Early to middle Miocene foraminifera from the deep-sea Congo Fan, offshore Angola

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ABSTRACT: Analysis of a 630m section of an exploration well penetrating the distal part of the Congo Fan (~2000m water depth) yielded high abundance and diversity assemblages of agglutinated and calcareous benthic foraminifera. Planktonic foraminifera constrain the age to Early – Middle Miocene, and $\delta^{18}O$ records reveal the Mi1 (~16.3 Ma) isotopic shift. Relatively few taxonomic studies of deep-water calcareous and agglutinated benthic foraminifera exist from this time period in this locality. All species encountered are therefore taxonomically described and documented using SEM photography (over 170 species), along with 27 species of planktonic foraminifera. Faunas show close affinities to those of the eastern Venezuela Basin, Gulf of Mexico and Central Paratethys.

Seven assemblages are defined and analysed using morphogroup analysis and Correspondence Analysis, documenting the response of benthic foraminifera to three primary environmental-forcing factors; energy levels in the benthic boundary layer, oxygen levels relating to changing surface water productivity, and fluctuations in the level of the CCD. Near the top and bottom of the studied section both foraminiferal abundance and diversity decrease, corresponding with increased sand content implying greater energy levels and environmental disturbance. The majority of the section consists of shales with very low percentage sand, high foraminiferal abundance and diversity, and high sedimentation rates of ~10cm/kyr. Morphogroup analysis reveals a major switch in the fauna at around oxygen isotope event Mi1, with the transition from an epifaunal-dominated *Cibicidoides* assemblage to shallow infaunal-dominated *Bulimina* assemblage. We regard this as likely due to expansion of the oxygen minimum zone (paleobathymetric estimates are ~1000m) related to increased surface-water productivity and global cooling. Shifts in calcareous foraminiferal percentage over the studied interval overprint these signals and are believed to be related to a shoaling CCD, linked to reduced oceanic acidity and global atmospheric CO_2 levels during the early Middle Miocene Monterey Carbon Isotope Excursion.
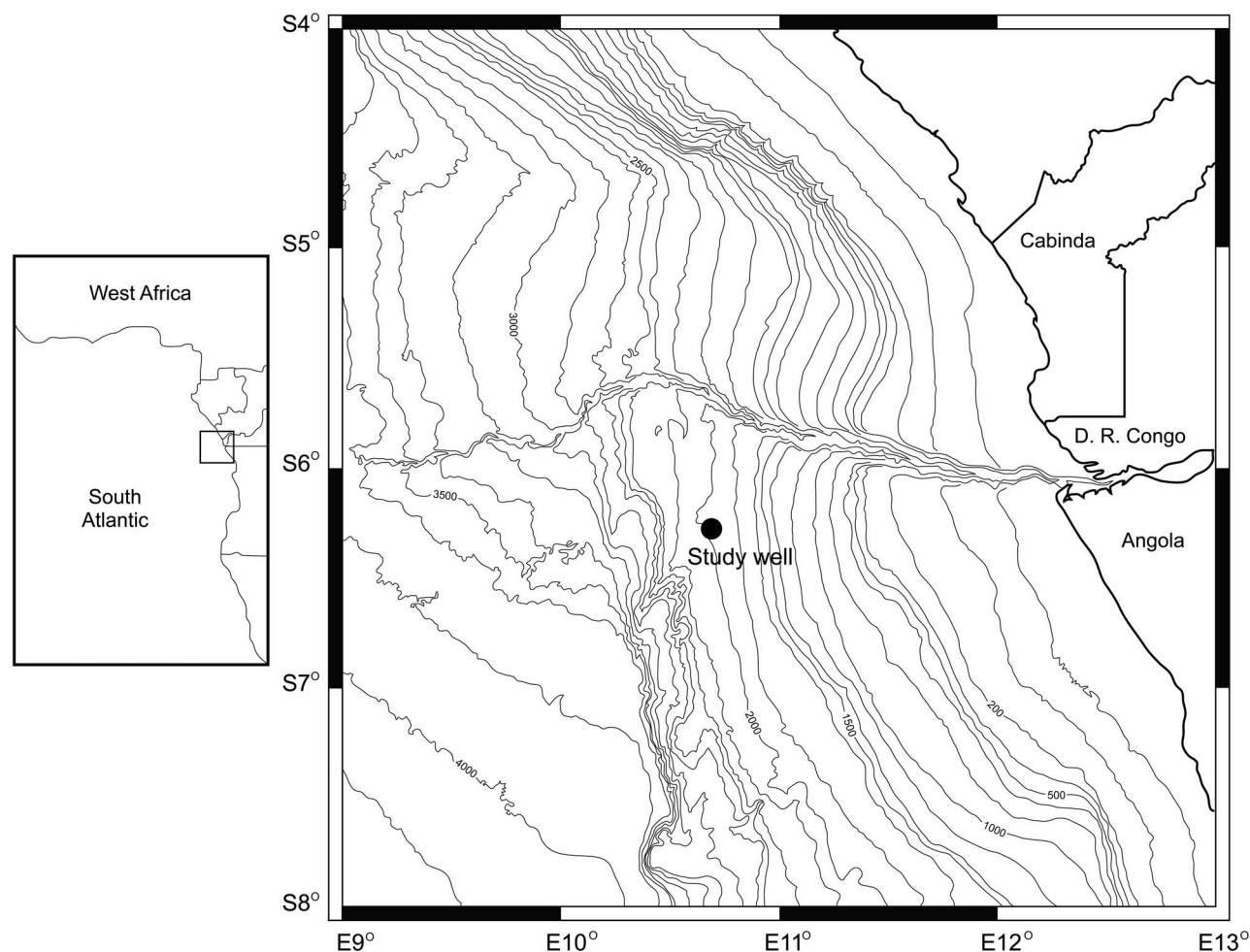
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INTRODUCTION

The Congo Fan has been the subject of an increasing number of earth science studies in recent literature, not least due to the increase in hydrocarbon interest in the region over the last few years (Evans 2002). Although this has lead to the publication of many geological studies (Anderson et al. 2000; Lavier et al. 2001; Anka and Séranne 2004; Broucke et al. 2004; Giresse 2005), architectural studies (Savoye et al. 2000; Babonneau et al. 2002; Sultan et al. 2004), geochemical studies (Bentahila et al. 2006) and seismic studies (Uenzelmann-Neben et al. 1997; Uenzelmann-Neben 1998), relatively little has been published on the micropaleontology of the Congo Fan. A series of foraminiferal studies from West Africa focussed on Cretaceous and also Cenozoic outcrops in which many species were described (Chenouard et al. 1960; de Klasz et al. 1960; de Klasz and Rérat 1962a, 1962b; de Klasz et al. 1963; Graham et al. 1965; Le Calvez et al. 1971; Volat et al. 1996). Cameron (1978) studied Neogene benthic foraminifera from DSDP Sites 360 and 362 offshore Angola, basing their taxonomic work largely on comparisons from New Zealand. Seiglie and Baker (1983) described several new Cenozoic species of complex-walled agglutinated foraminifera from West Africa. Preece (1999) and Preece et al. (1999; 2000) studied Miocene benthic foraminifera from exploration wells offshore Cabinda, describing new species and paleoenvironmental implications. The present authors published a taxonomic and paleoenvironmental study of the Oligocene section of the well in this study (Kender et al. 2006; Kender et al. 2008) which contained almost exclusively agglutinated foraminifera. This study aims to provide a complete taxonomic and paleoenvironmental analysis of the benthic foraminifera from a 630m section of Lower-Middle Miocene shales from the distal section of the Congo Fan (text-fig. 1), with over 200 species of agglutinated, calcareous and planktonic foraminifera photographed and described.

GEOLOGY AND SEDIMENTOLOGY

The Congo Fan is the second largest delta system in the world (3.7 x 10^6 km^2), draining most of central Africa through the Congo River and its associated tributaries. A general lithologic column is given in text-figure 2. The Congo Fan is a terrigenous wedge largely built of Oligocene and Miocene sands and shales organised into thick sedimentary packages containing paleocanyons, paleochannels, and overbank deposits (Anderson et al. 2000; Lavier et al. 2001; Anka and Séranne 2004; Broucke et al. 2004; Giresse 2005). The unique meandering paleochannels contain sands that have proved high quality traps for migrating hydrocarbons (Evans 2002). In this study we analyse the foraminiferal microfauna from the Miocene section of a well drilled in the distal part of the Congo Fan (text-fig. 1).

The West African margin has been depositionally active since initial rifting took place in the Early Cretaceous (Jansen et al. 1984; Nürnberg and Müller 1991), resulting in three sub-basins developing along the West African passive margin, including the Lower Congo basin (Broucke et al. 2004). The earliest marine sediments consist of Aptian evaporites (<1000m thick) which overlie lacustrine deposits and form the complex of diapirs seen throughout the overlying strata.

TEXT-FIGURE 1
Bathymetric map of the Congo Fan, showing the location of the well analysed in this study, Block 31, water depth ~2000m.

From the Late Cretaceous to Early Oligocene, aggradational carbonate/siliciclastic ramp sediments formed ~200m of deposits, which form the principal source rock for the overlying hydrocarbon-bearing sands. These are directly overlain by a significant Oligocene unconformity of several million years, followed by prograding terrigenous turbidite deposits that continue through the Neogene forming up to 3000m of sediment. These consist of shale and sand overbank, levee and channel deposits, containing foraminifera in varying abundances.

The well in this study largely spans the Oligocene to Middle Miocene distal section of the turbiditic fan. It has been sampled at 10m intervals from about 4270-2760m depth, has a water depth of ~2000m, and is located ~170km offshore Angola (Block 31). The Upper Oligocene section (4270-3710m), analysed by Kender et al. (2008), consists of predominantly black muds and silts with interbedded sandy horizons, which continues into the Lower Miocene with little sedimentological change until reaching a large sand/silt body interpreted as a submarine paleochannel. The foraminifera are almost entirely agglutinated, and are present in most samples at medium to low abundances (average 150 specimens per 100g). Typical cosmopolitan Paleo-

gene forms can be identified (*Nothia robusta*, *Ammodiscus latus*, *Reticulophragmium amplectens*), along with several dominating high productivity forms (e.g. *Portatrochammina profunda* and *Scherochorella congoensis*). The diversity ranges from medium to low (average 24, maximum 40 species per 100g) with significant faunal variation possibly related to productivity fluctuations.

The overlying sand horizon (3700-3420m) becomes barren after foraminiferal diversity and abundance drops away leaving only rare specimens of *Nothia* spp. and *Ammodiscus* spp. Above this, the sand abruptly gives way to the Lower and Middle Miocene silts and muds analysed in this report (3410-2760m), containing gradually more calcareous and planktonic foraminifera as well as persistent agglutinated forms. The diversity and abundance is high, and shows significant variation in calcareous content which could be related to fluctuations in the CCD during the Middle Miocene. Sedimentation rates over this interval are in the order of 10cm/kyr. Faunas become more diverse and reveal typical Middle Miocene calcareous and agglutinated foraminifera, along with some persisting typical Paleogene forms (see Taxonomy).

EARLY-MIDDLE MIOCENE PALEOCEANOGRAPHY

The Early-Middle Miocene represents an important time in Earth's history as it was a transitional phase between the Paleogene climatic high and the 'icehouse' climate of the Neogene. The Early Miocene witnessed a series of fluctuating Antarctic glacial and interglacial episodes which culminated in the warmest period of the Neogene around the early/middle Miocene boundary, before a significant cooling phase and the final transition into the cold icehouse world at around 14 Ma (Miller et al. 1987, 1991; Flower and Kennett 1994, 1995; Flower et al. 1997; Holbourn et al. 2005).
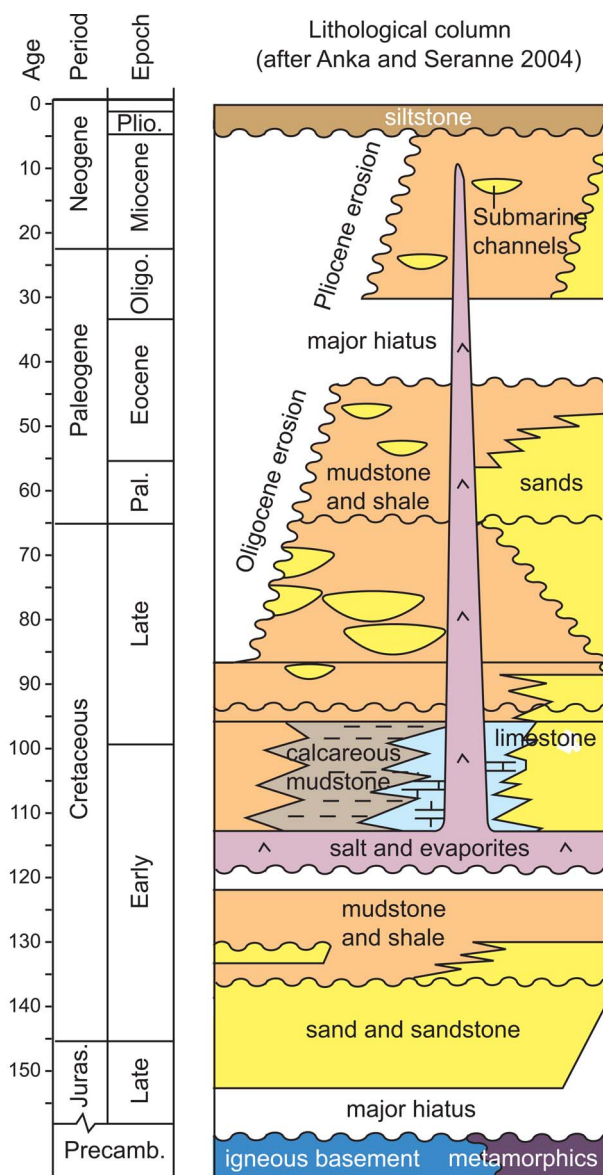
Early Miocene oceanic circulation is relatively poorly understood due in part to widespread unconformities in ocean sediments at this interval (Keller and Barron 1983; Wright et al. 1992). Barron and Keller (1982) record a widespread deep-sea hiatus at around 15–16 Ma which they related to increased bottom current strength associated with polar cooling. Carbon isotope signals are however thought to indicate that there was only a small contribution of Northern Component Water (NCW) to the South Atlantic at this time (Wright et al. 1992). The formation of warm saline deep water in the Indian Ocean has been suggested by several authors (Woodruff and Savin 1989; Flower and Kennett 1994, 1995), and may have contributed a significant component of Atlantic waters through the open Tethys Ocean at this time. Around the early/middle Miocene boundary a major reorganisation of global circulation occurred that resulted in the well-documented 'silica switch', representing a change in the locus of biosilica production from the North Atlantic to the Indo-Pacific Oceans (Barron and Baldauf 1990). This coincided with the intermittent closure of Tethys (Jones 2006) and the emergence of the Iceland Plateau (Schnitker 1980; Flower et al. 1997). The final transition to icehouse world at around 14 Ma has been found to be coincident with a period of prolonged Antarctic low summer insolation creating the boundary conditions needed for large-scale cooling (Holbourn et al. 2005).

MATERIALS AND METHODS

Sample Processing

Ditch cutting samples were collected at 10m intervals from a near-vertical exploration well in Block 31, offshore Angola, at a water depth of ~2000m (text-fig. 1). Samples of approximately 100g were weighed, washed over a 63μm sieve to remove silt content, dried in an oven, and weighed again. All foraminifera > 125μm were picked from each sample, or fraction of sample if abundances were significantly higher than 300, sorted into species, glued onto cardboard reference slides and counted (Appendix 1). Smaller fractions were not included in the analysis as the fossilisation potential of small specimens is even lower than larger ones, thus introducing an even greater element of bias into results. Photographic images were taken using JEOL JSM-648OLV SEM at University College London, after coating specimens in gold. Image brightness and contrast were adjusted using Adobe Photoshop©.

Due to the scarcity of benthic foraminifera in some samples oxygen isotopes were obtained from *Cibicidoides* spp. (*C. mundulus* and *C. pachyderma* were preferentially used where available), 2-5 specimens >250μm taken where possible. Crushed specimens were then immersed in 3% hydrogen peroxide for 30min, ultrasonicated in methanol for 15s, excess residue and liquid removed, and dried at 45ºC. Stable isotope analysis was conducted using a ThermoFinnigan MAT 252 and
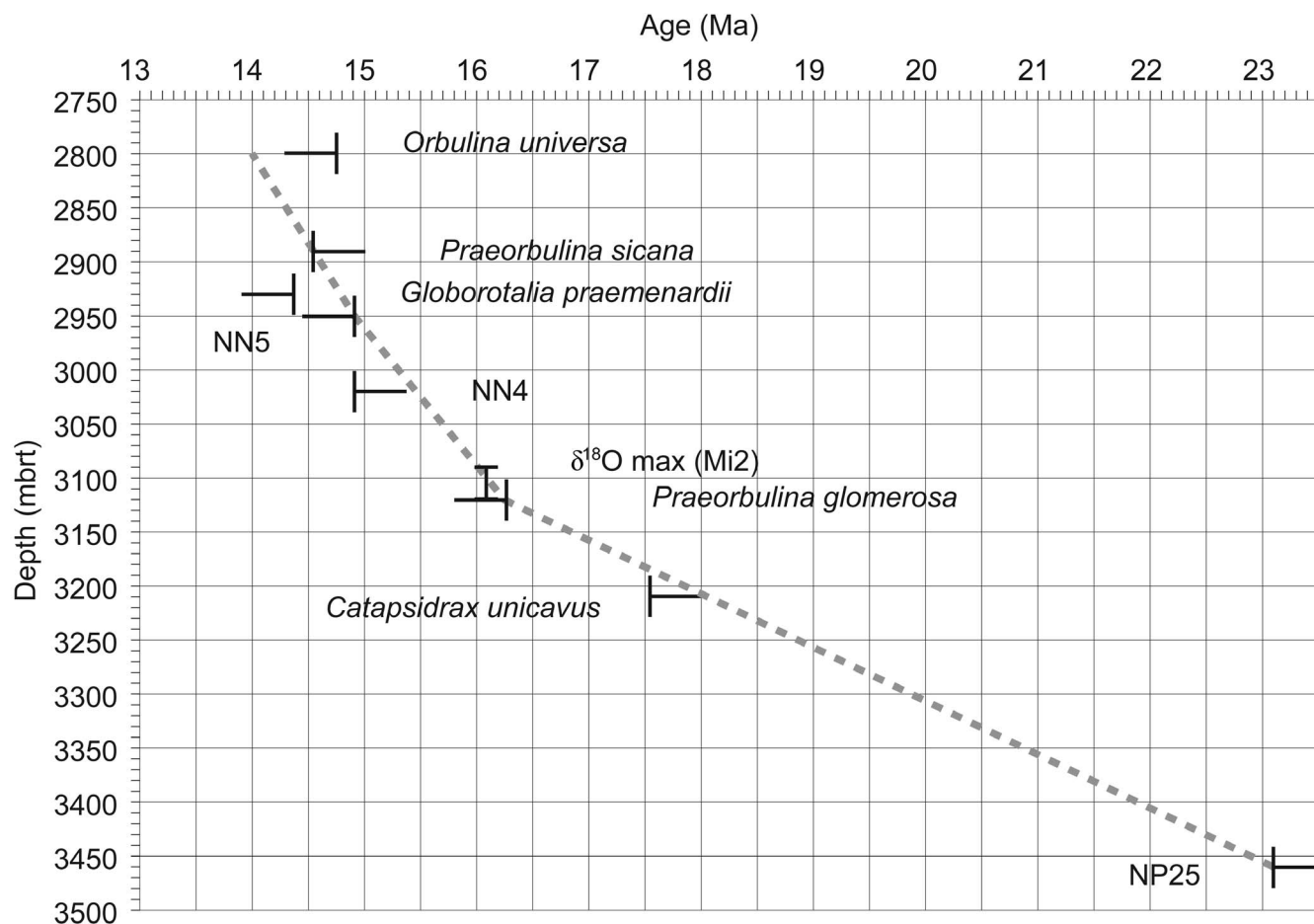

TEXT-FIGURE 2
Generalised geological column for the Lower Congo basin, West African passive margin. The Congo Fan has been depositionally active since the mid-Oligocene and makes up the majority of sediment in this region.

coupled carbonate preparation device at Cardiff University, with an external reproducibility of =0.08‰ for $\delta^{18}O$ and reported on the VPDB scale. Values of $\delta^{18}O$ recorded from *Cibicidoides* spp. have been adjusted by +0.64‰ to align them with equilibrium calcification at given temperature and $\delta^{18}O_{sw}$ (Shackleton 1974).

Data Analysis and Statistics

Sand percentage was obtained by subtracting the weight of the sample containing least sand (practically none) from all samples, giving the remaining weight as a percentage of the total unwashed sample. Absolute abundance was calculated by dividing the number of foraminifera picked from each sample by the fraction picked, and then dividing by the number of grams originally sampled (around 100g for each sample) to obtain speci-

TEXT-FIGURE 3
Age / depth model for the well in this study (Block 31, offshore Angola). Age diagnostic planktonic foraminifera are rare in most samples.

mens per gram. Diversity is given both as number of species encountered per sample, and as Fisher's alpha (α) in order to normalise for the differing number of specimens picked per sample (Fisher et al. 1943). The quantity α is found using the following equation (calculated by PAST of Hammer et al. 2005):

$$\frac{N}{S} = \frac{(e^{S\alpha} - 1)}{S / \alpha}$$

Where N is the number of specimens and S is the number of species per sample. The total value α is given for each sample, and this is interpreted as the number of species in each population that are represented by just one specimen (Hayek and Buzas 1997), and is independent of sample size (N). Fisher's α has been used successfully by many authors (e.g. Kuhnt et al. 2002; Gooday and Hughes 2002; Murray and Pudsey 2004) due to its ease of use and results as reliable as any other method (Hayek and Buzas 1997).
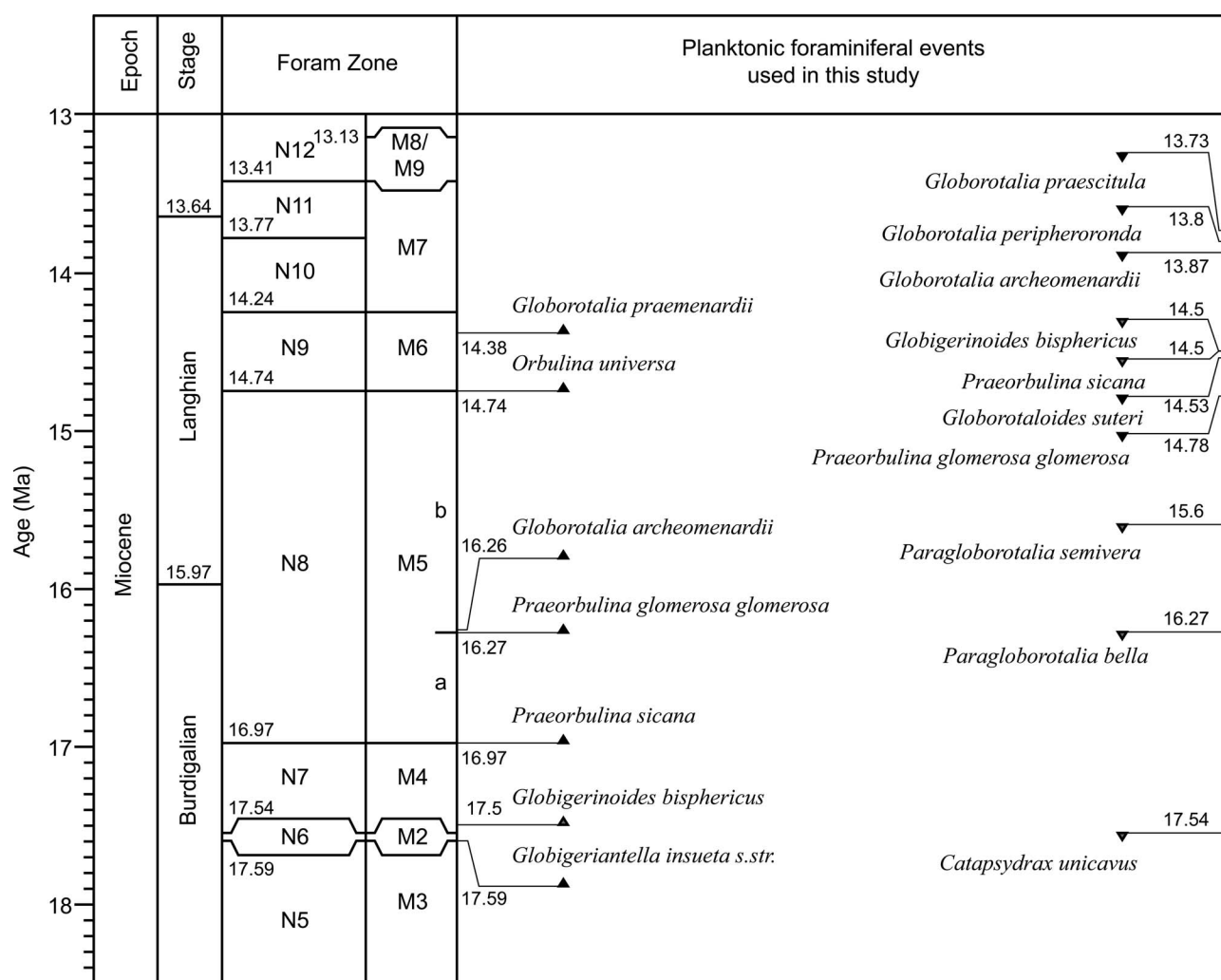
Correspondence Analysis (CA) results have been obtained using PAST (Hammer et al. 2005), using the entire dataset (Appendix 1) unaltered. CA is similar to Principal Components Analysis in that it attempts to show multidimensional data in fewer dimensions (Teil 1975; Greenacre 1984), and has been used by many authors to characterise biological gradients from taxonomic counts (Hammer and Harper 2006; Kuhnt et al. 2002). Rather than finding the principal component along which greatest variance is apparent, CA places both species and samples in the same space, samples and species that are clustered together sharing similar assemblages or distributions. Values for samples and species are found using a reciprocal averaging algorithm that averages abundances and species values by abundances, and vice-versa with sample values, continuously until minimal change is obtained through successive iterations (Benzecri 1992). The first axis has been found to represent primary ecological gradients (Hammer and Harper 2006), and in our results may represent oxygen concentration, although we generally use the technique to gain evidence for deriving assemblages.

RESULTS

Biostratigraphy and Age / Depth Model

The age model for the study well (text-fig. 3) has been constructed using planktonic foraminiferal events, an oxygen isotope event (Mi2) and nannofossil events, with a linear sedimentation rate inferred between tie-points. All events are

TEXT-FIGURE 4
Absolute ages for planktonic foraminifera encountered in this study against the timescale of Lourens et al. (2004). Events compiled from Ogg and Lugowski (2007); Berggren et al. (1995); Bolli and Saunders (1995); and Kennett and Srinivasan (1983).

fitted to the Lourens et al. (2004) timescale. The age ranges used for all planktonic foraminifera found in this study are given in text-figure 4, based on the works of Ogg and Lugowski (2007); Berggren et al. (1995); Bolli and Saunders (1985); Kennett and Srinivasan (1983), and a brief discussion of each species is presented in the taxonomic part of this paper. As the recovery of planktonic foraminifera was relatively low (see Appendix 1), first and last occurrences are not a useful indication of age and so in most cases we have used these only as a guide.

The upper section of the well (2760-2890m) is constrained to Middle Miocene (Langhian, zone N9) by the occurrence of *Orbulina universa*, and *Praeorbulina sicana*, whose ranges overlap in this interval. The occurrence of *Globorotalia praemenardii* at 2930m suggests an earlier age but may be caved as the older form *P. sicana* occurs significantly higher in the section.

The occurrence of *Praeorbulina glomerosa glomerosa* at 3120m suggests an age of no older than about 16.3 Ma (Berggren et al. 1995), and this depth also coincides with oxy-

gen isotope event Mi2 (Miller et al 1991) at 16.1 Ma seen in the isotope record from this study (text-fig. 5) as the beginning of global cooling (δ^{18}O increase). The δ^{13}C record also fits the global trend at this location (unpublished data). Nannofossil dating (unpublished BP data, text-fig. 3) supports these ages.

The appearance of *Catapsydrax unicavus* at depth 3210m suggests that the samples below this point are older than the top of zone N6 (Kennett and Srinivasan 1983) at 17.5 Ma. Samples below this depth are more impoverished in planktonic foraminifera and dating is more difficult. Nannofossil dating (unpublished BP data) places the Oligo-Miocene boundary at approximately 3475m. The presence of *Paragloborotalia mayeri* sensu Bolli and Saunders (1985) in sidewall core sample 3521m suggests that this level is no older than Chattian.

Benthic Foraminiferal Assemblages

Benthic foraminiferal results reveal a taxonomically diverse fauna with over 200 species identified (Appendix 1). Abundance and diversity vary up the section (text-fig. 6), along with