Carbonate budget mass estimates for Neogene discoasters from the Equatorial Atlantic (Ceara Rise: ODP Site 927)

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ABSTRACT – Mass estimates for Late Miocene and Pliocene (8.6–3.25 Ma) Discoaster species and Sphenolithus are determined using samples of the equatorial Atlantic (Ceara Rise: ODP Site 927). Based on morphometric measurements, 3D computer models were created for 11 Discoaster species and their volumes calculated. From these, shape factors (k_s) were derived to allow calculation of mass for different-sized discoasters and Sphenolithus abies. The mass estimates were then used to calculate the contribution of nannofossils to the total nannofossil carbonate. The discoaster contribution ranges from 10% to 40%, with a decreasing trend through the investigated interval. However, our estimates of total nannofossil carbonate from size-corrected abundance data are consistently 30–50% lower than estimates from grain-size measurement; this suggests that data based on mass estimates need to be interpreted with caution. J. Micropalaeontol. 31(2): 169–178, July 2012.

KEYWORDS: Discoaster, Sphenolithus, carbonate budget, Neogene, Atlantic, shape factors

INTRODUCTION
Since their evolution, calcareous plankton have significantly altered the carbonate cycle and so played an important part in marine biogeochemistry. The quantification of the relative contributions of different fossil groups to this is desirable, in order to understand past and thus future feedback mechanisms. Here we focus on mass estimates of some of the smallest calcareous plankton, the nannofossils. This is not easy to do since nannofossils are too small to weigh directly. Instead estimates of nannofossil mass have been established for some species and groups of nannofossils from morphometric measurements. The first approach used to estimate coccolith mass was to measure the surface area and multiply by a value of thickness and density of a coccolith (Honjo, 1976; Samtleben & Bickert, 1990; Knappertsbusch & Brummer, 1995; Beaufort & Heussner, 1999). Subsequently, a more sophisticated volume of rotation approach was applied by Young & Ziveri (2000) for coccoliths with rotational symmetry. These mass estimates were applied to sediment trap data and sediment cores to convert count data to carbonate flux estimates. To date there has been no work on producing mass estimates for Neogene species and, whilst the masses of most Neogene coccoliths can be estimated using data from extant species, there are also several important extinct nannolith groups. This work is intended to fill the gap by presenting an approach for discoasters and sphenoliths, which contribute significantly to pelagic Neogene sediments and so to carbonate budgets.

Discoasters have a striking appearance under the microscope and are invaluable for biostratigraphy. They show similar abundance, size and distribution patterns to coccoliths, so it is reasonable to assume that they formed the cell cover of marine nanoplanктон, and probably of Haptophyte algae. Specimens of Discoaster occur in the sedimentary record from the Late Paleocene (c. 60 Ma) and became extinct at the end of the Pliocene (Bukry, 1971). It has been noted that there is a secular trend in Discoaster morphology, with progressive evolution from massive skeletal elements to more delicate forms, and a parallel reduction in ray number (Bramlette & Riedel, 1954; Bukry, 1971). Discoasters are also relatively dissolution resistant and so have been used as a dissolution proxy (Ramsay, 1972; Flores et al., 1995; Gibbs et al., 2004). The ecology of Discoaster has traditionally been attributed mostly to warm oligotrophic low latitude surface waters (Haq & Lohmann, 1976), supported by geochemical evidence (Minoletti et al., 2001).

This work presents twelve 3D models of Discoaster and Sphenolithus based on morphometric measurements on scanning electron microscope (SEM) images from sediments of the Ceara Rise, western equatorial Atlantic, ODP Site 927. The goal of the modelling is to relate a linear dimension (ray length, r_r) to a volume, which can then be transferred to mass. The volume (V) will be represented by the cube of this measure and a shape factor k_s:

\[ V = k_s \times r_r^3. \] (1)

This approach of calculating size-independent shape factors (k_s) for different species has been used previously for determination of the mass of coccoliths with rotational symmetry (Young & Ziveri, 2000). Since the discoaster shape cannot be obtained through a rotating constant cross-section a 3D modelling approach was applied. In combination with size corrections, shape factors were used to estimate the mass of discoasters through a time slice from 8.6 to 3.25 Ma. The interval includes the major Pliocene coccolith turnover during which significant changes in the morphologic strategy of coccoliths appear to have occurred (Aubry, 2007), which is regarded as a precursor of the subsequent Pleistocene morphologic strategy in nannofossil lineages favouring small sizes and leading to the successive disappearance of Discoaster at the end of the Pliocene.

METHODS AND MATERIAL
Thirteen samples from ODP Site 927 from the Ceara Rise were taken through an interval from 8.60 Ma to 3.25 Ma (age
model after Shackleton & Crowhurst, 1997). The Ceara Rise is an aseismic ridge located 700 km to the north-east of the mouth of the Amazon River, below the oligotrophic subtropical South Atlantic gyre (Fig. 1). Its sediments are composed of terrigenous clay supplied by fluvial discharge and carbonates from nannofossils and foraminifera. ODP Site 927 sediments are composed of 70–80% carbonate. Site 927 is located at 3300 m water depth, well above the lysocline. Bulk sediments were split, with one portion for carbonate measurements and SEM sample preparation, whilst the other portion was wet-sieved at 63 µm. Bulk samples were analysed for total carbon (TC) and, after removal of carbonate, for total organic carbon (TOC) using a LECO infrared combustion analyser. Carbonate contents were calculated after:

\[
\text{CaCO}_3 [\text{wt\%}] = \left( \frac{\text{TC} [\text{wt\%}] - \text{TOC} [\text{wt\%}]}{8.33} \right) \times 100.
\]

**SEM preparation and image analysis**

For SEM analysis, approximately 70 mg of bulk sediment were disaggregated in Ammonia buffered water and treated for 3 s in an ultrasonic bath. The samples were then sub-sampled using a wet splitter and final splits were filtered on to polycarbonate membranes (pore size 0.45 µm, diameter 47 mm; for method details see Andruleit, 1996). By macroscopic examination, filters with obvious contribution of foraminifera were excluded and preparation was repeated. Filters were then dried, and 0.5 cm squares were cut out, fixed to SEM stubs and given a gold-palladium coating. Morphometric data were taken from a mixture of all 13 Ceara Rise (denoted ‘CRmix’) bulk samples. Images were taken at magnifications from ×1000 to ×5000. For the morphometric measurements, the modelling and the calculation of 3D-geometric parameters, a suite of open source software was applied. For image analysis and morphometric measurements ImageJ (http://rsbweb.nih.gov/ij/) was used. Three-dimensional modelling and editing was carried out with Blender (www.blender.org/) and, for model simplification and geometric calculations, Meshlab was used (http://meshlab.sourceforge.net/).

**Morphometry of Discoaster and Sphenolithus from SEM images**

Image analysis was carried out on size-calibrated SEM images. The following parameters (Fig. 2) were measured on each ray: Ray length \(r_1\), area \(A\), central area width \(r_3\), half ray width \(d_1\) and, if present, also the base of the ray tip extension \(r_2\) – \(D. hamatus\), \(D. surculus\), \(D. variabilis\), \(D. calcaris\), \(D. pentaradiatus\). The base of the ray tip extension was defined differently for \(D. hamatus\) and \(D. calcaris\) (see Fig. 2a) compared to the other
species. The ray thickness \(d_r\) could be determined in some cross-sectional debris of single rays or in upright positioned specimens; the thickness was then measured at half of the ray length. Area calculations were based on thresholded images delineating the borders of the particle outline. Some low contrast SEM images did not respond well to thresholding and for these images the outline was drawn manually.

*Sphenolithus* nannoliths are formed of calcareous blades with a Y-shaped cross-section, radiating from a common origin. The height \((H)\)/length \((L)\) of *Sphenolithus* and the width of the base \((W)\) were measured. The total number of elements was estimated to be on average 40. The model consists of 12 elements forming a concave base followed by a second and a third cycle of 12 elements. The last cycle is formed by four elements. Within the first two cycles the elements build hexagonal honeycomb-like forms while, in the third and fourth cycle, the structure is pentagonal (angles between adjacent cycles are shown in Fig. 2b). Apical spines were not observed and so were not included in the model.

The following models (see Plate 1) are based on one or more species:

1. *Discoaster variabilis*: 6-rayed *D. variabilis*, contains also *D. challengeri*, *D. loeblichi* and more massive forms like *D. deflandrei*. Bifurcation of ray tips is always evident and distal and proximal bosses are common but weak; large bosses typical of *D. bollii* or *D. petaliformis* were very rarely observed. Some specimens of this group are similar to *D. surculus*; however, they have bifurcate ray tips while *D. surculus* shows three ray tip extensions.
2. *Discoaster bellus*: 5-rayed discoasters with straight rays and almost undifferentiated central area.
3. *Discoaster brouweri*: 6-rayed discoasters with flat central area, deflected rays and a distal knob, also *D. braruudii*.
4. *Discoaster pentaradiatus*: 5-rayed *D. prepentaradiatus* and more delicate *D. pentaradiatus* showing V-shaped bifurcations.
5. *Discoaster quinqueramus-group*: 5-rayed discoaster with deflected rays, distal and proximal knobs
6. *Discoaster bergenii*: as *D. quinqueramus* but rays with 0.8 times width of the central area.
7. *Discoaster berggrenii*: as *D. quinqueramus* but rays with 1.5 times width of the central area.
8. *Discoaster surculus*: heavily calcified 6-rayed discoaster with deflected rays, distal ridges and distal and proximal knobs.
9. *Discoaster hamatus*: 5-rayed discoaster with almost straight rays, asymmetric ray-tips are deflected, no knobs.
10. *Discoaster calcarius*: 6-rayed discoaster otherwise similar to *D. hamatus*.
11. *Discoaster exilis*: 6- rayed discoaster with straight rays, bifurcations on ray tips and weak distal knob.
12. *Sphenolithus*: predominantly *S. abies* with cuspy outlines and as described above.

**Obtaining statistical relationships from distal, proximal and cross-sectional views of specimens**

Of all the measurable parameters of planar nannofossils, area \((A)\) should represent the closest relationship to the volume, so linear regression was used to investigate the dependence of all other, linear, parameters on area (see Fig. 2) (except thickness – \(d_r\) – see below) assuming that the underlying relationship generally is:

\[
A = k_A \times (\text{parameter})^2, \tag{3}
\]

with \(k\) being a constant shape factor for each parameter. The factor \(k_A\) is a first hint of the degree of calcification. Increasing \(k\) points to heavy calcification independent of size. The calculated \(k\)-values and coefficients of determination are reported in Table 1.

Having established the correlation between the surface and surface-parallel measurements, the third dimension was added to the model. Unfortunately, it is not possible to measure the thickness, the area and the other parameters on the same specimen from SEM pictures. Thus, for cross-sectional views broken rays or vertically orientated discoasters were measured. These images gave thickness \((d_r)\) and ray length \((r)\) for which the underlying relationship is supposed to be:

\[
r = d_r \times c, \tag{4}
\]

with \(c\) being a constant between 0 and 1. Estimates for this relationship are reported in Table 2.

**From morphometrical measures to model**

To synthesize the morphometric data into a 3D model we chose the area for the model as being the mean of the surfaces measured. From this mean area subsequently all other parameters \((r_1, r_2, r_3, d_1, d_2)\) were calculated for the model measurements according to the correlations given in Tables 1 and 2. Models were constructed as polygonal objects in *Blender* (see Plate 1). The model volumes were calculated with *Meshlab* using the in-built algorithm, which is based on the finite element method. The length of one ray was then related to volume, thus it is represented by the cube of the length \((r)\) and a shape factor \(k\) (equation 1).

**Sedigraph analysis**

In order to evaluate the mass estimates, further grain-size measurements were made. Grain-size measurements on the silt fraction (2–63 µm) of six samples were carried out using a Sedigraph 5100 particle size analyser following the procedure of Frenz *et al.* (2005) after removal of clay (<2 µm) through repeated settling (up to 30 times) in Atterberg tubes. The Sedigraph assigns settling diameters (equivalent spherical diameter – ESD) to the grains.

The calcareous silt fraction of open ocean pelagic sediments often shows an almost bimodal distribution (Fig. 3), in which the coarser part is constituted of foraminifera and their fragments divided by a minimum from coccoliths and other nannoliths in the fine silt and clay fraction (McCave *et al.*, 1995; Frenz *et al.*, 2005). The position of this minimum varies from about 8–10 µm (see Fig. 3) depending on the technique and sample.

According to our results (Preiß-Daimler, unpublished PhD thesis, University of Bremen, 2011) and Frenz *et al.* (2006), the non-carbonate fraction is predominantly terrigenous, owing to the absence of opal. Furthermore, it is predominantly enriched in the fine silt and clay fractions. In Pliocene samples of Site 927
Carbonate budget mass estimates for Neogene discoasters

proportions of terrigenous silt comprise 0.8–2% in the coarse silt (10–63 µm), with a tendency to lower values in the Miocene. For simplicity we, therefore, allocate the terrigenous fraction to the fine silt (<8 µm ESD) and clay fraction (<2 µm ESD). According to this the nannofossil carbonate fraction <63 µm is:

\[
\text{Nannofossil carbonate (wt%)} = \frac{\text{fine fraction} < 63 \mu m (g) - \text{terragenous fraction (g)}}{\text{fine fraction (g)}} \times 100.
\]

RESULTS

Assemblage counts and estimation of Ceara Rise Site 927 nannofossil mass distribution

In the following we applied our \( k \) estimates and \( k \) values from the literature (Beaufort & Heussner, 1999; Young & Ziveri, 2000; Table 3) to calculate the relative contributions of different species to carbonate flux from assemblage counts on 13 samples of Ceara Rise Site 927. In order to reduce errors, size corrections were introduced. During assemblage counting size assignments had already been made for Reticulofenestra (Table 3) and Calcidiscus leptopus; for further size correction about 30 specimens were measured using placolith diameter, spine length, sphenolithus length or discoaster ray length. This mean size was calculated as a mean volume following the suggestion of Young & Ziveri (2000), in order to avoid under-estimation due to deviations from normally distributed sizes.

Throughout the record the smallest specimens are numerically dominant, such as Reticulofenestra spp., Florisphaera profunda and Umbilicosphaera spp.. However, the lower half of the record contains up to 15% discoasters (see Fig. 4a). Discoasters show a decreasing trend over the interval in both abundance and mass. Together with Discoaster, Reticulofenestra, Helicosphaera and Calcidiscus form 70–80% of the total nannofossil carbonate. Most mass within discoaster carbonate is contributed by the D. variabilis, D. brouweri, D. quinqueramus, D. pentaradiatus and D. surculus specimens (Fig. 4c).

Granulometric estimate of nannofossil carbonate

The silt distribution offers a method to discriminate foraminiferal carbonate from nannofossil carbonate and so allowed an estimation
of the nannofossil carbonate share (equation 5). The results (Table 4) show a consistent discrepancy between these two estimates. The Sedigraph-based estimate of the contribution of the nannofossil fraction to the <63 µm fraction ranges from 24% to 44%, whilst the assemblage count data suggest nannofossils account for only 15–22%.

**DISCUSSION**

First, considerations regarding errors in the group concept are described, and possible errors in the basic data of the modelling approach are discussed. However, it should be stressed here that the main uncertainty in mass estimates is related to the size variation. Afterwards the nannofossil carbonate budgets are evaluated with respect to grain-size-based budget estimates. And, finally, the results of the application of $k_s$-values to Ceara Rise Site 927 sediments and possible implications are discussed.

**Error sources in modelling concept and in model setup**

A key assumption in the volume and mass estimates is that the form is scale invariant (Young & Ziveri, 2000) or at least that size-dependent shape-change causes trivial differences in volume. However, our mixed sample includes about 6 million years of Discoaster evolution, during which time the group underwent changes in genotypes and phenotypic expression and, indeed, some of the morphometric groups contain more than one species. Thus, some of the observed data variance can probably be assigned to the group concept, allowing for some differences in the morphology. An example for this is given by the D. pentaradiatus group which contains specimens of D. prepentaradiatus which is rather robust and the typically delicate D. pentaradiatus (see Plate 1 – right side of first row). Here our group-based $k_s$ estimate underrates the smaller but more massive shape of D. prepentaradiatus and overrates D. pentaradiatus values (see Plate 1).
Fig. 4. Nannofossil assemblage data of Site 927 from 8.6 Ma to 3.25 Ma. (a) Cumulative counts of nannofossils; (b) cumulative mass of the assemblage; (c) cumulative discoaster mass and mean $k_i$ of Discoaster (dashed line).
Such allometric tendencies have also been shown, for example, within the *D. quinqueramus* group. There is a trend from smaller more heavily calcified forms (*D. bergenii* and *D. berggrenii*) toward larger less heavily calcified forms (*D. quinqueramus*). Obviously overgrown specimens were excluded from our calibration dataset but overgrowth is evident in some samples. Other errors may be induced by minor breakage, dissolution or by slight tilting of specimens. In general the more delicate forms (lower \( k_s \)) would be more prone to these forms of errors.

**Underestimation in mass estimates – a comparison to nannofossil carbonate estimate from granulometry**

The splitting of the samples resulted in the distribution of a known mass on the filter representative of the bulk sample. However, even one foraminiferal test can exceed the weight of the fraction used for investigations, thus filters with adult foraminifera tests were excluded (see Methods above). Accordingly, the calcareous fine fraction distributed on the filter is represented by juvenile foraminifera, their fragments and nannofossils from the silt fraction. The nannofossil carbonate share could be corrected for this foraminifera carbonate. Despite these corrections mass estimates involving \( k_s \)-based estimates are lower than Sedigraph-based estimates. One probable explanation for the

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### Table 4. Comparison of nannofossil carbonate content by two methods.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Total nannofossil carbonate – SEM method (wt%)</th>
<th>Total nannofossil carbonate –&lt;63 µm (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 927–</td>
<td>14.7</td>
<td>24.0</td>
</tr>
<tr>
<td>C 15-2-125.5 cm</td>
<td>18.3</td>
<td>31.0</td>
</tr>
<tr>
<td>A 19-5-29 cm</td>
<td>15.0</td>
<td>33.2</td>
</tr>
<tr>
<td>B 22-5-12 cm</td>
<td>21.5</td>
<td>32.8</td>
</tr>
<tr>
<td>B 23-5-26 cm</td>
<td>22.5</td>
<td>44.3</td>
</tr>
<tr>
<td>C 23-5-93.5 cm</td>
<td>17.5</td>
<td>36.6</td>
</tr>
</tbody>
</table>

---

**Fig. 5.** Abundance data of *Discoaster* spp. from other low latitude locations. From left to right: ODP Site 846 in the Eastern Equatorial Pacific (data from Kamko & Sato, 2000; nannofossil datums according to Raffi & Flores, 1995); ODP Site 999 in the Caribbean (data from Kamko & Sato, 2000; nannofossil datums according to Kamko & Bralower, 1995); ODP Site 806 in the WEP (data and position of nannofossil datums from Takayama, 1993). In each core the reductions in the discoaster abundance record are associated with the base of the paracme of *R. pseudoumbilicus*. In the figure, *R. pseudoumbilicus* is depicted as 846, 500, and 100 on the Y-axis, and 806, 999, and 100 on the X-axis.
Carbonate budget mass estimates for Neogene discoasters consistently lower values is given by the occurrence of aggregates and broken nannofossils on the filters, which are not part of the budget estimate (a discoaster that comprises more than half of a test was considered to be part of the budget and double counting was avoided). The presence of overgrowth is evident and probably also contributes to this discrepancy. However, it has been shown from sediment trap data that flux results in underestimations compared to the fraction <32 µm CaCO₃ wt% even in well-preserved samples (Broerse et al., 2000).

Significance of discoaster carbonate contribution in low latitudes of the late Miocene to Pliocene

The time interval chosen for the application of new shape factors is part of the gradual Mid-Miocene to Pleistocene cooling. The onset of bipolar glaciation leads to the successive disappearance of discoaster species (from about 3–2 Ma). This progressive disappearance of discoasters provides well-established biostratigraphic events and is accompanied by decreasing ray numbers, and so decreasing degree of calcification, in discoasters. The carbonate budget results show that discoasters contribute significant amounts of nannofossil carbonate, in the order of 10–40%, despite relative abundance counts as low as 2–15%. Both discoaster abundance and mass estimates show a long-term decrease. A change in shape accompanies this trend, as summarized by progressive decrease in mean $k_{\text{discoaster}}$ which was calculated according to the proportion of morphological groups:

$$\text{mean } k_{\text{discoaster}} = \sum k_{\text{group}} \times \text{proportion}_{\text{group}}$$

(6)

The trend (Fig. 3c) is caused by the progressive dominance of more slender nannoliths recorded as increasing abundance of $D. \text{pentaradiatus}$ and $D. \text{brouweri}$ at the expense of $D. \text{variabilis}$ and $D. \text{surculus}$.

Abundance data from three low latitude sites are compared in Figure 5. This suggests that the decline in abundance of discoasters in the Caribbean (Site 999), the Eastern Equatorial Pacific (EEP – Site 846) and Western Equatorial Pacific (WEP – Site 806) occurred at about the same time as in the record of Ceara Rise, within zone NN10 of the Late Miocene, and associated with the small Reticulofenestra interval (beginning at 8.85 Ma). The most obvious explanation for this pattern is that dilution through smaller but higher abundance coccoliths caused the rapid decrease in abundance of discoasters (in counts of about 300 particles). Additionally, dissolution might produce this type of downcore pattern. The interval is known to follow the carbonate crash events (12–9 Ma), which are characterized by strong carbonate dissolution in the EEP, the Atlantic and the Caribbean (Lyle et al., 1995; King et al., 1997; Roth et al., 2000). However, Site 806 (WEP – 2530 m water depth) is situated above the local lysocline and foraminifera are well to moderately preserved (Kroeneke et al., 1991; Janecek, 1993). In order to evaluate whether the abundance changes are accompanied by flux changes, counts of specimens per weight and subsequent application of mass calculations as outlined here would be invaluable to constrain the actual causes of this major assemblage shift.

CONCLUSIONS

1. Shape factors of discoasters as determined from 3D models range from 0.04 up to 0.54 with increasing degree of calcification. For Sphenolithus abies, $k_s$ is calculated to be 0.05.
2. The size-corrected estimate of carbonate mass from discoaster nannoliths comprises 10–40 wt% of the total calculated nannofossil carbonate.
3. Both the abundances of discoasters and estimates of their mass contribution decline through the studied interval (8.6–3.25 Ma), associated with a general trend to more slender forms.
4. The nannofossil content estimates from granulometric measurements (Sedigraph) are consistently higher that the nannofossil contents calculated using nannofossil counts and shape factors. The most likely causes of this discrepancy are uncounted aggregates, breakage and overgrowth, all resulting in the count-based calculation being an underestimate. Thus, shape-factor-based nannofossil carbonate estimates might be referred to as minimum contents.

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APPENDIX A: TAXONOMIC LIST

Following the descriptions of Perch-Nielsen (1985) and references therein.

*Discoaster bellus* Bukry & Percival, 1971
*Discoaster bergrenii* Knuttel, Russell & Firth, 1989
*Discoaster berggrenii* Bukry, 1971
*Discoaster brouweri* Tan, 1927
*Discoaster braarudii* Bukry, 1971
*Discoaster bollii* Martini & Bramlette, 1963
*Discoaster calcaris* Gartner, 1967
*Discoaster challenger* Bramlette & Riedel, 1954
*Discoaster defflandrei* Bramlette & Riedel, 1954
*Discoaster hamatus* Martini & Bramlette, 1963
*Discoaster loeblichii* Bramlette & Riedel, 1954
*Discoaster pentaradiatus* Tan, 1927
*Discoaster petaliformis* Moshkovitz & Ehrlich, 1980
*Discoaster prepentaradiatus* Bukry & Percival, 1971
*Discoaster quinqueramus* Gartner, 1969
*Discoaster surculus* Martini & Bramlette, 1963
*Discoaster variabilis* Martini & Bramlette, 1963
*Sphenolithus abies* Deflandre in Deflandre & Fert, 1954
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