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Nannofossil palaeoecology of Lower Miocene sapropels from IODP Expedition 359, the Maldives

Jeremy R. Young^a, Odysseas A. Archontikis^a, Xiang Su^b, Santi D. Pratiwi^c

a. Department of Earth Sciences, University College London, Gower Street, London, WC1E 6BT, UK

b. Key Laboratory of Marginal Sea Geology, South China Sea Institute of Oceanology, Chinese Academy of Sciences, West Xingang Road, Guangzhou 510301, P.R. China <sup>[L]
[SEP]</sup>

c. Department of Geological Engineering, Faculty of Earth Technology and Energy, Universitas Trisakti, Jakarta-Indonesia. <sup>[L]
[SEP]</sup>

Corresponding author: J.R. Young email: jeremy.young@ucl.ac.uk

E-mail addresses of other authors: odysseas.archontikis@ucl.ac.uk (O. A. Archontikis), suxiang@scsio.ac.cn (X. Su), rhabdosphaera@gmail.com (S.D. Pratiwi)

Abstract

During IODP expedition 359 multiple holes recovered Modern to Middle Miocene sediments from the Kardive Drift which is strongly influenced by monsoonally-driven currents. Two holes continued below the drift into Lower Miocene sediments that were deposited under rather different conditions following Oligocene subsidence of the Maldives Ridge. These sediments are characterized by marked alternation between dark organic-rich sapropelic sediments and pale nannofossil oozes. This interval is also characterised by generally good to excellent nannofossil preservation. Nannofossil assemblages from the sapropel and non-sapropel intervals are broadly similar; both sediment types contain diverse normal marine assemblages and no taxa are confined to either sediment type. In the sapropels nannofossil abundance and diversity tends to be lower and *Cyclicargolithus floridanus* specimens are smaller. In addition *Umbilicosphaera* abundances are higher in the non-sapropel layers whilst *Discoaster* abundance is higher in most sapropels. These differences are more marked in the better developed sapropels. The nannofossil evidence supports the interpretation from geochemistry that sapropel formation was primarily driven by changes in bottom water ventilation linked to sea-level change rather than surface water productivity.

Keywords

Coccoliths; Early Miocene; Anoxic sediments; Indian Ocean; microfossils; Age-models

1. Introduction

The Maldives are a north-south trending double string of reef-rimmed atolls separated by an Inner Sea up to 500 m deep, within the western Indian Ocean. The modern system is part of the Chagos-Laccadive ridge which formed as a volcanic hot-spot trail during the Eocene. A shallow marine carbonate bank formed during the Oligocene across the ridge. During the Late Oligocene this changed to a system with marginal carbonate banks and a deep Inner Sea within which platform-derived and hemiplegic carbonates accumulated continuously throughout the Neogene, well-above the calcite-compensation depth (Aubert and Droxler 1992, Ludmann et al. 2018)

International Ocean Discovery Program Expedition 359 drilled a series of sites in the Maldives in late 2015 (Betzler et al. 2017). Primary objectives of the expedition were to document the Neogene development of the Maldives carbonate system and to use them to investigate aspects of the palaeoceanography of the Indian Ocean, especially the onset of strong monsoonal current systems (Betzler et al. 2016). Nannofossil biostratigraphy played a major role in this work, and is documented in the initial report (Betzler et al. 2017). Sediments were recovered ranging in age from late Oligocene to the present day. Much of the succession was dominated by carbonate drift deposits (e.g. Ludmann et al. 2018), these formed thick accumulations of coarse-grained platform-derived sediments of limited interest for planktonic micropalaeontology, although it was possible to usefully date them. The initial Lower Miocene basin fill, however, was formed in a different sedimentary environment with weaker current influence, lower sedimentation rates and greater hemipelagic input. This part of the succession was recovered at two sites, U1466 and U1469 (Fig. 1). It contains more abundant and better preserved planktonic microfossils than the later Miocene sediments, and is of more interest since the Lower Miocene is less well studied. Most notably this interval is characterised by cyclic sedimentation, with alternating organic-carbon rich and poor sediments. This pattern commences in the basal Miocene with deposition of intense black sapropels with organic carbon contents up to 30% (Swart et al. 2019). Subsequently the pattern continues through the rest of the Lower Miocene but with colour contrast and organic carbon content progressively declining (Betzler et al. 2017, Swart et al. 2019). Post-cruise study of these sapropels was undertaken by Swart et al. (2019) including organic carbon analyses, trace element geochemistry, stable isotope geochemistry and cyclicity analysis. As well as highlighting that this succession represents an invaluable geochemical archive from a key interval of geological time, this study demonstrated that the colour alternation reflected organic carbon content and concluded that the signal was primarily driven by changes in organic carbon preservation rates rather than by changes in organic carbon production. They inferred the most likely cause to be variable ventilation of a perched basin in response to sea-level changes, driven by Antarctic sea ice volume change and so ultimately to orbital cyclicity.

This sapropelic interval contained the best preserved Miocene nannofossils recovered during Expedition 359, and laminated sediments deposited in anoxic conditions have often proven rich sources of palaeobiological data on nannofossils (e.g. Goy 1981, Young and Bown 1991, Lees et al. 2006, Thomsen 1988, Crudele et al. 2006). Consequently this interval

was selected for detailed post-cruise study of the nannofossils in order to investigate the relationship between the nannofossil assemblages and the changing environment and to provide an improved age-model for the sapropels.

2. Material and methods

Detailed analysis of nannofossil assemblages was concentrated on the intervals with the best preserved nannofossils and darkest sapropels. These were cores U1466B-56R and 57R (4.933°N, 73.028°E, 518.1 m water depth) and U1468-99X (4.933°N, 73.071°E, 521.5 m water depth). The age models suggest that the sampled sequence from U1468A was probably slightly younger than that from U1466B.

Images of these cores are shown in Figure 3, along with the sampling levels. The entirety of core 56R was sampled at 5 cm frequency. Core 57R was initially sampled at 20 cm spacing with a second sampling at precisely targeted levels to include the darkest sapropel levels and palest intervening levels (sampling conducted by our colleague K. Hagino of Kochi University). Core U1468A-99R was sampled at 5 cm spacing.

2.1 Sample colour

Detailed scan data is available for the cores (e.g. Swart et al., 2019). However the cores are fragmented and it proved impossible to precisely correlate nominal sample depths to sample depths on e.g. core images. For example some samples supposedly collected from depths of sapropels on the core images were in fact pale chalk. So, we also made a subjective assessment of colour - ranking the samples into categories - 1 white (Munsell colour 9/0); 2 off-white; (Munsell colour 8/0); 3 pale grey (Munsell colour 7/0 to 6/0); 4 medium grey; (Munsell colour 5/0 to 4/0); 5 dark grey; (Munsell colour 3/0 to 2/0); 6 black (Munsell colour 1/0 to 0/0). These values are based directly on the samples used for nannofossil analysis, not on the core images. The scale is crude but reproducible and is used to give an indication of actual colour and so intensity of the sapropels in Figures 4-8.

2.2 Nannofossil analysis

Samples were prepared as rippled smear slides (Bown and Young 1998), mounted with Norland optical adhesive, and examined with an Olympus BX51 light microscope at x1250 magnification. Selected samples were also examined by scanning electron microscopy from both dark and light layers. Small rock chips were mounted on aluminum stubs using epoxy resin, sputter-coated with gold-palladium and examined using a Zeiss Ultra Plus Field Emission SEM at the Natural History Museum, London.

Assemblage counts were carried out by light microscopy on ten fields of view with full enumeration of the assemblage (400-2000 specimens per slide). Each field of view was examined in both cross-polarised light and phase contrast (for accurate count of taxa such as *Umbilicosphaera*, *Hughesius* and *Discoaster*). Taxonomic concepts primarily follow Young (1998), full taxonomic citations and bibliographic references for all taxa can be found on the Nannotax website (Young et al. 2019a). Similarly citations, taxonomic references and associated data for all cited planktonic foraminiferal species can be found on the pforams@mikrotax reference website (Young et al. 2019b).

Samples from the sapropel layers were often significantly harder than those from the pale inter-beds. This made it impossible to completely disaggregate them and so prevented calculation of absolute abundances of nannofossils. Instead all count data were converted into percentage abundances of the counted assemblage.

To study size variation of *Cyclicargolithus* coccoliths 50 specimens were imaged at random from each sample using a digital camera. Since *Cyclicargolithus* coccoliths are circular and have a narrow central area only a single size measurement was made. These images were measured using the Fiji open-source image analysis software program (Schindelin et al. 2012).

The PAST Palaeontological statistics software package (Hammer et al. 2001) was used for data plotting and for Factor Analysis. Age-depth plots (Fig. 3) were produced using the program NSB Age-Depth Plot Program by Johan Renaudie (U. Berlin) and available from <https://github.com/plannapus>. The program plotted the raw data but the line of correlation was drawn manually.

3 Results

3.1 Age models

Age models for the two sites are given in Figure 2. These are based primarily on the shipboard biostratigraphic data. For the Lower Miocene interval, shown in detail in the lower panels, there is some additional nannofossil data from our work. For Site U1466A the planktonic foraminifera have been restudied in detail by Prof. Silvia Spezzaferri and data from this work (Spezzaferri pers. comm. 2019) are used. Neither of these changes significantly affects the overall age model but they do allow a slightly better constraint on the age and sedimentation rate for the sapropel intervals, and for each site an initial interval of lower sedimentation rate is inferred.

At both sites the top most sediments are Quaternary and Pliocene in age with well-dated assemblages and moderate sedimentation rates (10-20 m/Myr). There is then a gap in the sediment record, likely due to erosion, with the entire Upper Miocene missing. Below this there is a very thick sequence of coarse sediments deposited in current drifts with clinoform bedding surfaces (Fig. 1). These had low abundances and poor preservation of planktonic microfossils and are only poorly dated. The nannofossils are of NN6-7 age throughout with few age-diagnostic species. These sediments are inferred to have been deposited at sedimentation rates of 150 m/Myr (Site U1466) and 160 m/Myr (U1468). There is then an extended Lower Miocene sequence in which the preservation and abundance of microfossils progressively improves until in the lowest part, where the sapropels occur, microfossils are abundant and well-preserved. Hole U1466B was terminated in this part of the sequence, whilst, Hole U1468 was continued until the basement of Oligocene reefal limestone was reached. At both sites only a single hole was drilled through the Lower Miocene - Oligocene interval. At Hole U1466A 292 m (32 cores) of Lower Miocene were drilled using rotary coring with an average of recovery of 19%. At U1468A 311 m (32 cores) of Lower Miocene and Upper Oligocene were drilled using the extended core barrel (XCB) system with an average of recovery of 35%. The limited recovery means that the

precise depth location of recovered cores is not known and this significantly lowers the precision possible for age models.

At site IODP359 U1466 the age of the base of the core is well constrained by the presence of *Sphenolithus delphix*, which has a short and well-established range (e.g. Backman et al. 2012) and this age is conformed by the absence of *Sphenolithus ciperoensis*. The shipboard age model assumed a uniform sedimentation rate through the Lower Miocene. We have now established two additional events - the crossover in abundance between *Helicosphaera euphratis* and *H. carteri* and the top of common *Triquetrorhabdulus carinatus*. Both events are based on abundance shifts but they were recommended as zonal markers for this interval by Backman et al. (2012) based in part on work from low-latitude Indian Ocean ODP cores. These events agree with shipboard data from the last occurrence of the planktonic foraminifera *Paragloborotalia kugleri* and suggest a lower sedimentation rate (ca. 14 m/Myr vs. 50 m/Myr) in the lower part of the site (Fig. 4B), approximately corresponding to the interval with the sapropels. Above this interval the preservation is worse and patchy and only a few key marker events could be reliably identified, particularly the top and base of *S. heteromorphus*. An anomaly is the absence of *S. belemnos*, this does fall in an interval of poor preservation but might also indicate an hiatus.

At Site U1468 the recovery of the Lower Miocene - Oligocene interval is better than at U1466 but preservation is worse in the upper part. The hole penetrated further, to the basement, and in the lower cores the presence of *Sphenolithus ciperoensis* and *S. distentus* clearly indicate an Oligocene age, also confirmed by the planktonic foraminiferal assemblages. A succession of markers can be identified in the interval from core 70 to core 109 suggesting a uniform sedimentation rate of ca 30 m/Myr, without the reduction inferred in Hole U1466B. Neither the top common *T. carinatus* nor the *Helicosphaera carteri* vs. *euphratis* abundance crossover event could be confidently placed in this hole. A reduced sedimentation rate is inferred in the basal part of the section, but this is below the sapropel interval.

3.1.1 Dating of the sapropels

The age model shown in Figure 2 was based on the biostratigraphy alone. The interval in which intense sapropels occur is also indicated on Figures 2B and 2D based on the presence of well-developed black layers, as recorded in the core images (Betzler et al. 2017). In addition for Site U1468A downhole gamma log data is available and this is also plotted on Figure 2D. Peaks in the gamma ray correspond to the organic-rich sapropels (as confirmed by gamma ray measurements on the cores, Swart et al. 2019). It should be noted, however, that the depth scale for downhole logging is not precisely correlated with the core depth scale indeed there could easily be a few meters discrepancy between them. Unfortunately the downhole logging had to be stopped prematurely due to drillhole instability at both sites, at 835 m in hole U1468A and at 350m, well above the sapropel layers, in hole U1466B. At both sites the top of the interval of intense sapropels is marked by a very thick dark layer, this occupies all of core U1468-97X and most of IODP359 U1466-53R and U1466-54R. The interval is also clearly shown in the gamma ray data. Core U1466-53R contains approximately 1.3 m of pale sediments overlying 2.3m of dark sediments and

was recovered from 760.5 mbsf to 770.2 mbsf so the top of the thick sapropel interval must lie between 761.8 and 767.9 mbsf. In Figure 2B this interval is extrapolated onto the line of correlation of the age model to give an estimated age of 21.0-21.2 Ma. Similarly in hole U1468A the top of the interval should lie between 724.6 mbsf (maximum height possible in core 96X) and 734.9 mbsf (minimum depth possible in core 97X). Again this interval is shown on Figure 2D and used to infer an age 21.3 to 21.8 Ma. This age range does not include any estimate of an error in the age model which should be at least ± 0.3 Ma, so the age estimates are basically congruent, strongly suggesting that the interval is directly correlatable between the two sites. This is a new interpretation, but it is not surprising given the proximity of the sites and the evidence of the seismic section (Fig. 1). If there had been continuous recovery then bed by bed correlation between the sites would almost certainly have been possible, with the limited coring available this correlation, of the top of the interval of intense sapropels, is probably the best available.

The age of the base of interval of intense sapropels at Site U1468 can also be estimated (dotted line on Fig 4D), giving an age of ca 24-24.5 Ma. By comparison the age of the base of the drilled section at Site U1466 is about 24 Ma based on the age model of Figure 2C, suggesting that almost the entire intense sapropel sequence was recovered at the site.

This indicates that the period of intense sapropel formation was about 3Ma long and spanned the Oligo-Miocene boundary. Swart et al. (2019) carried out spectral analysis of the downhole gamma and resistivity data from Site U1468 based on the age model of the initial report and identified cyclicity in the orbital band (ca. 40 kyr). The emended age model given here does not significantly change the sedimentation rate for that part of the section (30 m/Myr vs. 32 m/Myr with the previous age model) so this conclusion is not affected. At the sedimentation rate of 30 m/Myr obliquity cycles would have an average length of 1.2 m and precession cycles 0.66 m.

3.2 Nannofossil assemblages

The results of the detailed nannofossil analyses are presented in Figures 4-7 (and the original data is given in the supplementary data). Figures 4 and 5 present a summary of the overall nannofossil composition variation through the cores plotted against depth. In Figures 6 and 7 the data for each taxon is plotted separately and scaled to their maximum abundances, so as to highlight fluctuations in the abundance of each taxon (although since this is percentage abundance data closed sum effects are possible). Figures 8 and 9 illustrate, respectively representative rock surfaces show the general nannofacies and significant nannofossils. Surfaces entirely composed of nannofossil and nannofossil debris were common, although in other parts, especially in the sapropelic layers organic matter obscured areas. Assemblages were often dominated by single species, either *Cyclicargolithus floridanus* or *Umbilicosphaera jafari* and coccospheres of these species were common. However, these are both species which are very common in the assemblages and which form robust coccospheres. There was no clear evidence of bloom assemblages of these species or of coccospheres of delicate species. Lamina-scale

variation in assemblages as documented for instance by Goy (1981) or Thomsen (1987) were not detected.

3.2.1 Major taxa

Five genera were consistently common throughout the assemblages, often forming >10% of the assemblage; *Cyclicargolithus*, *Discoaster*, *Sphenolithus*, *Umbilicosphaera* and *Helicosphaera*, additionally *Hughesius* was common in core U1468A-99X. (Figs 4 and 5).

Cyclicargolithus is the dominant taxon frequently forming more than 50% of the assemblage. This essentially comprises *C. floridanus*, specimens large enough to qualify as *C. abisectus* (>11 µm) were absent and other reticulofenestrids were very rare in these samples. In hole U1466B (Figs 4, 6) *Cyclicargolithus* relative abundance increases in the upper sapropels (above mid core 67-1) but this is not seen in the lower sapropels. A slight increase in relative abundance of *Cyclicargolithus* occurs in the sapropels in U1468A.

In addition to the abundance variation there was strong variation in the size of *Cyclicargolithus* with specimens ranging in diameter from 3 to 10 µm and with populations clearly showing some variation between samples. To investigate this 50 specimens were measured per sample (see methods). Raw data from this is given in the supplementary data. To illustrate trends in the data we determined the median size, and the size of the upper quartile and of the upper decile (i.e. from a count of 50 specimens the size of the 5th largest, 12th largest and 25th largest specimens). These data are plotted in Figures 4 and 5. There is a rather consistent relationship in the data with *Cyclicargolithus* coccolith size tending to decrease in the sapropels. This trend is clearly shown in the data from the upper samples of Site U1466B (sections 57-1 to 56-1) and in those from Site U1468A-99X. The lower samples from site U1466B show lower size in general and a less clear relationship to sapropels.

Discoaster abundances range from 0-20%, and since these are large nannofossils they formed the bulk of the carbonate in the samples in which they showed peak abundances. This is entirely *Discoaster deflandrei* (*sensu lato*). Discoasters showed more overgrowth than other taxa, a common result of their relatively large size and so fine taxonomy of the type proposed by de Kaenel et al. (2017) was not practical. *Discoaster* abundance clearly peaked in the sapropels of core U1468-99X and in the lower part of core U1466B, however in the upper sapropels of core U1466 (above mid section 67-1) this behaviour was not seen and abundances were generally lower.

Sphenolithus abundances were also highly variable, ranging from 2-30%. The assemblages were mostly dominated by *S. moriformis* group sphenoliths (arguably including *S. moriformis*, *S. puniceus* and *S. apoxis*). *S. dissimilis* group specimens were also present but could not be consistently separated from small *S. moriformis* group specimens. We also observed a few specimens of *S. capricornutus*, and in the lower part of core U1466-57 *S. delphix*. *S. ciproensis* and *S. distentus* occur in Hole U1468 A, but below the level of the intense sapropels. Sphenoliths were well preserved, showing open textures with well-separated laths (e.g. Fig. 9 E)

In order to allow rapid and consistent counts all sphenoliths were grouped into a single category. *Sphenolithus* abundance tended to co-vary with

that of *Discoaster*, especially in the lower sapropels of core U1466B, but with slightly less obvious relation to the sapropels.

Umbilicosphaera abundances ranged from 2 to >30% and in the SEM surfaces covered with *Umbilicosphaera* were seen (Fig. 8 B & C). Most specimens were small with relatively narrow central openings and broadly conforming to *U. jafari* but *U. rotula* type specimens also occur (Fig. 9 B) and quite possibly two or three actual species are represented. *Umbilicosphaera* abundance was generally high in the pale beds and reduced in the sapropels, this was most obviously the case in the upper set of samples from U1466 and in U1468. By contrast in the lower part of U1466B (below mid core 57-1) *Umbilicosphaera* abundances are uniformly low (typically <10%).

Helicosphaera abundances range up to about 10% but show no consistent relationship to sapropel development (Figs. 4, 5). Three taxa are consistently separable in these samples, *H. euphratis*, *H. obliqua* and *H. recta*. *H. euphratis* is used here for *H. carteri* group specimens with a disjunct core and includes *H. intermedia* (NB in these basal Miocene assemblages *H. carteri* does not occur). *H. obliqua* is used here in a broad sense also including *H. perch-nielseniae*, *H. lenticulata* and *H. elongata*, *sensu* Boesiger et al. (2017). These morphotypes intergrade and separating them was neither practical nor useful. *H. recta* however is a discrete form and was separated. The three species are plotted separately in Figures 6 and 7. *H. euphratis* and *H. obliqua* tend to co-vary in both sets of samples with a weak tendency to be more abundant in the sapropels in core U1468A-99X and in the lower samples from U1466B but to be more abundant in the intervening pale beds in the upper samples from U1466B. *H. recta* show a few major peaks in abundance but no clear relation to either the other *Helicosphaera* species or the sapropel development.

Hughesius is the final common genus, with peak abundances up to 15%, it includes both *H. gizoensis* and *H. youngii*. The coccoliths are small and easily overlooked and like *Umbilicosphaera* require use of phase contrast for accurate counting in the light microscope. It shows a rather inconsistent distribution pattern with no clear relationship to either *Umbilicosphaera* abundance (despite having similar preservation potential) or sapropels.

3.2.2 Secondary and minor species

Additional genera that were consistently present at low to moderate abundances (1 - 5%) were *Coccolithus*, *Calcidiscus* and *Triquetrorhabdulus* - represented respectively by *Coccolithus pelagicus*, *Calcidiscus cf. pataecus* and *T. carinatus* (with rare *T. milowii*). All three taxa show a weak tendency to increase in abundance in the sapropels of U1468A-99X and the lower samples from U1466B but to decrease in abundance in the upper set of sapropel samples from U1466B.

Several additional species were noted but at abundances too low and erratic to meaningfully discuss distribution patterns. These included *Coronocylus nitescens*, *Clausicoccus fenestratus* (primarily in the lower samples from U1466B), *Camuralithus pelliculatus*, *Ilseolithina fusa*, *Pontosphaera* sp., *Hayaster perplexa*, *Syracosphaera* sp., *Rhabdosphaera* sp cf. *clavigera* (both spine-bearing and spine-less coccoliths Fig. 9 B, D and F), and *Calciosolenia* sp. In SEM we also observed fragments of coccoliths with a distinctive fabric closely

resembling that of *Solisphaera tegula* (Fig. 9 J), this is interesting in bridging the gap between the known Eocene (Bown et al. 2009, 2016) and modern occurrences of the genus.

3.2.3 Summary of assemblage changes

A series of changes do occur more or less systematically between the sapropel and sapropel layers but these are variably expressed in different parts of the cores. In particular there seems to be a change in the effect of the sapropel layers on the nannofossil assemblages, between the lower set of samples from U1466B and those from the upper part, with the change occurring within section U1466B-57-1. There are two main sapropels in this section, at 30-50 cm and at 65-80 cm (Fig. 1), and the change in behaviour usually occurs between them - for example there is a clear decrease in *Cyclicargolithus* size in the upper of these sapropels but only a weak one in the lower, and conversely there is a strong peak in *Discoaster* and *Sphenolithus* abundance in the lower sapropel but only a weak one in the upper sapropel. These patterns are generally reflected in the sequences above and below. The trends and how they are expressed in the different sample-sets are summarised in Table 1.

3.2.4 Principal components analysis

Figure 10 shows the results of a Principal Components Analysis of the assemblage count matrix from U1466B cores 56R and 57R. The principal component scores are plotted with against sample depth, with the sample colour data plotted for comparison and grey bars indicating the sapropel levels, as in Figures 4 and 6. PC1 accounted for 51% of the variance with high loadings for *Cyclicargolithus* (-0.802) and *Umbilicosphaera* (0.587). The scores for this show strong anti-variation with the colour values in the top half of the core; i.e. the scores on the component are lower in the sapropels. In the lower part of the core, however, the correlation is much weaker and more variable. PC2 accounted for 28% of the variance with strong loadings for *Sphenolithus* (-0.533), *Cyclicargolithus* (0.779) and *Umbilicosphaera* (-0.618). This factor showed rather random loadings in the upper part of the core but anti-variation with the colour scores in the lower part half of the core.

This separation of signals appears to support the separation of the sequence into upper and lower parts showing different responses to the sapropels. As a test of this further PCA analyses were carried out separately on the upper and lower sets of samples (PC1 top and PC1 base in Figure 8). In each case the first principal component accounted for >75% of the variance. In the upper sample set the “PC1 top” developed for this part of the core is virtually identical to PC1 for the entire sample set. Similarly in the lower part of the sequence “PC1 base”, developed for this sample set, is very similar to PC2 for the entire sample set. These results reinforce the subjective interpretation that there is a relationship between sapropel development and assemblage composition, but that this relationship changes between the upper and lower part of the sample sequence. A range of further statistical investigations of the data were carried out but these did not usefully improve the interpretation.

4 Discussion

Overall the assemblages are similar in all samples, no taxa are confined to either the sapropel or non-sapropel intervals, indeed with an extended count almost all taxa can probably be found in almost all samples. Likewise the overall assemblage is typical of the time period and directly comparable to assemblages reported from the Indian Ocean by, for example Rio et al. (1990). The most unusual feature is the very high abundance of *Umbilicosphaera* but this may reflect the better than normal preservation of the samples and the fact that the species is often overlooked. Overall the assemblages strongly indicate that broadly normal marine conditions persisted throughout sapropel formation, as concluded by Swart et al. (2019).

4.1 Effect of preservation

Preservation varies from very good to slightly overgrown through the studied sections with no consistent observable pattern. Nonetheless, even weak preservation variation can significantly affect nannofossil assemblages (e.g. Gibbs et al. 2004) and so might be responsible either for creating the overall pattern of assemblage variation between sapropels and non-sapropels, or conversely for blurring this signal and making it less consistent. In this respect it is noteworthy that aspects of the overall signal are contradictory in terms of a preservation cause. Thus the increase in *Discoaster* and *Cyclicargolithus* abundance and decrease in *Umbilicosphaera* abundance might be interpreted as due to declining preservation in sapropels favouring larger and more robust specimens, but in this case the *Cyclicargolithus* size should decrease rather than increase. Likewise we might expect a clear co-variation between the abundance of *Umbilicosphaera* and *Hughesites* since these are similar sized coccoliths which we would expect to have similar preservation potential. So it seems unlikely that the overall pattern has been created by preservation but somewhat more likely that it may have obscured the pattern and possibly created some of the inconsistency.

4.2 Environmental interpretation

It appears likely that the basic pattern of assemblage change between sapropels and non-sapropelic layers is related to environmental change, rather than to preservation. The overall change however, is relatively subtle and inconsistent. Given this it is unlikely that the environmental changes indicated by the changing nanoplankton community reflect the sort of strong changes in plankton community that would be large enough to drive the sapropel formation. So, it seems unlikely that the sapropels were produced as a result of fluctuations in the surface productivity and resultant organic carbon flux, but rather that they were the result of differential carbon preservation and burial, as concluded by Swart et al. (2019). This conclusion of Swart et al. (2019) was based on geochemical evidence, which showed only weak evidence for enhanced productivity from trace element analysis and no evidence from carbon or nitrogen isotopes, in contrast to very strong geochemical and sedimentological evidence for anoxia. As argued by Bralower and Thierstein (1984) enhanced preservation of organic matter is a much more effective mechanism for increasing concentrations of organic carbon than productivity, and it should be

remembered that there can be complex linkages between organic matter preservation and production (Pedersen and Calvert, 1990, Rohling 1994, Grant et al. 2016). Swart et al. (2019) concluded that the most likely driver was sea-level change due to variable Antarctic ice-sheet development causing fluctuations in the ventilation of the ponded basin, with restricted circulation occurring during glacial sea-level lowstands. In support of this they also noted that oxygen isotope evidence indicates strong ice-volume fluctuations at this period leading to inferences of sea level change of ca 50 m on Milankovitch timescales (Zachos et al. 2001, Liebrand et al. 2017). Sea-level change in itself should not directly affect phytoplankton communities, however, it is reasonable to predict that the climate change which caused substantial changes in the Antarctic ice volume would also affect the climate and so plankton ecology, even in low latitude surface waters. This model is compatible with a weak and variable nannofossil assemblage change broadly coinciding with strong sedimentological change.

The primary controls on phytoplankton communities are generally assumed to be temperature and nutrient availability. Several of the assemblage changes are compatible with productivity as a driver. In particular small reticulofenestrid coccoliths are characteristic of modern upwelling environments (e.g. Young 1994, Takahashi and Okada 2000) and so increased abundance of small reticulofenestrids is often used as evidence of higher productivity in the Neogene (e.g. Flores et al. 2000, López-Otálvaro 2008, Imai et al. 2015). *Cyclicargolithus* is a reticulofenestrid coccolith and so the increase in *Cyclicargolithus* dominance and decrease in size are both suggestive of increased productivity. Likewise *Umbilicosphaera* appears to be an oligotrophic taxon (e.g. Ziveri et al. 2004) at the present day. Increased productivity could be the result of more intense circulation or increased terrestrial runoff. However, *Discoaster* which also increases in most of the sapropels is widely interpreted as a low productivity species (e.g. Bukry 1973, Chepstow-Lusty et al. 1989, 1992, Imai et al. 2015). Unfortunately at our present knowledge of nannofossil palaeoecology, at least in the Lower Miocene, it is difficult to form any strong conclusions from the observed changes other than that they probably were environmentally driven. Given this it may be more useful to note that the trace element evidence (Swart et al. 2019) indicates that the sapropels were likely formed during intervals of increased upwelling. From this we can tentatively infer that, for Lower Miocene nannofossil assemblages, a combined trend of decreasing abundance of *Umbilicosphaera* and decreasing *Cyclicargolithus* size is likely an indicator of cooler, more productive waters.

5. Conclusions

1. The interval of intense sapropels runs from about 21.5 Ma to 24 Ma, and so spans the Oligocene-Miocene boundary including the top of the Chattian and almost all the Aquitanian, or nannofossil zones NP26 (*sensu* de Kaenel et al. 2017) to lower NN2. This is an important interval of global change for which the site may provide a useful organic geochemical archive.
2. The nannofossil assemblages in the sapropels, compared to the intervening units, typically show reduced abundances of *Umbilicosphaera* and of minor species, smaller *Cyclicargolithus floridanus*, more abundant *Discoaster* and *Cyclicargolithus* and *Sphenolithus*.

3. Within this general pattern there is significant variability both between individual sapropels and through the sequence with the upper and lower sample sets from U1466 showing consistent differences.
4. The relatively weak and inconsistent signal is consistent with the interpretation of Swart et al. (2019) that the sapropel formation was primarily driven by Antarctic glaciation causing sea-level drop and so reduced ventilation of a perched basin and so with only indirect linkage, via climate, to the surface plankton.
5. For the interpretation of Lower Miocene nannofossil assemblages it is notable that the evidence from trace metal analysis, that the sapropels were likely intervals of enhanced productivity (Swart et al. 2019), supports the inference that increasing abundance of small *Cyclicargolithus* and decreasing abundance of *Umbilicosphaera* are an indicator, in this interval, of higher productivity.

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Data availability

The data reported here is archived at, and freely available from, the UK National Geoscience Data Centre (www.bgs.ac.uk/services/ngdc), deposit IDs 126925 (detailed Early Miocene count data) and 73709 (nannofossil assemblage data for the entire expedition).

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	U1468A 99X	U1466B- upper samples (top to 57-1 50 cm)	U1466B- lower samples (below 57-1 50 cm)
<i>C. floridanus</i> size	down	down	(down)
<i>C. floridanus</i>	(up)	up	(up)
<i>Umbilicosphaera</i>	down	down	(down)
<i>Discoaster</i>	up	no clear pattern	up
<i>Sphenolithus</i>	no clear pattern	(up)	up
minor species	no clear pattern	down	down

Table 1 Summary of changes in the nannofossil seen within sapropels as opposed to in the intervening pale beds. Apart from *C. floridanus* size these are changes in relative abundance. Up - increase in abundance, down - decrease, ()-weaker effect.

Figure Captions

Figure 1 Geographical and geological setting of the studied material

Top left - overview map of the Maldives with box indicating location of location map. Top right - location of the cores drilled during expedition IODP-359, with the two cores studied here highlighted. Centre - geological section across the Maldives ridge. Bottom - seismic section going through the studied drill sites. Diagrams modified from IODP 359 Initial Report (Betzler et al. 2017)

Figure 2 core photos

Core photographs for the cores studied in detail: U1466-56R, U1466-57R and U1468-99X. Stars indicate the location of samples studied in detail, red stars samples also studied by SEM. Diagram modified from IODP 359 Initial Report (Betzler et al. 2017).

Figure 3 Age depth plots

Plots of biostratigraphic data against depth in core and geological age, and an interpolated line of correlation. A, B Data from Site; U1466 (holes A and B) A - entire record, B detail of basal part including the sapropel interval. C, D Data from Site U1468A; C entire record, D detail of basal part. Vertical bars indicate uncertainty in placement of the events

Nannofossil events are directly labelled (b = base; t = top; tc = top common). Planktonic foraminiferal events are numbered on A and C; 1 t *Globigerinoides ruber* pink; 2 t *Globigerinoides fistulosus*; 3 b *G. truncatulinoides*; 4 t *Globorotalia limbata*; 5 b *G. truncatula*; 6 t *Dentoglobigerina altispira*; 7 t *Globoquadrina dehiscens*; 8 t *C. linguaensis*; 9 t *F. fohsi*; 10 b *F. robusta*; 11 b *F. praefohsi*; 12 b *F. peripheralis*; 13 b *O. suturalis*; 14 b *P. glomerosa*; 15 b *T. sicanus*; 16 t *P. kugleri*; 17 t *G. dehiscens*; 18 b *P. pseudokugleri*; 19 t *C. cubensis*.

Black lines to right of figs. B and D indicate schematically the position of the most prominent sapropel layers. On fig. D downhole gamma ray log is included for comparison (downhole logging data was not carried out on the lower part of hole U1466B due to instability of the hole). Broad grey lines in B and D indicate likely position and age of the top of the interval of intense sapropels. Dashed line in D indicates likely position and age of the base of the interval of intense sapropels.

Figure 4; Nannofossil assemblages from IODP359 U1466B, cores 56R and 57R

From left to right. Core photographs, note that both cores were discontinuously drilled and recovered from an 18m interval, the actual location of gaps between parts of the cores is thus unknown. Colour - numerical summary of the colour of the sampled rock fragments (see methods). *Cyclicargolithus* size - median, upper quartile and upper decile sizes from sets of 50 specimens (see methods). Percentage abundances of the assemblage - D - *Discoaster*; H - *Helicosphaera*; S - *Sphenolithus*; Cgl - *Cyclicargolithus*; 5 secondary taxa not individually labelled (*Coccolithus*; *Calcidiscus*; *Triquetrorhabdulus*; minor species;

Hughesius); U-*Umbilicosphaera*. Grey horizontal bands indicate the sapropelic intervals

Figure 5; U1468A - Nannofossil assemblages from site U1468A, cores 99X.

See caption of figure 4 for details. On the percentage abundance plot the taxa are labelled D - *Discoaster*; H - *Helicosphaera*; S - *Sphenolithus*; Cgl - *Cyclicargolithus*; Co - *Coccolithus*; Cd - *Calcidiscus*; Tq - *Triquetrorhabdulus*; m - minor species; Hu- *Hughesius*; U-*Umbilicosphaera*.

Figure 6; Changes in abundance of individual taxa from site U1466B, cores 56R and 57R.

Core photographs, colour, and *Cyclicargolithus* size as per Figure 4. Note that plots for individual taxa are scaled to the maximum value for that taxon.

Figure 7; Changes in abundance of individual taxa from U1468A, core 99X

Core photographs, colour, and *Cyclicargolithus* size as per Figure 5. Note that plots for individual taxa are scaled to the maximum value for that taxon.

Triq'rhabdulus - *Triquetrorhabdulus*, *U'phaera* - *Umbilicosphaera*.

Figure 8 SEM images of rock-chip surfaces.

A-C from pale chalk layers between sapropel beds. D-F from a dark sapropel bed.

- A. Mixed assemblage with common *Cyclicargolithus*; image JRY326-028; sample IODP359 U1466 56-1 35 cm (pale),
- B. Assemblage dominated by *Umbilicosphaera jafari*; image JRY326-051; sample IODP359 U1468-99-1 70 cm (pale).
- C. Assemblage dominated by *Umbilicosphaera jafari*; image JRY326-036; sample IODP359 U1466 56-1 120 cm (pale).
- D. Assemblage dominated by *Cyclicargolithus*; image JRY326-094; sample IODP359 U1466-56-1 45 cm (dark)
- E. Assemblage dominated by *Cyclicargolithus* with planktonic foram shell; image JRY326-019; sample IODP359 U1466-56-1 45 cm (dark)
- F. Assemblage dominated by *Cyclicargolithus*, with planktonic foram shell; image JRY326-011; sample IODP359 U1466-56-1 45 cm (dark)

Figure 9 SEM images of selected taxa.

These illustrate the generally good preservation, including preservation of small, delicate species, and document the occurrence of some unusual taxa. Scale bars one micron

- A. *Cyclicargolithus floridanus* (coccosphere) image JRY326-013; sample IODP359 U1466-56-1 45 cm (dark)
- B. *Umbilicosphaera jafari*, (x2 distal) image JRY326-036; sample IODP359 U1466 56-1 120 cm (pale)

- C. *Pontosphaera* sp., (proximal) image JRY326-032; sample IODP359 U1466 56-1 35 cm (pale)
- D. *Rhabdosphaera clavigera*, (proximal) image JRY326-102; sample IODP359 U1466-56-1 45 cm (dark)
- E. *Sphenolithus* sp. (x2), *Ilselethina fusa* (proximal) and *Umbilicosphaera rotula* (x2) image JRY326-100; sample IODP359 U1466-56-1 45 cm (dark)
- F. *Hughesius* sp. (x2, proximal), *Syracosphaera* sp. and *Rhabdosphaera* sp. (body coccolith without spine) image JRY326-008; sample IODP359 U1466-56-1 45 cm (dark)
- G. *Helicosphaera obliqua* (distal) image JRY326-026; sample IODP359 U1466 56-1 35 cm (pale)
- H. *Helicosphaera euphratis* (proximal) image JRY326-021; sample IODP359 U1466-56-1 45 cm (dark)
- I. *Ilselethina fusa* (distal) image JRY326-093; sample IODP359 U1466-56-1 45 cm (dark)
- J. *Solisphaera tegula* (process fragments) image JRY326-026; sample IODP359 U1466 56-1 120 cm (pale)

Figure 10; Principal Components Analysis

PCA analysis of nannofossil assemblages from U1466B cores 56R and 57R (unscaled percentage count data). Colour plot as per Figure 4. PC1, PC2 scores of the first two principal components of the Factor Analysis on each sample. PC1 top - first principle component from PCA analysis of the top set of samples alone (see text for explanation). PC1 base - first principle component from PCA analysis of the lower set of samples alone. Eigenvalues and species scores are given in supplementary data.

Conflict of Interest Statement
There are no conflicts of interest

Journal Pre-proof

Nannofossil palaeoecology of Lower Miocene sapropels from IODP Expedition 359, the Maldives.

Jeremy R. Young, Odysseas Archontikis, Xiang Su, & Santi D. Pratiwi

HIGHLIGHTS

- Well-preserved nannofossil assemblages are described from sapropels.
- The sapropels are dated to 21.5-24Ma (Early Miocene and end Oligocene)
- The sapropels assemblages are quantitatively different from those in the intervening beds.
- The assemblage changes are suggestive of increased productivity during sapropel formation.
- Increased productivity is unlikely to be the prime driver of sapropel formation