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Authors response
Submission of revised manuscript

point-by-point response to reviewers

Dear Editor,

Here, we submit the revised version of our manuscript entitled “Stable carbon isotope deviations in benthic foraminifera as proxy for organic carbon fluxes in the Mediterranean Sea” by Marc Theodor, Gerhard Schmiedl, Frans Jorissen, and Andreas Mackensen to Biogeosciences for consideration of publication. The manuscript has been prepared in accordance with the Instruction for Authors and none of the authors have any conflicts of interest (duplicate publication, financial, etc.).

Referee #1

General comment:

The paper in review aims to develop a transfer function for determining organic carbon flux to the Mediterranean Sea based on the d13C composition of a pair of epibenthic and endobenthic foraminifera species. For that, the authors studied a large number of sites in the western and eastern Mediterranean (Aegean Sea) from intermediate water depths covering a wide trophic range (from eutrophic to oligotropchic). The study was based on the analysis of living as well as dead specimens (separately). For calibration and understanding the isotopic and environmental setting, the authors used different sizes of the analyzed foraminifera, median living depth of the endobenthic species, re- dox boundary depth of the analyzed sediment, TOC of top sediment layer and primary production flux estimates in order to establish the proxy.

The authors discuss their results in a very methodological and systematic way. Dis- cussing first what contributes to the wide d13C range of the epibenthic species in the different locations

(mainly Aegean vs western Mediterranean and within each part of the Sea) and for the species used (mainly two), being aware of the different water masses, the habitat that they occupy and their isotopic signal. Next they discuss the endobenthic species Uvigerina mediterranea and what controls its d13C values in the different parts of the sea. And finally they discuss the basis for establishing a transfer function for organic carbon flux based on d13C difference between the isotopic com- position of the above mentioned epi- & endobenthic foraminifera species.

The knowledge about the factors that control the isotopic composition of d13C of the analyzed species exist for more than two decades. In this study the authors went a step further and tried to develop a transfer function for organic carbon, based on the "rules of the game" something that was not done so far and something that the paleoceanographic community is looking for eagerly. However, this seems to be a complicate task and it works only for certain places in the Mediterranean while in others the picture is still unclear. Still the enormous work that was invested in this study is worthwhile because it shows the potential that exist in this direction. It also shows that some parts of the puzzle are still missing but the authors are on the right way.

Right now the final result, the transfer function that was developed is applicable only for certain conditions in the Mediterranean Sea. This was clearly stated by the authors and should be clear also to potential users in the future. The paper should be considered as an important step in the attempt to progress in producing a transfer function however more work and understanding is still needed.

Finally the paper is warmly recommended to be published in Biogeosciences Discussion as it is. I had very minor suggestions, see below.

Response: Thank you for the generally very positive vote, especially for appreciation of our attempt for establishing a transfer function of organic carbon fluxes in the Mediterranean Sea.

Specific comments:

Comment: *Please indicate how many specimens were used for the stable isotope analysis*

Response: In total 417 tests were measured. The differentiation between epi- and infauna as well as stained and unstained tests was added in the "material and methods" chapter. In addition, the range of measured specimens was added for each species.

Comment: *Line188 – should be site 602*

Response: corrected

Comment: *Line 216 fig. 4 – the redox boundary depth appears in 4b and not in 4a while the MLD (line 217) appears in 4a – just replace*

Response: corrected

Comment: *Line 218 – in these figs there is no difference between stained and unstained thus it is not clear to what do the authors refer in their statement in line 218/9*

Response: we agree, the statement was removed

Comment: *line 221 – this statement is true only for a few cases – in many cases this relation do not exist (see sites 592, 595 596 an 599)*

Response: we agree, the text was specified accordingly and the existing mismatches have been explained.

Comment: *line 252 – were the suspicious relocated specimens removed from the database?*

Response: Yes, relocated specimens were removed; they were also marked in Fig. 2. For the estimation of the $\delta^{13}C_{Epi}$ see response to comment on line 272

Comment: *line 265 – the 2nd on is extra: on surface on*

Response: corrected

Comment: *line 272 – I can understand the logic of choosing the highest d13Cepi value in table 1 but what about values that were used and their origin is not mentioned at all at that table - for example for sites 601, 394, 395, Canyon and Slope? – please add explanation what is the basis for choosing these values*

Response: This is an important issue. We have chosen the $\delta^{13}C$ values of *P. ariminensis* as the best bottom water reference. If no specimens of *P. ariminensis* were available, we had to substitute the bottom water signal by the other measured epifaunal species or interpolate the value from nearby sites. We have specified the description for the estimation of $\delta^{13}C_{Epi}$ in the revised manuscript and discussed the possible uncertainties for the sites where no data of *P. ariminensis* were available.

Comment: *line 889 – difficult to see in fig. 2 different symbol sizes for different test sizes.*

Response: We removed the sentence because it referred to a previous version of figure 2.

Comment: *line 890 - In the same fig. it is difficult to understand how the authors determined which value to use for d13CDIC – they should be more specific in their explanation.*

Response: The explanation was extended. In order to account for the different ways of $\delta^{13}C_{DIC}$ estimation, we also referred to the discussion chapter 4.1 (see also comment and response to line 272)

Comment: *An example of how the picture is still partial is looking at the database of the dead foraminifera. The transfer function was developed on the database of the living (stained) foraminifera. At the same time also the dead (unstained) foraminifera were studied. Unfortunately, the dead assemblage failed in showing the same trend as the living ones (as shown clearly in fig. 5) – something that need to be addressed by the authors.*

Response: Although the values of dead specimens do not seem to fit the transfer function, this mismatch can be explained by the presence of relocated tests. Especially sites 537 and 396 revealed much lighter $\delta^{13}C_{Umed}$ values for unstained tests compared to heavier values for stained tests. Including these values strongly alters the correlation and also illustrates a potential bias in the application of the transfer function on fossil data. We have extended the discussion of this problem in chapter 4.3.

Comment: *Another thing that should be taken into account is that the authors based the use of several proxies such as primary productivity flux, TOC etc on external sources, something that should be taken into consideration. Moreover – the authors should comment on that describing how much this should affect their final results.*

Response: Although the TOC values were partly used from published data (Möbius et al., 2010), the measurements were carried out on samples from the identical locations, thus minimizing incompatibilities. External data were used for primary production based on satellite data, which allowed generation of a homogenous data set for all sites. In chapter 4.3, we have addressed the reasons, sources and possible errors of external data in order to accommodate this issue appropriately.

Comment: *And another problem is using the complicate region of the Aegean – for understanding general processes in the Mediterranean. It might be that this region should be kept for more advanced studies and not for those that want to establish the rules of the game.*

Response: The Aegean Sea was initially chosen as an ideal test bed because it is characterized by strong trophic N-S-gradients, i.e. with oligotrophic conditions in the South and meso- to eutrophic conditions in the North. In the course of our study it turned out that the regional benthic foraminiferal $\delta^{13}C$ values include the signal of significant lateral organic matter fluxes resulting in a decoupling of the $\delta^{13}C$ signal from the vertical organic matter fluxes. Nevertheless, we have decided to include these data in our study because they clearly highlight the potential uncertainties and pitfalls of our transfer function, which could also occur in other environmental settings such as continental margins or offshore river mouths etc. We consider the proper illustration of this bias crucial for further development and application of our approach.

Referee #2

General comment:

Theodor et al. are utilizing stable carbon isotope gradients between epifaunal and shallow infaunal foraminifera as a proxy for organic matter flux rates to the sediments in the Mediterranean Sea. Their work is novel; being able to predict/measure organic carbon fluxes to sediment in the past is a big unknown in Paleoceanography. The work clearly outlines caveats and limitations, and I recommend publication after some minor corrections. Specifically the abstract should reflect the main text better (e.g. in the discussion the authors make it clear that Cibicidoides pachyderma likely occupies a very shallow infaunal habitat and that it's d13C has a pore-water influence, which is also reiterated in the conclusions). Please also check your figures and captions and provide details of how certain values (d13C DIC bottom water, Fig. 2) were calcualted/estimated.

Response: Thank you very much for this positive assessment and the specific comments. We followed the suggestions and changed the abstract, text and figure captions accordingly.

Specific comments:

Comment: *Abstract: Lines 29-30 'Because...evalution.' place before line 27-29 'The...sites.'.*

Response: done

Comment: *Lines 38-39 change 'considering' to taking into account?*

Response: done

Comment: *Introduction: Correction for ontogenetic effects (line 123-124)? Restricting to measurements from the size fraction >600 um is not really a correction procedure.*

Response: This is true; we have changed the wording of this sentence.

Comment: *Material and methods: Line 159 'with a micrometer of an accuracy of 10 um?' not sure what this is meant to say.*

Response: We have changed the wording of this sentence to be more precise.

Comment: *Discussion: Lines 242-245. Strange way of putting it as a fact and then dismissing this claim later?*

Response: We agree. We have changed the first sentence to express the preferred assumption of the isotopic composition of epifaunal species and their actual much greater variability.

Comment: *Lines 245 - 247. Why are these data not plotted in the Figures?*

Response: Also referring to the previous comment on Fig. 2, the isotopic compositions of Mediterranean water masses were added to the figure.

Comment: *Line 262 change 'on' to 'at'.*

Response: done

Comment: *Lines 404-405: Lateral input of organic matter through submarine canyons. could such process also bring in juvenile benthic foraminifera from different water depth/environment and be a suitable explanation for lines 354 and onwards?*

Response: Although relocation of living foraminifera has been reported from different environments (e.g. from prodelta systems) it appears highly improbable that this effect is the reason for lower $\delta^{13}C_{Umed}$ values in smaller tests since this signal is consistently observed at all studied sites. However, relocation of dead specimens may be problematic for the application of the transfer function to fossil data sets. We have discussed this problem in some detail in chapter 4.3. It appears important to note that in our study this problem occurred at sites with reduced lateral organic matter transport (including the Strait of Sicily and the Mallorca Channel), while the sites with a strong lateral component seemed to be less affected by reworked and displaced tests.

Comment: *Conclusion: Line 456 allochtonous tests? This should be discussed much more thoroughly in the discussion and not appear as a slight statement at the end in the conclusions (e.g. see comment above for lines 404-405 etc).*

Response: We agree and extended the discussion on this issue. See also response to the previous comment.

Comment: *Figures Figure 2: Is estimated d13Cepi the same as approx. DIC bottom water? If so please use the same terminology to avoid confusion.*

Response: Yes it is; we have modified the figure using consistent terminology.

Comment: *Provide details of how the estimated d13Cepi/ approx. DIC bottom water values are calculated?*

Response: The explanation was extended. We have chosen the $\delta^{13}C$ values of *P. ariminensis* as the best bottom water reference. If no specimens of *P. ariminensis* were available, we had to substitute the bottom water signal by the other measured epifaunal species or interpolate the value from nearby sites. We have specified the description for the estimation of $\delta^{13}C_{Epi}$ in the revised manuscript and discussed the possible uncertainties for the sites where no tests of *P. ariminensis* could be measured.

Comment: *It is not possible to decipher different symbol sizes from a (they all look the same size), so please remove Line 889 about symbol sizes indicating different test sizes.*

Response: done

Comment: *Put Mediterranean water mass endmember d13C DIC values in 2b.*

Response: The measured data of Pierre (1999) for the depth distributions of $\delta^{13}C_{\Sigma CO2}$ from different regions of the Mediterranean Sea were added to this figure for a better comparison.

Comment: *Figure 3: I presume this Figure shows the d13C difference between the d13Cepi/approx. DIC bottom water and U. mediterranea, and does not include C. pachyderma d13C? Please make this clear in the Figure caption.*

Figure 4: Same as 3.

Response: Both figures have been modified including a more detailed description.

Comment: *Why do only some stations have uncertainties plotted for their Median Living Depth? Do you know uncertainties relating to the other parameters (redox boundary depth, export)?*

Response: Unfortunately, uncertainties for other parameters cannot be provided due to single measurements. MLD uncertainties refer to seasonal contrasts of the living depth of foraminifera in the Gulf of Lions sites (Canyon and Slope), which were sampled in spring and late summer (Schmiedl et al., 2000). This was additionally mentioned in the figure caption.

Referee #3

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 C_{org} flux – $\Delta\delta^{13}C$ 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 $\Delta\delta^{13}C$ signals. On the other hand, the $\Delta\delta^{13}C$ 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 $\Delta\delta^{13}C$ 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. C_{org} flux; R2=0.243 for TOC vs. $\Delta\delta^{13}C_{\textit{Umed}\text{-Epi}}$). The exclusion of the North and Central Aegean Sites, however, improved R2 towards values of 0.493 (TOC vs. C_{org}) and 0.608 (TOC vs. $\Delta\delta^{13}C_{\textit{Umed}\text{-Epi}}$). Therefore, the results of the Central to North Aegean Sea remain problematic, suggesting a decoupling of TOC content from vertical Corg fluxes and observed $\Delta\delta^{13}C_{\textit{Umed}\text{-Epi}}$ 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 ex-*

plain 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 $\delta^{13}C_{DIC}$ 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 $\Delta\delta^{13}C_{Umed\text{-}Epi}$ signal is still relatively low in this area because Corg fluxes and associated decomposition rates are low causing a shallow $\delta^{13}C_{DIC}$ 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 $\Delta\delta^{13}C_{Umed\text{-}Epi}$ signal is relatively high because of high Corg fluxes and associated decomposition rates causing a steep $\delta^{13}C_{DIC}$ 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 $\delta^{13}C_{DIC}$ 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 $\delta^{13}C_{DIC}$ gradient. On a first approximation the pore water $\delta^{13}C_{DIC}$ 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 $\delta^{13}C_{DIC}$ 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 $\delta^{13}C_{DIC}$ were available for our sites, we had to rely on measurements of epifaunal taxa as proxy for bottom water $\delta^{13}C_{DIC}$. For better comparison, we have now added the $\delta^{13}C_{\Sigma CO2}$ 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

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List of all relevant changes in the manuscript

1. Improvements in grammar and writing as mentioned by the referees
2. Improvement of the abstract
3. Description of the number of measured specimens in greater detail (l. 162-165)
4. Extensive discussion of problems due to reworking and dissolution (l. 256-261)
5. Explanation how and which epifaunal specimens were used to estimate the bottom water $\delta^{13}C_{DIC}$ (l. 264-272, l. 284-290)
6. A comparison of epifaunal values with surrounding water masses and possible reasons for differences (l. 292-305, fig. 2)
7. Description of possible reasons for unexpected results in environmental parameters of the Aegean Sea (l. 385-389)
8. A comprehensive discussion on uncertainties in the application of fossil tests (l. 470-480)
9. Improvements of the figure captions (figs. 2, 3, 4) and figures itself (figs. 2,3,4,5,6)

Stable carbon isotope gradients in benthic foraminifera as proxy for organic carbon fluxes in the Mediterranean Sea

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Abstract

We have determined stable carbon isotope ratios of epifaunal and shallow infaunal benthic foraminifera in the Mediterranean Sea to relate the inferred gradient of pore water $\delta^{13}C_{DIC}$ to varying trophic conditions. This is a prerequisite for developing this difference into a potential transfer function for organic matter flux rates. The data set is based on samples retrieved from a well-defined bathymetric range (400–1500m water depth) of sub-basins in the western, central and eastern Mediterranean Sea. Regional contrasts in organic matter fluxes and associated $\delta^{13}C_{DIC}$ of pore water are recorded by the $\delta^{13}C$ difference ($\Delta\delta^{13}C_{Umed\text{-}Epi}$) between the shallow infaunal *Uvigerina mediterranea* and epifaunal species (*Planulina ariminensis*, *Cibicidoides pachydermus, Cibicides lobatulus)*. Within epifaunal taxa, highest $\delta^{13}C$ values are recorded for *P. ariminensis,* providing the best indicator for bottom water $\delta^{13}C_{DIC}$. In contrast, *C. pachydermus* reveals minor pore water effects at the more eutrophic sites. Because of ontogenetic trends in the $\delta^{13}C$ signal of *U. mediterranea* of up to 1.04‰, only tests larger than 600µm were used for the development of the transfer function. The recorded differences in the $\delta^{13}C$ values of *U. mediterranea* and epifaunal taxa ($\Delta\delta^{13}C_{Umed\text{-}Epi}$) range from -0.46 to -2.13‰, with generally higher offsets at more eutrophic sites. The measured $\delta^{13}C$ differences are related to site-specific differences in microhabitat, depth of the principal sedimentary redox boundary, and TOC content of the ambient sediment. The $\Delta\delta^{13}C_{Umed\text{-}Epi}$ values reveal a consistent relation to C_{org} fluxes estimated from satellite-derived surface water primary production in open-marine settings of the Alboran Sea, Mallorca Channel, Strait of Sicily and southern Aegean Sea. In contrast, $\Delta\delta^{13}C_{Umed\text{-}Epi}$ values in areas affected by intense resuspension and riverine organic matter sources of the northern to central Aegean Sea and the canyon systems of the Gulf of Lions suggest higher C_{org} fluxes compared to the values based on recent primary production. Taking regional biases and uncertainties into account, we establish a first $\Delta\delta^{13}C_{Umed\text{-}Epi}$ based transfer function for C_{org} fluxes for the Mediterranean Sea.

Key words: benthic foraminifera, stable carbon isotopes, microhabitat, organic matter fluxes, Mediterranean Sea, transfer function

1. Introduction

The stable isotope composition of benthic foraminifera is used in a wide range of paleoceanographic applications. The $\delta^{18}O$ signal of benthic foraminifera provides information on bottom water temperature and salinity, and has been applied to estimate global ice volume changes (e.g. Shackleton & Opdyke, 1973; Adkins et al., 2002; Marchitto et al., 2014). The benthic foraminiferal $\delta^{13}C$ signal is mainly used for the reconstruction of changes in deep-sea circulation, bottom water oxygen concentrations, and organic carbon fluxes to the sea floor (Curry & Lohmann, 1982; Zahn et al., 1986; McCorkle & Emerson, 1988; Mackensen & Bickert, 1999; Pahnke & Zahn, 2005). Recently, more quantitative approaches have been applied to the reconstruction of past changes in deep-water oxygenation (Stott et al., 2000; Schmiedl & Mackensen, 2006; Hoogakker et al., 2015). There have also been attempts to use multi-species $\delta^{13}C$ records to reconstruct past organic carbon fluxes (Zahn et al., 1986; Schilman et al., 2003; Kuhnt et al., 2008). However, all of these studies lack a regional calibration based on living specimens and modern organic carbon flux data.

The $\delta^{13}C$ gradient of pore water dissolved inorganic carbon (DIC) in the uppermost surface sediment is directly related to the flux and decomposition rates of organic matter (McCorkle & Emerson, 1988; McCorkle et al., 1990; Holsten et al., 2004). With increasing depth in the sediment more ^{13}C depleted organic matter ($\delta^{13}C$ around -18 to -23‰, e.g. Mackensen, 2008) is remineralized by microbial activity (McCorkle et al., 1985). This process results in $\delta^{13}C_{DIC}$ pore water depletions of up to -4‰ relative to the bottom water signal (McCorkle & Emerson, 1988; McCorkle et al., 1990; Holsten et al., 2004). The preferential release of ^{12}C to the pore water stops when no more OM is remineralized, which mostly coincides with the total consumption of electron acceptors, of which oxygen, nitrate and sulfate are the most energy-efficient ones (McCorkle & Emerson, 1988; McCorkle et al., 1990; Koho & Pina–Ochoa, 2012, Hoogakker et al., 2015).

The $\delta^{13}C_{DIC}$ pore water gradient is reflected in the $\delta^{13}C$ signal of benthic foraminifera from defined microhabitats on and below the sediment–water interface (Grossman, 1984a; b; McCorkle et al., 1990; 1997; Rathburn et al., 1996; Mackensen & Licari, 2004; Schmiedl et al.,

2004; Fontanier et al., 2006). Although benthic foraminifera can migrate through the sediment (Linke & Lutze, 1993; Ohga & Kitazato, 1997) and living individuals may occur across a relatively wide depth interval, the $\delta^{13}C$ of a species exhibits relatively little scatter, and all specimens tend to reflect the same calcification depth (Mackensen & Douglas, 1989; McCorkle et al., 1990, 1997; Mackensen et al., 2000; Schmiedl et al., 2004). The study of McCorkle & Emerson (1988) has shown that the difference between $\delta^{13}C_{DIC}$ of bottom water and $\delta^{13}C_{DIC}$ of pore water at the depth in the sediment where oxygen approaches zero is directly related to the oxygen content of the bottom water mass. Based on this observation, the $\delta^{13}C$ difference of epifaunal (e.g. *Cibicidoides*) and deep infaunal (*Globobulimina*) taxa was used as proxy for the quantification of past changes in deep-water oxygenation (Schmiedl & Mackensen, 2006; Hoogakker et al., 2015). In well-oxygenated bottom waters, enhanced organic matter fluxes and decomposition rates result in steepening $\delta^{13}C_{DIC}$ gradients in the uppermost sediment, which is then reflected by the $\delta^{13}C$ difference between epifaunal and shallow infaunal (e.g., *Uvigerina*) species (Zahn et al. 1986; Mackensen et al., 2000; Brückner & Mackensen, 2008). A simple relation between observed $\delta^{13}C$ gradients and organic matter fluxes is obscured by the ability of infaunal species to shift their microhabitat in response to changing trophic conditions (Schmiedl & Mackensen, 2006; Theodor et al., 2016). Interspecific differences in the $\delta^{13}C$ composition of benthic foraminifera are further influenced by species-specific "vital effects", which can be as large as 1‰ (Schmiedl et al., 2004; McCorkle et al., 2008; Brückner & Mackensen, 2008) and are a reflection of metabolic processes and test calcification rates (McConnaughey, 1989a; b). Of minor impact, but still traceable, is the influence of carbonate ion concentration and alkalinity gradients in pore waters (Bemis et al., 1998). Finally, significant ontogenetic $\delta^{13}C$ trends have been documented for certain taxa, particularly for the genera *Uvigerina* and *Bolivina* (Schmiedl et al. 2004; Schumacher et al., 2010; Theodor et al., 2016).

The complexity of factors influencing the stable isotope composition of deep-sea benthic foraminifera and differences between species in different depths in the sediment motivates isotopic studies on living foraminifera in relation to their biology and microhabitat. In particular, combined ecological and biogeochemical studies on a statistically relevant number of sites and

on live specimens from areas with well-defined environmental gradients are required for the establishment of reference data sets and transfer functions that could then be used for a more quantitative assessment of organic matter fluxes. The Mediterranean Sea is particularly suitable for such a study because the present deep-sea environments are characterized by systematically high oxygen contents along a gradient of trophic differences. In all basins, sub-surface water masses are highly oxygenated with O_2 concentrations of >160µmolkg^{-1} due to frequent replenishment of intermediate water in the Levantine Sea and deep water in the Gulf of Lions, Adriatic Sea, and Aegean Sea (Wüst, 1961; Lascaratos et al., 1999; Pinardi & Masetti, 2000; Tanhua et al., 2013; Pinardi et al., 2015). The inflow of nutrients with Atlantic surface waters causes an overall west-east gradient in primary production, from values of about 225gCm^{-2}yr^{-1} in the Alboran Sea to about 40gCm^{-2}yr^{-1} in the extremely nutrient-depleted oligotrophic Levantine Basin (Bosc et al., 2004; Lopez–Sandoval et al., 2011; Puyo–Pay et al., 2011; Huertas et al., 2012; Tanhua et al., 2013, Gogou et al., 2014). In areas influenced by nutrient input of larger rivers and Black Sea outflow, primary production can be locally enhanced, for example leading to a trend of decreasing primary production values along a N-S transect in the Aegean Sea (Lykousis et al., 2002; Skliris et al., 2010). In addition, resuspension and lateral transport of organic matter can lead to locally enhanced food availability in submarine canyons and isolated basins (Puig & Palanques, 1998; Danovaro et al., 1999; Heussner et al., 2006; Canals et al., 2013).

In this study we have compiled a data set on the stable carbon isotope composition of living and dead individuals of three epifaunal species (*Cibicidoides pachydermus*, *Planulina ariminensis*, *Cibicides lobatulus*) and one shallow infaunal species (*Uvigerina mediterranea*) from 19 Mediterranean sites. The sites are located in a well-defined depth interval (between 400 and 1500m) and represent a wide range of trophic conditions. Adjusted for ontogenetic effects, the $\Delta\delta^{13}C_{Umed\text{-}Epi}$ signal was compared to the microhabitat of *U. mediterranea*, the depth of the main redox boundary, TOC content, and organic carbon flux rates calculated from satellite-derived primary production or (if available) flux measurements from sediment trap studies. Major objective of this study is the development and evaluation of a transfer function

for organic matter fluxes applicable to the quantification of past trophic changes in the Mediterranean Sea.

2. Material and methods

This study is based on a compilation of new and published isotope data of multicorer samples retrieved from various Mediterranean sub-basins covering a water depth range of 424 to 1466m (Table 1). The study areas include the Alboran Sea and the Mallorca Channel (R.V. *Meteor* cruise M69/1 in August 2006, Hübscher et al., 2010; data published in Theodor et al., 2016), the Gulf of Lions, Spanish Slope off Barcelona and Strait of Sicily (M40/4 in February 1998, Hieke et al., 1999; this study and data published in Schmiedl et al., 2004), and the Aegean Sea (M51/3 in November 2001, Hemleben et al., 2003; this study) (Fig. 1). For each station, the sediment color change from yellowish brown to greenish gray was used as an indicator for the change in redox potential from positive to negative values, which serves as an approximation of oxygen consumption and penetration in the surface sediment (Lyle, 1983; Schmiedl et al., 2000).

The upper 10cm of the sediment were commonly sliced into 0.5 to 1cm intervals, in the Aegean Sea into coarser intervals below 3cm, and all samples were subsequently preserved in Rose Bengal stained alcohol (1.5g Rose Bengal per 1l of 96% ethanol) in order to stain cytoplasm of living or recently living foraminifera (Walton, 1952; Bernhard, 2000). In the laboratory, the sediment samples were wet-sieved over a 63µm sieve and, after drying at 40°C, dry-sieved over a 150µm (Aegean Sea samples) or 125µm (remaining samples) mesh, respectively. From the coarse fraction of the different down-core intervals, stained individuals of selected epifaunal and shallow infaunal taxa were counted and the Median Living Depths (MLD; Theodor et al. 2016) were calculated as reference for the respective microhabitat preferences. Only tests with at least three subsequent brightly red colored chambers were considered as living. The low number of stained individuals of epifaunal taxa impeded

157 analyses, except for Site 540B, where stained tests of *C. pachydermus* were available.
158 Likewise, stained tests of *U. mediterranea* were absent at Sites 586 and 589.

159 For stable isotope measurements, stained tests (and unstained tests if no stained tests
160 were available) of three epifaunal species (*C. pachydermus*, *P. ariminensis*, *C. lobatulus*) and
161 one shallow infaunal species (*U. mediterranea*) were selected and each test was measured
162 using an optical micrometer with an accuracy of 10µm. In total, 2 stained and 63 unstained
163 epifaunal tests as well as 155 stained and 197 unstained tests of *U. mediterranea* were
164 measured. Individual numbers of tests measured were 1-6 for *C. pachydermus*, 1-5 for *P.*
165 *ariminensis*, 1-5 for *C. lobatulus*, and 1-8 for *U. mediterranea*. The stable carbon and oxygen
166 isotope measurements were performed at the Alfred Wegener Institute, Helmholtz Centre for
167 Polar and Marine Research at Bremerhaven with two Finnigan MAT 253 stable isotope ratio
168 mass spectrometers coupled to automatic carbonate preparation devices (Kiel IV). The mass
169 spectrometers were calibrated via international standard NBS 19 to the PDB scale, with results
170 given in δ-notation versus VPDB. Based on an internal laboratory standard (Solnhofen
171 limestone) measured over a one-year period together with samples, the precision of stable
172 isotope measurements was better than 0.06‰ and 0.08‰ for carbon and oxygen, respectively.
173 The $\delta^{13}C$ difference between epi- and shallow infaunal taxa was calculated as a proxy for the
174 difference in $\delta^{13}C$ in DIC of bottom and shallow pore water. For *U. mediterranea* this procedure
175 was restricted to measurements from the size fraction >600µm in order to minimize ontogenetic
176 effects (Schmiedl et al., 2004; Theodor et al., 2016).

177 Total organic carbon (TOC) concentration in the surface sediment was measured with
178 a Carlo Erba 1500 CNS Analyzer with a precision of 0.02% on weighted sample splits in tin
179 capsules. Before measurement, $CaCO_3$ was removed from these weighted samples by adding
180 1N HCl. The TOC values of Sites 596, 601 and 602 were taken from Möbius et al. (2010a, b).
181 Bottom water oxygen concentrations are based on CTD measurements stored in the MedAtlas
182 data set. Primary productivity values in surface waters of the year preceding the sampling at
183 each site are based on satellite data of the GlobColour project, and were calculated with the
184 algorithms of Antoine & Morel (1996) as well as Uitz et al. (2008). If available, these estimates

were compared with nearby direct primary productivity and export flux measurements. The export fluxes down to the sea floor were estimated according to the function of Betzer et al. (1984) adapted by Felix (2014).

3. Results

Benthic foraminiferal $\delta^{13}C$ values of our samples cover a range of more than 3‰, with higher average values of epifaunal species than shallow infaunal *Uvigerina mediterranea* (Table 2). The epifaunal species *Cibicidoides pachydermus, Cibicides lobatulus* and *Planulina ariminensis* show average values between 1.90‰ at Site 586 (southern Aegean Sea) and -0.16‰ at Site 347 (Mallorca Channel) (Table 2; Fig. 2). The highest average epifaunal $\delta^{13}C_{Epi}$ values are in the southern and central Aegean Sea (Sites 586, 595), while further to the north at Site 602 (northern Aegean Sea) the average $\delta^{13}C_{Epi}$ value of 0.87‰ is among the lowest measured. At Site 540B in the Gulf of Lions, the average $\delta^{13}C_{Epi}$ value of 1.01‰ is in good agreement with 1.00‰ measured by Schmiedl et al. (2004) at the same site. Size-dependent measurements did not reveal any ontogenetic trend in the $\delta^{13}C$ signal of the epifaunal taxa (supplementary. table 1).

For *U. mediterranea* $\delta^{13}C_{Umed}$ values vary between -1.41 and 0.85‰ for stained tests and between -1.52 and 1.77‰ for unstained tests (Supplementary Table 1). The highest average values are recorded in the southern Aegean Sea, with 0.58‰ and 1.11‰ for stained and unstained tests, respectively. The lowest average values are recorded for the northern Aegean Sea, with -0.98‰ and -1.13‰ for stained and unstained tests, respectively. The variability at a single site reaches 1.38‰ in stained (Site 537) and 2.21‰ in unstained tests (Site 586). The ontogenetic $\delta^{13}C_{Umed}$ trends are generally comparable in the western Mediterranean Sea and the Strait of Sicily, with 0.11 ± 0.03‰ 100µm^{-1} for stained and 0.07 ± 0.03‰ 100µm^{-1} for unstained tests, except for Site 396 that shows an anomalous negative trend (Table 3; Fig. 3). In the Aegean Sea, the ontogenetic $\delta^{13}C_{Umed}$ trends are approximately 50 % steeper with an increase of 0.16 ± 0.04‰ 100µm^{-1} for stained tests. Unstained tests

212 reveal a higher variability and a less steep slope of 0.10 ± 0.07‰ 100µm^{-1} (Table 3, Fig. 3). In
213 order to avoid bias due to ontogenetic effects, only $\delta^{13}C$ values of *U. mediterranea* tests larger
214 than 600µm were used for comparison with $\delta^{13}C_{Epi}$ values.

215 The calculated $\Delta\delta^{13}C_{Umed\text{-}Epi}$ values for stained tests range from -0.64‰ in the Gulf of
216 Lion (slope Site) and -0.74‰ (Site 585) to -1.29‰ in the western Mediterranean Sea (sites 347
217 & 540A), to -1.85‰ in the northern Aegean Sea (Site 602) (Table 2). Due to the wider scattering
218 of the $\delta^{13}C$ values of unstained tests, $\Delta\delta^{13}C_{Umed\text{-}Epi}$ values range from -0.61‰ (Site 589) to -
219 2.0‰ (Site 602) in the Aegean Sea and from -0.55‰ (Site 540B) to -1.06‰ (Site 339) in the
220 western Mediterranean Sea and the Strait of Sicily (Table 2). The magnitude of $\Delta\delta^{13}C_{Umed\text{-}Epi}$
221 values exhibits a relation with trophic conditions at each site, revealing higher values at more
222 eutrophic sites.

223 The Median Living Depth of the shallow infaunal U. mediterranea (MLD_{Umed}) is used
224 here to describe its microhabitat and generally increases at sites with deep main redox
225 boundaries, at least in the western Mediterranean Sea. The deepest MLD_{Umed} are 2.13 and
226 2.25cm in the southern Aegean Sea, while the shallowest depths of 0.27cm and 0.38cm are
227 recorded in the central and northern Aegean Sea, respectively (Table 1). In the Gulf of Lions,
228 the MLD_{Umed} is between 0.43 and 0.49cm in the axis of the Lacaze–Duthiers Canyon and
229 around 1.22cm on the open slope (Table 1, Fig. 4a). The depth of the sediment color change,
230 which marks the shift in redox potential and thus oxygen penetration, ranges from 2.25cm in
231 the Gulf of Lions (Site 540A) to as much as 30cm in the central Aegean Sea (Site 596) (Table
232 1, Fig. 4b). The measured TOC contents of the surface sediment range from 0.41% (Site 586,
233 southern Aegean Sea) and 0.58% (Site 537, Strait of Sicily) to a maximum of 0.82% (Site 602,
234 northern Aegean Sea) (Table 1, Fig. 4c). The $\Delta\delta^{13}C_{Umed\text{-}Epi}$ and the MLD_{Umed} (Fig. 4a) as well
235 as the main redox boundary depth (Fig. 4b) show good correspondence, whereas the link to
236 %TOC is less distinct (Fig. 4c).

237 The estimated values for annual Primary Production (PP) range from 106 to
238 294gCm^{-2}a^{-1}. Application of the different algorithms of Antoine & Morel (1996) and Uitz et al.
239 (2008) resulted in an average offset of 54gCm^{-2}a^{-1}, with PP values consistently higher when

240 applying the algorithm of Antoine & Morel (1996). The highest PP values occur in the Alboran
241 Sea (274–294 versus 192–207gCm^{-2}a^{-1} according to Uitz et al., 2008) and the northern Aegean
242 Sea (196–237 resp. 139–164gCm^{-2}a^{-1}), while the lowest PP values occur in the southern and
243 central Aegean Sea (151–161 resp. 106–116gCm^{-2}a^{-1}) (Table 1).
244

245 # 4. Discussion

246 ## 4.1. Stable carbon isotope signal of epifaunal foraminifera in relation to
247 surrounding water masses

248 The $\delta^{13}C$ of *Cibicidoides pachydermus*, *Cibicides lobatulus,* and *Planulina ariminensis*
249 seems to reflect the $\delta^{13}C_{DIC}$ of the ambient bottom water since these species prefer an
250 epifaunal microhabitat (Lutze & Thiel, 1989; Kitazato, 1994; Schmiedl et al., 2000).
251 Comparison with published water $\delta^{13}C_{DIC}$ measurements confirms that $\delta^{13}C_{Epi}$ values are a
252 possible bottom water proxy for the Mediterranean Sea (Pierre, 1999; Schmiedl et al., 2004;
253 Theodor et al., 2016). Further, our new data corroborate previous observations that
254 ontogenetic effects in the $\delta^{13}C_{Epi}$ signal of these taxa are lacking (Corliss et al., 2002; Franco–
255 Fraguas et al., 2011; Theodor et al., 2016) (Supplementary Table 1).

256 Because of the lack of stained epifaunal tests at most sites, unstained tests were
257 integrated into the analysis. For empty tests a shift to higher $\delta^{13}C_{Epi}$ values due to potential
258 dissolution effects should be considered (Edgar et al., 2013). In addition, reworked or
259 allochtonous tests can bias the results as documented for the $\delta^{13}C_{Cpachy}$ of Site 396 in the
260 Mallorca Channel. At this site, fossil tests have been admixed in the surface sediment as
261 indicated by heavy $\delta^{18}O$ values of >4.0‰ (Supplementary Table 1). In the Alboran Sea (Sites
262 339 and 347), we measured inter-specific epifaunal $\delta^{13}C$ differences of up to 1.4‰. This
263 variability is a result of implausibly low $\delta^{13}C_{Clob}$ values, probably due to a relocation from
264 shallower depths closer to the coast. These unrealistic $\delta^{13}C_{Cpachy}$ and $\delta^{13}C_{Clob}$ values were
265 omitted for $\delta^{13}C_{Epi}$ estimation. In order to minimize these biases, a large number of tests were
266 measured, which was possible for *C. pachydermus* and *P. ariminensis*, showing commonly

0.3–0.5‰ higher $\delta^{13}C$ values for the latter species (Table 2, Fig. 2a). Despite the aforementioned uncertainties, data of *C. lobatulus* were used to estimate $\delta^{13}C_{Epi}$ at the Mallorca Channel Sites 394 and 395, when no tests of other species were available for analysis (Theodor et al., 2016). For proper $\delta^{13}C_{Epi}$ estimation of Sites 394 and 395 the difference between $\delta^{13}C_{Pari}$ and $\delta^{13}C_{Clob}$ ($\Delta\delta^{13}C_{Pari\text{-}Clob}$ = 0.30‰) at sSite 396 was added to the $\delta^{13}C_{Clob}$ values (Table 2; Fig. 2a).

The $\delta^{13}C$ offset between *C. pachydermus* and *P. ariminensis* is not constant and appears to increase at sites with deep main redox boundaries. This suggests a connection with increasing organic matter availability and the varying offsets can be attributed to slight differences in their microhabitat (Table 2; Fig. 2a). While *P. ariminensis* is a strictly epifaunal species, living attached on surfaces or above the sediment (Lutze & Thiel, 1989), *C. pachydermus* commonly lives at or slightly below the sediment–water interface (Rathburn & Corliss, 1994; Schmiedl et al. 2000; Licari & Mackensen, 2005). A very shallow infaunal microhabitat of *C. pachydermus* is corroborated by slightly lower $\delta^{13}C$ values relative to bottom water $\delta^{13}C_{DIC}$ suggesting pore water influence (Schmiedl et al., 2004; Fontanier et al., 2006). In order to compensate for potential pore water effects in the $\delta^{13}C$ signal of the epifaunal species, the highest $\delta^{13}C_{Epi}$ values, mostly of *P. ariminensis*, should be selected for further comparison with shallow infaunal $\delta^{13}C_{Umed}$ signals. This strategy could not always be realized, either due to the lack of *P. ariminensis* (Sites 537, 601, Canyon, and Slope) or when lower $\delta^{13}C$ values were recorded for *P. ariminensis* relative to *C. pachydermus* (Site 540C). In these cases, bottom water $\delta^{13}C_{DIC}$ measurements (Canyon, Slope; from Schmiedl et al., 2004), the addition of the $\Delta\delta^{13}C_{Pari\text{-}Cpachy}$ value of the nearby Site 602 (for correction of Site 601) or the $\delta^{13}C_{Cpachy}$ values (Sites 537, 540C) were used, accepting possible deviations of $\delta^{13}C_{Epi}$ from bottom water $\delta^{13}C_{DIC}$ (Table 2).

The applied $\delta^{13}C_{Epi}$ values are related to different Mediterranean water masses (Fig. 2b). The $\delta^{13}C_{Epi}$ values of the Gulf of Lions and the Spanish continental slope off Barcelona are around 1.0‰ matching the $\delta^{13}C_{DIC}$ signature of upper Western Mediterranean Deep Water (WMDW) (Pierre, 1999). Likewise, the slightly higher $\delta^{13}C_{Epi}$ values of 1.1‰ in the Strait of

295 Sicily fall in the range of $\delta^{13}C_{DIC}$ values of intermediate waters from the Eastern Mediterranean
296 Sea and reflect the transitional setting of this area. In contrast, the $\delta^{13}C_{Epi}$ values of the Mallorca
297 Channel and the Alboran Sea are even higher than those recorded for the Eastern
298 Mediterranean Sea (Fig. 2b). This inconsistent isotope pattern likely reflects a shift in deep-
299 water formation in the Eastern Mediterranean during the 1990s, the so called Eastern
300 Mediterranean Transient (EMT; Roether et al., 2007). The EMT was accompanied by an
301 enhanced deep-water formation in the Aegean Sea and also fostered a complete renewal of
302 Western Mediterranean Sea Deep Water (WMDW) during the mid-2000s (Schroeder et al.,
303 2006; 2008). Unfortunately, the imprint of WMDW change on $\delta^{13}C_{DIC}$ of the water mass was
304 not documented, but it should have affected the sites sampled after this transition, i.e. during
305 Meteor cruise M69/1 in 2006.

306 The broad range of recorded $\delta^{13}C_{Epi}$ values of 0.87 to 1.95‰ in the Aegean Sea reflects
307 the strong small-scale oceanographic differences of this region, including presence of various
308 small isolated basins (Figs. 1, 2b). The comparatively high $\delta^{13}C_{Epi}$ values of the shallower sites
309 indicate intensified vertical convection at sites of subsurface-water formation, which recently
310 resumed after the stagnation phase of 1994 to 2000 (Androulidakis et al., 2012), although the
311 main deep-water formation area is restricted to the Cretan Sea (Roether et al., 1996;
312 Lascaratos et al., 1999). Reduced replenishment of bottom waters at greater depth of isolated
313 basins (Zervakis et al., 2003; Velaoras & Lascaratos, 2005) is accompanied by relatively low
314 $\delta^{13}C_{DIC}$ and accordingly low $\delta^{13}C_{Epi}$ values in these environments.

315

316 **4.2. Biological and environmental effects on the stable carbon isotope signal of**
317 ***Uvigerina mediterranea***

318 Size-dependent changes in the $\delta^{13}C$ signal of *Uvigerina mediterranea* are attributed to
319 ontogenetic effects. Small tests are depleted in ^{13}C, while larger tests are closer to $\delta^{13}C_{DIC}$ of
320 the ambient pore water (Fig. 3). Relatively low $\delta^{13}C_{Umed}$ values of small tests suggest stronger
321 metabolic fractionation in younger individuals (Schmiedl et al., 2004; McCorkle et al., 2008;
322 Schumacher et al., 2010; Theodor et al., 2016). A linear ontogenetic increase of 0.11‰100µm^{-}

^{1} was observed at all sites of the western Mediterranean Sea, while a steeper slope of 0.16‰100µm^{-1} was recorded in the Aegean Sea (Fig. 3). In addition, the $\delta^{13}C_{Umed}$ values of small individuals from the Aegean Sea were of order 1‰ lower compared to those from the western Mediterranean Sea.

Differences in ontogenetic $\delta^{13}C$ slopes of the related species *U. peregrina* have been attributed to its highly opportunistic response to regional contrasts in organic matter quantity and quality, and seasonality of supply (Theodor et al., 2016). Obviously, similar effects are also operational in ontogenetic $\delta^{13}C$ trends of *U. mediterranea*. In the Aegean Sea, this species appears to respond to strong seasonal contrasts in organic matter fluxes (Siokou–Frangou et al., 2002) resulting in particularly high metabolic activity and low $\delta^{13}C_{Umed}$ values in young individuals. A steepening of the $\delta^{13}C_{Umed}$ slopes from the North to the South Aegean Sea has probably the same reasons as for *U. peregrina* in the Western Mediterranean Sea. Because of the higher number of measured tests, this shift of the slope angles is more obvious in unstained than stained tests (Fig. 3). Although the number of sites was larger than in Theodor et al. (2016), a similar trend in $\delta^{13}C_{Umed}$ is not recognizable for the Western Mediterranean Sea. This may express lower differences in the seasonal food supply between the sites or the in total higher input of organic matter compared to the Aegean Sea.

The $\delta^{13}C_{Umed}$ of unstained individuals from 5cm sediment depth in the western Mediterranean Sea and Strait of Sicily are on average 0.1 to 0.2‰ lower than those of stained specimens in the topmost centimeter. This adds to previous observations of Theodor et al. (2016) suggesting the influence of the Suess effect (Keeling, 1979; Quay et al., 1992) in living individuals while it is absent in sub-recent specimens. The Suess effect reduces $\delta^{13}C$ values in the atmosphere and oceans, due to the anthropogenic release of isotopically light CO_2 out of fossil fuels. A similar effect was not seen in the Aegean Sea since live and dead individuals were selected from the same sediment depth and thus had only minor age differences (Table 2, Fig.3). The only exception is Site 595 in the central Aegean Sea, where the deviation is even higher (0.5-0.7‰), when compared to the western Mediterranean Sea. Since this signal is

restricted to only one site it is probably due to relocation of fossil tests by the effects of bioturbation or lateral sediment transport.

Under well-oxygenated conditions, the pore water $\delta^{13}C_{DIC}$ gradient depends on the organic matter fluxes and associated decomposition rates of organic matter in the surface sediment (McCorkle and Emerson, 1988; McCorkle et al., 1985, 1990, Holsten et al., 2004). Organic matter fluxes also control the depth of the oxygenated layer (Rutgers van der Loeff, 1990) and thus the microhabitat range of infaunal foraminifera (Corliss, 1985; Jorissen et al, 1995; Koho et al., 2008; Koho & Pina–Ochoa, 2012). Subsurface waters in the Mediterranean Sea are well ventilated resulting in bottom water oxygen concentrations above 4.1ml l^{-1} at all sites in our study (MedAtlas, 1997). The $\delta^{13}C$ signal of *U. mediterranea* appears particularly suitable to monitor the pore water $\delta^{13}C_{DIC}$ signal in the surface-near sediment because it seems to be less influenced by species-specific "vital effects" (McConnaughy, 1989a; b) when compared to other shallow infaunal taxa, for example *U. peregrina* (Schmiedl et al., 2004; Theodor et al., 2016).

In this study, the deviation of $\delta^{13}C_{Umed}$ from bottom water $\delta^{13}C_{DIC}$ (reflected as higher $\Delta\delta^{13}C_{Umed\text{-}Epi}$ values, Fig. 4) suggests exponential relations with the MLD of *U. mediterranea*, the depth of the oxygenated layer and with the TOC content of the surface sediment. At the more oligotrophic to mesotrophic sites of the Mallorca Channel, the Gulf of Lions, the Spanish Slope off Barcelona, and the southern Aegean Sea, relatively low $\Delta\delta^{13}C_{Umed\text{-}Epi}$ values correspond to a relatively thick oxygenated layer and low TOC contents. The rather deep position of the redox boundary, exceeding 10cm at some sites, enables *U. mediterranea* to inhabit a relatively wide microhabitat range. In contrast relatively high $\Delta\delta^{13}C_{Umed\text{-}Epi}$ values at the more mesotrophic to eutrophic sites of the Alboran Sea coincide with relatively thin oxygenated layers and higher TOC contents. Here, the microhabitat range of *U. mediterranea* is compressed because of limited pore water oxygen (Fig. 4).

When comparing sites within the central and northern Aegean Sea, the foraminiferal stable isotope difference and the biogeochemical and ecological characteristics lack a consistent relation (Fig. 4). In these areas strongly negative $\Delta\delta^{13}C_{Umed\text{-}Epi}$ do not systematically

correspond to maximum TOC contents and the shallowest redox boundary (Fig. 4). The reasons for this absence of a clear relation between $\Delta\delta^{13}C_{Umed\text{-}Epi}$ and environmental parameters within this area cannot be unraveled with our data. It may be related to the high variability in oceanographic and biogeochemical conditions of the bottom water in the isolated basins that are characterized by focusing of organic-rich sedimentary material (Lykousis et al., 2002; Giresse et al., 2003; Poulos, 2009) and/or temporarily intermittent replenishment of deep waters on seasonal to decadal time scales (Zervakis et al., 2003; Velaoras & Lascaratos, 2005; Androulidakis et al., 2012). The first possibility can increase the supply of refractory C_{org}, recorded by higher TOC contents, and influence the foraminiferal microhabitat depths, but has minor effects on the $\delta^{13}C_{DIC}$ pore water gradient. Latter possibility refers to local ventilation events, which exchange aged bottom water with comparatively low $\delta^{13}C_{DIC}$ signature by surface waters enhanced in $^{13}C_{DIC}$. This may also push the pore water gradient towards stronger differences, explaining the more negative $\Delta\delta^{13}C_{Umed\text{-}Epi}$ values, compared to the remaining sites with similar conditions (Fig. 4).

4.3. Development of a stable carbon isotope based transfer function for organic carbon fluxes

Our results suggest a close relationship between the $\delta^{13}C$ gradient in pore waters of the surface sediment (expressed as $\Delta\delta^{13}C_{Umed\text{-}Epi}$) and the organic matter (OM) fluxes to the sea floor, for open-ocean settings of the western and central Mediterranean Sea and the southern Aegean Sea (Fig. 5). Based on these observations, we tested the potential for the development of a $\delta^{13}C$-based transfer function for OM flux rates. In open-ocean settings, the main food source of deep-sea environments is the exported OM from the surface layer, where photosynthetic primary production (PP) takes place (e.g. Boyd & Trull, 2007; Bishop, 2009). The majority of produced particulate organic carbon (POC) is recycled within the photic zone. In the open Mediterranean Sea, around 4% of the POC is exported out of the photic zone, which is lower than for other open oceans, caused by a specific nutrient distribution in the

405 Mediterranean Sea (Moutin & Raimbault, 2002; Gogou et al., 2014). The remineralization of
406 organic matter is intensified, which leads to reduced fluxes to the sea floor.

407 During transfer from the surface ocean to the deep-sea, the amount of exported OM
408 decreases exponentially reflecting microbial decay (Suess, 1980; de la Rocha & Passow,
409 2007; Packard & Gomez, 2013). Various functions have been developed for the estimation of
410 OM fluxes during sinking of particles through the water column integrating numerous
411 observational data (Suess, 1980; Betzer et al., 1984; Martin et al., 1987; Antia, et al., 2001).
412 The different functions reveal a high variability for the active surface layer, while the results for
413 deeper parts of the water column are within a comparable range (Felix, 2014). In our study
414 (Table 1, Fig.5), we applied the function of Betzer et al. (1984) for calculating the depth-
415 dependent C_{org} fluxes at the different Mediterranean sites using satellite-derived PP data
416 (Antoine & Morel, 1996; Uitz et al., 2008).

417 A comparison with direct PP and export flux measurements of sediment trap studies
418 revealed ambiguous results. The PP values calculated after Antoine and Morel (1996) are in a
419 comparable range to PP measurements in the western Mediterranean (Moutin & Raimbault,
420 2002; Sanchez–Vidal et al., 2004; 2005; Zúñiga et al., 2007, 2008). However, the estimated
421 export fluxes are too high in these areas compared to direct measurements of the referred
422 studies, probably due to the aforementioned high remineralization rate in the Mediterranean
423 Sea. However, the discrepancy in export fluxes is partly compensated by the application of the
424 21–30% lower PP values calculated after Uitz et al. (2008). For the Aegean Sea, in contrast,
425 distinctively higher measured PP values have been reported than were estimated (Siokou–
426 Frangou et al., 2002). For the Gulf of Lions measured OM export fluxes exceed the predicted
427 values (Heussner et al., 2006), which can be explained by the additional lateral input of organic
428 carbon channeled within the local canyon systems (Schmiedl et al., 2000). In order to
429 compensate for these possible additional C_{org} fluxes in marginal basin areas, the application
430 of the function of Antoine and Morel (1996) is more promising, hence a potential overestimation
431 of C_{org} fluxes in open-ocean areas has to be considered.

For both approaches of PP calculation (Antoine & Morel, 1996; Uitz et al., 2008) the relation between the estimated C_{org} fluxes and the $\Delta\delta^{13}C_{Umed\text{-}Epi}$ exhibits a complex pattern and at first instance lacks a simple and statistically significant correlation (Fig. 5). Particularly, strongly negative $\Delta\delta^{13}C_{Umed\text{-}Epi}$ in the central and northern Aegean Sea suggest high C_{org} fluxes, which however are not reflected in the estimated PP-based values. The eventual underestimation of C_{org} fluxes in these more marginal areas is likely caused by additional lateral OM input and the focusing of organic matter in isolated small basins. In fact, the northern and central Aegean Sea experiences high OM input from terrestrial sources through outflow of North Aegean rivers and the Black Sea (Aksu et al., 1999; Tsiaras et al., 2012). In contrast, the measured main redox boundary depth and the TOC contents do not indicate a higher supply in organic matter. However, sediment trap data from the northern Aegean Sea (Lykousis et al., 2002) reveal C_{org} fluxes of 35–81$gCm^{-2}a^{-1}$, which are 3 to 10 times higher than estimated values solely based on PP-based vertical fluxes. Although the high measured values can be partly attributed to the short sampling interval of two months in late spring and thus to elevated vertical fluxes during the spring bloom, elevated year-round lateral C_{org} fluxes can be expected, but of a clearly lower dimension. The measured ratio of primary to reworked OM in the sediment at this site is around 60–70% (Lykousis et al., 2002; Poulos, 2009), which leaves the PP as the main source of the C_{org} fluxes to the deep-sea. Similar results have been derived for canyon systems of the Gulf of Lions where OM resuspension, shelf to slope cascading and channeling results in significantly higher observed than PP-derived estimated C_{org} fluxes (Heussner et al., 2006; Pusceddu et al., 2010, Pasqual et al., 2010). Even in open slope settings, resuspended OM can significantly contribute to the total C_{org} flux (McCave et al., 2001; Tesi et al., 2010; Stabholz et al., 2013).

Despite these biases, it appears reasonable to develop a C_{org} flux transfer function at least for the more open marine settings of the western and central Mediterranean Sea and the southern Aegean Sea (Fig. 6). Here, vertical sinking of PP-derived OM appears to be the main source for C_{org} fluxes (Pusceddu et al., 2010) explaining the good correlation with the $\Delta\delta^{13}C_{Umed\text{-}Epi}$ values (Fig. 5). Elevated C_{org} fluxes of the upwelling-affected Alboran Sea

460 (Hernandez–Almeida et al., 2011) are reflected in rather negative $\Delta\delta^{13}C_{Umed\text{-}Epi}$ values while
461 the observed $\delta^{13}C$ differences in the more oligotrophic regions of the Mallorca Channel, the
462 Spanish Slope off Barcelona, the Strait of Sicily, and the southern Aegean Sea are lower. So,
463 omitting the data from the northern and central Aegean Sea, and considering sediment trap
464 data from the Gulf of Lions (Heussner et al., 2006) the derived function can be expressed as

465 $$C_{org}\ flux = -15.99 * \Delta\delta^{13}C_{Umed\text{-}Epi} + 0.34 \quad (1)$$

466 with a coefficient of determination (R^2) of 0.63 and a significance (p) of 0.0021 (Fig. 6). The
467 estimated C_{org} fluxes can be used to recalculate marine PP, but should be handled carefully,
468 due to the highly possible overestimation caused by lateral advection. Especially in more
469 marginal areas this bias can lead to unreliable recalculated PP values.

470 The application of this function to unstained *U. mediterranea* tests creates a higher
471 range of uncertainty. The main reason for this inconsistency seems to be the relocation of
472 fossil tests at particular sites, leading to significant contrasts between $\delta^{13}C_{Umed}$ values of
473 stained and unstained tests. For empty *U. mediterranea* tests, marked negative $\delta^{13}C_{Umed}$
474 outliers appear at Sites 537 and 396, which has already been mentioned in Theodor et al.
475 (2016) for the latter site. In the Alboran Sea (Sites 338 and 347) on the other hand, $\delta^{13}C_{Umed}$
476 values of unstained tests are about 0.50‰ higher than those of stained tests. Less distinct
477 $\delta^{13}C_{Umed}$ differences between autochthonous and allochthonous tests may not be detected so
478 easily. These potential uncertainties have to be considered in the application of the transfer
479 function to sediment cores, particularly to down-core records from sites influenced by strong
480 lateral transport such as Canyon environments or the Northern and Central Aegean Sea.
481 Likewise, the application of the transfer function to areas outside of the Mediterranean Sea
482 may be biased by contrasting remineralization rates, due to the specific oceanographic
483 conditions, especially the higher temperatures in the Mediterranean Sea. Further refinement
484 of this function will require an interdisciplinary effort including a larger number of direct C_{org}
485 flux measurements in sediment trap deployments, which can be directly related to the obtained
486 foraminiferal $\delta^{13}C$ signals.

5. Conclusions

The $\delta^{13}C$ signal of deep-sea benthic foraminifera from different areas of the western, central and eastern Mediterranean Sea reflects an integration of various environmental and biological signals. The application of epifaunal benthic foraminifera as an unbiased proxy for the $\delta^{13}C_{DIC}$ of the surrounding water mass is ambiguous, due to possible allochtonous tests, but also due to slight species-specific difference in the microhabitat that can result in significant $\delta^{13}C_{Epi}$ shifts. The $\delta^{13}C$ signal of the strictly epifaunal *Planulina ariminensis* should be preferred, in contrast to the $\delta^{13}C$ signal of the less strictly epifaunal *Cibicidoides pachydermus,* which appears to be influenced by pore water DIC and its $\delta^{13}C$ value.

The $\delta^{13}C$ signal of epifaunal taxa lacks ontogenetic effects supporting results from previous studies (Dunbar & Wefer, 1984; Corliss et al, 2002; Theodor et al., 2016). Significant ontogenetic effects were recorded in the $\delta^{13}C$ signal of *Uvigerina mediterranea*. While the ontogenetic increase of $\delta^{13}C_{Umed}$ is more or less comparable (0.11 ± 0.03‰ 100µm^{-1}) in the Western Mediterranean and the Strait of Sicily, a stronger increase and even a regional S-N trend is documented for the Aegean Sea (0.16 ± 0.04‰ 100µm^{-1}). In general, the $\delta^{13}C$ values of *U. mediterranea* from the Aegean Sea are more negative when compared to those from the western and central Mediterranean Sea. This regional contrast cannot be reconciled with different vital and pore water effects but instead seem to be caused by enhanced residence times of bottom waters in the partly isolated small basins within the Aegean Sea. In cases of well-oxygenated conditions the $\delta^{13}C_{Umed}$ signal, compared to bottom water, is mainly controlled by regional trophic contrasts and related remineralisation rates. The $\Delta\delta^{13}C_{Umed\text{-}Epi}$ are clearly related to the median microhabitat depth, the depth of the redox boundary (indicating the extent of the oxygenated layer), and to a lower extent to the TOC of the surface sediment. Based on satellite derived primary production estimates C_{org} fluxes were calculated and related to the recorded $\Delta\delta^{13}C_{Umed\text{-}Epi}$ values. Comparison with sediment trap data reveals underestimation of

satellite-derived C_{org} fluxes for the marginal areas of the central and northern Aegean Sea and the canyon systems of the Gulf of Lions. In these ecosystems additional lateral transport of resuspended and terrestrial OM contributes substantially to C_{org} fluxes. Considering these biases a first estimation for C_{org} fluxes in open-ocean settings of the Mediterranean Sea could be established.

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Appendix A. List of benthic foraminiferal taxa used in this study.

Cibicides lobatulus (Walker & Jakob) = *Nautilus lobatulus* Walker & Jacob, 1798, p. 642, pl. 14, fig. 36.

Cibicidoides pachydermus (Rzehak) = *Truncatulina pachyderma* Rzehak, 1886, p. 87, pl. 1, fig. 5.

Planulina ariminensis d'Orbigny = *Planulina ariminensis* d'Orbigny, 1826, p. 280, pl. 14, figs. 1–3.

Uvigerina mediterranea Hofker = *Uvigerina mediterranea* Hofker, 1932, p. 118–121, fig. 32.

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Table captions

Table 1. Position, water depth, median living depth (MLD) of *Uvigerina mediterranea*, geochemical, Primary Production (PP) and C_{org} flux values of the investigated multicorer sites. Annual PP values are averages for the year previous to sampling after data from the GlobColour project. C_{org} fluxes were calculated after Betzer et al. (1984) and the MLD after Theodor et al. (2016). Data of the Canyon and Slope Sites were taken from Schmiedl et al. (2004).

Table 2. Average stable carbon isotope composition of selected benthic foraminifera with standard deviations. Underlined values of epifaunal species were applied to estimate $\delta^{13}C_{Epi}$. Also given are values for *Uvigerina mediterranea* tests larger than 600µm and the difference of this species compared to the average epifaunal stable carbon isotope ratios ($\Delta\delta^{13}C_{Umed\text{-}Epi}$).

Table 3. Linear regressions of ontogenetic trends of $\delta^{13}C_{Umed}$. The measured number of stained and unstained tests as well as the significance values are added.

921 Table 1.

Site	latitude	longitude	station depth (m)	MLD_{Umed} (cm)	redox boundary depth (cm)	TOC (%)	PP (Antoine & Morel, 1996) ($gCm^{-2}a^{-1}$)	PP (Uitz et al., 2008) ($gCm^{-2}a^{-1}$)	C_{org} flux (Antoine & Morel, 1996) ($gCm^{-2}a^{-1}$)	C_{org} flux (Uitz et al., 2008) ($gCm^{-2}a^{-1}$)
537	37°02.14‘ N	13°11.35‘ E	472	0.83	2.75	0.560	173.06	120.18	12.26	7.33
540A	42°27.69‘ N	03°25.64‘ E	911	0.43	2.25		203.97	160.16	10.22	7.27
540B	42°25.70‘ N	03°41.34‘ E	812	1.22	7	0.750	193.99	151.44	10.24	7.22
540C	41°21.04‘ N	03°01.36‘ E	721	0.97	4.25	0.650	179.74	138.14	9.91	6.84
585	36°39.60‘ N	25°55.72‘ E	708	2.25	21	0.430	151.13	105.86	7.85	4.75
586	36°34.32‘ N	25°57.91‘ E	424	1.00	18	0.408	151.13	105.86	10.83	6.56
589	36°45.19’ N	26°35.38‘ E	584	2.13	14.5	0.698	150.87	105.59	8.84	5.34
592	37°47.65‘ N	26°15.72‘ E	1148	0.38	16	0.630	151.46	110.29	5.81	3.72
595	38°15.63‘ N	25°06.17‘ E	662	0.56	19		159.63	114.32	8.84	5.52
596	38°57.32‘ N	24°45.20‘ E	884	0.41	30	0.730	160.50	116.00	7.43	4.70
599	39°45.36‘ N	24°05.61‘ E	1084	0.47	16.5	0.579	195.88	138.51	8.66	5.31
601	40°05.22‘ N	24°36.62‘ E	977	0.27	6	0.750	206.68	145.42	9.97	6.07
602	40°13.03‘ N	24°15.39‘ E	1466	0.78	4	0.820	236.78	164.09	9.36	5.58
338	36°15.03‘ N	03°24.98‘ W	732	0.55	1.75	0.832	294.00	207.05	19.64	11.98
339	36°18.30‘ N	03°08.39’ W	849	0.81	2.25	0.766	280.09	197.86	16.71	10.24
347	36°27.90‘ N	02°55.50‘ W	629	0.63	1.5	0.835	273.71	192.02	19.53	11.85
394	38°53.39‘ N	02°38.40‘ E	646	1.28	8		171.05	124.55	9.90	6.33
395	38°57.70‘ N	02°31.51‘ E	834	0.81	7	0.463	170.54	125.07	8.40	5.42
396	39°09.60‘ N	02°28.78‘ E	562	0.88	10	0.403	167.82	123.45	10.52	6.82
Canyon ø	42°27.60‘ N	03°29.80‘ E	920	1.50	4	0.870			19.7	19.7
Canyon feb	42°27.60‘ N	03°29.80‘ E	920	0.49						
Canyon aug	42°27.60‘ N	03°29.80‘ E	920	2.50						
Slope ø	42°25.60‘ N	03°42.00‘ E	800	1.81	11	0.720			12.8	12.8
Slope feb	42°25.60‘ N	03°42.00‘ E	800	3.21						
Slope aug	42°25.60‘ N	03°42.00‘ E	800	0.41						

922

923 Table 2.

Site	$\delta^{13}C_{Pari}$ (‰ VPDB)	st. dev. (‰)	$\delta^{13}C_{Cpac}$ (‰ VPDB)	st. dev. (‰)	$\delta^{13}C_{Clob}$ (‰ VPDB)	st. dev. (‰)	$\delta^{13}C_{epi}$ (‰ VPDB)	st. dev. (‰)
537			1.11	0.32			1.11	0.32
540A	1.08	0.14	0.76	0.17			1.08	0.14
540B	0.99		1.01	0.13			1.01	0.11
540C	0.76		1.01	0.09			1.01	0.09
585	1.32	0.24					1.32	0.24
586	1.90	0.15					1.90	0.15
589	1.34	0.11					1.34	0.11
592	1.30	0.23					1.30	0.23
595	1.87	0.15					1.87	0.15
596	0.96	0.04					0.96	0.04
599	1.76	0.12					1.76	0.12
601			0.47	0.06			1.02	0.06
602	0.87		0.31	0.20			0.87	
338	1.22		0.64	0.21	0.92		1.22	
339	1.22	0.11	0.86		-0.12		1.22	0.11
347	1.16	0.07	0.82	0.06	-0.16		1.16	0.07
394			1.52	0.01	0.98		1.28	
395			1.54		0.80	0.02	1.1	0.02
396	1.22	0.22	1.76		0.92		1.22	0.22
Canyon ø			0.52	0.04			0.80	0.07
Slope ø			0.39	0.09			1.00	0.06

924

925 Table 2 (continued)

Site	$\delta^{13}C_{Umed}$ stained (‰ VPDB)	st. dev. (‰)	$\delta^{13}C_{Umed}$ unstained (‰ VPDB)	st. dev. (‰)	$\delta^{13}C_{Umed}$ stained (>600µm) (‰ VPDB)	st. dev. (‰)	$\delta^{13}C_{Umed}$ unstained (>600µm) (‰ VPDB)	st. dev. (‰)	$\Delta\delta^{13}C_{Umed\text{-}Epi}$ stained (>600µm) (‰)	st. dev. (‰)	$\Delta\delta^{13}C_{Umed\text{-}Epi}$ unstained (>600µm) (‰)	st. dev. (‰)
537	0.17	0.38	-0.88	0.16	0.35	0.26	-0.82	0.03	-0.76	0.58	-1.93	0.35
540A	-0.46	0.21			-0.21	0.09			-1.29	0.30		
540B	0.13	0.32	0.19	0.35	0.27	0.23	0.46	0.10	-0.74	0.34	-0.55	0.21
540C	-0.14	0.30	0.06	0.32	0.05	0.26	0.28	0.32	-0.97	0.41	-0.74	0.47
585	0.58	0.22	0.50	0.47	0.58	0.22	0.50	0.22	-0.74	0.46	-0.82	0.46
586			0.95	0.46			1.11	0.31			-0.79	0.46
589			0.51	0.46			0.73	0.39			-0.61	0.50
592	-0.14	0.02	0.15	0.25	-0.12	0.00	0.24	0.20	-1.42	0.23	-1.06	0.43
595	0.09	0.53	0.67	0.41	0.37	0.31	0.77	0.41	-1.49	0.46	-1.09	0.56
596	-0.38	0.38	-0.43	0.34	-0.23	0.33	-0.27	0.27	-1.19	0.37	-1.23	0.31
599	0.03	0.26	0.25	0.45	0.12	0.20	0.41	0.28	-1.63	0.32	-1.35	0.40
601	-0.53	0.27	-0.47	0.38	-0.34	0.14	-0.37	0.35	-1.36	0.20	-1.39	0.41
602	-1.11	0.31	-1.09	0.27	-0.98	0.32	-1.13	0.26	-1.85	0.32	-2.00	0.26
338	-0.05	0.26	0.29	0.37	0.07	0.28	0.55	0.23	-1.15	0.28	-0.67	0.23
339	0.02	0.46	0.06	0.20	0.22	0.28	0.16	0.19	-0.99	0.39	-1.06	0.30
347	-0.19	0.25	0.02	0.17	-0.13	0.13	0.41	0.00	-1.29	0.20	-0.75	0.07
394	0.58	0.31	0.61	0.23	0.64	0.26	0.71	0.13	-0.64	0.27	-0.58	0.14
395	0.47	0.30	0.53	0.21	0.53	0.27	0.63	0.13	-0.57	0.27	-0.46	0.13
396	0.66	0.22	-0.64	0.60	0.72	0.19	-0.91	0.42	-0.50	0.29	-2.13	0.52
Canyon ø	-0.32	0.29	-0.32	0.27	-0.17	0.20	-0.21	0.26	-0.97	0.27	-1.01	0.33
Slope ø	0.26	0.30			0.33	0.26			-0.67	0.32		

926

927 Table 3.

U. mediterranea stained

site	n	linear fit	R-squared	p-value
537	24	Y = 0.001379 * X - 1.810017	0.67	$1.1065*e^{-6}$
540A	23	Y = 0.001007 * X - 1.770373	0.70	$5.746*e^{-7}$
540B	14	Y = 0.001257 * X - 1.7208851	0.54	0.0027
540C	46	Y = 0.000943 * X - 1.639236	0.55	$3.769*e^{-6}$
585	3	Y = -0.00224 * X + 1.222667	1.00	0.0082
592	2	Y = 0.00034 * X - 1.6535	1.00	X
595	10	Y = 0.002013 * X - 3.012139	0.75	0.0012
596	7	Y = 0.001822 * X - 2.490764	0.60	0.0401
599	10	Y = 0.001600 * X - 2.789560	0.49	0.0289
601	11	Y = 0.001322 * X - 2.497314	0.70	0.0013
602	15	Y = 0.001143 * X - 2.709099	0.41	0.0102
338	10	Y = 0.001498 * X - 2.265059	0.72	0.0020
339	12	Y = 0.001527 * X - 2.323114	0.48	0.0124
347	7	Y = 0.001126 * X - 2.119201	0.68	0.0232
394	19	Y = 0.000968 * X - 1.680654	0.27	0.0221
395	23	Y = 0.001509 * X - 2.135640	0.40	0.0012
396	20	Y = 0.000789 * X - 1.304866	0.39	0.0034
Canyon aug	7	Y = 0.000516 * X - 1.297794	0.45	0.1015
Canyon feb	21	Y = 0.000701 * X - 1.634263	0.43	0.0012
Slope aug	6	Y = 0.000671 * X - 1.207976	0.34	0.2244
Slope feb	14	Y = 0.001223 * X - 1.518849	0.48	0.0060

U. mediterranea unstained

site	n	linear fit	R-squared	p-value
537	7	Y = 0.000408 * X - 2.169793	0.33	0.1784
540B	16	Y = 0.001017 * X - 1.457536	0.80	$2.4803*e^{-6}$
540C	9	Y = 0.000938 * X - 1.343878	0.53	0.0270
585	4	Y = 0.001610 * X - 1.910093	0.85	0.0808
586	29	Y = 0.001555 * X - 2.035859	0.48	$2.9156*e^{-5}$
589	25	Y = 0.001612 * X - 1.917381	0.58	$1.0482*e^{-5}$
592	28	Y = 0.001001 * X - 1.826222	0.48	$4.5201*e^{-5}$
595	36	Y = 0.000841 * X - 1.740275	0.17	0.0130
596	37	Y = 0.001065 * X - 2.004262	0.30	0.0005
599	12	Y = 0.001031 * X - 2.201211	0.31	0.0600
601	21	Y = 0.000312 * X - 1.871316	0.04	0.3927
602	14	Y = -0.000427 * X - 1.697763	0.12	0.2159
338	10	Y = 0.001343 * X - 1.735480	0.90	$3.0586*e^{-5}$
339	9	Y = 0.000456 * X - 1.408000	0.31	0.1197
347	10	Y = 0.000615 * X - 1.400530	0.71	0.0023
394	22	Y = 0.000573 * X - 1.221329	0.32	0.0060
395	15	Y = 0.000544 * X - 1.301955	0.33	0.0256
396	17	Y = -0.001682 * X - 1.020989	0.50	0.0016
Canyon aug	36	Y = 0.000584 * X - 1.469912	0.28	0.0009

928 **Figure captions**

929

930 Figure 1. Location of the study areas in the Mediterranean Sea and regional bathymetric maps
931 with locations of sample sites in the (a) Mallorca Channel, (b) Alboran Sea, (c) Gulf of Lions
932 and Spanish Slope off Barcelona, (d) Strait of Sicily, and (e) Aegean Sea.

933

934 Figure 2. (a) The $\delta^{13}C$ of epifaunal species (*Cibicidoides pachydermus*, *Cibicides lobatulus*,
935 *Planulina ariminensis*) for each investigated site. Each symbol represents a single
936 measurement. Red symbols mark relocated or fossil tests that haven't been used to calculate
937 $\delta^{13}C_{Epi}$. Green circles show $\delta^{13}C_{Epi}$ values used as approximation of the $\delta^{13}C$ of bottom water
938 DIC. Details on the selection of tests and procedure for the estimation of $\delta^{13}C_{Epi}$ values are
939 discussed in chapter 4.1. (b) The $\delta^{13}C_{Epi}$ versus water depth shows a wider scattering for the
940 Aegean Sea, than for the Western Mediterranean Sea. Colored lines in the background
941 indicate water mass end members of the Mediterranean Sea after Pierre (1999).

942

943 Figure 3. Correlation between $\delta^{13}C_{Umed}$ and $\delta^{13}C_{Epi}$ difference ($\Delta\delta^{13}C_{Umed\text{-}Epi}$) and size classes
944 of *U. mediterranea*. For a better clarity and due to the large number of measured data (see
945 Supplementary Table 1), the linear regressions for each site are given, showing clear
946 ontogenetic trends in $\delta^{13}C_{Umed}$ due to size-independent $\delta^{13}C_{Epi}$ values. The shown data are
947 from live (rose Bengal stained) and dead (unstained) individuals of *U. mediterranea* as well as
948 for the western Mediterranean Sea (left) and Aegean Sea (right). Dashed lines represent
949 already published data (Schmiedl et al., 2004; Theodor et al., 2016).

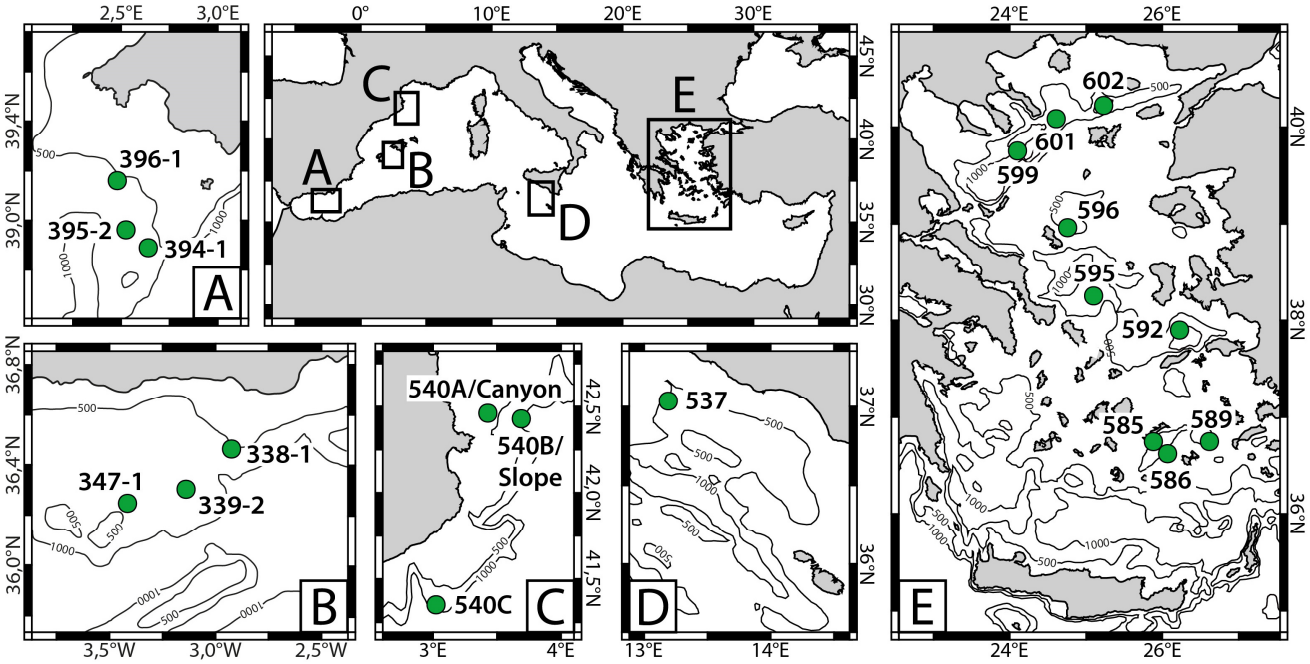
950

951 Figure 4. The $\delta^{13}C$ difference between live *Uvigerina mediterranea* and epifaunal taxa
952 ($\Delta\delta^{13}C_{Umed\text{-}Epi}$) plotted against (a) Median Living Depth (MLD) of *U. mediterranea*, (b) depth of
953 redox boundary in the sediment, (c) total organic carbon (TOC) content of the sediment. The
954 MLD error bars for the canyon and slope sites in the Gulf of Lions reflect the seasonal MLD
955 contrasts of *U. mediterranea* between February and August 1997 (Schmiedl et al., 2004).

Figure 5. The $\delta^{13}C$ difference between live and dead *Uvigerina mediterranea* and epifaunal taxa ($\Delta\delta^{13}C_{Umed\text{-}Epi}$) against organic carbon flux rates (C_{org} flux) calculated from primary productivity in surface waters after Betzer et al. (1984). As in figure 4, satellite derived Primary Production values of Antoine & Morel (1996) (top) and Uitz et al., (2008) (bottom) were used.

Figure 6: Correlation of the $\delta^{13}C$ difference between live *Uvigerina mediterranea* and epifaunal taxa ($\Delta\delta^{13}C_{Umed\text{-}Epi}$) and organic carbon flux rate (C_{org} flux) calculated according to Antoine & Morel (1996) and Betzer et al. (1984). Transparent data from the central and northern Aegean Sea and the Gulf of Lions have been removed from the function since PP-based C_{org} flux values are likely underestimated because of the additional influence of lateral organic matter fluxes on the $\delta^{13}C_{Umed}$ values in these areas.

968 Figure 1



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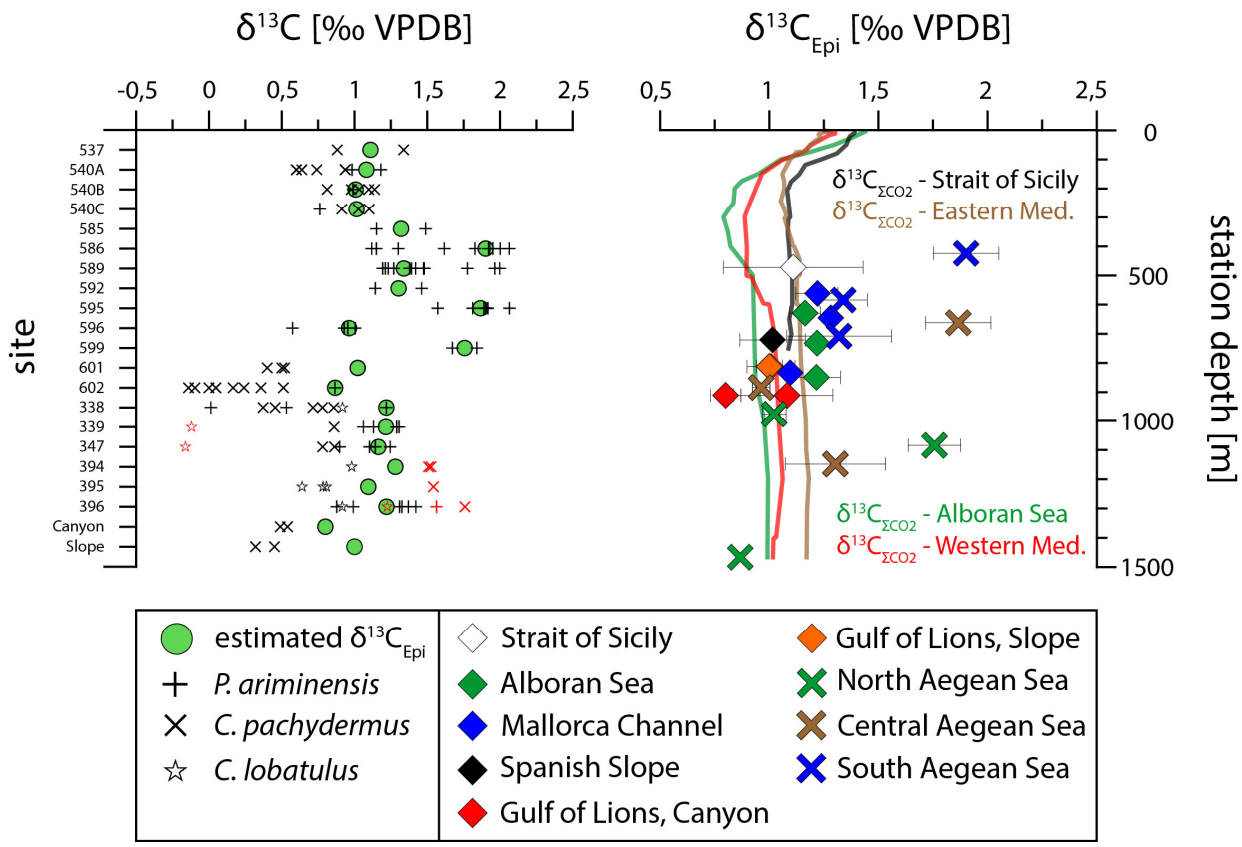
970 Figure 2.



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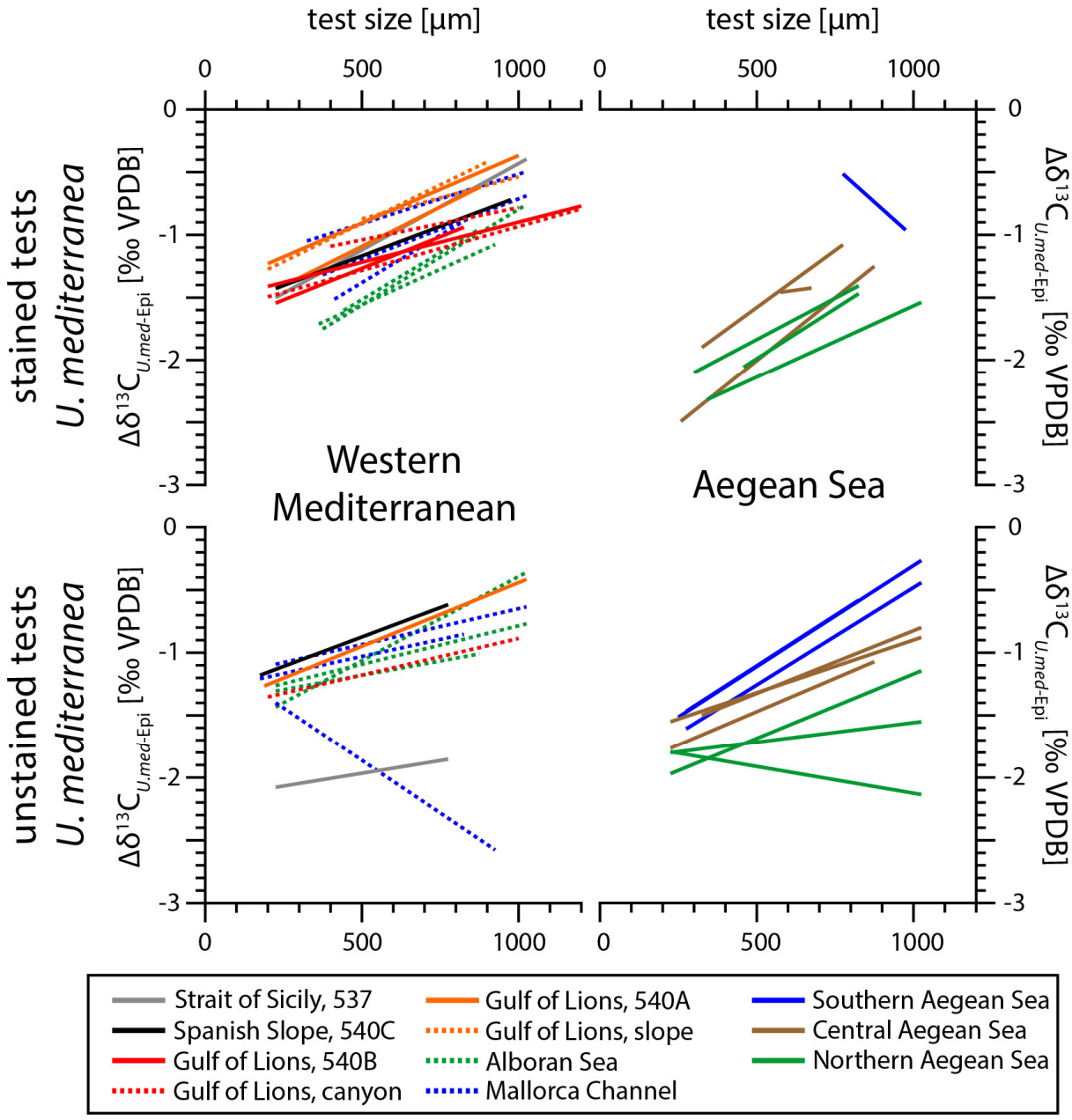
973 Figure 3.



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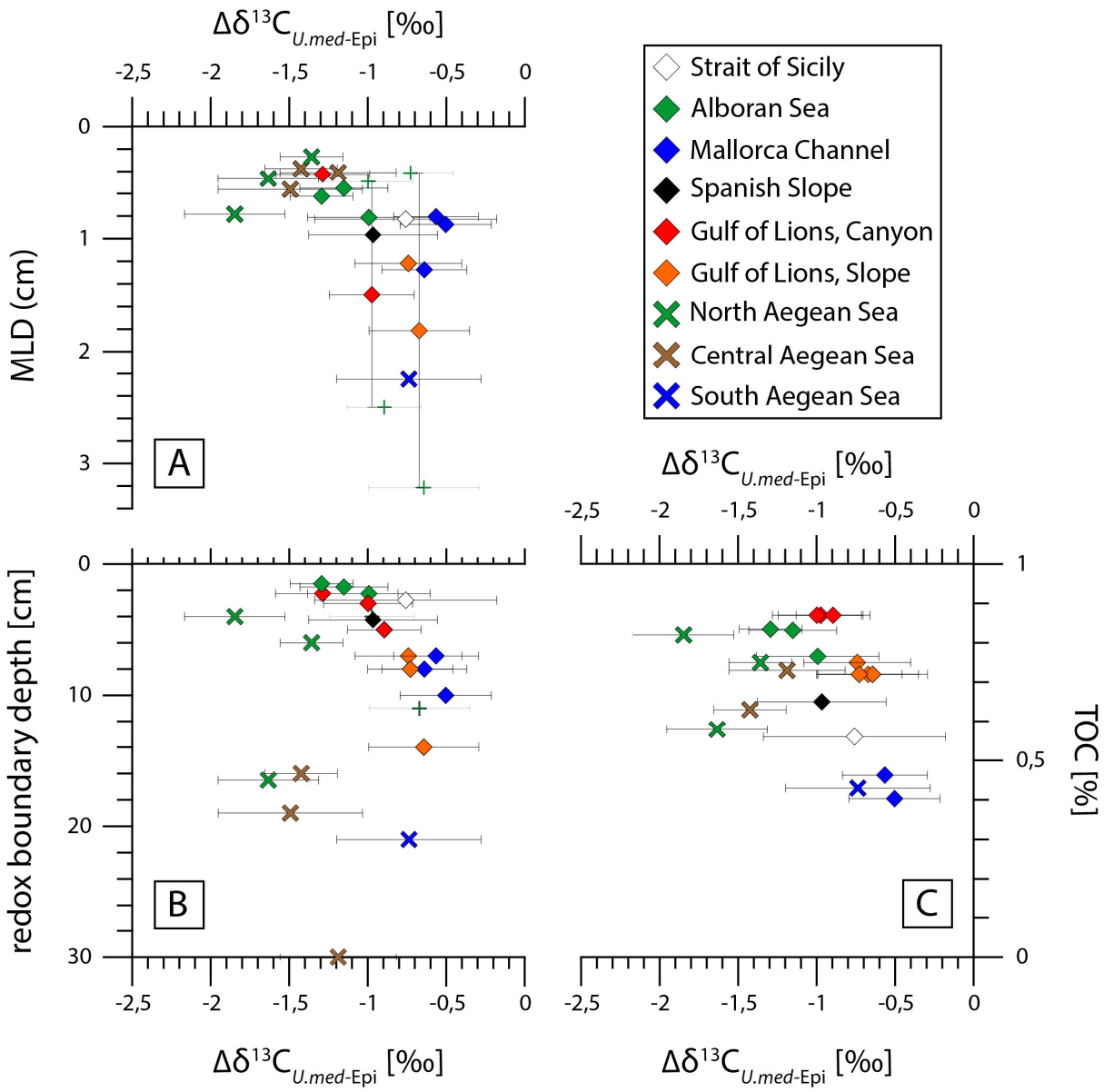
975

976 Figure 4.



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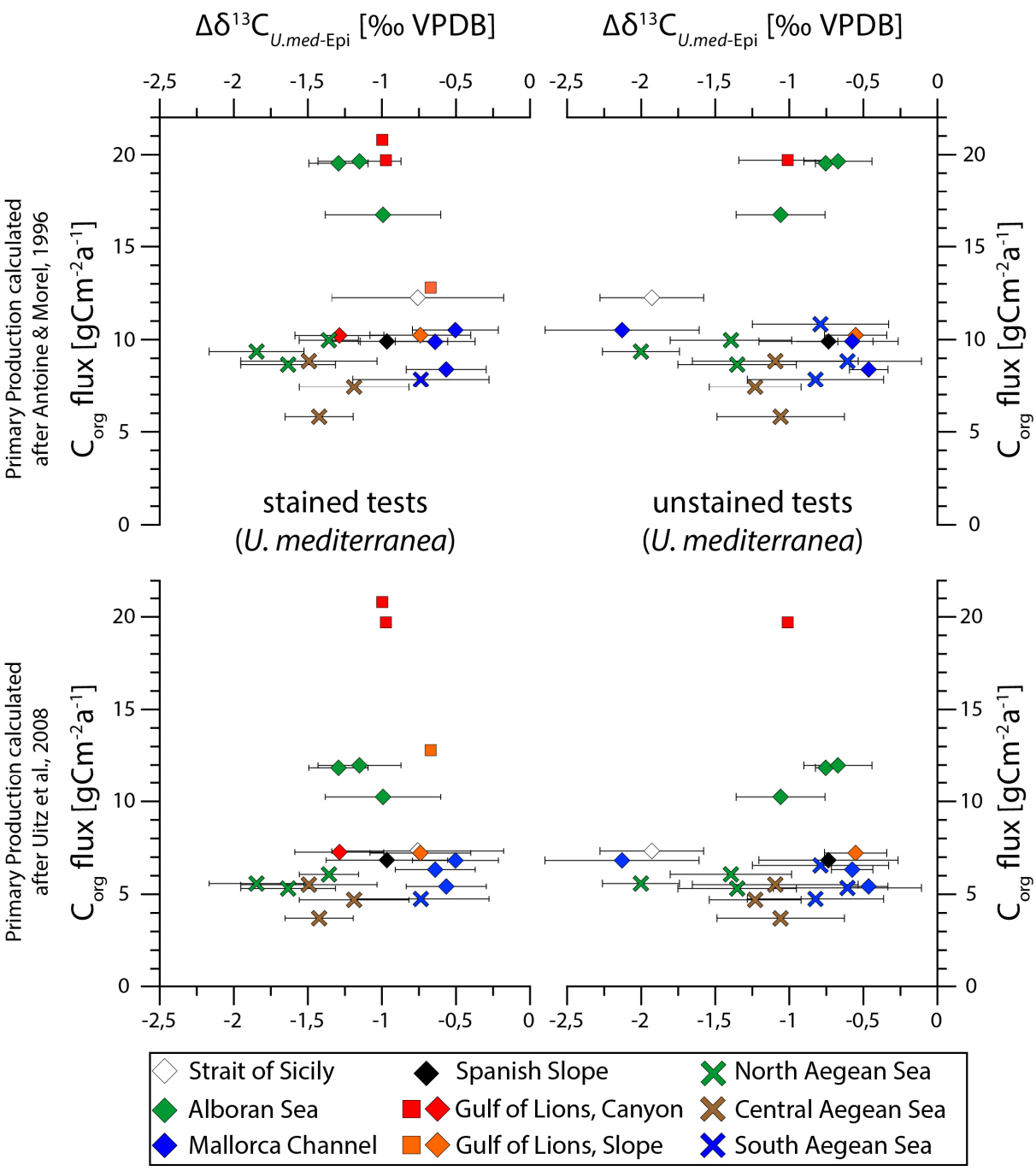
979 Figure 5.



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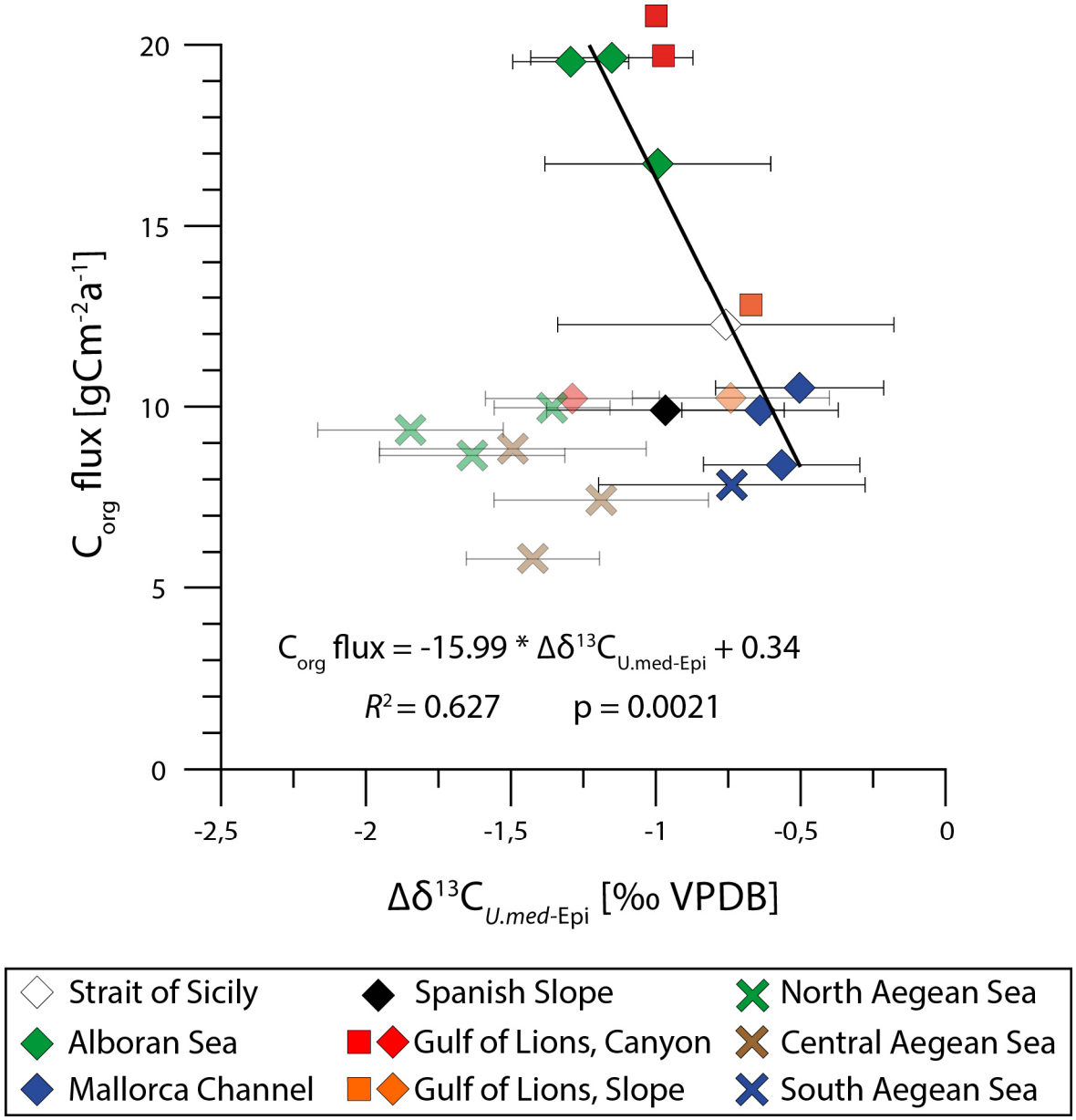
981

982 Figure 6.



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