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Climate of the Past Discussions

Interactive comment on "Productivity response of calcareous nannoplankton in the South Atlantic to the Eocene Thermal Maximum 2 (ETM2)" *by* M. Dedert et al.

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We thank reviewer 2 for the comments to this manuscript.

We address each comment separately below.

REFEREE: The purpose of the paper is stated as follows: "In this study we use Sr/Ca ratios in nannofossil calcite to reconstruct changes in primary productivity of calcareous nannoplankton in the South Atlantic during ETM2. This geochemical proxy has been shown in culture and field studies to be a good measure for the productivity of coccolithophores (Rickaby et al., 2002; Stoll et al., 2002a, b, 2007a). It is also shown that nutrient availability is the main controlling factor. In addition, Sr/Ca is an ideal

proxy to reconstruct productivity changes during ETM2, because of the fact that long residence time of both, Sr and Ca in seawater exceeds the duration of transient climatic events such as hyperthermals. Studies applying this new method have demonstrated increased primary production during upwelling events or in coastal (proximity) settings in both extant and fossil calcareous nannoplankton (Stoll et al., 2007a, b; Auliaherliaty et al., 2009)."

In this manuscript, Sr/Ca variability is viewed upon solely via a 'productivity' filter, and other information is pushed aside by sometimes light weight arguments so as not to disturb the faith in productivity as the key factor influencing Sr/Ca ratios in coccolith carbonate. Neglect of the complications involved in interpreting Sr/Ca ratios in coccolith carbonate implies that a thoroughly revised manuscript must be presented prior to publication.

In the early phase of analyzing Sr/Ca ratios in coccolith carbonate, productivity was not on the table (Stoll and Schrag 2000). Rickaby et al. 2002 (see above) don't mention productivity at all but concludes that "our empirically derived relationship between DSr and carbon-specific growth rate shows potential for a combined geochemical proxy approach, using Sr/Ca and !p, for reconstructing paleo-pCO2". Stoll et al. 2002b (ref. in present ms) arrived to the same conclusion: "Despite the dual influence of temperature and growth rate on coccolith Sr/Ca, coccolith Sr/Ca correlates with Òb,Ó the slope of the dependence of carbon isotope fractionation in biomarkers (!p) on CO2(aq) at a range of growth rates and temperatures. Consequently, using coccolith Sr/Ca in combination with alkenone !p may improve paleo-CO2 determinations." They also say: "The strong influence of calcification rate on Sr partitioning may be useful for inferring past variations in coccolithophorid productivity from Sr partitioning in coccolith sediments if the influence of temperature on Sr partitioning can be resolved." [my italics] And state that: "We obtain a 1% increase in Sr/Ca for a 1ÂąC increase in calcification temperature."

ANSWER: The first study of Sr/Ca in bulk carbonate of Cretaceous age (Stoll and

Schrag, 1996) were over long time-spans approaching 10 Ma and sought to reconstruct changes in the ratio of Sr/Ca in seawater since at that time the large variability in Sr partitioning in coccolithophores was not recognized. In this paper we document clearly that on timescales of 200ka, changes in seawater Sr/Ca are minimal (now citing the modeling studies of Stoll et al., 1998).

REFEREE: Stoll et al. 2002a (ref. in present ms) concludes: "Consequently, temperature changes could contribute significantly to variations in coccolith Sr/Ca in marine samples. It may be possible to separate these influences on coccolith Sr/Ca by separately analyzing Sr/Ca in species that produce calcite rapidly and those that produce calcite slowly, if both undergo comparable relative changes in calcification rates." [my italics].

ANSWER: The temperature effect has been well-documented in culture studies, and as we now mention, is of the order of 1-2% change in Sr/Ca per degree C warming. Over the ETM2, for which temperature changes are estimated to be of order 2-4 ËŽC, based on temperature reconstructions using benthic and planktic foraminifera (Stap et al., 2010) , this effect amounts to max. 4-8 % variation in Sr/Ca ratios. We now describe this explicitly in section 4.1.1. As several of these publications observe, productivity and Sr/Ca are highest in locations and seasons of maximum upwelling intensity, even though these locations/seasons are characterized by colder waters, indicating that the productivity effect is typically dominant over the temperature effect.

Coccolithophorid productivity and growth rate are highly correlated in the majority of oceanographic settings, as indicated in the very first paper describing the unique strong partitioning effects on coccolith Sr/Ca. Production of significant coccolithophorid biomass is possible when coccolithophorid cells divide rapidly. Sustained export (i.e. export production) of lots of coccolithophorid biomass is possible only if biomass is rapidly produced (ie grown rapidly) in the photic zone. Stoll and Schrag 2000 (Figure 7) show coccolith Sr/Ca compared to both the long- term average productivity as well as estimated growth rates of alkenone-producing coccolithophorids. Both facets of this re-

lationship have been contemplated in the array of publications, whether the application has been for correcting for growth rate effects in alkenone-d13C CO2 applications or inferring productivity changes in the past. Our understanding of the underlying mechanism responsible for the correlation between coccolith Sr/Ca and productivity or growth rate has evolved from early studies which envisioned a purely kinetic effect to subsequent ones which recognize that nutrient, but not light, limitation of growth stimulates the Sr/Ca variability.

REFEREE: Compare all the above discussion referring to the influence of temperature on Sr/Ca ratios in coccolith carbonate with the unreferenced statement in the purpose paragraph above: "It is also shown that nutrient availability is the main controlling factor." All the above inferences about Sr/Ca ratios in coccolith carbonate are made on modern floras, and applied, without comment, to early Eocene nannofossil assemblages.

ANSWER: In sediment traps and Quaternary sediments, coccolith Sr/Ca shows consistent primary relationships with known productivity forcing and with other productivity proxies such as excess Ba and accumulation rate of alkenones (See fig. 2 in revised ms). We also now clarify in the introduction that the influence of temperature on the Sr/Ca is modest (1-2% increase per degree C temperature increase), as stated above. We also now state that these primary relationships can be partly obscured by diagenetic processes in older sediments, so it is of high importance to use strict sample selection and analytical techniques that allow us to minimize and assess the role of diagenetic overprinting. We now clarify in the methods section that the placoliths employed for the Eocene study are the same genera (in the case of Coccolithus) or same lineage (in the case of Toweius) as the dominant species in the modern ocean and therefore it is reasonable to assume that the geochemical response in Eocene nannofossil assemblages would have been comparable to extant taxa.

REFEREE: "The amount of overgrowth on liths of Discoaster, Tribrachiatus and Zygrhablithus is strongly correlated to the carbonate content of the sediments, with the

degree of overgrowth decreasing within low carbonate content sediments of the Elmo horizon." This doesn't go along well with (see 3.3): "The contribution of abiogenic calcite .... in the Elmo horizon, whereas contribution of overgrowth to the discoaster fraction remains ∼50 %." Carbonate decreases to about 55-60 %. Would have expected that overgrowth increased on the above dissolution 'resistant' taxa when the amount of dissolved carbonate increased from dissolved, more dissolution prone taxa. Would be nice to get some more information about this.

ANSWER: An increase in overgrowth is observed on i.e. Discoaster within the CIE, and is not restricted to the Elmo horizon. In the Elmo horizon and increased contribution by abiogenic calcite results in a relatively high abiogenic carbonate contribution. Discoaster in the Elmo horizon can actually show signs of etching (though still very overgrown). Moreover, as shown by Stap et al. (2009), and repeated in this manuscript, a decrease to ∼55% in carbonate actually implies a dissolution of ∼94% of the carbonate. For Site 1263 (ETM2), where dissolution in the Elmo horizon was most pronounced (down to 42%), a very clear reduced overgrowth was observed on Discoaster and Tribrachiatus.

REFEREE:"Long-term trends in Sr/Ca measured in bulk fine (<20 "m) sediments reveal a cyclic forcing, possibly precessional, as was identified in #13C records (Stap et al., 2009), although Sr/Ca trends are less salient in proximity of the ETM2 interval (precession cycle numbers one, two and five; Fig. 4a)." Difficult to see cycles in the bulk record. Precession cycles in Stap's record gives three high values and three low values in the bulk Sr/Ca data.

ANSWER: We now clarify that there is background cyclic variation in bulk carbonate Sr/Ca ratios, which may be related to orbital forcing. Although with the constraints of the available age model, it is not possible to rigorously asses a relationship to orbital cycles, however, a precessional forcing in these parts of the ocean are widely documented, and Stap et al. identified precessional cycles in their bulk 13C record that match several of the Sr/Ca increases in bulk Sr/Ca. As we now discuss more extensively and clearly

in the text, a clear cyclic-background driven productivity is difficult to identify in bulk Sr/Ca records from the Walvis Ridge, given their poor preservation. Similar analyses done on better preserved assemblages may reveal a more clear correlation.

REFEREE: Other comments. Spell out 'CIE'.

ANSWER: Was done in line 63

REFEREE: No need to repeatedly state that an ion probe was used to analyze the Sr/Ca ratios. OK in Abstract and Methods, but not thereafter.

ANSWER: Because two techniques were used to measure Sr/Ca, in the results section it is necessary to distinguish which analyses are referred to. We are indicating what type of technique is used.

REFEREE: "We measured the Sr/Ca ratio by ion probe in four individual taxa, each with distinct environmental preferences." [see Methods]. First, it is not explained which these preferences are.

ANSWER: We have modified this sentence, in which is now explained the difference in ecological preferences of the selected taxa.

REFEREE: Second, compare this unreferenced statement with the introductory sentence under 4.2: "The Sr/Ca productivity trends presented in this study appear to contradict those inferred from changes in nannofossil assemblages for this site, in that meso-trophic and eutrophic placoliths decrease in abundance." This is followed by an argument that dismisses the nannofossil census data, blaming dissolution, so as to be able to go along the 'productivity' track; the 'productivity' bias/filter is clearly at work here, giving the impression that contradictory data sets are not going to disturb the preconceived ideas about how the Sr/Ca data should be interpreted.

ANSWER: Selective dissolution of species has been widely recognized as an influence on assemblages, both modern and ancient. Hyperthermals represent the intervals of most extreme dissolution in the early Eocene, therefore a dissolution overprint

on the assemblage is expected, and as at other sites, its consequence will be to remove fragile forms (e.g. placoliths) preferentially compared to more robust nannoliths like Discoaster, Sphenolithus, Fasciculithus. Ongoing diagenetic processes occurring over time and on relatively short temporal scales, such as overgrowth formation, can add further discrepancy to the fossil record, particularly for sites with poor assemblage preservation as at the Walvis Ridge. In our view, it is important to mention the result of these processes on assemblages at Site 1265, as the paleoecological signal indeed contradicts with the Sr/Ca record, but has a profound bias due to the processes mentioned above.

REFEREE: "The amount of overgrowth on liths of Discoaster, Tribrachiatus and Zygrhablithus is strongly correlated to the carbonate content of the sediments, with the degree of overgrowth decreasing within low carbonate content sediments of the Elmo horizon." This doesn't go along well with (see 3.3): "The contribution of abiogenic calcite .... in the Elmo horizon, whereas contribution of overgrowth to the discoaster fraction remains $\sim$50 %." Carbonate decreases to about 55-60 %. Would have expected that overgrowth increased on the above dissolution 'resistant' taxa when the amount of dissolved carbonate increased from dissolved, more dissolution prone taxa. Would be nice to get some more information about this.

ANSWER: As we now clarify in the text, overgrowth results from bottomwaters and shallow pore waters which are oversaturated with respect to CaCO3. Dissolution below the lysocline is a symptom of bottomwaters which are much less saturated (in some cases undersaturated) with respect to CaCO3 and therefore much less prone to form overgrowth on all nannofossils.

REFEREE: 4.1.1 - "genera" should be "genus"

ANSWER: Revised

REFEREE: The key message in this manuscript is that productivity increased during the ETM2,as based on a marked increase in the Sr/Ca ratio in coccolith carbonate.

This increase is clearly seen in the bulk sediment data (Fig. 4a). It is unclear why the authors go through the laborious process of separating and analyzing individual nannofossil genera. This certainly generates plenty of text, but does it really provide crucial information? Questionable.

ANSWER: As we have clarified in the text, the bulk carbonate record is subject to strong amplification of the Sr/Ca increase during the CIE due to decreased abundance of diagenetic processes such as overgrowth. Therefore for the CIE the bulk record is not a reliable indicator of the magnitude of change in Sr/Ca or productivity and its relationship with background variability.

REFEREE:It is difficult to agree with the conclusion (see Summary) that "...variations in Sr/Ca across the ETM2 interval and at certain intervals in the bulk fine Sr/Ca record imply a cyclic forcing on the productivity." In conclusion, this manuscript provides a very restricted, biased and unconvincing interpretation of the meaning of Sr/Ca variability in coccolith carbonate.

ANSWER: We disagree as the paper articulates the fundamental non-productivity influences and rigorously assesses the potential influence of variable diagenetic overgrowth on the measured Sr/Ca.

REFEREE:The paper is suitable for CP and provides new Sr/Ca data from ODP Site 1265. The conclusions are hardly substantial and hold some wishful thinking about cyclicity.

ANSWER: The inclusion of a longer term record to better characterize the background variability is a strength that provides a more balanced interpretation of the changes happening at the ETM2. This strategy is selected to avoid the pitfall of examining too narrow a time window at ETM2 and assigning too large a significance to changes during ETM2 when they might not represent a unique response.

REFEREE: The assertion/assumption that Sr/Ca data in coccolith carbonate can be

interpreted solely in terms of productivity is not convincing, considering other (cited) work.

ANSWER: As we have described above, the other influences (temperature) are minor in these records and are now articulated clearly in the paper. Previous work documents consistent relationships with productivity and growth rate of coccolithophorids – both of these parameters are coupled mechanistically in the majority of ocean settings as has been documented from the very first studies of variations in coccolith Sr/Ca. This work provides a new approach to evaluate the ecological response of calcareous nannoplankton to hyperthermals. In order to improve the accuracy we are taking into consideration the secondary effects on the proxy.

REFEREE: The interpretation of the Sr/Ca data stands in contrast to the nannofossil census data, which thus are dismissed by non-convincing arguments.

ANSWER: The intention of this paper is not to dismiss nannofossil census data but to increase awareness related to the proxy accuracy due to diagenetic processes such as carbonate abiogenic overgrowth and dissolution. This manuscript rigorously evaluates the role of variable dissolution and diagenesis on the geochemical indicators and discards some data as unreliable in this regard. These findings build on extensive analyses using various techniques (geochemical and detailed scanning electronic microscope analyses) to be presented in another article. These have, in addition to the paleoecological reconstruction correlating abundance patterns to carbonate preservation, clearly shown the impact of diagenetic processes affecting assemblage data, which are largely neglected in micropaleontological papers.F

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