[1]	age (Ma)[2]	age (Ma)[3]	age (Ma)[4]	age (Ma)[5]	age (Ma)[6]
Olduvai top	1.67	1.66	1.65	1.77	1.757	1.79
Olduvai base	1.87	1.88	1.82/1.83	1.95	1.983	1.95

[1]Mankinen & Dalrymple (1979)
[2]Berggren *et al.* (1985a, b)
[3]Ruddiman *et al.* (1989); Raymo *et al.* (1989)
[4]Shackleton *et al.* (1990)
[5]Cande & Kent (1992)
[6]Hilgen (1991); Valet & Meynadier (1993); Hilgen *et al.* (1993)

and COHMAP (1988) Projects and the Middle Pliocene PRISM investigation (Dowsett *et al.,* 1994).

Ocean Drilling Program (ODP) Legs 111, 115 and 138 cored a number of sites in the equatorial Indian (ODP Site 709) (Fig. 5) and eastern Pacific (ODP Sites 677, 847, 850, and 851) (Fig. 6) Oceans and recovered continuous sediment cores with high-resolution timescales based on the astronomical tuning of $\delta^{18}O$ and GRAPE density records (Shackleton *et al.,* 1990; Shackleton *et al.,* 1995; *Funnell *et al.,* 1996). The eastern equatorial Pacific was chosen for study, in particular, because it is the site of significant ocean-atmosphere interaction, in the form of interannual El Niño conditions which is accepted as having global impacts (Philander, 1989; Diaz & Markgraf, 1992). The area is also responsible for as much as 50% of the World Ocean's "new" bioproduction (Chavez & Barber, 1987), which has the ability to affect atmospheric pCO_2. An equatorial Indian Ocean site was also selected as a link into the climatic world of monsoons and monsoon-related phenomena. The palaeoceanographic investigations employed a multi-proxy analytical approach, using micropalaeontological (Radiolaria, diatoms, Foraminifera) and geochemical techniques, through a time interval of 2-1.75 Ma called the Olduvai timeslab, which is slightly longer than the subchron. The results have been published in a series of papers (*Haslett, 1994; *Haslett *et al.,* 1994a, b; *Haslett, 1996; *Haslett & Funnell, 1996; *Funnell *et al.,* 1996; *Kennington *et al.,* in press). The purpose of this report is to review these findings and to make a

Figure 5. Oceanography of the Indian Ocean and location of ODP Site 709 (from *Funnell et al.*, 1996). NEC and SEC = North and South Equatorial Currents; ECC = Equatorial Counter Current.
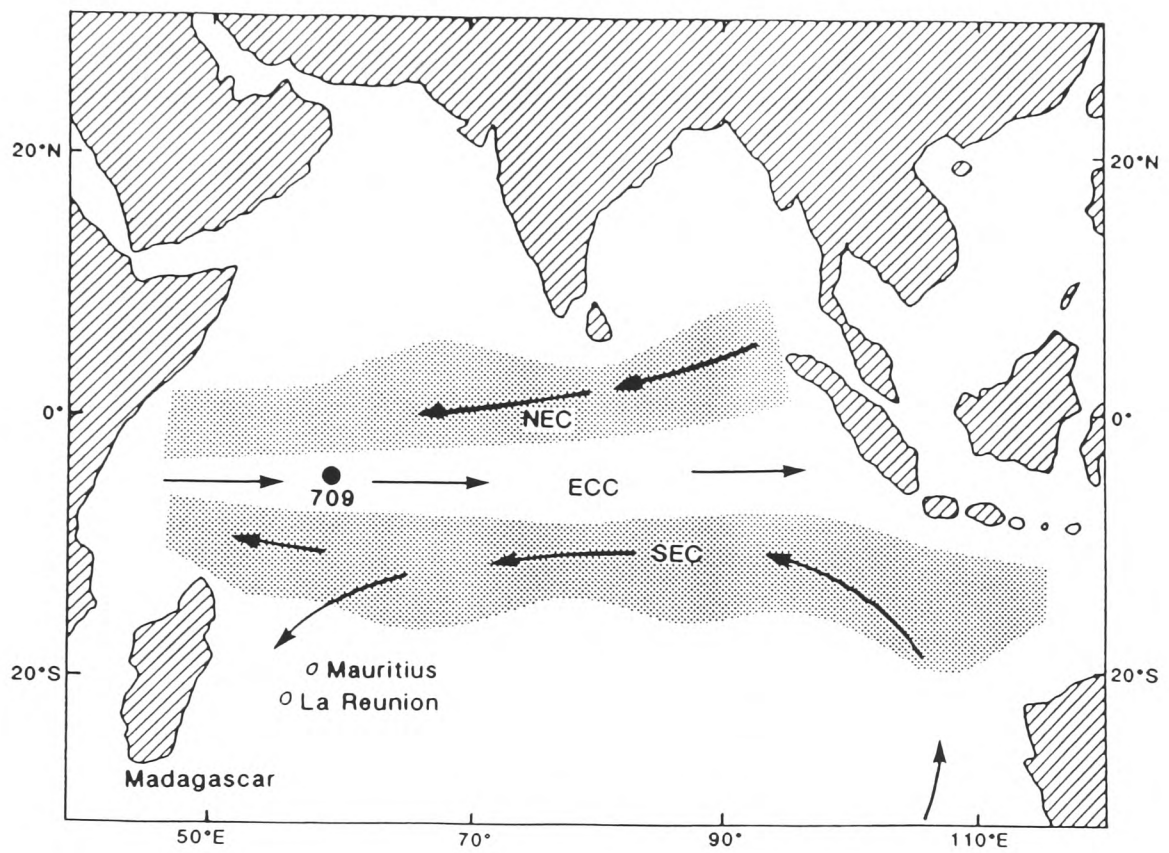
Figure 6. Oceanography of the eastern equatorial Pacific Ocean and location of ODP sites 677, 847, 850, and 851 (from *Funnell *et al.*, 1996). NEC and SEC = North and South Equatorial Currents; NECC = North Equatorial Counter Current; EUC = Equatorial Under Current; CC = California Current; PC = Peru Current.
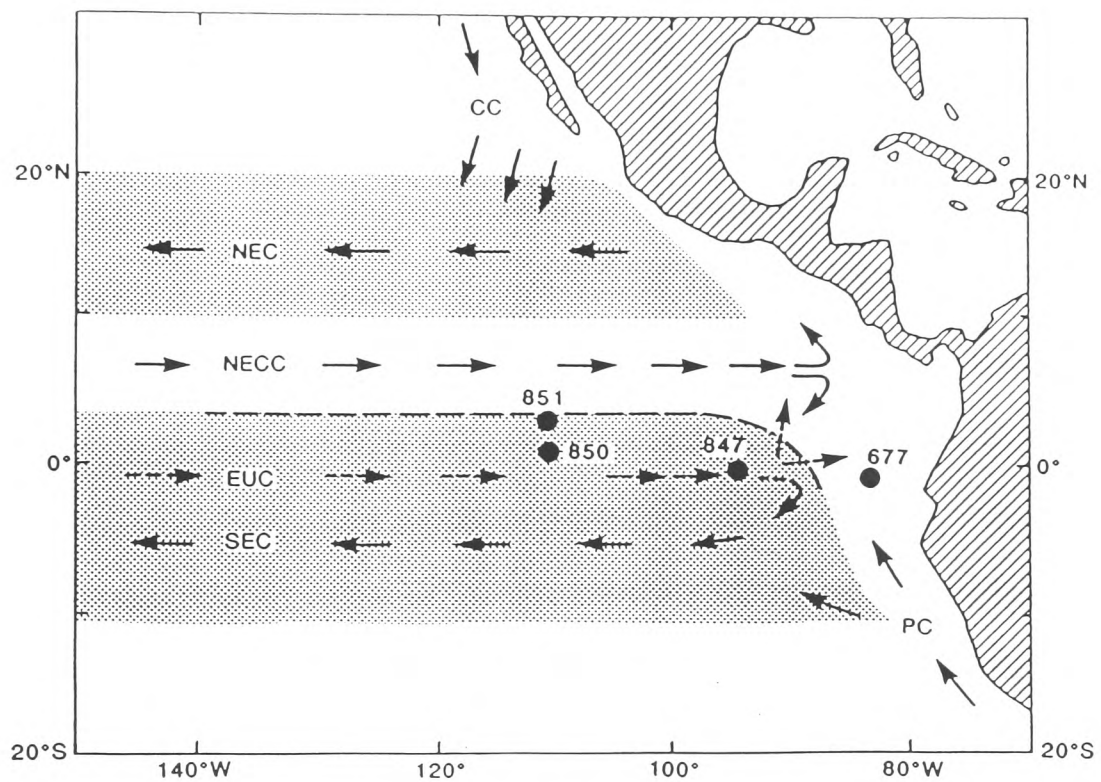
comparison with other sites around the world where the Olduvai

subchron has been securely identified, and for which a

palaeoenvironmental record is available. In this way, a qualitative picture

of global environments through the subchron may be constructed.

3.1 This Study

3.1.1 Eastern Equatorial Pacific

The oceanography of the eastern equatorial Pacific is dominated by a

number of latitudinally orientated currents, driven by strong trade winds

that induce divergence and coastal upwelling of nutrient-rich water which

supports surface bioproductivity (Wyrtki, 1967). Upwelling strength and

productivity fluctuates, particularly during El Niño events when trade wind

strength decreases, raising the thermocline and blanketing the colder

nutrient-rich waters at depth with a warm surface layer. Upwelling may

still occur at these times, but the water is advected from shallower depths

and is nutrient-poor.

ODP sites 677, 847, 850, and 851 were chosen for analysis and

represent an east-west transect along the equator (Fig. 6). At ODP site

677, the easternmost site, *Haslett et al. (1994a) constructed a

palaeoproductivity record based on calcite composition of the sediment

(Archer, 1991a, b) and a palaeo-upwelling record using the radiolarian

Lamprocyrtis neoheteroporos. These two proxy records correlate well

indicating moderately high productivity and strong upwelling during the early part of the Olduvai timeslab (prior to 1.93 Ma), low productivity and weak upwelling (with reduced sedimentation) during the mid Olduvai (1.93-1.82 Ma), and high productivity and strong upwelling during the upper part of the timeslab (after 1.82 Ma). This same tripartite division of the Olduvai timeslab is seen at the other three sites (*Haslett & Funnell, 1996; *Funnell et al., 1996), where Lamprocyrtis neoheteroporos is superceded as an upwelling indicator by the URI, and additionally the RTI is constructed. Overall there is a decreasing east-west trend in productivity and upwelling, and increasing trend in SST. This palaeoceanographic pattern is further supported by diatom trade wind and SST proxies (*Kennington et al., in press), which indicate strong trade winds and low SST during the early Olduvai, weak trade winds and high SST during the mid Olduvai, returning to strong trade winds and low SST during the late Olduvai (see Table 6).

The palaeoceanographic conditions characterising the mid Olduvai (weak trade winds, weak upwelling, low productivity, reduced sedimentation, high SST) are analogous to persistence of the present-day interannual El Niño state, although the magnitude and frequency of the El Niño events appear to lay beyond the present day natural limits of El Niño variability (Jin et al., 1994; Tziperman et al., 1994).

Table 6. Summary of palaeoenvironmental interpretations of Olduvai sequences at various localities, with a summary of modern El Niño conditions (see text for sources and further explanation).

Region	General environmental conditions			modern El Niño conditions
	Early Olduvai	Middle Olduvai	Late Olduvai	
South America - Bogota Basin	low precipitation	high precipitation	low precipitation	high precipitation
Central & Western Pacific	high bioproductivity	low bioproductivity	high bioproductivity	low bioproductivity
Loess Plateau - China	cool and dry	warm and wet	cool and dry	warm and wet
East Africa - Olduvai Gorge	moist conditions	arid conditions	moist conditions	drought
Eastern Equatorial Pacific	strong upwelling low SST high bioproductivity	weak upwelling high SST low bioproductivity	strong upwelling low SST high bioproductivity	weak upwelling high SST low bioproductivity
Equatorial Indian Ocean	weak SW monsoon	strong SW monsoon	weak SW monsoon	variable conditions
Northwest Pacific - Japan	cool temperatures	warm temperatures	cool temperature	warm temperatures
Mediterranean	low freshwater input	high freshwater input	low freshwater input	wetter than average
North America - New Mexico	arid conditions	floods	arid conditions	high precipitation

50

3.1.2 Equatorial Indian Ocean

The oceanography of the Indian Ocean is described by Wyrtki (1973). ODP Site 709 is located within the equatorial countercurrent and experiences divergence-driven upwelling, which is prevalent during the northeast monsoon (Northern Hemisphere winter) (Fig. 5). Equatorial upwelling is reduced during the Northern Hemisphere summer when the southwest monsoon dominates. *Haslett *et al.* (1994b) investigated the Olduvai timeslab employing calcite preservation and *L. neoheteroporos* as palaeoproductivity and palaeo-upwelling proxies respectively. An RTI was also constructed. The results again indicate a tripartite divsion of the Olduvai, with the mid Olduvai (1.895-1.81 Ma) experiencing reduced upwelling, productivity, and sedimentation. *Haslett *et al.* (1994b) and *Funnell *et al.* (1996) suggest that zonal trade winds are reduced during this period with a reciprocal increase in meridonal monsoonal circulation (*e.g.* strengthening of the southwest monsoon).

3.2 Other Studies of the Olduvai Subchron

This section examines previously published palaeoenvironmental records for the Olduvai subchron at various localities around the world where the Olduvai has been securely dated. The main palaeoenvironmental interpretations at each of the localities is discussed in detail below and is summarised in Table 6.

3.2.1 Central and Western Pacific

Beiersdorf *et al.* (1995) revisited DSDP site 317 (11°00.1'S, 162°15.8'W) on the Manihiki Plateau and retreived a new core (Core 34KL). High-resolution palaeomagnetic, $\delta^{18}O$ and $\delta^{13}C$ isotope (from *Globigerinoides sacculifer*), and biostratigraphic data were obtained from the 16 m long core, allowing a well-constrained timescale to be developed. Overall there is a significant reduction in the sedimentation rate at the base of the Olduvai subchron from 8.7 to 5.4 m/Myr which largely coincides with the start of the LaPlace Chron. This abrupt drop in Late Cenozoic sedimentation has also been noted in western Pacific ODP sites drilled on the Ontong Java Plateau (Berger *et al.*, 1993a, b), and Beiersdorf *et al.* (1995) consider it to be a regional phenomenon. Superimposed on this overall pattern, the calculated accumulation rates between each age-control point indicates that immediately prior to the Olduvai accumulation rates were c. 1.2 g/cm²/ka, whilst during the Olduvai they fell to c. 0.3 g/cm²/ka. At the end of the Olduvai the accumulation rate recovered slightly to c. 0.6 g/cm²/ka. The variance in sediment accumulation rates in the central and western Pacific is attributed to fluctuations in bioproductivity in the surface waters, with nannofossils and foraminifera constituting the bulk of the sediment. Therefore, productivity was relatively high prior to the Olduvai, whilst during the Olduvai productivity

was greatly reduced, and immediately following the subchron productivity

experienced a moderate recovery.

3.2.2 Northwest Pacific - Japan

In central Japan, Momohara (1994) describes floral changes from the

late Pliocene to middle Pleistocene based on plant macrofossil

occurrences (Momohara, 1990; Momohara et al., 1992). Because Japan

is situated within the East Asian monsoon zone, Momohara (1994) does

not consider precipitation to be a major factor in determining vegetation

distribution, but rather temperature is thought to be the dominant factor.

On this assumption, which is supported by the work of Honda (1928) and

Kira (1949), Momohara (1994) constructs a crude palaeotemperature

record for the Plio-Pleistocene Osaka Group and Shobudani Formation,

which are palaeomagnetically well-constrained (Itihara et al., 1975,

1984). The palaeotemperature record through the Olduvai shows that the

subchron is characterised by warm conditions, with cooler conditions

prevailing immediately prior to and following the subchron.

3.2.3 Loess Plateau - China

Loess-palaesol sequences extending back to c. 2.5 Ma are exposed in

several areas of the Loess Plateau of north-central China (Liu, 1985).

The climate of the Loess Plateau is strongly affected by the East Asia

monsoon which brings warm moisture-laden air masses onto the Plateau, from the Pacific, during the summer months. In the winter months cold-dry air from Siberia prevails over the Plateau, leading to marked seasonality. The climatic interpretation of the loess-palaesol sequence through the Plio-Pleistocene is based on studies of the Holocene sequence of Baoji (Rutter & Ding, 1993). Palaeosol horizons are considered to represent warm and humid conditions, mainly during interglacial periods, whilst Loess deposition signifies cold and dry conditions during periods when the summer monsoon was weakened, principally at glacial times when expanding high latitude ice sheets forced the summer monsoon to retreat southwards.

The principal chronostratigraphic control on a number of sections is provided by magnetostratigraphy, which in a number of cases clearly identifies the Olduvai subchron. At the Luochuan section (Liu, 1985) and Xifeng section (Liu *et al.,* 1987) palaeosol formation characterises the entire Olduvai, with weakly-weathered loess deposited before and after (see also Ding *et al.,* 1993). In the Baoji section (Rutter & Ding, 1993; Rutter, 1992) however, the Olduvai comprises two palaeosols (a lower thick palaeosol, S26, and a thinner upper palaeosol, S25) separated by a strongly-weathered loess (L26). The palaeosols are of the Bt-type (soils with pedogenic clay accumulation) indicating that relatively dense forest or steppe-forest vegetation was established during their development (Rutter & Ding, 1993). The strongly-weathered loess shows a strong ped structure with all primary calcite lost to leaching. Carbonate leaching is

attributed to rainfall associated with the summer monsoon, therefore, during the deposition of L26, although dominated by winter monsoonal conditions, the area was still influenced by the summer monsoon. It appears that throughout the Olduvai, the Loess Plateau experienced warm and humid conditons, being strongly influenced by the summer monsoon.

3.2.4 East Africa - Olduvai Gorge

The Olduvai Gorge in Tanzania, which is the type site for the Olduvai subchron (Grommé & Hay, 1963, 1967, 1971; Tamrat et al., 1995), has received much attention due to the abundant homonid remains that have been found there (Reck, 1914; Leakey, 1965; Leakey, 1971, 1975). Palaeoenvironmental studies have proceded in tandem with the archaeological investigations, and includes studies of veterbrates (Leakey, 1965; Butler & Greenwood, 1965, 1976; Jaeger, 1976; Gentry & Gentry, 1978a, b; Andrews, 1983; Kappelman, 1984, 1986), palynology (Bonnefille, 1979; Bonnefille & Riollet, 1980; Bonnefille et al., 1982), and isotopes (Hay, 1976; Cerling et al., 1977; Cerling & Hay, 1986). The combined results of these studies (particularly the faunal and floral work) allow for a palaeoenvironmental reconstruction through the Olduvai subchron at its type-site. Early in the Olduvai, before 1.91-1.89 Ma, the area was characterised by a moist environment with a high percentage of bush and tree cover, perhaps with some Acacia woodland. During the

mid Olduvai (1.89-1.8 Ma), the area experiences a switch to arid or semi-arid conditions with a low percentage of bush and tree cover. The latest Olduvai (following 1.8 Ma), sees a return to moist conditions.

3.2.5 Mediterranean

The Olduvai subchron has been intensively studied in the type-section of the Plio-Pleistocene boundary at Vrica (Aquirre & Pasini, 1985) and at other localities in Calabria (Italy) (Hilgen, 1990, 1991; Zijderveld et al., 1991; Hilgen et al., 1993). The sedimentary sequence at Vrica comprises alternating white to beige marls and dark sapropelic layers. In total, 21 sapropels have been distinguished which are considered to be indicative of periodic Mediterranean stagnation and anoxic bottom water formation (cf. Williams et al., 1978). The stratigraphic distribution of the sapropels in the Vrica section is not uniform (Hilgen, 1991) and occur as distinct clusters: small-scale clusters comprise 2-4 individual sapropels, and large-scale clusters comprise 2-3 small-scale clusters. Hilgen (1991) shows that sapropel formation is related to orbital parameters, with individual sapropels corresponding to minimum peak values of the precession index, clustered around 100 ka eccentricity maxima. Sapropels do not appear to form at 100 ka eccentricity minima.

Within the Olduvai, Hilgen (1991) singles out a very conspicuous small-scale cluster comprising four extraordinarily thick sapropels, which he terms a key-cluster. This key-cluster corresponds with precession

cycles 176-182, dated 1.875-1.81 Ma (Hilgen, 1991; *Funnell et al.,

1996). Hilgen (1991) states that this mid Olduvai key-cluster corresponds

not only to a 100 ka eccentricity maximum, but also to a maximum of the

400 ka eccentricity cycle. Therefore, the mid Olduvai in the

Mediterranean apears to have experienced a number of major orbitally

driven anoxic events, which appear to be linked to the African monsoons

(Rossignol-Strick, 1983).

3.2.6 North America - New Mexico

Mack et al. (1994) document a relatively complete Plio-Pleistocene

sequence of fluvial and palaeosol deposits from the southern Rio Grande

Rift in south-central New Mexico, for which magnetostratigraphy has

been obtained (Mack et al., 1993). The record of these sediments

provides a proxy for precipitation and aridity, with fluvial channel deposits

representing wet conditions, and calcic palaeosol formation indicating

aridity. At the only site where the Olduvai is exposed (Rincon Arroyo), the

subchron is characterised by fluvial channel deposits, whilst immediately

above and below the Olduvai the sediments comprise floodplain deposits

with frequent development of stage II calcic palaeosols, which may be

interpreted as intermiitent floodplain deposition separated by long

periods of non-deposition and pedogenesis (Mack et al., 1994). Thus,

here, the Olduvai appears to be characterised by wet conditions, with

drier conditions prevailing before and after the event.

3.2.7 South America - Bogotá Basin (Colombia)

Pliocene-Pleistocene lake sediments of the intramontane Bogotá Basin in the tropical Andes of Colombia have received much attention in recent years (Hooghiemstra, 1989; Hooghiemstra & Sarmiento, 1991; Andriessen *et al.*, 1993; Helmans & van de Hammen, 1994; Hooghiemstra & Ran, 1994). Subsidence of the Bogotá Basin through the Pliocene-Pleistocene allowed for the accumulation of *c.* 600m of sediment, which has been subdivided into the Tilatá (Pliocene), Subachoque (Late Pliocene-Early Pleistocene), and Sabana (Middle-Late Pleistocene) Formations. Much of the palaeoenvironmental studies have been based on lithostratigraphy and palynology. Dating the sequences however, has been slightly problematic. Attempts have been made to match pollen spectra with orbitally-tuned deep-sea $\delta^{18}O$ chronologies and this appears to work well for the Middle and Late Pleistocene. This chronology is supplemented by a number of zircon fission track dates from tephras. Only recently has there been an attempt to obtain a magnetostratigraphic chronology (Helmens *et al.*, 1997), but this has only been partially successful. The base of the Olduvai subchron has been firmly dated within the basal sequence of the Subachoque Formation (of the Guasca Section only), but the top of the subchron is only tentatively identified. Also, a pollen record for these sediments is apparently lacking, although one is available for the underlying Upper

Tilatá Formation at this section (Wijninga & Kuhry, 1993). However, lithostratigraphic and magnetic susceptibilty (MS) records are presented by Helmens et al. (1997) allowing general palaeoenvironmental reconstruction through the subchron. The lower and upper parts of the Olduvai sequence is characterised by fine-grained clays and silts with low MS values, whilst the mid Olduvai sequence comprises sand and gravel deposits and high MS values. Helmens et al. (1997) interpret all coarse sediments within the Bogotá Basin to be of glacio-fluvial origin. This is supported in their view by the associated high MS values, which they take to indicate cold climatic conditions. However, MS is related to bedrock erosion and the release and deposition of magnetite, thus high MS values indicate greater bedrock erosion which may not necessarily always be related to glacial activity, even given the site's geographical location. Without a matching pollen record for this sequence, these data might equally be interpreted as representing increased fluvial erosion, driven by an increase in regional precipitation.

3.3 Discussion

It has already been noted that the palaeoenvironmental interpretation of the eastern equatorial Pacific sites through the Olduvai is entirely analogous with present day interannual variability associated with La Niña/El Niño conditions (Philander, 1989). The effects of the El Niño/Southern Oscillation (ENSO) phenomena are widespread, not only

around the Pacific and Americas, but also in the Indian Ocean, Asia,

Africa, and Europe (Rasmusson & Wallace, 1983; Ropelewski & Halpert,

1987; Bigg, 1990; Glantz *et al.*, 1991). Table 6 summarises the

palaeoenvironmental interpretation for each region discussed above, and

outlines the conditions experienced during historic El Niño events in

each of the regions.

In the eastern equatorial Pacific, El Niño's are characterised by a

reduction in trade wind strength which weakens upwelling intensity,

raising SST's, lowering bioproductivity, and increasing the thermocline

depth. Along western South America, from Peru to Colombia,

precipitation increases, often resulting in flooding. A similar increase in

the level of precipitation is experienced in the southwestern United

States, which again may lead to flooding. In the palaeoenvironmental

records for the mid-Olduvai of the eastern equatorial Pacific, Colombia

and New Mexico, conditions consistent with an El Niño analogue are

observed (Table 6). The central Pacific also experiences lower

bioproduction during an El Niño event, which would result in reduced

sediment accumulation, as recorded during the mid-Olduvai of the

region. The northeast Pacific is also affected with abnormally warm

winter conditions in Alaska and western Canada (Ropelewski & Halpert,

1987), and the northwest Pacific experiences warming following major

ENSO events due to the northward re-routing of the Kuroshio Current,

which under normal conditions advects heat from the Japanese and

other East Asian coasts eastwards into the mid-latitude Pacific (Jacobs *et*

al., 1994). Such warming is observed through the Olduvai in Japan and conceivably may have influenced the East Asian Monsoon, leading to warm/moist conditions and palaeosol development on the Loess Plateau (Table 6).

The Indian Ocean basin and monsoon system is teleconnected to ENSO with a regional increase in atmospheric pressure, and drought conditions in eastern and southern Africa, India, Australia, and Indonesia during ENSO events (Bigg, 1990). The palaeoenvironmental record from the Olduvai Gorge in East Africa (Table 6) does indeed exhibit drought conditions through the mid-Olduvai. However, in India, drought is caused by a weakening of the Boreal summer (southwest) monsoon, although it must be noted that monsoon weakening and Indian droughts have not occurred in association with all historic El Niño events, such as during the prolonged 1991-1994 event when the southwest monsoon was wetter than normal (Kripalani & Kulkarni, 1997). The palaeoceanography of ODP Site 709 (tropical Indian Ocean) indicates a reduction in zonal trade winds, possibly with a strengthened southwest monsoon, during the mid-Olduvai (*Haslett *et al.,* 1994b; *Funnell *et al.,* 1996). Clemens *et al.* (1996) examine the variability of the Asian monsoon on a Plio-Pleistocene timescale and suggest that the southwest monsoon is strongly influenced by interhemispheric pressure gradients, caused by differential sensible heating over the region, between low pressure conditions over the warm Asian continent during the Boreal summer and high pressure over the cold southern subtropical Indian Ocean (SSIO)

during the Austral winter. Monsoonal variability is considered by

Clemens *et al.* (1996) to be related to the storage and export of latent

heat from the SSIO, which episodically increases the pressure gradient,

strengthening the Asian low pressure system and southwest monsoon.

Indian Ocean high pressure is also enhanced during ENSO events, and

if the event is prolonged, or a series of high frequency events of high

magnitude, then a situation may arise whereby the southwest monsoon is

intensified, as during the 1991-94 ENSO event. This would also enhance

the North African monsoon and increase freshwater input into the

Mediterranean, promoting sapropel formation (Rohling & Hilgen, 1991),

such as the sapropel key cluster identified by Hilgen (1991) in the

Olduvai of the Vrica type-section.

Also, it must be remembered that ENSO events decrease

bioproductivity in the eastern Pacific, an area responsible for 50% of

global new bioproduction, and if high frequency/magnitude ENSO events

occurred through the mid-Olduvai, then levels of atmospheric CO_2 would

increase enhancing the Greenhouse Effect leading to global warming

(*Funnell *et al.*, 1996). Jones (1994) recognises a positive correlation

between global warming and precipitation over India and in parts of the

Mediterranean catchment. Therefore, some palaeoenvironmental signals

obtained for the Olduvai, may represent a direct response to palaeo-

global warming, and only indirectly related to prolonged ENSO

conditions. Distinguishing the two signals in the geological record is

likely beyond the capability of the proxies currently available.

3.4 Conclusion

The palaeoceanographic conditions recognised during the Olduvai timeslab of the eastern equatorial Pacific appear to be analogous to modern El Niño conditions. A survey of palaeoenvironmental records through the Olduvai at other locations all appear to support this hypothesis. *Funnell et al. (1996) state that these El Niño-analogue conditions likely lay beyond the present day natural limits of ENSO interannual variability, producing a prolonged period (c. 100 ka) of anomalously warm conditions around the world. This has apparently (erroneously) conditioned the placement of the Plio-Pleistocene boundary (Funnell & Haslett, 1994), and may have influenced hominid evolution. The cause of such a protracted period of ENSO conditions is speculative. *Haslett et al. (1994b) suggest it may be related to orbital forcing, with the mid-Olduvai corresponding to a maxima in the 100 ka eccentricity cycle, however this is not unusual in itself, and it may be the phased maxima of both the 100 ka and 400 ka eccentricity cycles at this time (Hilgen, 1991) that are responsible.

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