Biogeosciences Discuss.,
doi:10.5194/bg-2016-247-AC3, 2016

Biogeosciences
Discussions

Interactive comment on "Stable carbon isotope deviations in benthic foraminifera as proxy for organic carbon fluxes in the Mediterranean Sea" *by* Marc Theodor et al.

Marc Theodor et al.

marc.theodor@uni-hamburg.de

Received and published: 30 September 2016

Response to interactive comment by anonymous referee #3

We acknowledge the constructive and critical comments by the reviewer, which proved useful to substantially improve our manuscript. Below we respond specifically to all comments raised by the reviewer.

General comment: In this manuscript, Theodor et al. explore the differences in the delta13C of epi- and infaunal benthic foraminifer calcite as a proxy for surface water productivity and organic carbon fluxes in the Mediterranean Sea. They analysed a large set of samples from 19 sediment cores situated in a defined water-depth interval spanning (relatively subtle) gradients of productivity and differences in depositional settings, including some where lateral transport of organic matter is likely. The spread of analyses includes differentiation of the delta13C of living and dead individuals, analysis of size-differentiated (ontogenetic) effects on the delta13C in individual species, preferred habitat depths of infaunal species, the depth of the redox boundary in the sediment (color change), and the differences in delta13C of calcite produced by the infaunal species Uvigerina mediterranea and by three epifaunal species. Together with satellite-derived annual PP estimates and fluxes of OM at the depths of the sampling sites calculated from empirical formulas, the extensive data set is the basis to explore the hypothesis that the Delta delta13C of epi- and infaunal calcite of living benthic foraminifers is a proxy for organic matter flux to the seafloor. The authors argue that this is indeed the case in a number of environmental settings of the present-day Mediterranean Sea, except in the Aegean sub-basins, where small-scale variability obscures the relationship. In the course of the manuscript it also becomes obvious that "non-living" tests complicate the issue considerably. This strikes me as being in itself an argument against using this novel proxy in older sediment sequences of environments where sediment reworking is a problem.

Response: Thank you very much for the evaluation and comments. It is true, that reworking of unstained tests poses a possible bias that needs to be considered when applying the Corg flux – $\Delta\delta$13C relationship to older sediment successions. Although the displacement of fossil tests can impede application of the established transfer function at certain sites (in our study at sites 396 and 537) it may be very useful for an accurate estimation of past organic matter fluxes at a variety of other sites. Likewise the accuracy of fossil data sets can be improved by measuring a larger number of tests and excluding possible outlier. We have followed this strategy in evaluating two Late Pleistocene and Holocene successions from the central and western Mediterranean Sea and received promising and reliable results (Theodor et al., in prep.).

General comment:

The results of the study are somewhat sobering, because a clear-cut relationship between the isotope gradient and productivity/OM burial was not evident to me. This may reflect the low range of productivity characteristic for the Mediterranean Sea, and an intense microbial loop that affects the fluxes out of the mixed layer. Its ranges of productivity and concomitant OM rain rates to the sea floor are at the lower end of the global ocean (Fig. 5 lower panels show that), and admixture of recalcitrant TOC near rivers and canyons is a known problem. Also, the small-scale hydrodynamic setting and multiple OM sources in the data-rich Aegean sub-basin may obscure a possibly robust and promising relationship. This is indicated in Figure 2, where delta13C of DIC in all Aegean sites is consistently higher than epifaunal delta13C. Furthermore, the authors had to piece together PP and OM flux estimates from a variety of methods that each have their own error margins, as acknowledged by the authors after comparing theoretical and observed (sediment trap) rain rates. In my assessment the manuscript should be published, because it is to my knowledge the first and systematic attempt to examine the epifaunal/infaunal delta13C gradient and to develop it as a proxy for organic carbon fluxes in an oligotrophic sea. And it describes results of a massive analytical effort and is in most parts very well balanced in terms of results versus expectations. But the manuscripts should be revised, mainly in terms of writing style. I will send my notes on the printout directly to the lead author.

Response: Thanks for acknowledging our efforts in the generation and evaluation of the data set. We fully agree (and this is one of the results of our study) that the Mediterranean Sea does not exhibit a simple relationship between surface water productivity/estimated vertical organic matter fluxes and the recorded $\Delta\delta$13C signals. On the other hand, the $\Delta\delta$13C signal appears to accurately reflect the trophic situation at the sea floor confirming available information from benthic ecosystem data. The main problem is a proper quantification and separation of vertical from lateral organic matter fluxes, especially for the more marginal basin areas (such as the Aegean Sea), where the lateral component can be substantial. We cannot solve this issue in the frame of our present study but clearly more efforts are needed to better quantify the various organic matter flux components. Such information may come from sediment trap studies, biogeochemical approaches and model experiments (see also specific comments below).

Specific comments:

Comment: Title: “Deviations” from what? I suggest that you use “gradients” Response: We changed the title.

Comment: The way chosen here to calculate OM rain rates for specific sites is somewhat convoluted (2 satellite derived PP estimates and the Betzer, 1984 estimate for OM flux at sample water depth, acknowledged to possibly be unsuitable in the Med). I would have used depth-specific rain-rate output of an NPZD model instead, which should be internally consistent and besides would resolve seasonal variations that may have some influence. If I am not mistaken, the authors may have access to such a model data set. (In the future, the authors might consider modeling expected delta13C gradients at given flux, sedimentation, and respiration rates to test their observed gradients against theory. This would also mark sites with significant lateral input of recalcitrant OM). Response: This is a very good suggestion. Indeed, we initially aimed at a comparison of the $\Delta\delta$13C values with organic matter fluxes derived from the baseline run of an ocean-biogeochemical model study (Grimm, 2012). Unfortunately, the modeled circulation and ocean climate of the western Mediterranean Sea exhibits considerable deviations from the observed conditions, specifically concerning summer temperatures and deep-water formation (Mikolajewicz, 2011, Adloff, 2011). These deviations also result in relatively large uncertainties concerning the estimated Corg fluxes. Additional model uncertainties occur in marginal areas and shelf edges because of high spatial variability of lateral Corg fluxes. Based on these uncertainties we have chosen to apply satellite-derived productivity values and calculated vertical organic carbon fluxes instead. This strategy allowed for a consistent estimation of Corg fluxes at all sites, although we are fully aware that we have likely underestimated the total Corg fluxes in the marginal basins such as the Aegean Sea. To date, comparison with the few available direct measurements from sediment trap studies demonstrated that our approach provided reasonable numbers. Future integrated studies should aim at sampling of surface sediments for stable isotope and biogeochemical studies in conjunction with direct Corg flux measurements through sediment trap studies and further validation by results from ocean-biogeochemical model experiments.

Comment: Did the authors test whether there is a relationship between %TOC in the sediment and calculated fluxes of OM? Figure 4 C looks as if there might be a relationship between the delta13C gradient and %TOC. Response: Yes, we have tested these relationships, but with ambiguous results. In both cases the coefficient of determination of linear regressions was below 0.25 (R2=0.224 for TOC vs. Corg flux; R2=0.243 for TOC vs. $\Delta\delta$13CUmed-Epi). The exclusion of the North and Central Aegean Sites, however, improved R2 towards values of 0.493 (TOC vs. Corg) and 0.608 (TOC vs. $\Delta\delta$13CUmed-Epi). Therefore, the results of the Central to North Aegean Sea remain problematic, suggesting a decoupling of TOC content from vertical Corg fluxes and observed $\Delta\delta$13CUmed-Epi signatures.

Comment: 354 ff: I was puzzled by the 15 cm up to 30 cm of oxygen penetration in 5 cores from the Aegean Sea. To me that suggests that sedimentation rates at these sites must be very low, which I would not have expected. What would very low sedimentation rates do to explain the anomalous delta13C gradients found at these sites? What is the expected relationship of the redox boundary depth in comparison to the Median Living Depth of U. med., which is relatively shallow at these sites? Response: The inferred oxygen penetration is based on the observed color change from yellowish brown to greenish gray which commonly indicates a change in redox potential from positive to negative values (Lyle, 1983). We are aware that this color change may not be identical to the penetration depth of oxygen but likely reflects the oxygen consumption in the surface sediment, which also reflects the Corg fluxes. Based on stratigraphic information from various sediment cores of the Aegean Sea, Late Holocene sedimentation rates commonly range between 7 and 15 cm/kyr (e.g., Geraga et al., 2000, 2010;

Kuhnt et al., 2007, Abu-Zied et al., 2008; Ehrmann et al., 2013) or are even higher in some of the North Aegean basins (Kotthoff et al., 2008). The δ13CDIC gradient in the sediment is basically controlled by the Corg flux rate as long as sufficient oxygen is present in the bottom water allowing for microbial decomposition of organic matter. In food-limited environments such as most parts of the modern Mediterranean Sea the average living depth of U. mediterranea is primarily controlled by the availability of a sufficient amount of organic matter. The high penetration depth of oxygen allows for vertical extension of the microhabitat range in some areas, e.g. in the South Aegean Sea. The expected and observed $\Delta\delta$13CUmed-Epi signal is still relatively low in this area because Corg fluxes and associated decomposition rates are low causing a shallow δ13CDIC gradient. In eutrophic environments, such as the Northern Aegean Sea and the Alboran Sea the MLD of U. mediterranea is relatively shallow because of limited oxygen in the deeper sediment layers and stronger competition with intermediate and deep infaunal taxa. The expected and observed $\Delta\delta$13CUmed-Epi signal is relatively high because of high Corg fluxes and associated decomposition rates causing a steep δ13CDIC gradient.

Comment: 366ff: When deep water is replaced the delta13C of DIC should become lower due to the Suess Effect imported from surface water? If it is lowered, how would that steepen the gradient? Response: Here, we primarily refer to a possible imprint of local deep-water formation in the North Aegean Sea and specified the text accordingly. Bottom waters of the Aegean basins are largely isolated from the large-scale Mediterranean thermohaline circulation but are temporarily exchanged by local formation of subsurface waters. The aging of bottom waters likely results in lowering of δ13CDIC values, which increase again in the course of ventilation events. Additional influence of the Suess effect appears likely and has been documented in surface waters from the eastern Mediterranean Sea (Sisma-Ventura et al., 2014). A rapid propagation of this anthropogenic signal into deeper layers can be expected since intermediate and deep-water masses are characterized by high turnover-rates and low residence times. Observations from the western Mediterranean Sea suggest that the Suess effect is already detectable at bathyal water depth (Theodor et al., 2016).

Comment: 408 ff: Elsewhere you state that lateral OM input (because it is recalcitrant) has little effect on the delta13C gradient. Response: It is difficult to quantify the contribution of refractory organic matter to the observed δ13CDIC gradient. On a first approximation the pore water δ13CDIC gradient is controlled by the total Corg flux and associated decomposition rates (McCorkle et al., 1985). It appears likely that also laterally advected organic matter contributes to the observed δ13CDIC signals. We have modified the text in order to avoid contradictory statements.

Comment: DIC delta13C of bottom waters shown in Figure 2 appear to have been estimated from the values of delta13C analysed here on epifaunal species. Why is there a shift in the Aegean samples, and how do the estimates compare to the values of Pierre (1999)? Have there been more recent analyses of delta13C of DIC to pinpoint the Suess effect on deep-water DIC? Response: Since no direct measurements of bottom water δ13CDIC were available for our sites, we had to rely on measurements of epifaunal taxa as proxy for bottom water δ13CDIC. For better comparison, we have now added the δ13CΣCO2 end members of the different depths and regions of the Mediterranean Sea (as published by Pierre, 1999) in figure 2. The observed differences of some sites in the Aegean Sea might be the result of the intermittent replenishment of bottom waters in the smaller basins although a contribution of the Suess effect cannot be excluded (see also comment on line 366 ff.). In the revised version of the manuscript we have addressed the possible reasons for these differences in some detail.

Comment: 372: I wouldn't call it a close relationship Response: 'close' was removed

Comment: Figure 3: Re-arrange "stained tests" etc as figure title – they are not axis labels Response: done

Comment: Figure 5 and 6: symbols don't match legend for Gulf of Lyons samples? Response: corrected

Cited references:

Adloff, F., 2011. Early Holocene Eastern Mediterranean ocean climate and the stability of its overturning circulation. Reports on Earth System Science, 107, 1-146.

Abu-Zied, R.H., Rohling, E.J., Jorissen, F.J., Fontanier, C., Casford, J.S.L., Cooke, S. 2008. Benthic foraminiferal response to changes in bottom water oxygenation and organic carbon flux in the eastern Mediterranean during LGM to Recent times. Marine Micropaleontology, 67,46-68.

Betzer, P.R., Showers, W.J., Laws, E.A., Winn, C.D., DiTullio, G.R., and Kroopnick, P.M., 1984. Primary productivity and particle fluxes on a transect of the equator at 153°W in the Pacific Ocean, Deep-Sea Res., 31, 1-11.

Ehrmann, W., Seidel, M. and Schmiedl, G., 2013. Dynamics of Late Quaternary North African humid periods documented in the clay mineral record of central Aegean Sea sediments. Global and Planetary Change, 107, 186-195.

Geraga, M., Tsaila-Monopolis, S., Ioakim, C., Papatheodorou, G. and Ferentinos, G., 2000. Evaluation of palaeoenvironmental changes during the last 18,000 years in the Myrtoon basin, SW Aegean Sea. Palaeogeography, Palaeoclimatology, Palaeoecology, 156, 1-17.

Geraga, M., Ioakim, C., Lykousis, V., Tsaila-Monopolis, S. and Mylona, G., 2010. The high-resolution palaeoclimatic and palaeoceanographic history of the last 24,000 years in the central Aegean Sea, Greece. Palaeogeography, Palaeoclimatology, Palaeoecology, 287, 101-115.

Grimm, R., 2012. Simulating the early Holocene eastern Mediterranean sapropel formation using an ocean biogeochemical model. Reports on Earth System Science, 123: 1-156.

Kotthoff, U., Müller, U.C., Pross, J., Schmiedl, G., van de Schootbrugge, B., Lawson, I.T., Schulz, H., 2008. Lateglacial and Holocene vegetation dynamics in the Aegean region: an integrated view based on pollen data from marine and terrestrial archives. The Holocene, 18, 1019-1032.

Kuhnt, T., Schmiedl, G., Ehrmann, W., Hamann, Y. and Hemleben, C., 2007. Deep-sea ecosystem variability of the Aegean Sea during the past 22 kyr as revealed by benthic foraminifera. Marine Micropaleontology, 64, 141-162.

Lyle, M., 1983. The brown–green color transition in marine sediments: a marker of the Fe(III)–Fe(II) redox boundary. Limnol. Oceanogr., 28, 1026–1033.

McCorkle, D.C., Emerson, S.R., Quay, P.D., 1985. Stable carbon isotopes in marine porewaters. Earth Planet. Sci. Lett., 74, 13–26.

Mikolajewicz, U., 2011. Modeling Mediterranean Ocean climate for the Last Glacial Maximum. Climate of the Past, 7, 161-180.

Pierre, C., 1999. The oxygen and carbon isotope distribution in the Mediterranean water masses. Mar. Geol. 153, 41–55.

Sisma-Ventura, G., Yam, R., Shemesh, A., 2014. Recent unprecedented warming and oligotrophy of the eastern Mediterranean Sea within the last millennium. Geophys. Res. Lett. 41, doi:10.1002/2014GL060393.

Theodor, M., Schmiedl, G. and Mackensen, A., 2016. Stable isotope composition of deep-sea benthic foraminifera under contrasting trophic conditions in the western Mediterranean Sea. Marine Micropaleontology, 124: 16-28.

Interactive comment on Biogeosciences Discuss., doi:10.5194/bg-2016-247, 2016.