

Partial collapse of the marine carbon pump after the Cretaceous-Paleogene boundary

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SUPPLEMENTARY INFORMATION

Adjustment factors

Improved understanding of modern and early Paleocene planktonic foraminifera ecologies and their associated carbon disequilibrium effects (Birch et al., 2013) allows refinement of K/Pg $\delta^{13}\text{C}$ gradients through the application of $\delta^{13}\text{C}$ adjustment factors. Two principal $\delta^{13}\text{C}$ vital effects are considered. The procedure of selecting realistic adjustment factors is discussed.

1. The metabolic effect. This effect results from the decreasing influence of metabolic (isotopically light) CO_2 on test calcite $\delta^{13}\text{C}$ through ontogeny (Berger et al., 1978). Metabolic fractionation, which influences small ($<150\text{ }\mu\text{m}$) tests, has been suggested to depress test $\delta^{13}\text{C}$ by up to 2‰ relative to ambient DIC $\delta^{13}\text{C}$ values.

Most planktic foraminifera species occurring in the immediate aftermath of the K/Pg extinction, both survivors and newly evolved taxa, are small ($<150\mu\text{m}$) and record $\delta^{13}\text{C}$ that is consistently lower than inferred ambient DIC by ~ 0.3 to 0.5‰ (D'Hondt and Zachos, 1993; Birch et al., 2012). For this reason our Site 1262 *G. cretacea* and *H. holmdelensis* records were adjusted by adding 0.4‰ to each $\delta^{13}\text{C}$ value (adjusted $\delta^{13}\text{C}$ Option-1 (Table DR1, Figure DR2). This value of 0.4‰ was selected initially because the isotopic depletion was previously shown to

be greatest in the smallest size fractions (80-125 μ m) and specimens of these taxa from the early Danian are particularly small (65-125 μ m).

2. The photosymbiosis effect. In some planktonic foraminifera species of larger test sizes (>150 μ m) have a relationship with symbiotic algae, which causes $\delta^{13}\text{C}$ values to be enriched by up to 1.5‰ (Spero and DeNiro, 1987; D'Hondt and Zachos, 1994; Norris 1996). The amount of $\delta^{13}\text{C}$ enrichment is dependent on the test size and the species in question.

Analysis of $\delta^{13}\text{C}$ – test size relationships in early Paleocene planktonic foraminifera reveals that this signal first appears in *Praemurica* .ca. 63.5Ma (Birch et al., 2012). At first the $\delta^{13}\text{C}$ – test size correlations and, thus inferred dependence on symbiosis, were relatively weak, but strengthened in later species of *Morozovella*, including *M. angulata*, which was analyzed in the upper part of the section, implying increased dependence on symbiosis over time. For this reason the adjustment factor for symbiosis has been split into two categories; weak symbiosis and full symbiosis. Weak symbiosis is associated with ^{13}C enrichment between 0.1 and 0.3‰ (relative to ambient DIC $\delta^{13}\text{C}$) over the full test size spectrum for a single taxon (Birch et al., 2012). The specimens picked here were at the larger end of the spectrum (>212 μ m), thus they were ‘adjusted to’ ambient DIC values by subtracting 0.3‰ from measured test $\delta^{13}\text{C}$. Full symbiosis is associated with ^{13}C enrichment in the range of 0.5 to 1.5‰. The specimens of *M. angulata* analyzed here were of medium to large size (180 to >250 μ m) thus, an adjustment value of 1.0‰ was subtracted from measured test $\delta^{13}\text{C}$. These adjustment factors are incorporated in ‘adjusted $\delta^{13}\text{C}$ Option-1’ (Table DR1, Figure DR2). *Praemurica taurica* and *Subbotina* sp. show no marked size related disequilibrium effects and therefore are not adjusted.

When applied to the down-hole $\delta^{13}\text{C}$ record (Figure DR2) the adjustment factors of Option-1 moved some species to unrealistic positions relative to others and bulk values.

Significantly, *H. holmdelensis* $\delta^{13}\text{C}$ values increased above those of co-occurring asymbiotic surface mixed dweller *Gl. falsostuarti*. The ‘weak photosymbiosis-adjusted’ *Praemurica* and *M. praeangulata* $\delta^{13}\text{C}$ values plot just above the thermocline species and in line with the bulk carbonate $\delta^{13}\text{C}$ values, which makes sense for a species living in the photic zone. However, application of the Option-1 ‘full photosymbiosis’ adjustment to *M. angulata* and *R. fruticosa* forces these taxa to $\delta^{13}\text{C}$ values lower than the thermocline (i.e. base of the mixed layer/photic zone) species *Subbotina* spp. Consequently we came up with a second combination of adjustment factors (‘adjusted $\delta^{13}\text{C}$ Option-2’; Table DR1, Figure DR2; Figure 2 Panel E) that better meet the expected water column targets as predicted by paired $\delta^{18}\text{O}$ (depth) ecology and other reference species. Our preferred solution (Table DR1; Figure 2 Panel E) ‘Option 2’: added 0.4‰ to $\delta^{13}\text{C}$ of *G. cretacea* to account for the metabolic vital effect, but left *H. holmdelensis* as it was; *Pr. inconstans* and *M. praeangulata* $\delta^{13}\text{C}$ were left with subtracting 0.3‰, in which evidence for ‘weak’ photosymbiotic fractionation was detected. 0.3‰ was subtracted from early smaller (<250µm) *M. angulata* $\delta^{13}\text{C}$ and 0.6‰ to larger (>250µm) specimens found after 61.98Ma, as this species becomes increasingly enriched in ^{13}C . The values used in this more refined option 2 were achieved by looking at the species specific $\delta^{13}\text{C}$ gradient change with size from Birch *et al.*, (2012). *R. fruticosa*, with test sizes >300 µm, had the larger value of 0.6‰ subtracted. This exercise emphasizes the need for repeatedly evaluating planktonic foraminiferal paleoecologies and the magnitude of likely disequilibrium fractionation effects because they vary depending on the evolutionary phase as well as between location and environments.

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Table DR1

Species	Test Size	Type of disequilibrium	$\delta^{13}\text{C}$ Offset Range	Option 1 $\delta^{13}\text{C}$ Adjustment	Option 2 $\delta^{13}\text{C}$ Adjustment
G. cretacea	<150 μm	Metabolic	- 0.3 - 0.5 ‰	+ 0.4 ‰	+ 0.4 ‰
H. holdelensis	<150 μm	Metabolic	- 0.3 - 0.5 ‰	+ 0.4 ‰	not adjusted
M. praeangulata	>150 μm	Weak symbiosis	+ 0.1 - 0.3 ‰	- 0.3 ‰	- 0.3 ‰
Pr. inconstans	>150 μm	Weak symbiosis	+ 0.1 - 0.3 ‰	- 0.3 ‰	- 0.3 ‰
M. angulata	<250 μm	Weak symbiosis	+ 0.1 - 0.3 ‰	Weak & full not separated	- 0.3 ‰
M. angulata	>250 μm	Full symbiosis	+ 0.5 - 1.5 ‰	- 1.0 ‰	- 0.6 ‰
R. fructifera	>150 μm	Full symbiosis	+ 0.5 - 1.5 ‰	- 1.0 ‰	- 0.6 ‰

Table DR1- Calculated $\delta^{13}\text{C}$ adjustment factors (option 1 & 2) applied to species with known isotopic disequilibrium effects, taken from Birch et al., (2012).

Table DR2 - Benthic and planktonic foraminifera stable isotopes ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) results from ODP Site 1262 against astronomically tuned ages (Dinarès-Turrell et al., 2014) and meters composite depth (MCD).

Figure caption

Figure DR1 - Location of ODP Site 1262 at Walvis Ridge, South East Atlantic.

Figure DR2 - Benthic and planktonic foraminifera stable isotopes ($\delta^{13}\text{C}$), **A** - before adjustment, **B** - with adjustment option 1 and **C** - with adjustment option 2 (Table DR1), against age (Ma) based on the time scale of Dinarès-Turrell *et al.*, (2014) from site 1262. Genera abbreviations as follows M= *Morozovella*, Pr = *Praemurica*, S = *Subbotina*, N = *Nuttallides*, R = *Racemiguembelina*, Gl = *Globotruncana*, G = *Guembelitra*, and H = *Hedbergella*.

Supplementary information

Figure DR1 - Location of ODP Site 1262 at Walvis Ridge, South East Atlantic

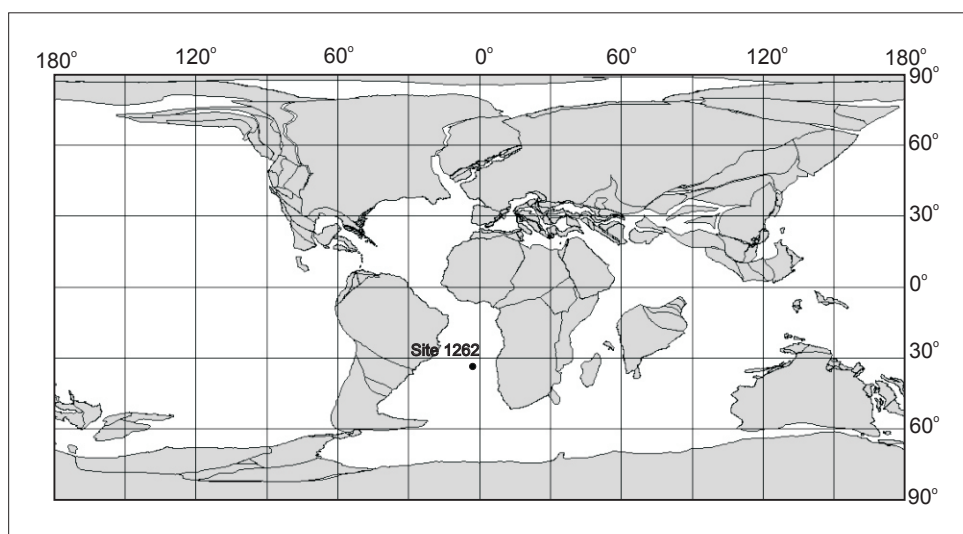


Figure DR2 - Benthic and planktonic foraminifera stable isotopes ($\Delta^{13}\text{C}$) A - before adjustment, B - with adjustment option 1 and C - with adjustment option 2 (Table DR1), against age (Ma) based on the time scale of Dinarès-Turell et al., (2014) from site 1262. Genera abbreviations as follows M= Morozovella, Pr = Praemurica, S = Subbotina, N = Nuttallides, R = Racemiguembelina, Gl = Globotruncana, G = Guembelitra, and H = Hedbergella.

