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The effects of the Chesapeake Bay impact on calcareous nannofossil assemblages: patterns from the Watkins School core, Newport News, Virginia (USA)

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Abstract The goal of this study was to assess the effect that the Late Eocene Chesapeake Bay bolide impact had on local patterns of calcareous nannofossil species composition, richness and preservation. Although calcareous nannofossil assemblages have been described from a handful of coreholes drilled within the impact structure, this is the first study to examine the calcareous nannofossils from the Watkins School core, which was recovered along the outer rim of the crater. A detailed stratigraphic assessment of the calcareous nannofossil assemblages across the synimpact-postimpact boundary was performed to determine whether the impact produced any local extinction. The results obtained suggest that, despite its size, the Chesapeake Bay impact did not significantly affect the local calcareous nannoplankton community. Little or no change was documented across the synimpact-postimpact boundary in calcareous nannofossil species composition, richness or preservation quality. These findings do not support the existence of a calcareous nannofossil 'dead zone' in this particular core; however, the presence of impact-fractured calcareous nannofossils does attest to the tremendous pressures generated by the impact.

Keywords Late Eocene, Chesapeake Bay impact structure, CBIS, impact crater, nannoplankton, coccolithophore, Watkins School core, dead zone, Exmore beds, Chickahominy Formation

1. Introduction

The Chesapeake Bay impact occurred in the Late Eocene, approximately 35.5±0.3Ma (Glass *et al*., 1986; Poag *et al*., 2003; Self-Trail, 2004; Horton *et al*., 2005a), when a comet or meteorite 2-3km in diameter struck the Atlantic Coastal Shelf (Poag *et al*., 1994; Johnson *et al*., 1998; Powars & Bruce, 1999; Powars, 2000). The resultant impact crater (the so-called Chesapeake Bay Impact Structure, or CBIS) is a roughly circular structure, 80-90km in diameter and centred near Cape Charles, Virginia (Poag, 1997a; Figure 1). Although the structure and geology of the CBIS have been explored in detail (Poag, 1996; Johnson *et al*., 1998; Powars & Bruce, 1999; Powars, 2000), the palaeontological aspects of the impact have received considerably less attention (Poag, 1997b, 2002; Edwards & Powars, 2003; Poag *et al*., 2003; Self-Trail, 2003).

The goals of this research were: 1) to determine the effects of the impact on local calcareous nannofossil assemblages; 2) to describe the preservation quality of calcareous nannofossils across the synimpact-postimpact boundary; and 3) to document the occurrence of impact-altered calcareous nannofossils. To address these goals, samples were collected and examined from the Watkins School continuous corehole, which was drilled by the US Geological Survey (USGS) in Newport News, Virginia in

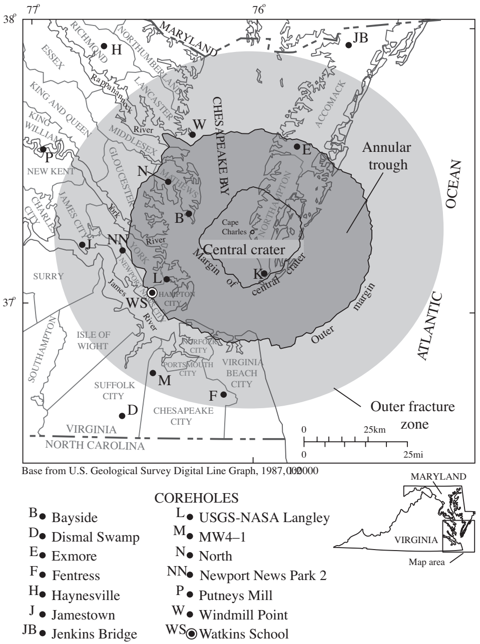

Figure 1: Map showing the location and dimensions of the buried CBIS. Locations of the coreholes discussed in the text are provided, including the Watkins School corehole. Outline of the central crater and outer margin provided by Powars & Bruce (1999). Location of the outer fracture zone based on Powars (2000) and Johnson *et al*. (2001)

2002. Although the calcareous nannofossil assemblages from the Exmore (Poag & Aubry, 1995), Kiptopeke (Poag & Aubry, 1995; Poag *et al*., 2004), Jamestown (Powars & Bruce, 1999), USGS-National Aeronautics and Space Administration (NASA) Langley (Self-Trail, 2003; Edwards *et al*., 2005) and Bayside (Self-Trail, 2004) cores have been described (Figure 1), this is the first study documenting the calcareous nannofossil assemblages from an outer rim core. The CBIS is the largest extraterrestrial impact crater in the US (Earth Impact Database, 2005) and provides an ideal system in which to study the biological effects of an extraterrestrial impact on a siliciclastic continental shelf environment.

2. Background

2.1 Chesapeake Bay Impact Structure: structure and stratigraphy of the outer rim

The CBIS is presently buried beneath 150-400m of overlying Coastal Plain sediment and stretches from the lower Chesapeake Bay to its surrounding peninsulas and to the continental shelf east of the Delmarva Peninsula (Poag *et al*., 1994; Powars & Bruce, 1999; Powars, 2000). The existence of the CBIS was not reported until the 1990s (Powars *et al*., 1993; Poag *et al*., 1994), and its discovery owes much to the hydrogeologic studies of D.J. Cederstrom, the surficial mapping efforts of G.H. Johnson, and the subsurface investigations of the USGS and Virginia Department of Environmental Quality (see references cited in Powars & Bruce, 1999).

Thirteen continuous coreholes have been drilled and recovered from both inside and outside the CBIS in southeastern Virginia and on the Delmarva Peninsula of Virginia (Poag, 1997a; Poag *et al*., 2004). Additional data on the CBIS structure have been obtained through single, two-channel, and multi-channel seismic profiles along the Lower Chesapeake Bay and Delmarva Peninsula (Poag *et al*., 1994; Poag, 1996; Powars & Bruce, 1999; Poag, 2005). The CBIS, which is approximately 1.3km deep, is composed of an outer fracture zone, an outer rim, a flat-floored annular trough, an inner peak ring, and a central crater in contact with Proterozoic basement rock (Poag, 1997a; Johnson *et al*., 1998; Powars & Bruce, 1999; Powars, 2000). The corehole examined in the present study was drilled to a depth of 300.3m at the Dorothy R. Watkins Elementary School in Newport News, a site located just outside the outer rim of the crater, and approximately 27km outside the central crater (Horton *et al*., 2005b).

The oldest sediments recorded in the Watkins School core are Cretaceous in age and do not exhibit sand fluidisation or other evidence of impact disruption (Horton *et al*., 2005b). These Cretaceous sediments are overlain by the synimpact Exmore beds (Crater unit C of Self-Trail, 2003), which are thought to represent mixed debris-flow sediments generated by impact resurge (Gohn *et al*., 2005; Horton *et al*., 2005b). The matrix of these beds is an unsorted, muddy quartz-glauconite sand derived from pre-impact Lower Cretaceous fluvial and Upper Cretaceous and Lower Tertiary marine sediments originally deposited in the target area (Horton *et al*., 2005b). The matrix supports granule- to cobble-sized clasts of displaced debris, the majority of which are derived from Cretaceous, Paleocene and Eocene sedimentary units (Frederiksen *et al*., 2005; Gohn *et al*., 2005). Overlying the Exmore beds is the Upper Eocene Chickahominy Formation, a silty marine clay layer that records the rapid postimpact filling of the crater (Poag, 1997a; Poag *et al*., 2004; Edwards *et al*., 2005; Poag & Norris, 2005; Powars *et al*., 2005). Deposition of the Chickahominy Formation spanned approximately 2my, preserving an outer neritic to upper bathyal facies, the top of which has been eroded as a result of subsequent changes in sea-level (Poag, 2004; Edwards *et al*., 2005). Detailed descriptions of the CBIS structure and stratigraphy have been provided most recently by Powars & Bruce (1999), Powars (2000), Poag *et al*. (2004), Horton *et al*. (2005c) and Gohn *et al*. (2005). The stratigraphic nomenclature and interpretation used here follows Gohn *et al*. (2005).

2.2 Palaeontology of the crater-fill deposits

The majority of palaeontological investigations into the CBIS have focused almost exclusively on establishing age estimates for the impact, based on microfossil occurrences (Poag & Aubry, 1995; Poag, 1997b, 2002; Poag *et al*., 2003), rather than assessing its effects on species composition, richness or preservation. The biochronological age of the CBIS has been constrained on the basis of calcareous nannofossil, bolboformid and planktonic foraminiferal assemblages (Poag & Aubry, 1995; Poag & Commeau, 1995; Poag, 1997a; Self-Trail, 2003; Poag & Norris, 2005), linked to numerical dates using the chronostratigraphic framework of Luterbacher *et al*. (2004).

More recently, palaeontological studies have focused on the taphonomy of impact-altered microfossils documented from multiple coreholes (Edwards & Self-Trail, 2002; Self-Trail, 2002; Edwards & Powars, 2003; Self-Trail, 2003). This alteration was first described in dinoflagellates, which display a range of melting, bubbling, and welding features (Edwards & Powars, 2003), and has subsequently been observed in calcareous nannofossils, which are fractured (Self-Trail, 2003). The unusual fracturing of the calcareous plates of nannofossils occurs primarily in the genus *Discoaster*, and appears as sharp angles cut straight across ray tips of the specimens. Both the fracturing and melting have been attributed to the intense heat and pressure produced by the initial impact into Upper Eocene Coastal Plain sediments.

3. Materials and methods

Sediments from within the Watkins School core were sampled and analysed for calcareous nannofossil content.

Closely-spaced sampling (ranging from 1-6cm) was conducted across the synimpact-postimpact boundary (*i.e.*, the boundary between the Exmore beds and Chickahominy Formation). The boundary occurs at 188.84m (L.E. Edwards and D.S. Powars, pers. comm., 2005; Figure 2), coinciding with a lithological change from sandy clay with sand-filled burrows and no layering below, to tight clay with sand-filled burrows that show faint layering above (D.S. Powars, pers. comm., 2005).

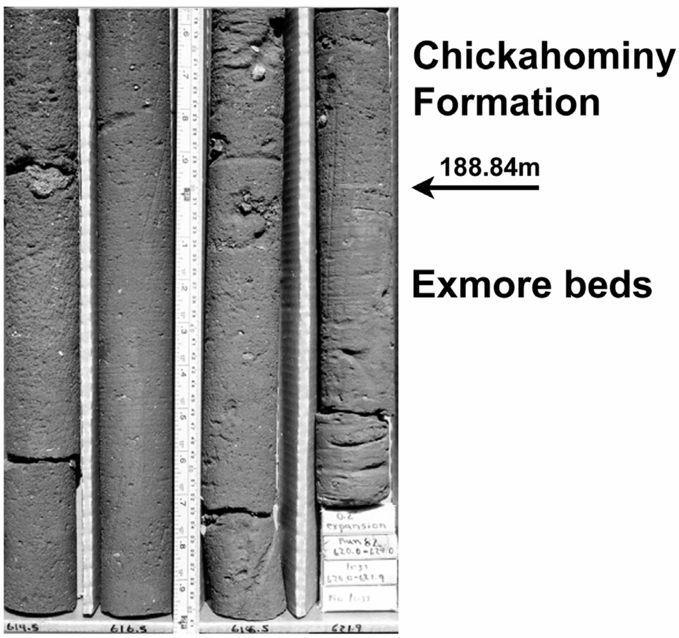

Figure 2: Photograph of the contact between the Exmore beds and Chickahominy Formation in the Watkins School core (188.84m, denoted by the arrow). Photograph courtesy of D.S. Powars, USGS

Thirty-five samples, from 189.76 to 187.76m, were collected for calcareous nannofossil analysis. The outer layer of the cleaned core was removed to minimise the likelihood of sample contamination and a small, clean metal spatula, with a scoop diameter of less than 1cm, was used to collect a small amount of sample material at each depth. A portion of this sample was then placed on the surface of a new coverslip, mixed with one drop of deionised water, and smeared across the surface of the coverslip using a small glass rod. The coverslip was dried, and Norland Optical Adhesive 61 was used to attach each coverslip to a slide.

Each slide was viewed using one of two different microscopes: a Zeiss Axiophot 2 (10x ocular lenses, 100x objective lens, 2.0 optivar) at the USGS in Reston, Virginia, or an Olympus BX41 (15x ocular lenses, 100x objective lens) at the Geology Department of The College of William and Mary in Williamsburg, Virginia. All sample slides are archived in the calcareous nannofossil laboratory at the USGS in Reston, Virginia.

Each slide was scanned visually. Average scanning time ranged from three to five hours per slide, depending on whether the slide was scanned partially or in its entirety. The presence or absence of calcareous nannofossil species identified on each slide was recorded on species occurrence sheets, and special attention was paid to the abundance and species identification of taxa that occurred above or below their expected biostratigraphic ranges. Biostratigraphic ranges for species were compiled from Perch-Nielsen (1985) and from an extensive unpublished biostratigraphic database compiled by LMB. A species was judged to occur out of biostratigraphic range (*i.e.*, to be reworked) if the biostratigraphic range recorded in the two sources ended below combined Nannofossil Biozones NP19/20, in which the impact event occurred (Poag & Aubry, 1995).

Quality of calcareous nannofossil preservation was also recorded for each sample, based on light microscope observation and using a four point classification system, consisting of poor, moderate, good and excellent categories (Edwards *et al.*, 2005). Distinctions between levels of preservation quality were based on a variety of factors, including levels of dissolution and/or recrystallisation, and preservation of particularly delicate species. Occurrences of coccospheres and impact-fractured calcareous nannofossils were also documented.

4. Results

A total of 64 calcareous nannofossil species, representing 31 genera, were identified (see Appendix). The Appendix summarises the occurrence data obtained in this study and denotes samples that were scanned partially. These samples were not included in subsequent analyses, because the species richness and reworking data obtained from them may be underestimated. Of the 64 species identified, 19 occurred above their known biostratigraphic range and were considered to be reworked. The reworked species range in age back to the Late Cretaceous and provide a minimum estimate of reworking, since species that have been reworked within their known stratigraphic range cannot be distinguished and are not included in this estimate. Below the synimpact-postimpact boundary, these reworked species represent a significantly higher percentage of the calcareous nannofossil assemblages than above the boundary (Figure 3). The average percentage of reworked species documented below the boundary is 20.48%, compared to 9.3% above, which is a statistically significant difference (Mann-Whitney *U* test: $Z_{8,15} = -2.78$, $p = 0.004$). The increase in the percentage of reworked species immediately above the Exmore beds-Chickahominy Formation boundary is thought to be the result of burrowing at the contact (L.E. Edwards, pers. comm., 2006). Despite this, the Exmore beds-Chickahominy Formation boundary represents a significant shift in the frequency of reworked calcareous nannofossil species, regardless of whether reworking is quantified as the percentage or number (Mann-Whitney *U* test: $Z_{8,15} = -2.18$, $p = 0.03$) of reworked species.

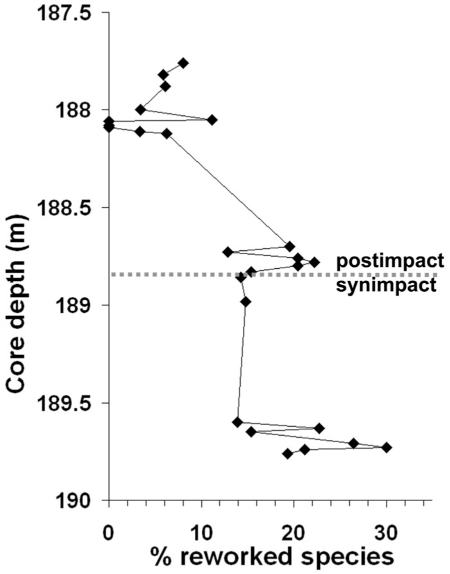

Figure 3: Percentage of species recorded above their known biostratigraphic range (*i.e*., reworked) in the Watkins School core. Percentage and number of reworked species are statistically significantly higher below the boundary than above

4.1 Species compositional changes across the synimpact-postimpact boundary

To assess changes in species composition across the synimpact-postimpact boundary, both reworked species and partially-examined samples were removed from the dataset and the presence/absence data for each species were qualitatively examined for changes across the boundary. Of the 42 species sampled within their known biostratigraphic range, 29 were documented in both samples spanning the boundary (188.86m and 188.83m) and show no evidence of local extinction. Two species (*Discoaster distinctus* and *Neococcolithes* sp.) occur only below the boundary; however both of these species occur in only one sample and neither occurs within 0.6m of the boundary. One species (*Goniolithus fluckigeri*) first occurs in the sample immediately above the boundary (188.84m). However, this species is long-ranging (Coniacian?-Tertiary) and is often very sporadic in occurrence (Burnett, 1998). Six species occur both below and above the boundary, but not in the two samples spanning the boundary (188.86-188.83m), suggesting that they may have experienced local extinction (*Braarudosphaera bigelowii, Chiasmolithus* cf. *C. oamaruensis*, *Pemma* sp., *Discoaster nodifer, Discoaster tanii* and *Reticulofenestra daviesii*). None of these species are recorded in the sample immediately below the boundary (188.98m) though, and only one (*R. daviesii*) is recorded in the sample below that (189.6m). All of these species have particularly poor fossil records and two of them are taxonomically poorly constrained (*Chiasmolithus* cf. *C. oamaruensis* and *Pemma* sp.).

To examine these qualitative patterns with a more quantitative approach, this dataset was subjected to non-metric multidimensional scaling (NMDS). This technique is particularly useful for ordinating non-normally distributed ecological data using pairwise comparisons of rank-order dissimilarity (in this case, Euclidean distance) between the samples (Clarke, 1993). It works *via* an iterative search for a ranking and placement of *n* entities on *k* dimensions (axes) that minimises the stress of the *k*-dimensional configuration (McCune & Mefford, 1999). NMDS, which produced three ordination axes, yielded very similar results to those described qualitatively above (Figure 4). Samples from the Exmore beds (189.76-188.96m), the synimpact-postimpact boundary (188.86-188.83m), and the Chickahominy Formation (188.8-187.76m) can be differentiated from each other on a plot of NM axes 1 and 2 (Figure 4A) and on a plot of NM axes 2 and 3 (Figure 4B). Samples from the three intervals differ significantly from each other for NM axis 2 (Kruskal-Wallis $X^2_{25} = 6.45$, $p = 0.04$), but not axis 1 (Kruskal-Wallis $X^2_{25} = 4.31$, $p = 0.12$), nor axis 3 (Kruskal-Wallis $X^2_{25} = 3.17$, $p = 0.21$). It is also worth noting that the distribution of samples from the Exmore beds along NM axis 2 is broader than the distribution of samples from the Chickahominy Formation, a pattern which may be indicative of the greater levels of time-averaging observed in the former. The spatial distribution of the boundary samples in this ordination is heavily influenced by *B. bigelowii*, *C.* cf. *C. oamaruensis*, *D. distinctus, Neococcolithes* sp.,

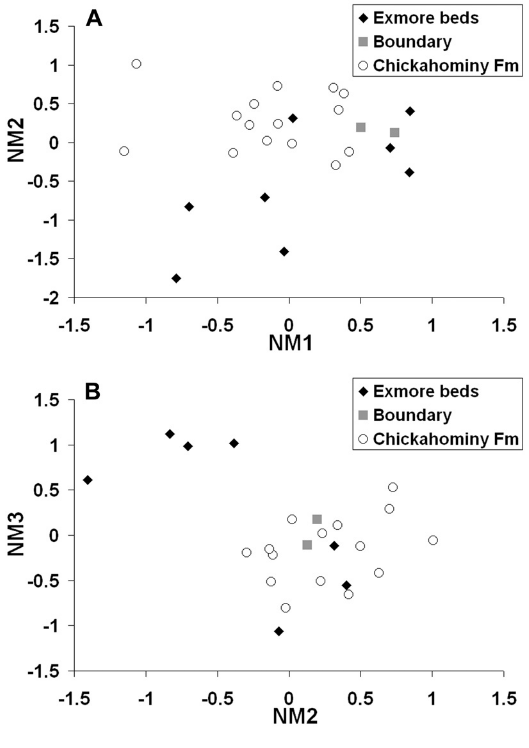

Figure 4: **A**) Plot of NM axes 1 and 2 resulting from the NMDS analysis on presence/absence data for species recorded within their known biostratigraphic range. Samples from the boundary are distributed on the right-hand side of the plot. **B**) Plot of NM axes 2 and 3 resulting from the NMDS analysis on presence/absence data for species recorded within their known biostratigraphic range

Pemma sp., *D. nodifer* and *G. fluckigeri,* which are all distributed on the lower left-hand side and right-hand side of Figure 4A. These species were discussed in the qualitative description provided above, and represent a mix of species that occur in only one sample or disappear temporarily across the boundary. These taxa exert a tremendous influence over this ordination, effectively defining the endpoints of NM axis 1 and the negative endpoint of NM axis 2. It is therefore important to consider how reliable the presence/absence data for these taxa are.

Species may be absent from a sample due to sampling bias, preservational bias, or true absence from that particular location at that particular time. Preservation is unlikely to exert a sizeable bias in this dataset because preservation quality does not vary substantially across the synimpact-postimpact boundary, and the calcareous nannofossil species sampled do not differ considerably according to size or mineralogy. Sampling bias is more likely to present a problem. To explore the effects of sampling bias on these data, the 'gappiness' of occurrences was calculated for species that may have undergone local extinction or origination across the boundary. If a species is recorded in two samples at two different corehole depths, it is not unreasonable to suggest that it may have occurred, but not have been sampled, in the intervening corehole depths. It is then possible to calculate the percentage of gaps, or samples within the local stratigraphic range of the species in which the species is not recorded. It should be emphasised that gappiness is calculated based on the local, rather than global, stratigraphic range of these species.

Of the six species that disappear completely across the boundary, only to reappear afterwards, all six have extremely gappy records (occurring in only 11-59% of possible intervals, indicating a gappiness of 41-89%), suggesting that their disappearance is related to sampling rather than local extinction. Average gappiness for all of the species sampled in this study is 28%, by comparison. Both qualitative and quantitative examination of species composition across the synimpact-postimpact boundary suggests that the impact had little, if any, effect on calcareous nannofossil species composition locally, especially when sampling bias is taken into consideration.

4.2 Species richness changes across the synimpact-postimpact boundary

To assess changes in calcareous nannofossil species richness across the synimpact-postimpact boundary, both reworked species and partially examined samples were removed from the dataset and the presence/absence data for each sample were used to calculate richness (*i.e.*, number of species). Richness was calculated both including and excluding range-through occurrences. The range-through technique assumes that taxa that occur below and above an interval actually occur locally in that interval and can be counted towards species richness, even if they are not recorded.

Not surprisingly, species richness excluding range-through occurrences fluctuates considerably more throughout this interval than richness including range-through occurrences (Figure 5). Species richness excluding range-through occurrences varies from 21 to 35, with large fluctuations recorded at the base of the sampled interval, between 189.76m and 189.6m. A major decrease in richness was recorded at 188.98m, which represents an approximately 75% decrease in richness. Although the drop at 188.96m does coincide with an interval of slightly worse preservation quality (Figure 6), richness does not, as a general rule, correspond closely to preservation quality. The species richness curve, excluding range-through occurrences, is likely to be strongly affected by sampling bias and may also closely track changes in reworking throughout this interval. Although species that are clearly reworked (*i.e.*, occur above their known biostratigraphic range) were removed from these calculations, it was impossible to identify species that may have been reworked within their known biostratigraphic range, since differences in preservation quality were not obvious. If the degree to which species are reworked varies within these data, one might expect reworking to correspond with intervals of high species richness (*i.e.*, at 189.63m, 188.73-188.84m, 188.05-188.06m and 187.82m). It is particularly interesting to note that the synimpact-postimpact boundary corresponds to an increase in species richness in these samples, suggesting either that the impact had a positive effect on local diversity or, more likely, that reworking across the boundary, and the integration of material from all over the crater, artificially increased richness. Regardless of the explanation, this increase in richness suggests that the impact had no negative effect on local calcareous nannofossil richness.

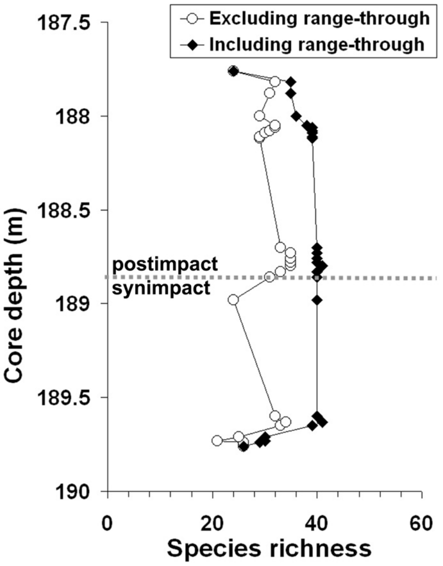

Figure 5: Species richness of calcareous nannofossils in the Watkins School core. Species richness is calculated both excluding and including range-through occurrences and shows no evidence for extinction across the boundary

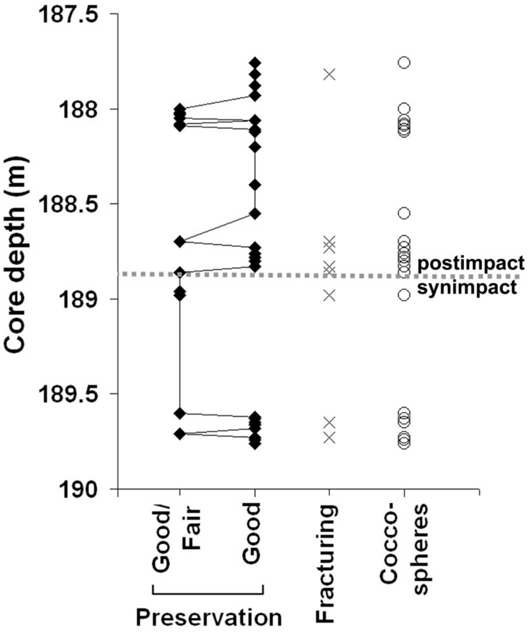

Figure 6: Preservation quality, occurrence of fracturing and occurrence of coccospheres recorded in the Watkins School core. Preservation quality does not change significantly across the boundary

Turning to the results for species richness including range-through occurrences (Figure 5), richness ranges from 24 to 41 and remains remarkably stable across the entire interval sampled. The increase and decrease in richness recorded at the beginning and end of this interval are most likely artifacts of the range-through calculations, since these samples would not benefit from range-through increases. Similarly to the results for species richness excluding range-through occurrences, the synimpact-postimpact boundary corresponds with a minor increase in species richness.

4.3 Preservation and impact taphonomy across the synimpact-postimpact boundary

Preservation quality was categorised for each sample and plotted throughout the sampled interval, as shown in Figure 6. Preservation varies between 'good' and 'good/fair' throughout this interval, and no major changes in preservation quality were noted across the synimpact-postimpact boundary. The only deviations from good preservation were recorded in samples 189.71m, 189.6m, 188.98-188.86m, 188.7m, 188.09-188.08m and 188.03-188m. These samples all displayed good/fair preservation and, as such, do not represent a significant change in preservation quality. Preservation of whole coccospheres was observed in 21 of the 35 intervals sampled, including across the synimpact-postimpact boundary (Figure 6). Whole coccospheres are often preserved in assemblages that have undergone relatively little dissolution (Self-Trail, pers. comm., 2005).

Impact-fractured calcareous nannofossils were documented at eight depths throughout the sampled interval, including at least one sample immediately above the synimpact-postimpact boundary (188.83m; Figure 6). Fracturing was observed exclusively in the genus *Discoaster*, primarily in *D. barbadiensis* and, to a lesser extent, in *D. saipanensis* (Self-Trail, 2003).

5. Discussion

5.1 No evidence for a calcareous nannofossil 'dead zone'

Little or no change in calcareous nannofossil species composition, richness or preservation was recorded across the synimpact-postimpact (*i.e*., Exmore-Chickahominy) boundary in the Watkins School core. Six species do disappear across the boundary and reappear in stratigraphically younger samples; however, all of these species are taxonomically poorly constrained or sporadically recorded throughout the interval, and their disappearances are more likely to represent sampling bias than true local extinction. Species richness actually appears to increase slightly, rather than decrease, across the synimpact-postimpact boundary in the Watkins School core, regardless of how richness is calculated. Species that occur outside their known biostratigraphic range are not included in these calculations, however, reworking may still be partly responsible for this pattern. Preservation quality is good throughout the sampled interval and does not differ significantly across this boundary.

Few studies have assessed the biospheric effects of the Chesapeake Bay impact, and none have found solid evidence for global mass extinction (Poag, 1997b; Poag *et al*., 2003, 2004). The age of the impact and its associated ejecta deposits does not correspond with global extinctions recorded at either the end of the Middle Eocene or the Early Oligocene (Poag, 1997b; Poag *et al*., 2003), despite earlier studies that postulated a link (Alvarez *et al*., 1982; Asaro *et al*., 1982; Ganapathy, 1982; Rampino & Haggerty, 1994). Deposition of the ejecta layer may have been associated with a minor decrease in radiolarian diversity (Glass & Zwart, 1977; Sanfilippo *et al*., 1985) and a reorganisation of dinoflagellate (Clymer *et al*., 1996) and planktonic foraminiferal (Keller, 1986; MacLeod *et al*., 1990; Poag & Aubry, 1995) assemblages in the deep sea. However, the magnitude and causes of these changes remain unclear (Poag, 1997b).

The response of local marine communities to the impact itself has been studied in detail for benthic foraminifera collected from the USGS-NASA Langley and Kiptopeke cores. In his examination of the synimpact-postimpact boundary in the USGS-NASA Langley core, Poag (2002) noted a lack of 'indigenous' microfossil species, combined with reworked, size-sorted, stratigraphically-mixed and diagenetically-altered microfossil specimens. According to Poag (2002), these features occur within a discrete, thin (19cm) unit of laminated sand, silt and clay, which immediately underlies the Chickahominy Formation (Poag, 2002; Poag *et al*., 2004). Poag (2002) has described pyrite lattices from this unit, which he interpreted as evidence for microspherules (Poag, 2002; Poag *et al*., 2004), while Horton *et al*. (2005b) interpreted them as features that formed around glauconite pellets. Poag (2002) referred to this unit as a 'dead zone', and identified similar intervals in the North and Bayside coreholes, which he believed represented a recovery period of 1-10 000 years before the local microfossil community returned to pre-impact conditions (Poag, 2002; Poag *et al*., 2004).

This dead zone has proven somewhat difficult to define, either palaeontologically or sedimentologically, in other cores or for other microfossil groups. Pyrite lattice structures have not been identified in any core other than the USGS-NASA Langley core (Poag, 2002; Poag *et al*., 2004). In fact, CBIS workers differ on whether the unit should even be recognised sedimentologically (Gohn *et al*., 2005). Horton *et al*. (2005b) mentioned that the transition from the Exmore beds to the dead zone is gradational and that impact debris continued to settled out of the water-column after normal marine sedimentation had resumed. Palaeontologically, the dead zone is defined by the presence of reworking, size-sorting, diagenetic alteration and stratigraphic mixing of microfossils; however, many of these processes are documented throughout the Exmore beds and Chickahominy Formation in all of the coreholes (Self-Trail, 2002 and unpublished data). It is not clear why foraminiferal specimens from the dead zone are considered non-indigenous and specimens from the Chickahominy Formation are not, when the species represented are exactly the same (Poag, 2002; see Poag *et al*., 2004, fig.13.2). Of the 17 benthic foraminiferal species Poag *et al*. (2004) identified from the dead zone in the Kiptopeke core, all of them occur in the basal 2.4m of the Chickahominy Formation, suggesting that they could, in fact, have been living during the interval represented by the dead zone.

Despite the confusion surrounding the dead zone, Poag *et al*. (2004) have provided the most in-depth examination of the fossil record across the synimpact-postimpact boundary, including documentation of microfossil community structure, generic predominance, species richness and palaeoenvironment. All of these variables fluctuated widely across the synimpact-postimpact transition in both the USGS-NASA Langley and Kiptopeke cores (see, for example, Poag et al., 2004, fig.13.9), suggesting either that the impact had little effect on local microfossil communities, or that the effect cannot be differentiated in the record. Despite the abundance and richness of microfossils documented in crater deposits, no attempt has been made, until now, to extend these investigations across the synimpact-postimpact transition beyond benthic foraminifera.

In contrast to the benthic foraminiferal data from the USGS-NASA Langley and Kiptopeke coreholes, calcareous nannofossil data from the Watkins School core provide no evidence for a dead zone. Sedimentary indicators of a dead zone, including pyrite lattices, appear to be missing from the Watkins core (Horton *et al*., 2005b). Reworked species and stratigraphically-mixed and diagenetically-altered calcareous nannofossil specimens occur throughout the Exmore beds, the synimpact-postimpact boundary and the Chickahominy Formation, and do not define a specific interval. Indigenous species were documented throughout the Exmore-Chickahominy boundary, with no discernible change in preservation quality. Poag (2002) used the poor preservation of benthic foraminifera in the USGS-NASA Langley and Kiptopeke cores to argue that all of the specimens in the dead zone are reworked and therefore not indigenous. Regardless of whether preservation can be used as a valid indicator of reworking, it is clear that similar patterns are not recorded for calcareous nannofossils in the Watkins School core.

One possible explanation for why a dead zone might occur in the Kiptopeke but not in the Watkins School core may relate to the location of the coreholes relative to the crater rim. The Kiptopeke core was recovered within the inner crater rim, on the Delmarva Peninsula (Powars & Bruce, 1999), a region that is expected to have sustained greater damage as a result of the impact. The location of the Watkins School corehole on the outer rim places it further away from the crater centre. The problem with this explanation is the location of the USGS-NASA Langley corehole, along the outer crater rim, in close proximity to the Watkins School corehole.

Another possible explanation for the absence of a calcareous nannofossil dead zone in the Watkins School core relates to the life habit of calcareous nannoplankton, which are planktonic, as opposed to the benthic foraminifera. The Chesapeake Bay impact may have had a stronger effect on those organisms inhabiting the sea-floor because of the complete destruction of these benthic habitats. While the local water-column was greatly disturbed, it may have returned to normal conditions faster than the sea-floor, due to the settling out of impact-suspended sediment. The upper water-column (*i.e*., photic zone) would have settled out most quickly, allowing the habitat of calcareous nannoplankton to return to normal conditions. The time-averaged nature of these sediments may, in addition, have precluded the preservation of such a short interval of environmental and biotic perturbation. Conditions on the sea-floor would have taken longer to recover due to continued settling from the water-column and additional slumping of megablocks created during the impact. Prolonged environmental disturbance may have extended the recovery of benthic foraminiferal communities, which may then have been preserved as a dead zone in the fossil record. Although Poag (2002) suggested that calcareous nannofossil and dinoflagellate data from the USGS-NASA Langley corehole may have supported the presence of a dead zone in that core, attempts to verify these patterns have not been successful (Self-Trail, 2003; Edwards *et al*., 2005).

5.2 Impact-fracturing in calcareous nannofossils

The impact damage described in this study supplements the detailed observations made by Self-Trail (2003) for calcareous nannofossil specimens from the USGS-NASA Langley core. Impact-fracturing is common in a number of Watkins School core samples and restricted to the same genus, *Discoaster*, documented in earlier studies. The impact-fracturing in calcareous nannofossils observed in this study and previous studies (Edwards & Self-Trail, 2002; Self-Trail, 2002, 2003), differs considerably from the melting documented in dinoflagellates (Edwards & Powars, 2003). Calcareous nannofossils are usually fragmented through chemical processes, such as dissolution, because their microscopic size makes them unlikely to undergo physical fracturing. However, the fractured nature of the calcareous nannofossils observed in this study suggests an obvious physical cause. This fracturing is significant in that it may be indicative of the tremendous pressures generated during the impact.

The impact-fractured and reworked material in the Chickahominy Formation may be derived from a variety of sources. Firstly, this material may have been reworked from outcrops of Exmore bed material that were once located outside the crater. Alternatively, it is possible that compressional fracturing exposed Exmore bed material for submarine transport. Finally, and perhaps most likely, this material could be derived from the underlying beds *via* burrowing and bioturbation, especially given the fact that these samples were collected across the synimpact-postimpact boundary.

6. Conclusions

The Chesapeake Bay impact had surprisingly little effect on the local calcareous nannoplankton assemblages preserved in the Watkins School continuous corehole. Calcareous nannofossil species composition, richness and preservation quality do not change across the synimpact-postimpact (Exmore-Chickahominy) boundary in this core. These findings do not support the occurrence of a calcareous nannofossil 'dead zone' following the impact, suggesting that this zone, which was originally defined on the basis of foraminiferal data from the USGS-NASA Langley core, may be limited to benthic organisms. The record of impact-fractured discoasters throughout the sampled interval represents the first in-depth documentation of impact taphonomy in the Watkins School core. Despite the substantial size of this impact, and its potential effects on primary productivity, the forces it generated were insufficient to significantly influence the composition or richness of calcareous nannofossil assemblages preserved locally.

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Appendix

Occurrence chart for calcareous nannofossil species identified in the Watkins School core. Sample depths provided in both their original measurements (feet) and converted to metres (rounded to two decimal places). Nannofossil zonation is provided for the Chickahominy Formation. Santonian through Late Eocene nannofossil zones are represented in the Exmore beds (crater fill). Known biostratigraphic range data for each species are provided next to each species name. Gray shading highlights the synimpact-postimpact boundary (188.84m).'X' denotes presence of a species in the sample from that particular depth.'X(?)' denotes probable, but somewhat questionable, presence of a species. '†' denotes a species that occurs above its known biostratigraphic range (*i.e.*, reworked). '≠'denotes a previously unidentified species.'*' denotes a sample that was not examined in its entirety.'^' denotes core loss from 189.56m to 188.98m

622.55ft	622.50ft	622.45ft	622.40ft	622.30ft*	622.25ft*	622.20ft	622.15ft	622.10ft*	622.05ft	CORE LOSS^	620.00ft	619.95ft*	619.60ft	619.50ft	619.40ft	619.35ft	619.30ft	619.20ft	619.10ft	618.60ft*	618.10ft*	617.45ft*	617.20ft	617.15ft	617.10ft	617.05ft	617.00ft	616.95ft	616.90ft*	616.85ft*	616.80ft	616.55ft*	616.40ft	616.20ft	616.00ft	**Depth (ft)**
189.76m	189.74m	189.73m	189.71m	189.68m	189.66m	189.65m	189.63m	189.62m	189.6m		188.98m	188.96m	188.86m	188.83m	188.8m	188.78m	188.76m	188.73m	188.7m	188.55m	188.4m	188.2m	188.12m	188.11m	188.09m	188.08m	188.06m	188.05m	188.03m	188.02m	188m	187.93m	187.88m	187.82m	187.76m	**Depth (m)**
MIXED ZONES														NP19/20																						**Nannofossil zones**
EXMORE BEDS														CHICKAHOMINY FORMATION																						**Stratigraphic units**
X	X	X		X	X	X(?)		X	X		X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X		X	X	X	X	X	X	X	*Blackites spinosus* NP14-21
X	X		X	X	X	X	X	X	X				X	X	X	X	X	X	X				X	X	X	X	X	X	X		X	X	X	X	X	*Blackites tenuis* NP13-21
X	X	X	X	X			X					X			X	X	X		X			X								X						*Braarudosphaera bigelowii*
						X	X		X		X		X	X			X	X			X(?)										X					*Bramletteius serraculoides* NP15-22
		X	X		X	X	X(?)		X(?)						X	X	X		X																	*Campylosphaera dela*† NP9-17
	X	X	X						X				X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	*Cepekiella lumina* NP11-24?
																	X																			*Chiasmolithus eograndis*† NP10-13
			X		X		X								X																					*Chiasmolithus grandis*† NP14-17
	X		X			X	X		X		X	X	X	X	X	X	X	X	X		X	X		X	X	X	X	X	X	X	X	X	X	X	X	*Chiasmolithus oamaruensis* NP18-22
X	X			X								X				X				X		X	X					X								*Chiasmolithus* cf. *C. oamaruensis* NP18-22(?)
X	X	X	X			X	X		X		X	X	X		X	X	X	X	X	X		X						X				X		X		*Chiasmolithus solitus/bidens*† NP5-16
X	X	X	X	X	X	X	X		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	*Coccolithus pelagicus*
	X		X(?)			X		X	X		X		X	X	X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	*Coronocyclus nitescens* NP19/20-25
X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	*Cribrocentrum reticulatum* NP16-19/20
X	X	X	X	X	X	X	X		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	*Cyclococcolithus formosus* NP12-21
X		X				X	X		X					X	X	X	X	X	X	X		X	X	X	X	X	X	X	X				X		X	*Cyclococcolithus protoannulus* NP14-21
						X	X		X		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	*Dictyococcites bisectus* NP16-NN1
X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	*Dictyococcites scrippsae* NP16-24?
X	X	X	X	X		X	X		X		X		X	X	X	X	X(?)	X	X				X	X	X	X	X	X				X	X	X	X	*Discoaster barbadiensis* NP11-19/20
X																																				*Discoaster distinctus* NP12-NN7
	X																																			*Discoaster lodoensis*† NP12-14
																												X(?)								*Discoaster multiradiatus*† NP9-11
X	X		X(?)	X	X	X						X				X	X	X	X								X							X		*Discoaster nodifer*
X	X	X	X	X	X		X	X	X		X		X	X	X		X	X	X	X			X	X	X	X	X	X	X		X	X	X	X		*Discoaster saipanensis* NP14-19/20
	X		X				X											X					X		X	X			X		X			X(?)		*Discoaster tanii*
															X																					*Goniolithus fluckigeri*
						X	X							X	X	X	X	X(?)	X(?)							X		X(?)				X		X		*Helicosphaera bramlettei* NP17?-25
				X		X	X(?)		X				X	X	X	X	X	X	X				X		X	X	X	X		X	X	X	X	X(?)		*Helicosphaera compacta* NP16-24
						X								X	X		X																X	X		*Helicosphaera intermedia*
		X(?)				X								X	X	X			X	X				X				X			X(?)	X				*Helicosphaera seminulum*† NP12-17?
X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	*Isthmolithus recurvus* NP19/20-21
						X	X		X				X		X	X	X	X	X				X	X	X	X	X	X	X	X	X	X	X	X(?)	X	*Lanternithus minutus* NP14-21?
X	X	X	X	X		X	X		X				X	X	X	X	X	X	X	X			X	X	X	X	X	X	X		X	X	X		X	*Markalius inversus* NP1-21
X	X		X	X	X	X	X		X		X		X	X	X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	*Micrantholithus vesper*
					X		X		X		X	X		X	X	X	X																			*Micula* sp.† (Cretaceous)
X	X		X	X			X		X		X	X	X(?)	X	X	X	X	X											X				X	X		*Neococcolithes dubius*† NP10-17?
							X																													*Neococcolithes* sp.
X	X	X	X	X	X		X						X	X	X	X	X																			*Pemma basquense basquense*† NP14-18?
				X			X																													*Pemma basquense crassum*† NP15-17
X	X	X	X	X	X	X	X		X			X	X	X	X	X	X	X(?)	X																	*Pemma serratum*† NP16-18?
X																							X				X(?)									*Pemma* sp.
																			X																	*Placozygus sigmoides*† NP1-10
		X																																	X	*Pontosphaera fimbriata*† NP?-16
X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	*Pontosphaera multipora*
	X			X		X	X							X	X	X	X		X				X	X	X	X	X	X	X	X		X	X	X		*Pontosphaera* sp. (with oblique bridges)
																				X																*Pontosphaera wechesensis*
							X		X				X	X	X	X	X	X	X					X	X	X		X			X	X	X	X	X	*Pontosphaera* sp.A≠
X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X		*Pontosphaera* sp.B≠
		X(?)	X																X			X(?)														*Pseudotriquetrorhabdulus inversus*† NP14?-17
						X	X		X						X	X	X	X					X	X	X	X	X	X			X		X	X	X	*Reticulofenestra daviesii* NP13-?
X	X	X	X	X		X	X		X		X		X	X	X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	*Reticulofenestra floridana* NP13?-NN6?
X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		*Reticulofenestra umbilicus* NP16-22
						X	X				X		X	X	X	X		X	X																	*Rhabdosphaera* sp.
																						X(?)	X(?)												X	*Rhomboaster orthostylus*† NP10-12
X		X	X	X	X	X	X		X		X(?)		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		*Sphenolithus moriformis*
X	X	X	X	X	X	X	X					X			X	X		X	X	X			X										X(?)			*Transversopontis pulcher*† NP9-17?
X	X	X	X	X	X	X	X	X	X		X		X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	*Transversopontis pulcheroides* NP12-24?
X	X	X	X	X	X	X	X		X		X	X	X	X	X	X	X	X	X	X	X	X		X			X	X	X	X	X	X	X	X		*Transvers*. aff. *T. pulcheroides* (holes on bar)
						X	X		X				X	X		X	X	X					X				X	X		X					X	*Transversopontis zigzag* NP14-24
		X	X			X	X	X	X		X		X	X	X	X	X	X	X			X		X	X	X	X	X	X		X	X	X	X	X	*Transversopontis* aff. *T. zigzag* (holes on bar)
																X	X																			*Zeugrhabdotus* sp.† (Cretaceous)
X	X	X	X	X	X	X	X	X	X		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		*Zygrhablithus bijugatus* NP5?-NN1
X	X	X	X	X		X	X				X	X	X	X		X	X	X	X									X(?)								Indet. Cretaceous form†
X	X					X	X	X	X		X		X	X	X	X	X	X	X					X	X	X	X	X	X		X	X	X	X	X	Indet. form (N-shaped)≠