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Stable carbon isotope deviations 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 to relate the inferred gradient of pore water $\delta^{13}C_{DIC}$ to varying trophic conditions, and to test the potential of developing a 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)*. The $\Delta\delta^{13}C_{Umed\text{-}Epi}$ values range from -0.46 to -2.13‰, with generally higher offsets at more eutrophic sites. Because of ontogenetic shifts in the $\delta^{13}C$ signal of *U. mediterranea* of up to 1.04‰, only tests larger than 600µm were used for the quantitative environmental evaluation. The measured $\delta^{13}C$ deviations are related to site-specific differences in microhabitat, depth of the principal redox boundary, and TOC content. 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 surface primary production. Considering the regional biases and uncertainties, a first $\Delta\delta^{13}C_{Umed\text{-}Epi}$ based transfer function for C_{org} fluxes could be established for the Mediterranean Sea.

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

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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 for the estimation of 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, 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 been also attempts to use multi-species $\delta^{13}C$ records for the estimation of 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 environmental 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 isotopically light organic matter (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 ^{12}C release to the pore water stops when no more OM is remineralized, which mostly coincides with the total consumption of electron acceptors, of which oxygen and nitrate are the usually most important 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.,

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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 $\delta^{13}C$ signal of a certain species exhibits relatively little scattering, 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). Under the influence of well-oxygenated bottom waters, enhanced organic matter fluxes and associated decomposition rates result in steepening of $\delta^{13}C_{DIC}$ 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 inferred $\delta^{13}C$ gradients and organic matter fluxes is impeded 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 demonstrates the necessity of isotopic studies on living foraminifera in relation to their biology and microhabitat. In particular, combined ecological and biogeochemical studies

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on a statistically relevant number of sites and 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 appears particularly suitable for such a study because the present deep-sea environments are characterized by systematically high oxygen contents contrasting with substantial 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 through 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 life 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. Corrected 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 target of this study is the development and evaluation of a transfer function for

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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 live 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 have been 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

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

For stable isotope measurements, stained tests (and unstained tests if no stained tests were available) of three epifaunal species (*C. pachydermus*, *P. ariminensis*, *C. lobatulus*) and one shallow infaunal species (*U. mediterranea*) were selected and each test was measured with a micrometer of an accuracy of 10µm. The stable carbon and oxygen isotope measurements were performed at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research at Bremerhaven with two Finnigan MAT 253 stable isotope ratio mass spectrometers coupled to automatic carbonate preparation devices (Kiel IV). The mass spectrometers were calibrated via international standard NBS 19 to the PDB scale, with results given in δ-notation versus VPDB. Based on an internal laboratory standard (Solnhofen limestone) measured over a one-year period together with samples, the precision of stable isotope measurements was better than 0.06‰ and 0.08‰ for carbon and oxygen, respectively. The $\delta^{13}C$ difference between epi- and shallow infaunal taxa was calculated as a proxy for the pore water signal, i.e. the $\delta^{13}C$ gradient between bottom water and shallow pore water DIC. For *U. mediterranea* this procedure was restricted to measurements from the size fraction >600 µm in order to minimize ontogenetic effects (Schmiedl et al., 2004; Theodor et al., 2016).

Total organic carbon (TOC) concentration in the surface sediment was measured with a Carlo Erba 1500 CNS Analyzer with a precision of 0.02%. Before measurement, $CaCO_3$ was removed by adding 1N HCl. The TOC values of Sites 596, 601 and 602 were taken from Möbius et al. (2010a; b). Bottom water oxygen concentrations are based on CTD measurements stored in the MedAtlas data set. Primary productivity values in surface waters of the year previously to sampling at each site are based on satellite data of the GlobColour project, and were calculated with the 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).

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3. Results

Benthic foraminiferal $\delta^{13}C$ values cover a range of more than 3‰, with higher average values of epifaunal species than the 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 601 (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 for 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 reach 1.38‰ in stained (Site 537) and 2.21‰ in unstained tests (Site 586). The ontogenetic $\delta^{13}C_{Umed}$ trends are generally comparable for 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 reveal a higher variability and a less steep slope of 0.10 ± 0.07‰(100µm)$^{-1}$ (Table 3, Fig. 3). In order to avoid bias due to ontogenetic effects, only $\delta^{13}C$ values of *U. mediterranea* tests larger than 600µm were used for comparison with $\delta^{13}C_{Epi}$ values.

The calculated $\Delta\delta^{13}C_{Umed\text{-}Epi}$ values for stained tests range from -0.64‰ in the Gulf of Lion (slope Site) and -0.74‰ (Site 585) to -1.29‰ in the western Mediterranean Sea (sites 347

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& 540A), to -1.85‰ in the northern Aegean Sea (Site 602) (Table 2). Due to the wider scattering of the $\delta^{13}C$ values of unstained tests, $\Delta\delta^{13}C_{Umed\text{-}Epi}$ values range from -0.61‰ (Site 589) to -2.0‰ (Site 602) in the Aegean Sea and from -0.55‰ (Site 540B) to -1.06‰ (Site 339) in the western Mediterranean Sea and the Strait of Sicily (Table 2). The magnitude of $\Delta\delta^{13}C_{Umed\text{-}Epi}$ values exhibits a relation with trophic conditions at each site, revealing higher differences at more eutrophic sites. Good accordance with the $\Delta\delta^{13}C_{Umed\text{-}Epi}$ show the main redox boundary depth (Fig. 4a) as well as the Median Living Depth of the shallow infaunal *U. mediterranea* (MLD_{Umed}) (Fig. 4b) and less distinctive also the TOC (Fig. 4c). However, a direct correlation with surface water productivity isn't recognizable, neither for stained nor unstained test values (Fig. 4d, e).

The MLD_{Umed}, which is used here to describe its microhabitat, increases at the sites with deeper main redox boundaries. The deepest MLD_{Umed} are 2.13 and 2.25cm in the southern Aegean Sea, while the shallowest depths of 0.27cm and 0.38cm are recorded in the central and northern Aegean Sea, respectively (Table 1). In the Gulf of Lions, the MLD_{Umed} is between 0.43 and 0.49cm in the axis of the Lacaze–Duthiers Canyon and around 1.22cm at the open slope (Table 1, Fig. 4a). The depth of the sediment color change, which marks the shift in redox potential and thus oxygen penetration, ranges from 2.25cm in the Gulf of Lions (Site 540A) to as much as 30cm in the central Aegean Sea (Site 596) (Table 1, Fig. 4b). The measured TOC contents of the surface sediment range from 0.41 % (Site 586, southern Aegean Sea) and 0.58 % (Site 537, Strait of Sicily) to a maximum of 0.82 % (Site 602, northern Aegean Sea) (Table 1, Fig. 4c).

The estimated values for annual Primary Production (PP) range from 106 to 294$gCm^{-2}a^{-1}$. Application of the different algorithms of Antoine & Morel (1996) and Uitz et al. (2008) resulted in an average offset of 54$gCm^{-2}a^{-1}$, with PP values consistently higher when applying the algorithm of Antoine & Morel (1996). The highest PP values occur in the Alboran Sea (274–294 versus 192–207$gCm^{-2}a^{-1}$ according to Uitz et al., 2008) and the northern Aegean Sea (196–237 resp. 139–164$gCm^{-2}a^{-1}$), while the lowest PP values occur in the southern and central Aegean Sea (151–161 resp. 106–116$gCm^{-2}a^{-1}$) (Table 1).

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239 4. Discussion

240 4.1. Stable carbon isotope signal of epifaunal foraminifera in relation to
241 surrounding water masses

242 The $\delta^{13}C$ signal of *Cibicidoides pachydermus*, *Cibicides lobatulus,* and *Planulina*
243 *ariminensis* primarily reflects the $\delta^{13}C_{DIC}$ of the ambient bottom water since these species
244 appear to prefer an epifaunal microhabitat (Lutze & Thiel, 1989; Kitazato, 1994; Schmiedl et
245 al., 2000). Comparison with published water $\delta^{13}C_{DIC}$ measurements confirms $\delta^{13}C_{Epi}$ values
246 close to equilibrium also for the Mediterranean Sea (Pierre, 1999; Schmiedl et al., 2004;
247 Theodor et al., 2016). Further, our new data corroborate previous observations of lacking
248 ontogenetic effects in the $\delta^{13}C_{Epi}$ signal of these taxa (Corliss et al., 2002; Franco–Fraguas et
249 al., 2011; Theodor et al., 2016) (Supplementary Table 1).

250 In the Alboran Sea (Sites 339 and 347), we measured inter-specific $\delta^{13}C_{Epi}$ differences
251 of up to 1.4‰ in unstained individuals. This variability is a result of implausible low $\delta^{13}C_{Clob}$
252 values, probably due to a relocation from shallower depths closer to the coast. Conversely, the
253 $\delta^{13}C_{Cpachy}$ signal in the Mallorca Channel represents glacial values and is probably affected by
254 the admixture of reworked fossil tests at the sediment surface, as indicated by $\delta^{18}O$ values of
255 >4.0‰. For all unstained tests also a shift to higher $\delta^{13}C_{Epi}$ values due to potential dissolution
256 effects should be considered (Edgar et al., 2013). In order to minimize these effects, a large
257 number of tests, if possible, were measured for *C. pachydermus* and *P. ariminensis,* showing
258 commonly 0.3–0.5‰ higher $\delta^{13}C$ values for latter species (Table 2, Fig. 2a). Data of *Cibicides*
259 *lobatulus* have only been used for further evaluation where no tests of other species were
260 available for analysis (Fig. 2a; Theodor et al., 2016).

261 The $\delta^{13}C$ offset between *C. pachydermus* and *P. ariminensis* isn't constant and seems
262 to increase on sites with deeper main redox boundaries. Suggesting a connection therefore
263 with increasing organic matter availability, the varying offsets can be attributed to slight
264 differences in their microhabitat (Table 2; Fig. 2a). While *P. ariminensis* is a strictly epifaunal

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species, living attached on surfaces on 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 (Table 1).

The recorded $\delta^{13}C_{Epi}$ values can be related to different Mediterranean water masses (Fig. 2b). The $\delta^{13}C_{Epi}$ values of the Gulf of Lions and the Spanish Slope off Barcelona are as low as 0.8‰ suggesting a strong Levantine Intermediate Water (LIW) influence (Pierre, 1999). The $\delta^{13}C_{Epi}$ values of the Alboran Sea, the Mallorca Channel, and the Strait of Sicily commonly vary between 1.1 and 1.2‰ and thus reflect the influence of deeper water masses. For the western sites an influence of the Tyrrhenian Deep Water can be assumed. This water mass originates in the Tyrrhenian Sea from a mixture of Levantine Intermediate Water (LIW) and Western Mediterranean Deep Water (WMDW) (Rhein et al., 1999; Send et al., 1999) and is characterized by a $\delta^{13}C_{DIC}$ signature between 1.0 to 1.1‰ (Pierre, 1999). For the Strait of Sicily the eastern position explains the influence of less mixed LIW of Eastern Mediterranean origin with a $\delta^{13}C_{DIC}$ signature of 1.15‰ (Pierre, 1999).

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

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294 **4.2. Biological and environmental effects on the stable carbon isotope signal of**
295 ***Uvigerina mediterranea***

296 The size-dependent changes in the $\delta^{13}C$ signal of *Uvigerina mediterranea* can be
297 attributed to ontogenetic effects. Small tests are depleted in ^{13}C, while larger tests are closer
298 to $\delta^{13}C_{DIC}$ of the ambient pore water (Fig. 3). Relatively low $\delta^{13}C_{Umed}$ values of small tests
299 suggest stronger metabolic fractionation in younger individuals (Schmiedl et al., 2004,
300 McCorkle et al., 2008; Schumacher et al., 2010, Theodor et al., 2016). A linear ontogenetic
301 increase of 0.11‰(100µm)$^{-1}$ was observed at all sites of the western Mediterranean Sea, while
302 a steeper slope of 0.16‰(100µm)$^{-1}$ was recorded in the Aegean Sea (Fig. 3). In addition, the
303 $\delta^{13}C_{Umed}$ values of small individuals from the Aegean Sea were in the order of 1 ‰ lower
304 compared to those from the western Mediterranean Sea.

305 Differences in ontogenetic $\delta^{13}C$ slopes of the related species *U. peregrina* have been
306 attributed to its highly opportunistic response to regional contrasts in organic matter quantity
307 and quality, and seasonality of supply (Theodor et al., 2016). Obviously, similar effects are also
308 operational in ontogenetic $\delta^{13}C$ trends of *U. mediterranea*. In the Aegean Sea, this species
309 seems to respond to strong seasonal contrasts in organic matter fluxes (Siokou–Frangou et
310 al., 2002) resulting in particularly high metabolic activity and low $\delta^{13}C_{Umed}$ values in young
311 individuals. A steepening of the $\delta^{13}C_{Umed}$ slopes from the North to the South Aegean Sea has
312 probably the same reasons as for *U. peregrina* in the Western Mediterranean Sea. Because
313 of the higher number of measured tests, this shift of the slope angles is more obvious in
314 unstained than stained tests (Fig. 3). However, even with an increased number of investigated
315 sites compared to Theodor et al. (2016), a similar trend in $\delta^{13}C_{Umed}$ is not recognizable for the
316 Western Mediterranean Sea. This might be caused by lower differences in the annual food
317 supply between the sites or the in total higher input of organic matter compared to the Aegean
318 Sea.

319 The $\delta^{13}C_{Umed}$ values of unstained individuals from 5cm sediment depth in the western
320 Mediterranean Sea and Strait of Sicily are on average 0.1 to 0.2‰ lower than those of live

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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 live individuals while it is absent in sub-recent specimens. The Suess effect displays the reduction of $\delta^{13}C$ values in the atmosphere and oceans, due to the anthropogenic release of isotopically light CO_2 out of fossil resources, e.g. oil or coal. A similar effect could not be monitored in the Aegean Sea since live and dead individuals were selected from the same sediment depth suggesting 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 could be 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). Similarly, 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). In the Mediterranean Sea subsurface waters are well ventilated resulting in bottom water oxygen concentrations above 4.1mll^{-1} at all sites of 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 logarithmic relations with the MLD of *U. mediterranea*, the depth of the oxygenated layer and to 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

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boundary, exceeding 10cm at some sites, enables *U. mediterranea* to inhabit a relatively wide microhabitat range. In contrast, at the more mesotrophic to eutrophic sites of the Alboran Sea relatively high $\Delta\delta^{13}C_{Umed\text{-}Epi}$ values 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 signature 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 available 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 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 and isotopically heavy C_{org}, recorded by higher TOC contents, but with minor effects on the $\delta^{13}C_{DIC}$ pore water gradient. Latter possibility may not just reduce the $\delta^{13}C_{DIC}$ of the bottom water, but 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 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

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376 $\delta^{13}C$-based transfer function for OM flux rates. In open-ocean settings, the main food source
377 of deep-sea environments is the exported OM from the surface layer, where photosynthetic
378 Primary Production (PP) takes place (e.g. Boyd & Trull, 2007; Bishop, 2009). The majority of
379 produced particulate organic carbon (POC) is recycled within the photic zone. In the open
380 Mediterranean Sea, around 4% of the POC is exported out of the photic zone, which is lower
381 than for other open oceans, caused by a specific nutrient distribution in the Mediterranean Sea
382 (Moutin & Raimbault, 2002; Gogou et al., 2014). So, the remineralization of organic matter is
383 intensified, which leads to reduced fluxes to the sea floor.

384 During transfer from the surface ocean to the deep-sea, the amount of exported OM
385 decreases exponentially reflecting microbial decay (Suess, 1980; de la Roche & Passow,
386 2007; Packard & Gomez, 2013). Various functions have been developed for the estimation of
387 OM fluxes during sinking of particles through the water column integrating numerous
388 observational data (Suess, 1980; Betzer et al., 1984; Martin et al., 1987; Antia, et al., 2001).
389 The different functions reveal a high variability for the active surface layer, while the results for
390 deeper parts of the water column are within a comparable range (Felix, 2014). In our study
391 (Table 1, Fig.5), we applied the function of Betzer et al. (1984) for calculation of the C_{org} fluxes
392 at the different Mediterranean sites using satellite-borne PP data (Antoine & Morel, 1996; Uitz
393 et al., 2008).

394 A comparison with direct PP and export flux measurements of sediment trap studies
395 revealed ambiguous results. The PP values calculated after Antoine and Morel (1996) are in a
396 comparable range to PP measurements in the western Mediterranean (Moutin & Raimbault,
397 2002; Sanchez–Vidal et al., 2004; 2005; Zúñiga et al., 2007, 2008). However, the estimated
398 export fluxes are too high in these areas compared to the direct measurements of the refered
399 studies, probably due to the aforementioned higher remineralization rate in the Mediterranean
400 Sea. However, the discrepancy in export fluxes is partly compensated by the application of the
401 21–30% lower PP values calculated after Uitz et al. (2008). For the Aegean Sea, in contrast,
402 distinctively higher measured PP values have been reported than were estimated (Siokou–
403 Frangou et al., 2002). For the Gulf of Lions measured OM export fluxes exceed the predicted

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values (Heussner et al., 2006), which can be explained by the additional lateral input of organic carbon channeled within the local canyon systems (Schmiedl et al., 2000). In order to compensate these possible additional C_{org} fluxes in marginal basin areas, the application of the function of Antoine and Morel (1996) appears more useful, taking into account a potential overestimation of C_{org} fluxes in open-ocean areas.

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, strong 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 North Aegean rivers and the Black Sea outflow (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 35–81gCm^{-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 on 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 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).

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

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

with a coefficient of determination (R^2) of 0.63 and a significance (p) of 0.0021 (Fig. 6). The estimated C_{org} fluxes can be used to recalculate marine PP, but should be handled carefully, due to the highly possible overestimation caused by lateral advection. Especially in more marginal areas this bias can lead to unreliable recalculated PP values. Likewise, the application outside of the Mediterranean Sea should be biased by differing remineralization rates, due to the specific oceanographic conditions, especially the higher temperatures, in this basin. Therefore, further refinement of this function would require interdisciplinary efforts including a larger number of direct C_{org} flux measurements in sediment trap deployments.

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 slight species-specific difference in the microhabitat can result in significant $\delta^{13}C_{Epi}$

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458 shifts. The $\delta^{13}C$ signal of the strictly epifaunal *Planulina ariminensis* should be preferred, in
459 contrast to the $\delta^{13}C$ signal of the very shallow infaunal *Cibicidoides pachydermus,* which seems
460 to be influenced by pore water DIC.

461 The $\delta^{13}C$ signal of epifaunal taxa lacks ontogenetic effects supporting results from
462 previous studies (Dunbar & Wefer, 1984; Corliss et al, 2002; Theodor et al., 2016). Significant
463 ontogenetic effects were recorded in the $\delta^{13}C$ signal of *Uvigerina mediterranea*. While the
464 ontogenetic increase of $\delta^{13}C_{Umed.}$ is more or less comparable (0.11 ± 0.03‰(100µm)$^{-1}$) in the
465 Western Mediterranean and the Strait of Sicily, a stronger increase and even a regional S-N
466 trend is documented for the Aegean Sea (0.16 ± 0.04‰(100µm)$^{-1}$). In general, the $\delta^{13}C$ values
467 of *U. mediterranea* from the Aegean Sea are more negative when compared to those from the
468 western and central Mediterranean Sea. This regional contrast cannot be reconciled with
469 different vital and pore water effects but instead seem to be caused by enhanced residence
470 times of bottom waters in the partly isolated small basins within the Aegean Sea. In cases of
471 well-oxygenated conditions the $\delta^{13}C_{Umed}$ signal, compared to bottom water, is mainly controlled
472 by regional trophic contrasts and related remineralisation rates. The $\Delta\delta^{13}C_{Umed\text{-}Epi}$ are clearly
473 related to the median microhabitat depth, the depth of the redox boundary (indicating the extent
474 of the oxygenated layer), and to a lower extent to the TOC of the surface sediment. Based on
475 satellite derived primary production estimates C_{org} fluxes were calculated and related to the
476 recorded $\Delta\delta^{13}C_{Umed\text{-}Epi}$ values. Comparison with sediment trap data reveals underestimation of
477 C_{org} fluxes for the marginal areas of the central and northern Aegean Sea and the canyon
478 systems of the Gulf of Lions. In these ecosystems additional lateral transport of resuspended
479 and terrestrial OM contributes substantially to C_{org} fluxes. Considering these biases a first
480 estimation for C_{org} fluxes in open-ocean settings of the Mediterranean Sea could be
481 established.

482

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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).

Table 2. Average stable carbon isotope composition of selected benthic foraminifera with standard deviations. Underlined values of epifaunal species were applied to estimated bottom water $\delta^{13}C_{DIC}$. 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.

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874 Table 1.

Site	latitude	longitude	station depth (m)	MLD_{Umed} (cm)	redox boundary depth (cm)	TOC (%)	PP ($gCm^{-2}a^{-1}$)	C_{org} flux ($gCm^{-2}a^{-1}$)
537	37°02.14‘ N	13°11.35‘ E	472	0.83	2.75	0.560	173.06	12.26
540A	42°27.69‘ N	03°25.64‘ E	911	0.43	2.25		203.97	10.22
540B	42°25.70‘ N	03°41.34‘ E	812	1.22	7	0.750	193.99	10.24
540C	41°21.04‘ N	03°01.36‘ E	721	0.97	4.25	0.650	179.74	9.91
585	36°39.60‘ N	25°55.72‘ E	708	2.25	21	0.430	151.13	7.85
586	36°34.32‘ N	25°57.91‘ E	424	1.00	18	0.408	151.13	10.83
589	36°45.19‘ N	26°35.38‘ E	584	2.13	14.5	0.698	150.87	8.84
592	37°47.65‘ N	26°15.72‘ E	1148	0.38	16	0.630	151.46	5.81
595	38°15.63‘ N	25°06.17‘ E	662	0.56	19		159.63	8.84
596	38°57.32‘ N	24°45.20‘ E	884	0.41	30	0.730	160.50	7.43
599	39°45.36‘ N	24°05.61‘ E	1084	0.47	16.5	0.579	195.88	8.66
601	40°05.22‘ N	24°36.62‘ E	977	0.27	6	0.750	206.68	9.97
602	40°13.03‘ N	24°15.39‘ E	1466	0.78	4	0.820	236.78	9.36
338	36°15.03‘ N	03°24.98‘ W	732	0.55	1.75	0.832	294.00	19.64
339	36°18.30‘ N	03°08.39‘ W	849	0.81	2.25	0.766	280.09	16.71
347	36°27.90‘ N	02°55.50‘ W	629	0.63	1.5	0.835	273.71	19.53
394	38°53.39‘ N	02°38.40‘ E	646	1.28	8		171.05	9.90
395	38°57.70‘ N	02°31.51‘ E	834	0.81	7	0.463	170.54	8.40
396	39°09.60‘ N	02°28.78‘ E	562	0.88	10	0.403	167.82	10.52
Canyon ø	42°27.60‘ N	03°29.80‘ E	920	1.50	4	0.870		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
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				

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876 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

877

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878 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		

879

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880 Table 3.

site	n	*U. mediterranea* stained 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

site	n	*U. mediterranea* unstained 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

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881 **Figure captions**

882

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

886

887 Figure 2. (a) The $\delta^{13}C$ signals of epifaunal species (*Cibicidoides pachydermus*, *Cibicides*
888 *lobatulus*, *Planulina ariminensis*) with estimated $\delta^{13}C_{Epi}$ value for each investigated site.
889 Symbol sizes indicate different test sizes. Red symbols mark relocated fossil tests. Green
890 circles show $\delta^{13}C_{DIC}$ value of the bottom water approximated after $\delta^{13}C_{Epi}$ values. (b) The
891 $\delta^{13}C_{Epi}$ versus water depth shows a wider scattering for the Aegean Sea, than for the Western
892 Mediterranean.

893

894 Figure 3. Ontogenetic trends in the $\delta^{13}C$ difference between *Uvigerina mediterranea* and
895 epifaunal taxa ($\Delta\delta^{13}C_{Umed\text{-}Epi}$) based on different size classes of *U. mediterranea*. Data shown
896 are for live (rose Bengal stained) and dead (unstained) individuals of *U. mediterranea* and for
897 the western Mediterranean Sea (left) and Aegean Sea (right). Dashed lines represent already
898 published data (Schmiedl et al., 2004; Theodor et al., 2016).

899

900 Figure 4. The $\delta^{13}C$ difference between live *Uvigerina mediterranea* and epifaunal taxa
901 ($\Delta\delta^{13}C_{Umed\text{-}Epi}$) plotted against (a) Median Living Depth (MLD), (b) depth of redox boundary, (c)
902 total organic carbon (TOC) content, (d, e) Primary Production in surface waters of the year
903 previous to sampling. The satellite derived PP was calculated with the algorithms of Antoine &
904 Morel, 1996 (d) and Uitz et al., 2008 (e).

905

906 Figure 5. The $\delta^{13}C$ difference between live and dead *Uvigerina mediterranea* and epifaunal
907 taxa ($\Delta\delta^{13}C_{Umed\text{-}Epi}$) against organic carbon flux rates (C_{org} flux) calculated from primary

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908 productivity in surface waters after Betzer et al. (1984). As in figure 4, satellite derived Primary
909 Production values of Antoine & Morel (1996) (top) and Uitz et al., (2008) (bottom) were used.
910
911 Figure 6: Correlation of the $\delta^{13}C$ difference between live *Uvigerina mediterranea* and epifaunal
912 taxa ($\Delta\delta^{13}C_{Umed\text{-}Epi}$) and organic carbon flux rate (C_{org} flux) calculated according to Antoine &
913 Morel (1996) and Betzer et al. (1984). Transparent data from the central and northern Aegean
914 Sea and the Gulf of Lions have been removed from the function since PP-based C_{org} flux values
915 are likely underestimated because of the additional influence of lateral organic matter fluxes
916 on the $\delta^{13}C_{Umed}$ values in these areas.

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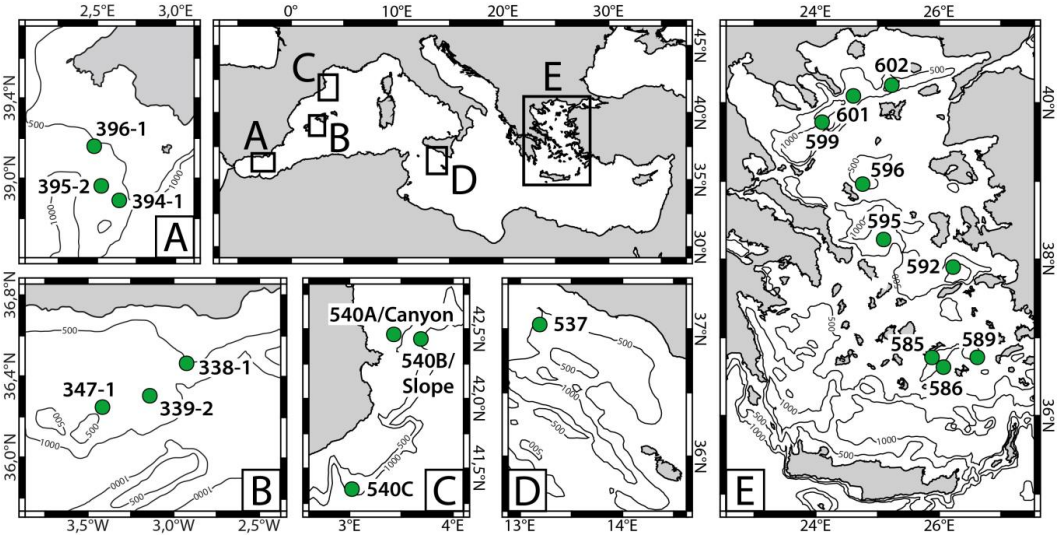
917 Figure 1



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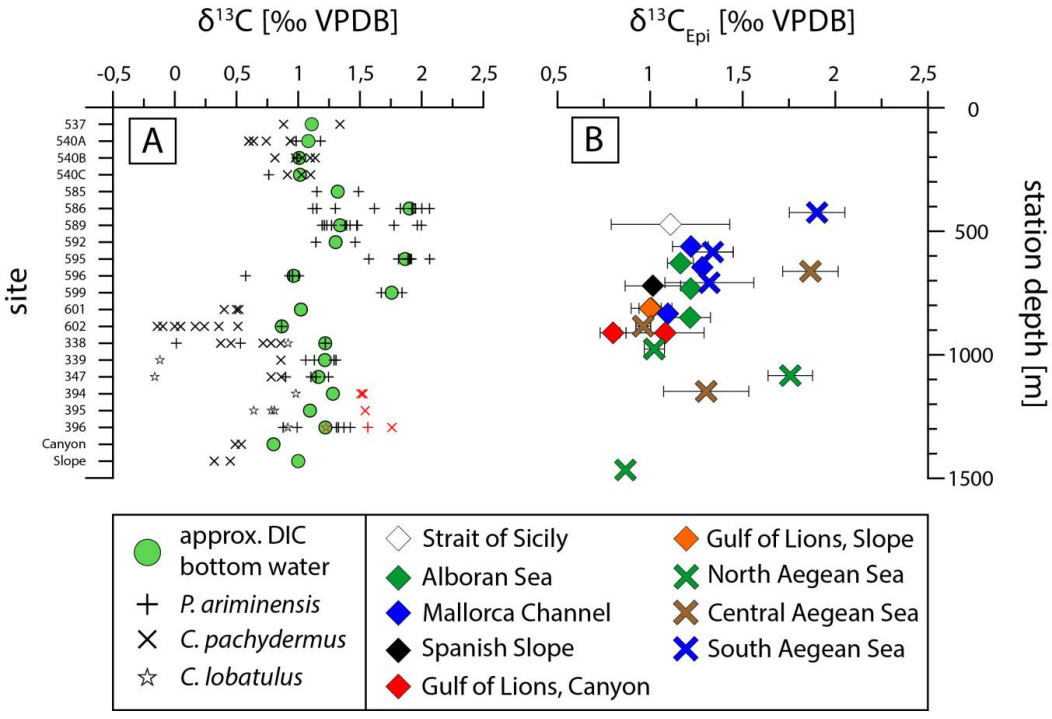
919 Figure 2.



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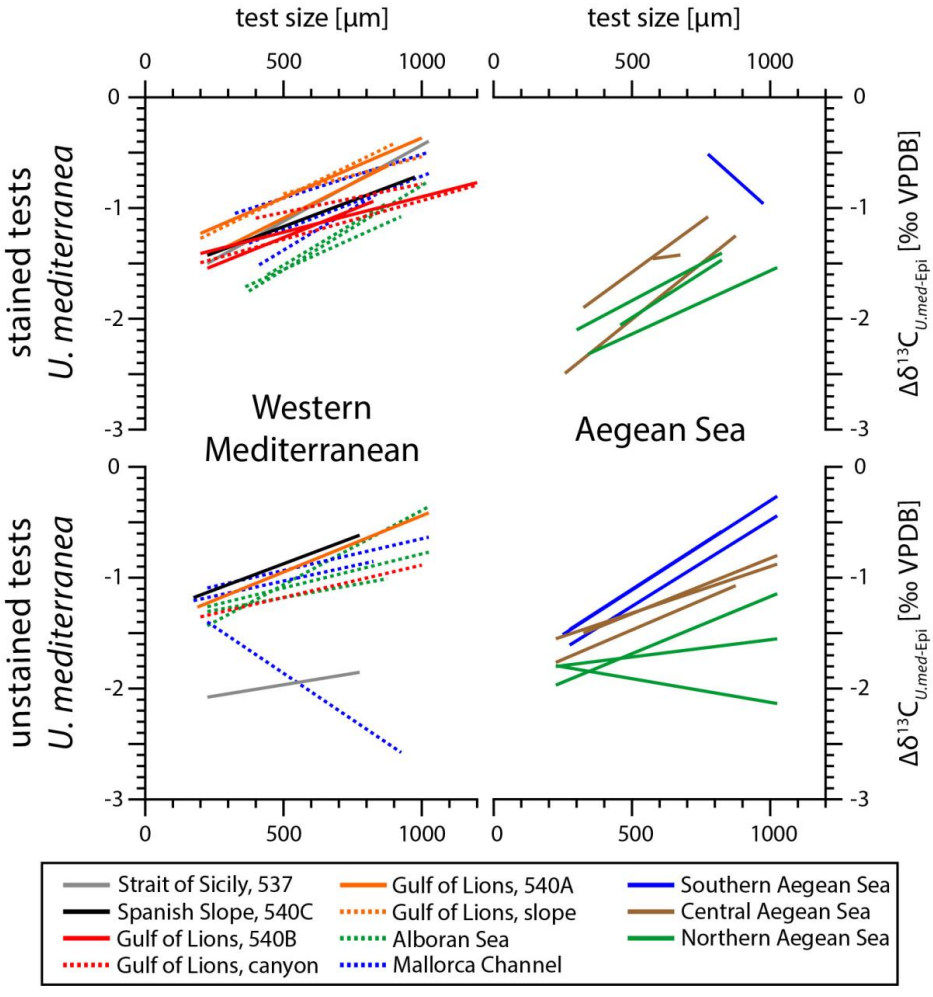
921 Figure 3.



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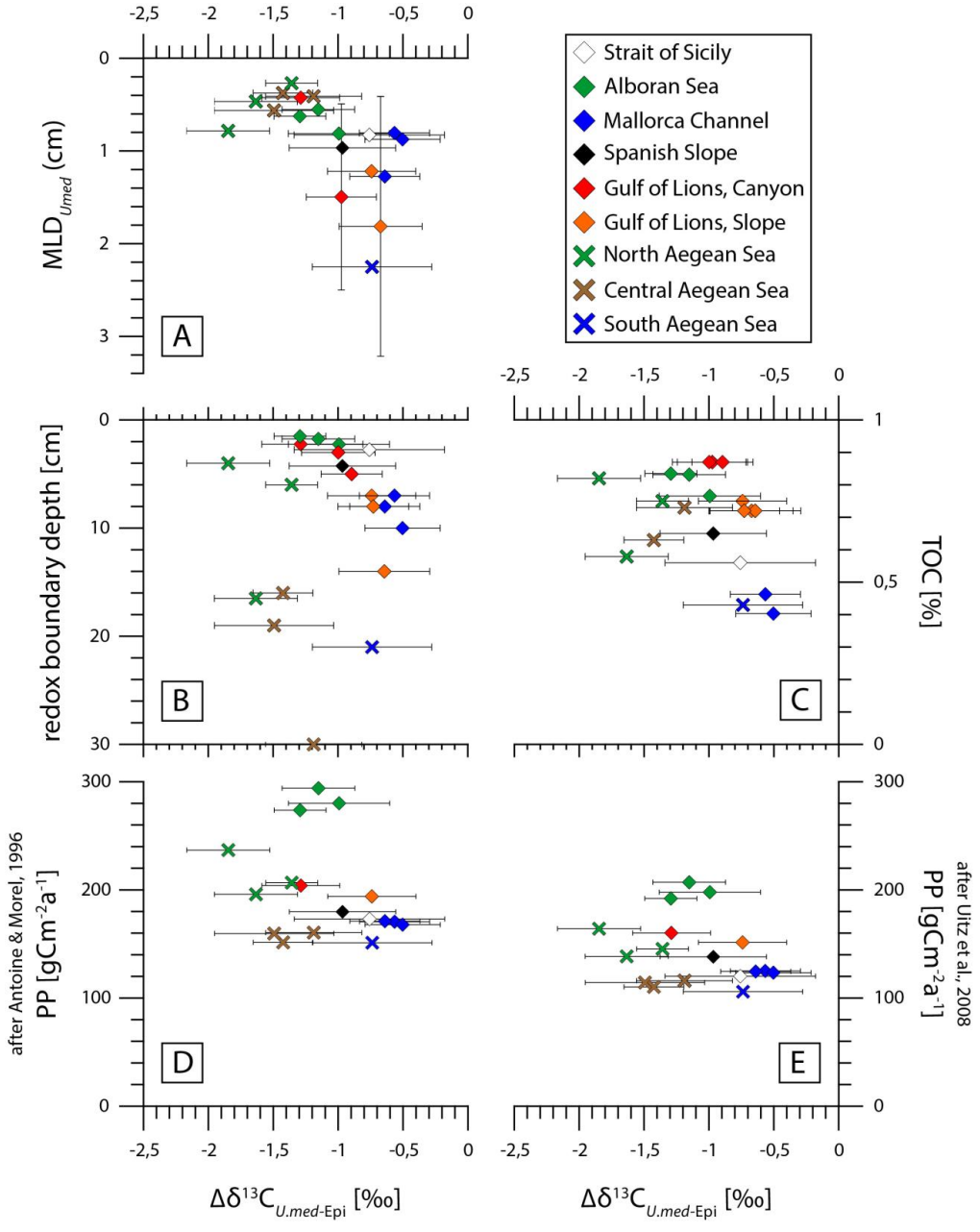
923 Figure 4.



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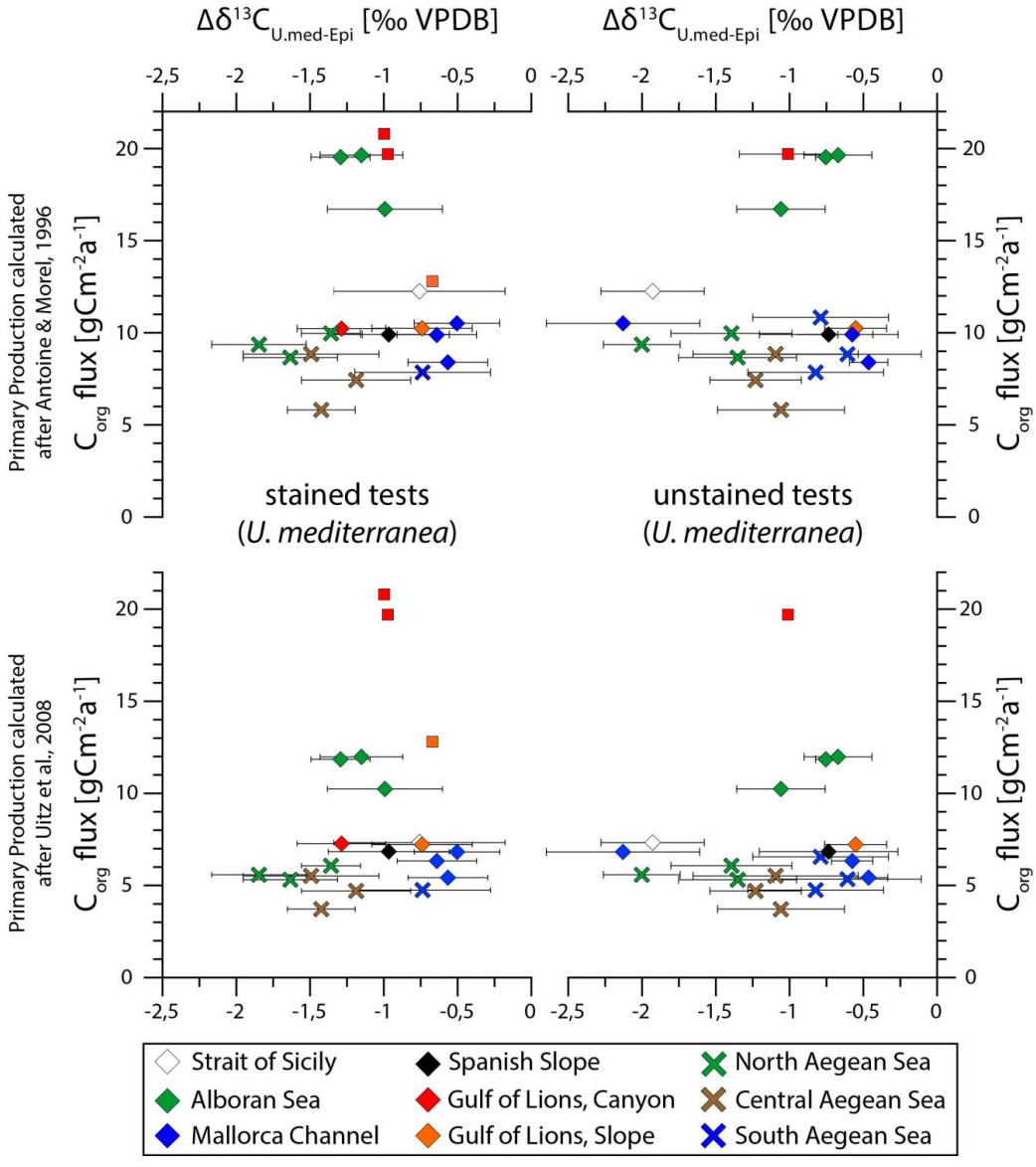
925 Figure 5.



926

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927 Figure 6.