Editor Decision and Response by Authors (primarily Patrick Rafter)

In preparing your revised manuscript, I would request that you please highlight the changes that have been made.

Response: Please find our manuscript—with text updated based on these comments—as both a PDF (with tracked changes highlighted) and a MS Word document (also with tracked changes). The latter should provide the necessary text for publication, assuming our changes are acceptable. We re-state the editor's "additional points" and provide a response to each below.

1. Given the emphasis on 'monospecificity' in this study, I think it is important that your figures illustrating the new benthic foraminiferal radiocarbon data (Fig. 5 and 6) show four curves in each instance (one for each species 'category' shown in Figure 5). Indeed, I think that Figure 5E would also be more informative if the different records from each 'species category' were plotted together with different symbols/lines, instead of a single connected line). This suggestion was made by Reviewer 1 and was not taken up in your response, despite the very useful addition of differentiated benthic dates to Figure 2 (new Figure 3). The further suggestion of Reviewer 2 to also illustrate species used in the CU record with different symbols is also a good one. The interspecies offsets remain a major unresolved issue that is worth highlighting.

Response: The updated manuscript applies the approach from Figure 2 (new Figure 3) to illustrate the different species' values in Figures 5E and 7. We also updated the California Undercurrent site to illustrate the different species' values (data from Marchitto et al. 2007 and Lindsay et al. 2015). These new figures are a more clear visualization of the species differences. We did not apply separate lines connecting each species' values because this would result in a total of 6 overlapping lines (California Undercurrent data, 4 mono-species results, and mixed species results)— a true 'spaghetti'-like plot of lines. We felt that these plots are complicated enough with two lines overlapping plus symbols.

2. Again on Figure 5: it is not clear to me what the lines and symbols represent. Each figure has the CU record in red, and then another line with small black symbols, where some of these small symbols also correspond to large open symbols. Please clarify in the caption what the latter two are, as it currently only refers to one dataset for each subplot as far as I can tell.

Response: We have updated the caption. The larger symbols represent measurements at foraminifera abundance maxima.

3. On the subject of the wood-based age-model: the caution and clear explanation of the fact that these dates reflect maximum ages for a given sediment depth is a welcome inclusion, however, you emphasise in your response to Reviewer 2 that an important aspect of your 'quantitative test' is that the wood dates are

younger than both planktic and benthic dates. In this case it would be helpful to also add to Figure 2 (new Figure 3) all of the existing planktic dates, so that the reader can see how many of the wood dates can be 'tested' in this way. I think that it is important to acknowledge (as Zhao and Keigwin did not, but your manuscript arguably does better) that this is a situation where it is possible to know when the dates are 'really' wrong (e.g. by as much as the surface reservoir age), but not necessarily when they are right. I would note that a 100yr Gaussian uncertainty may not be the best way of dealing with this, given that we know the error in the wood ages is more likely to be biased in one direction (i.e. too old; ages are a maximum for a given depth). I appreciate that this is a tricky issue to address, beyond underlying the caveats, but the addition of the planktic dates to Figure 2 would help the reader see the extent to which they help act as 'tests' for the wood dates (and for how many).

Response: We have added the planktic 14C ages to Figure 3 and new text describing the potential errors when using wood 14C ages to constrain the age model (see paragraph beginning line 280).

4. On the conclusions: I concur with the reviewers that the consistency of the UC and Gulf records with others from around the word is overstated, and that perhaps some more careful wording of the conclusions is warranted, based on a consideration of a wider range of data and models For example, I think that the statement: "...a box model by (Hain et al., 2011) suggests that matching the observed $\Delta 14C$ depletions in the intermediate depth, Northern Hemisphere sites requires unrealistic changes in ocean chemistry (e.g., lower surface ocean alkalinity) and ocean dynamics (i.e., mixing)" needs some further clarification (i.e. in terms of what exactly that model experiment consisted of, and was able to address strictly). Also, the statement that "evidence in support of depleted seawater 14C content during the deglaciation (although often with different timing) includes deep-sea coral $\Delta 14C$ measurements in both the Southern Ocean and North Atlantic (Adkins et al., 1998; Burke and Robinson, 2012; Chen et al., 2015; Robinson et al., 2005)" is accurate but not quite apposite, since none of the coral data referenced show anything like the level of radiocarbon depletion exhibited in the Gulf and CU, and all show a step change around the Bolling-Allerod. This is a notable fact, as is the fact that the vast bulk of existing radiocarbon data from the LGM (i.e. prior to the putative 'flushing events') show that extreme radiocarbon depletion existed at a few sites, but was not at all widespread. 'From whence was this extremely old carbon flushed therefore?', one wonders.

Response 1: Beginning on Line 582, we have adjusted the text to follow your suggestions:

However, using an 18-box geochemical ocean-atmosphere model to simulate glacial-interglacial ocean circulation and carbon cycling, Hain et al., (2011) argue that matching the observed Δ^{14} C depletions in the intermediate depth, Northern Hemisphere sites requires unrealistic changes in ocean chemistry

(e.g., lower surface ocean alkalinity) and ocean dynamics (i.e., mixing). Specifically, to appropriately "age" deep-sea ¹⁴C requires deep-sea anoxia, which is not observed. Furthermore, the release of this deep-sea ¹⁴C to intermediate depths would dissipate much quicker than the several thousand year anomaly shown in Figure 5E.

Response 2: We adjusted the text above and added text (see below) to more accurately and appropriately represent the deep-sea coral 14C (w.r.t. timing and magnitude):

If the extreme deglacial depletion of benthic foraminifera Δ^{14} C at these northeastern Pacific sites cannot be explained by species or habitat bias, bioturbation, or poor age model control, the remaining explanation is that they reflect a change in seawater DIC Δ^{14} C. Looking to other proxy systems, deep-sea coral Δ^{14} C in the North Atlantic and Southern Ocean—archives with excellent age model control and different diagenetic influences—also display depleted deglacial Δ^{14} C during the deglaciation (Adkins et al., 1998; Burke and Robinson, 2012; Chen et al., 2015; Robinson et al., 2005). However, the deep-sea coral Δ^{14} C depletion have a different timing and are not as extreme as observed for the Gulf of California and California Undercurrent sites (Figure 5E).

Extreme lowering of deglacial seawater radiocarbon recorded by both epifaunal and infaunal benthic foraminifera in a wood-dated

sediment core

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- 13 Key Points
- 14 Carbon Cycle
- 15 Climate
- 16 Ice ages 17

18 Abstract:

- 19 For over a decade, oceanographers have debated the interpretation and reliability of
- 20 sediment microfossil records indicating extremely low seawater radiocarbon (¹⁴C)
- 21 during the last deglaciation—observations that suggest a major disruption in
- 22 marine carbon cycling coincident with rising atmospheric CO₂ concentrations.
- Possible flaws in these records include poor age model controls, utilization of mixed,
- 24 infaunal foraminifera species, and bioturbation. We have addressed these concerns
- using a glacial-interglacial record of epifaunal benthic foraminifera ¹⁴C on an ideal
- 26 sedimentary age model (wood calibrated to atmosphere ¹⁴C). Our results affirm—
- 27 with important caveats—the fidelity of these microfossil archives and confirm
- 28 previous observations of highly depleted seawater ¹⁴C at intermediate depths in the
- 29 deglacial northeast Pacific.30

31 1.0 Introduction

- 32 Given modern carbon cycle perturbations (Keeling, 1960), it is critical to understand
- 33 the drivers of natural atmospheric carbon dioxide (CO₂) variability. A prime
- $34 \qquad \text{example of this `natural' atmospheric CO_2 variability is the increase that occurs at} \\$
- 35 the end of each late-Pleistocene ice age (Figure 1) (Petit et al., 1999). The ocean's
- 36 ability to store and release CO_2 makes it a likely driver of past changes in this
- 37 important greenhouse gas (Broecker, 1982).
- 38
- A valuable tool in the effort to characterize the marine carbon cycle over the most
- 40 recent of these intervals is the ¹⁴C content of benthic and planktic foraminifera tests
- 41 (Broecker et al., 1988), which are assumed to reflect the ¹⁴C content of dissolved
- 42 inorganic carbon (DIC) in the waters in which they grew. This tracer provides a
- geochemical "clock" with a predictable decay but ¹⁴C is also affected by a variety of
- other processes, including the time since the water mass exchanged CO_2 with the
- 45 atmosphere, the degree of this exchange, variations in the atmospheric



concentration of ¹⁴C at the time of exchange (Figure 1), as well as the contribution of 46 47 ¹⁴C-depleted carbon via mixing and / or other carbon sources (e.g., seafloor 48 volcanism (Ronge et al., 2016)). 49 We can relate seawater ¹⁴C content to modern ocean conditions by using delta 50 51 notation or Δ^{14} C (Figure 1), which corrects for ¹⁴C decay: 52 $\Delta^{14}C = e^{-14}C age/8033 / e^{-Calendar Age/8267} - 1$ 53 (1)54 (Equation (1) is multiplied by 1000 to give units of per mil [%]). The ¹⁴C age 55 Calendar Age is given in years before 1950 or "before present" (BP).) 56 57 58 The available benthic foraminifera Δ^{14} C records paint a complicated picture of glacial to interglacial seawater ¹⁴C content. For example, a record of benthic 59 for a minifera Δ^{14} C from the intermediate depth subtropical eastern North Pacific 60 (Lindsav et al., 2015; Marchitto et al., 2007) shows Δ^{14} C depleted relative to the 61 62 atmosphere by >400% during the deglaciation (from \approx 19-to-11,000 years BP; see Figure 1). Later work showed benthic foraminifera with similar or even lower Δ^{14} C 63 64 values during the deglaciation in other parts of the intermediate depth ocean (\approx 500-1000 m), such as the 617 m deep Eastern Equatorial Pacific (Stott et al., 2009) and 65 the 596-820 m deep Arabian Sea (Bryan et al., 2010). Given that the lowest observed 66 67 modern intermediate-depth seawater Δ^{14} C is about -300‰ (or only \approx 300‰ lower than the atmosphere) (Key et al., 2004), the low benthic foraminifera Δ^{14} C / old 14 C 68 69 ages suggest much lower Δ^{14} C and older seawater DIC ¹⁴C ages during the 70 deglaciation. 71 72 A leading explanation of these low intermediate depth Δ^{14} C values involves the 73 storage of carbon in an isolated deep-sea reservoir during the glacial period followed by the rapid flushing of this low Δ^{14} C / old 14 C aged carbon through the 74 75 intermediate-depth ocean during the deglaciation-a deep-sea carbon flush that 76 also explains the observed elevation of atmospheric CO₂ concentrations and 77 lowering of atmospheric CO_2 ¹⁴C content (Marchitto et al., 2007). This interpretation 78 is qualitatively supported by observations of lower deep-sea dissolved oxygen 79 concentrations before the deglaciation (Jaccard et al., 2016; Jaccard and Galbraith, 80 2011). 81 82 The ocean carbon flushing hypothesis predicts that deep-sea Δ^{14} C during the glacial period will be lower than the extreme Δ^{14} C lowering of the intermediate-depth Δ^{14} C 83 84 during the deglaciation (Figure 1) because of mixing with shallower waters with 85 higher Δ^{14} C. However, while deglacial Δ^{14} C as low or lower than in Figure 1 is observed in some deep-sea waters during the glacial period (Sikes et al., 2000; 86 87 Skinner et al., 2010; Keigwin and Lehman, 2015) and intermediate-depth waters 88 (Burke and Robinson, 2012)—observations that are consistent with the flushing 89 <u>hypothesis</u>—jt is not clear how these low Δ^{14} C signals are <u>not mixed away en route</u> 90 to the lower latitudes (Hain et al., 2011). Additionally, the lower Δ^{14} C in Figure 1 is

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97 not observed at all intermediate depth sites during the deglaciation (De Pol-Holz et 98 al., 2010; Rose et al., 2010). Furthermore, the extreme Δ^{14} C lowering observed in 99 intermediate-depth benthic foraminifera during the deglaciation does not appear to 100 be quantitatively consistent with an isolated deep-sea reservoir (Hain et al., 2011). 101 102 The inconsistency of the available Δ^{14} C records is compounded by assumptions 103 about the reliability of the foraminifera archive as a recorder of seawater DIC 14C. 104 For example, an important assumption when using planktic foraminifera is that the 105 depth of calcification does not vary based on modern observations (e.g., (Field, 106 2004)). The use of benthic foraminifera seemingly circumvents this problem, and 107 those that live at the sediment-water interface ("epifaunal") have been 108 demonstrated to record seawater carbon chemistry (Keigwin, 2002; Roach et al., 109 2013). However, the abundance of epifaunal benthic foraminifera is typically low 110 relative to benthic species that abide within the sediment ("infaunal"). Rather than 111 recording seawater ¹⁴C content directly, the infaunal species provide a record of 112 sediment pore water carbon chemistry, which may or may not reflect bottom water 113 conditions. 114 115 A further complication to published benthic foraminifera Δ^{14} C observations is that 116 both the epifaunal and infaunal species are typically rare in sediments, leading to 117 the common use of mixed benthic species. The mixed species approach has led, in 118 some rare cases, to anomalously low Δ^{14} C values / old ¹⁴C ages by inclusion of 119 anomalously depleted ¹⁴C Pyrgo spp. (Magana et al., 2010),—an anomaly that may 120 not be a global phenomenon (Thornalley et al., 2015). While mono-species epifaunal 121 benthic foraminifera ¹⁴C measurements exist (Thornalley et al., 2011, 2015; Voelker 122 et al., 1998), we are unaware of any continuous glacial-interglacial records of mono-123 species epifaunal foraminifera ¹⁴C content. (One study used mixed planispiral 124 species, whose morphology predicts an epifaunal habitat (Galbraith et al., 2007).) 125 An additional influence on benthic foraminifera Δ^{14} C is bioturbation (Keigwin and 126 Guilderson, 2009), which is infrequently guantified, even though it can dramatically 127 affect the observed ¹⁴C age (Costa et al., 2018). The doubts raised by the above 128 complications are amplified by converting the benthic foraminifera ¹⁴C age to Δ^{14} C. 129 which requires the user to assign a calendar age to the sediment. 130 131 Finally, constraining the age model of sediment cores typically relies upon several 132 assumptions. For example, planktic foraminifera ¹⁴C is commonly used to identify 133 the calendar age of sedimentary material, although this requires assumptions about 134 the depth habitat of the planktic foraminifera and the 'reservoir age' of the surface 135 waters (the offset between atmosphere and ocean ¹⁴C). Other means for 136 determining the calendar age involve tying temporal variability to other 137 paleoclimate/paleoceanographic records (Marchitto et al., 2007; Stott et al., 2009). 138 In rare instances, the ¹⁴C of wood from terrestrial plants provides a direct recording 139 of atmospheric ¹⁴C, which is well-dated and provides an excellent sedimentary age 140 model (Broecker, 2004; Zhao and Keigwin, 2018), although this work provides some 141 recommendations for utilizing this technique (see below). For our understanding of

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- 155 past and future carbon cycling processes, it is essential that we thoroughly explore
- 156 these influences and build confidence in these sediment proxy records.
- 157

- 158 Here, we provide a test of the fidelity of the benthic foraminifera Δ^{14} C proxy using 159 ¹⁴C measurement of benthic foraminifera species from two sediment cores near th
 - ¹⁴C measurement of benthic foraminifera species from two sediment cores near the mouth of the Gulf of California (white diamond in Figure 2). These sediment cores
- are unusual in that both epifaunal and infaunal benthic foraminifera microfossils areplentiful and allow us a unique opportunity to test the fidelity of the benthic
- for a minifera Δ^{14} C proxy. The for a miniferal abundance were quantified to account
- 164 for bioturbation and the age model is calibrated to the well-constrained
- 165 atmospheric ¹⁴C record (Reimer et al., 2013) via wood found alongside the
- 166 for a minifera. These cores (from hereon, the 'Gulf' sites) allow us to present glacial-
- 167 interglacial ¹⁴C measurements produced from 4 benthic foraminifera, including the
- 168 preferred epifaunal species *Planulina ariminensis* (Keigwin, 2002). The Gulf core
- 169 sites are bathed in the subsurface, northward flowing Mexican Coastal Current (MCC 170 in Figure 2), which are the source of the California Undercurrent (Gómez-Valdivia et
- in Figure 2), which are the source of the California Undercurrent (Gómez-Valdivia et
 al., 2015)—waters that also bathe the well known sites on the Pacific margin of Baja
- al., 2015)—waters that also bathe the well known sites on the Pacific margin of Baja
 California shown in Figure 1 (from hereon, the 'California Undercurrent' sites). This
- 172 cantorna shown in Figure 1 (noninercon, the cantorna of a cantorna shown in Figure 1 (noninercon, the cantorna of a cantorna shown in Figure 1 (noninercon, the cantorna of a cantorna of a cantorna shown in Figure 1 (noninercon, the cantorna of a can
- 174 sedimentary locations—an expectation that we exploit to examine the potential for
- 175 diagenetic alteration of the benthic foraminifera Δ^{14} C observations relative to
- 176 sedimentation rates, which are significantly lower at the Gulf sites (≈ 2 to 5 cm kyr⁻¹;
- 177 our study) relative to the Undercurrent sites (>25 cm kyr⁻¹; (Lindsay et al., 2015;
- 178 Marchitto et al., 2007)) (where 'kyr' is 1000 years). These and other hydrological,
- geochemical, and diagenetic influences on benthic foraminifera Δ^{14} C are examined
- below with the goal of answering an important question: are these benthic
- 181 for a for a minifera Δ^{14} C records recording an extreme lowering of seawater Δ^{14} C during 182 the deglaciation?
- 183

184 **2.0 Materials and Methods**

- 185 Sediment from Gulf of California sites LPAZ-21P (22.9°N, 109.5°W; 625 m) and
- 186 ET97-7T (22.9°N, 109.5°W; 640 m) (white diamond in Figure 2<u>; Table 1</u>) was
- 187 washed using de-ionized water in a 63- μ m sieve. Foraminifera abundance estimates
- 188 of *Planulina ariminensis* (benthic; epifaunal species), *Uvigerina peregrina* (benthic;
- 189 shallow infaunal species), *Trifarina bradyi* (benthic; deep infaunal species), mixed
- 190 *Bolivina* (benthic; deep infaunal species), and *Globogerina bulloides* (planktic
- 191 species) were made after quantitatively dividing <u>the >150 μ m fraction of</u> each
- sample using a Green Geological aluminum microsplitter. These estimates were
- made for all samples from core LPAZ-21P and select samples from core ET97-7T.
- Preliminary work measured the ¹⁴C age of mixed benthic species from the ET97-7T
- core site and although the species abundance was not quantified, they primarily
- 196 included *Planulina* spp., *Uvigerina* spp., and *Trifarina* spp.
- 197
- 198 **2.1** Radiocarbon measurements
- 4

- 200 Monospecies for aminifera and wood were selected for ¹⁴C analysis from the >250
- $201 \hspace{0.5cm} \mu m \ fraction \ from \ both \ Gulf \ sediment \ cores. \ Each \ for a minifera \ sample \ was \ sonicated$
- 202 in methanol (\approx 1 minute) to release detrital carbonates trapped within open
- 203 microfossil chambers. At least 10% of each sample was dissolved using HCl to
- remove secondary calcite (precipitated post-deposition), though in-house tests with
- and without this pretreatment yielded identical results for these core sites. Wood
- fragments from the >250 μm fraction were prepared using standard acid-base-acid
 treatments.
- 208

Samples were graphitized following (Santos et al., 2007) and analyzed at the Keck
 Carbon Cycle Accelerator Mass Spectrometry (KCCAMS) laboratory at University of

- 211 California, Irvine (Southon et al., 2004). We report radiocarbon as Δ^{14} C in units of
- 212 per mil [‰] (see equation (1) above), which is corrected for decay based on its age 213 normalized to 1950, according to convention (Stuiver and Polach. 1977). Analysis of
- 213 normalized to 1950, according to convention (Stuiver and Polach, 1977). Analysis of
 214 a sedimentary standard (FIRI-C) alongside measurements indicates a combined
- 14 a set line for a set line f
- 216 | full size sample ($\approx 0.7 \text{ mg of C}$) to ±500 years for very small samples (< 0.1 mg of C).
- Because of the similar location of the sites near the mouth of the Gulf of California,
- we combined the 14 C measurements from both cores.
- 219

220 **2.2** Oxygen and carbon stable isotopic measurements

The ¹⁸O/¹⁶O and ¹³C/¹²C of benthic foraminifera was measured using a Kiel IV Carbonate Device coupled to a Delta XP isotope ratio mass spectrometer at the University of California, Irvine. Isotopic ratios are reported in delta notation, where: $\delta^{13}C = ({}^{13}C/{}^{12}C_{sample} / {}^{13}C/{}^{12}C_{standard} - 1)$ and $\delta^{18}O = ({}^{18}O/{}^{16}O_{sample} / {}^{18}O/{}^{16}O_{standard} - 1)$. Each was multiplied by 1000 to give units of "per mil". The standard for both measurements is VPDB.

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228 2.3 Age model construction for Gulf of California sediment cores

229 The age model for LPAZ-21P (between 30,000-to-12,100 years Before Physics or 230 "BP," where BP is 1950) is constrained by 13 microscopic wood fragments 231 calibrated to calendar ages using CALIB7.1 (Stuiver et al., 2017) with the IntCal13 232 atmospheric ¹⁴C dataset (Reimer et al., 2013) (<u>squares</u> in Figure 3<u>A and 3C</u>). Five 233 wood measurements from LPAZ-21P did not pass our test for use as an age model 234 constraint (upside-down triangles in Figure 3C and see text below). All LPAZ-21P 235 depths shallower than 63 cm are notably darker, changing from light to very dark 236 brown over a depth interval of ≈ 2 cm. The onset of this change is constrained to be 237 vounger than 12,100±1,100 years BP (12.1±1.1-kyr BP) by a calibrated wood ¹⁴C 238 age (see Appendix). There was a lack of suitable wood in LPAZ-21P in Holocene-239 aged sediments and our age models for this interval are constrained using U. 240 peregrina ¹⁴C ages (circles in Figure 3A), corrected for a modern reservoir age of 241 1240 years based on nearby seawater DIC ¹⁴C age observations at 600 m (Key et al., 242 2004) and converted to calendar ages using CALIB7.1 (Stuiver et al., 2017). These 243 Holocene ¹⁴C ages are not tied to foraminifera abundance maxima and hence the

244 Holocene calendar ages should be considered preliminary. The youngest calendar

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- 248 age for LPAZ-21P was 5.3-kyr BP, suggesting piston core over-penetration during 249 sediment coring. Samples younger than the LPAZ-21P coretop were obtained from 250 the LPAZ-21PG core, whose age model was constrained identical to the Holocene-251 aged sediments of LPAZ-21P (see above). The Bayesian age model program BACON 252 (Blaauw and Christen, 2011) was used to estimate the age and model error between 253 the age model constraints. 254 255 The ET97-7T age model is constrained in three ways: using ¹⁴C ages of 5 pieces of 256 microscopic wood from 18.9- to 15.3-kyr BP (diamonds in Figure 3A and 3C); using 257 U. peregrina ¹⁴C ages corrected for reservoir age in Holocene-aged sediment; and by 258 synchronizing the apparently region-wide transition from light to dark-colored 259 sediments (van Geen et al., 2003) to 12.1-kyr based on the wood-constrained age 260 from LPAZ-21P ("X"s in Figure 3A and 3D). In lieu of reflectance data to quantify the Patrick Rafter 9/20/2018 10:04 AM 261 brightness of the sediment cores, we present Ca/Al estimated using X-Ray Deleted: pink square 262 Fluorescence (see Method below). The reasoning behind using Ca/Al is that this 263 metric: (1) Normalizes changes in terrestrial Ca input by dividing by Al and (2) Is 264 sensitive to the abundance of calcium carbonate microfossils. The sudden lowering 265 of Ca/Al at \approx 65 cm in LPAZ-21P and \approx 71 cm in ET97-7T is coincident with 266 decreased abundance of foraminifera and this presumably causes the darkening of 267 these and other Holocene-aged sediments across the region. Ages between these Patrick Rafter 9/20/2018 10:07 AM 268 constraints were estimated using BACON, as was done for the LPAZ-21P cores. Moved (insertion) [2] 269 270 2.4 X-Ray Fluorescence 271 We estimated the Ca/Al of LPAZ-21P and ET97-7T using an Avaatech XRF core 272 scanner at the Scripps Institution of Oceanography Sediment Core Repository. The 273 archived halves of the sediment cores were lightly scraped to expose less oxidized 274 sedimentary material before analysis. More detailed methods (including software 275 and signal processing) are identical to those previously described in (Addison et al., 276 2013). 277 Patrick Rafter 9/20/2018 10:07 AM 278 2.5 Wood ¹⁴C age test Moved up [2]: Ages between these 279 Terrestrial plant life must have a younger ¹⁴C age / higher Δ^{14} C than all constraints were estimated using BACON, as 280 contemporaneous foraminifera because of the air-sea difference in ¹⁴C content (e.g., was done for the LPAZ-21P cores. 281 see Figure 1) and we used this inherent ¹⁴C age difference to check for Patrick Rafter 9/27/2018 4:34 PM contemporary deposition of the wood and microfossils in Gulf sediments. Fourteen 282 Deleted: out of 20 microscopic wood fragment ¹⁴C ages passed the test and include one 283 Patrick Rafter 9/27/2018 9:02 AM 284 interval that may have been influenced by macrofauna consumption and excretion Deleted: Fifteen 285 has a wood ¹⁴C age that is younger than foraminifera (see below). 286 287 One wood measurement that spectacularly failed this test came from presumably 288 mid-to-late-Holocene sediment (i.e., <12-kyr BP aged sediments based on the depth 289 below seafloor). However this wood yielded a ¹⁴C age of >25-kyr (see upside down 290 triangles in Figure 3). We explain this remarkable ¹⁴C age difference as the erosion 291 and deposition of relict wood stored on land before washing to the Gulf during a 292 rain event. The other wood measurements that failed this test gave ¹⁴C ages typically 293 within measurement error or were $\approx 1000^{14}$ C years older than for a minifera 14 C age.
 - 6

300 In total, 5 out of 20 wood ¹⁴C measurements were older than foraminifera in our 301 sediment cores relative to 1 out of 26 wood ¹⁴C measurements by the only other 302 study with similar length age model (Zhao and Keigwin, 2018). This difference may 303 be because faster sedimentation rate of Zhao and Keigwin, (2018) (20-60 cm kyr-1) 304 leads to less bioturbation and a faster burial of the wood alongside foraminifera 305 microfossils. Otherwise, the difference in rejections could be explained by our 306 measurement of all wood, whereas (Zhao and Keigwin, 2018) only measured wood 307 that still retained bark.

308 309 In light of this unusual application of calibrated ¹⁴C ages on wood in a marine setting, 310 it is important to understand the potential errors. We assigned all calibrated wood ages a ± 100 year uncertainty added in quadrature to the measurement and 311 312 calibration error to account for possible lag in seafloor deposition. Note that the 313 asymmetry of any errors associated with assuming contemporary growth of wood 314 and foraminifera must be considered: if we underestimate the time from wood 315 growth to sediment deposition, the actual calendar age of the sediment would be 316 *younger* than the calendar age given in this study; hence foram Δ^{14} C values would be 317 even *lower* than the large depletions shown here (see equation 1 and Results). 318 Additionally, it is possible that a longer-than-expected time period between wood 319 growth and sediment deposition could be "masked" by declining atmospheric ¹⁴C 320 concentrations (Figure 1), allowing the wood ¹⁴C age to pass our test for inclusion in 321 the age model. These different histories for the wood found in our sediment cores 322 would mean the calendar age is younger than we have assumed, adjusting our 323 benthic foraminifera Δ^{14} C values to lower values than reported below. Given these 324 potential influences on a wood ¹⁴C age-constrained age model, the uncertainty 325 should primarily include the younger calendar age and not the ±100 year Gaussian 326 uncertainty we assume. However, without a more exhaustive statistical study of age 327 model errors when using wood, it is simpler and more conservative to utilize a 328 Gaussian age model error. 329

330 Given these potential errors, it is worth considering the modern ¹⁴C age difference 331 between seawater at the sediment-water interface and the atmosphere. A measurement of seawater DIC ¹⁴C age close to our core site and depth (at 22°N. 332 333 110°W at 598 m), gives a ¹⁴C age of 1240 years BP. Assuming that DIC at this depth 334 has not vet been seriously impacted by bomb ¹⁴C (Key et al., 2004) this would 335 predict a pre-bomb wood-to-benthic foraminifera ¹⁴C age difference of 1240 years 336 <u>BP.</u> This is consistent with our data presented below, where the ¹⁴C age difference 337 between concurrent wood and benthic foraminifera *P. ariminensis* and *U. peregrina* 338 varies between this and even larger ¹⁴C age differences (Table 2). 339

340 **3.0 Results**

- 341 **3.1 Age model and sedimentation rates**
- 342 The old coretop age for the LPAZ-21P core (5.3-kyr BP) indicates a poor recovery of
- 343 the youngest sediments by the piston core, similar to nearby coring sites on the
- 344 Pacific margin (van Geen et al., 2003). The LPAZ-21PG gravity core calendar ages

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Moved up [3]: A measurement of seawater DIC ¹⁴C age close to our core site and depth (at 22°N, 110°W at 598 m), gives a ¹⁴C age of 1240 years BP. Assuming that DIC at this depth has not yet been seriously impacted by bomb ¹⁴C (Key et al., 2004) this would predict a pre-bomb wood-to-benthic foraminifera ¹⁴C age difference of 1240 years BP.

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Deleted: A measurement of seawater DIC seawater DIC ¹⁴C age close to our core site and depth (at 22°N, 110°W at 598 m), gives a ¹⁴C age of 1240 years BP. Assuming that DIC at this depth has not yet been seriously impacted by bomb ¹⁴C (Key et al., 2004) this would predict a pre-bomb wood-to-benthic foraminifera ¹⁴C age difference of 1240 years BP. However, the average ¹⁴C a [...]

- 363 range from 7954 to 504 years BP, suggesting that it recovered much of the material 364 missed by the piston core. Both cores give similar sedimentation rates of 16 to 18 365 cm kyr⁻¹ over this Holocene interval (see Figure 3A). The nearby trigger core ET97-366 7T gives a slightly lower sedimentation rate for this time interval (pink in Figure 3), 367 which may result from regional hydrographic differences, different seafloor 368 dynamics, or sediment recovery based on different coring technology. Core recovery 369 equipment may also explain differences in downcore sedimentation rates between 370 the sites (5 cm kyr⁻¹ versus 19 cm kyr⁻¹ in ET97-7T during the 13-to-15-kyr BP 371 interval; Figure 3). 372 373 A wood ¹⁴C age-constrained age model has only been applied twice before (Broecker, 374 2004; Zhao and Keigwin, 2018) and it is worth quantifying the suitability of this 375 approach in our cores. First, we applied a quantitative test: the wood ¹⁴C age must 376 be older than all coexisting foraminifera ¹⁴C ages. This test included planktic
- 377 foraminifera measurements that will be discussed in a following manuscript. The 378 difference between benthic foraminifera and wood ¹⁴C ages is illustrative of the 379 effectiveness of this test. The difference between the ¹⁴C age of benthic foraminifera 380 (P. ariminensis and U. peregrina) and coexisting, wood that passed our test is 381 2346±1599 years (n=14) and 2309±1063 years (n=14), respectively (Table 2). Only 382 comparing wood with foraminifera abundance maxima gives a ¹⁴C age difference of 383 3353±1957 years (P. ariminensis; maximum of 5815 years, minimum of 1077 years, 384 n=6) and 2697±1117 years (U. peregrina; maximum of 4145 years, minimum of 385 1480 years, n=6). These values are consistent with bottom water at our core sites 386 that are near or older than the modern, pre-bomb seawater - atmosphere ¹⁴C age 387 difference of 1240 years (see above). Given these results, we argue that our test for 388 excluding wood ¹⁴C ages is appropriate, but that unlikely circumstances may have 389 existed that could hide the timescale of deposition. In the event of a longer-than-390 expected time between wood growth and deposition in the sediment, the calendar 391 age would be biased to younger ages, making benthic foraminifera Δ^{14} C values even 392 more depleted than calculated (Figure 5).

394 The excellent age model controls provided by wood ¹⁴C provide us with a powerful 395 (and not always flattering) insight to the sedimentation rates of the Gulf cores. For 396 example, our wood-constrained calendar ages identify two periods of slow 397 sedimentation (or possibly hiatus events) in LPAZ-21P (between 22.7- to 19.5-kyr 398 BP and 12.1- to 9-kyr BP; see grey bars in Figures 3, 4, and 6). The earlier interval is 399 bracketed by wood-constrained calendar ages while the shallower / more recent 400 sedimentation rate slowdown begins approximately at the end of the Younger Dryas 401 or less than \approx 12.1-kyr BP.

402

403 **3.2 Foraminifera abundance estimates**

404 The abundance of four benthic and one planktic foraminifera in the LPAZ-21P core

405 is highly variable with the planktic species *G. bulloides* as high as >6000 g⁻¹ of

406 sediment (Figure 4). The least abundant foraminifera was P. ariminensis, which had

407 peak values just over 200 g⁻¹. Abundance of *G. bulloides* and all other planktic

408 for a minifera (not shown) in these sediments dropped sharply after 12.1-kyr BP—a



- 409 loss of planktic foraminifera preservation that is also seen at the nearby California
- 410 Undercurrent site (red diamond in Figure 2) (Lindsay et al., 2015). The abundance
- 411 of *P. ariminensis* also drops to zero after 12.9-kyr BP, while *U. peregrina* and *T.*
- 412 *bradyi* decline to lower, but persistent values \approx 2-kyr later. *Bolivina* spp. are known
- 413 to persist in low oxygen waters and are the most abundant foraminifera in LPAZ-
- 414 21P and LPAZ-21PG sediments for the past 7-kyr.
- 415
- 416 It is important to identify the abundance of sedimentary foraminifera when
- 417 measuring ¹⁴C because the vertical mixing of sediment by macro- and micro-fauna
- 418 (bioturbation) can grossly bias the ¹⁴C results (Keigwin and Guilderson, 2009)
- 419 causing foraminifera ¹⁴C ages to be older on the shallow side of abundance peaks,
- 420 and vice versa. This effect was recently shown for Juan de Fuca Ridge sediments,
- 421 where foraminifera ¹⁴C measurements shallower than a large abundance maxima
- were biased to "old" ¹⁴C ages (Costa et al., 2018). Below we explore the ¹⁴C age and 422
- 423 Δ^{14} C trends for each benthic foraminifera species. 424

425 3.3 Comparing benthic foraminifera ¹⁴C measurements <u>Examining the</u> differences in the ¹⁴C age of the four benthic foraminifera species 426 427 (Figure 5), we find a maximum 5775 year offset between *U. peregrina* and *T. bradyi* 14 C age (the former being older). Even though the sample sizes are small (7 to 42), 428 429 comparing the preferred epifaunal P. ariminensis (Keigwin, 2002) to the other species suggests that: (1) Bolivina spp. ¹⁴C age is older, (2) T. bradyi ¹⁴C age is 430 younger, and that (3) *U. peregrina* gives a ¹⁴C age that is most similar to the 431 432 epifaunal species (<u>Table 3</u>; left side). 433 434 The comparisons above, however, are likely influenced by bioturbation and a more 435 appropriate examination would only compare the ¹⁴C ages of foraminifera at 436 abundance maxima where the influence of bioturbation is minimized (see above). 437 One drawback to an abundance maximum-only comparison is that it draws from a 438 smaller pool of observations (e.g., n=2 for the *P. ariminensis* vs. *Bolivina* spp.), which 439 limits the significance of these statistics. This comparison suggests that—on 440 average—*U. peregrina* (n=8) and *T. bradyi* (n=4) give similar ¹⁴C ages to epifaunal 441 species, but with a large $(10\pm861 \text{ years})$ to very large $(35\pm1125 \text{ years})$ range of 442 variability. On average, *Bolivina* spp. at abundance maxima (n=2) gives an even 443 older ¹⁴C age difference from the preferred epifaunal species (<u>Table 3</u>; right side). 444 445 Despite the monospecies Δ^{14} C differences, the glacial-deglacial trends of all four 446 benthic foraminifera ¹⁴C (corrected for decay and shown as Δ^{14} C in Figure 5) from 447 our cores near the mouth of the Gulf of California (the 'Gulf' sediment core sites) are 448 depleted relative to the atmosphere during the deglaciation, but are considerably 449 higher during the Holocene. The shallowest and therefore most recent benthic

- for a for a minifera Δ^{14} C are roughly equal to modern DIC Δ^{14} C measurements of -173‰ at 450
- 451
- the depth of the cores (Key et al., 2004). Error bars denote 1 sigma calendar age and
- 452 Δ^{14} C errors and symbols represent measurements at abundance maxima. Triangles

453 with error bars at bottom of each plot indicate the calendar ages and 1 sigma Deleted: We find significant Patrick Rafter 9/20/2018 10:53 AM Deleted: with Patrick Rafter 9/27/2018 9:28 AM Deleted: Table 2 Patrick Rafter 9/20/2018 10:56 AM Deleted:

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- 469 uncertainties provided by wood dates. The ¹⁴C ages of foraminifera on either side of 470 abundance peaks can also be "corrected", although this requires an assumption
- 471 about bioturbation rates, but this will be the subject of future work.
- 472

473 Each monospecies Δ^{14} C record in Figure 5A to D is compared with the nearby 474 benthic foraminifera Δ^{14} C record from the open Pacific margin of Baja California (a 475 combination of mixed and mono-species benthic foraminifera on the original age 476 model; see core locations in Figure 2 and Table 1) (Lindsay et al., 2015; Marchitto et 477 al., 2007). Additionally, a series of mixed benthic Δ^{14} C measurements (preliminary 478 work on ET97-7T where species abundance was not quantified) is shown in Figure 479 5D. All Gulf benthic foraminifera Δ^{14} C measurements are compiled in Figure 5E 480 (black) to illustrate the overall range of values given by the 4 benthic and mixed 481 species measurements relative to the atmospheric (grey; (Reimer et al., 2013)) and 482 the Undercurrent site Δ^{14} C (red). As can be seen by these multiple views of the 483 dataset, all benthic foraminifera Δ^{14} C trends at both Gulf and Undercurrent sites 484 shift to lower values after 20-kyr BP. These depletions relative to atmospheric Δ^{14} C are very large, but even lower Δ^{14} C values are observed for intermediate depth 485 486 sediment core sites in the eastern equatorial Pacific (Stott et al., 2009). 487 488 3.4 Influence of macrofaunal consumption and excretion on sediment ¹⁴C 489 ages? 490 In a single interval from 106 to 110 cm of the LPAZ-21P core, which was predicted 491 to be \approx 25.5-kyr based on interpolation from our Bayesian statistical age model, the 492 wood and benthic and planktic foraminifera ¹⁴C ages were conspicuously younger 493 than expected, giving a Δ^{14} C value well above the contemporary atmosphere 494 (956.3%); see circle in Figure 6). In fact, wood found within this sedimentary 495 interval suggests a calendar age of only 19.2-kyr BP, giving a much lower U. 496 *peregrina* Δ^{14} C of -88.6‰. This lower Δ^{14} C value is consistent with values for the 497 wood-constrained calendar age (see square in Figure 6). If these anomalous but self-498 consistent observations are not simply a result of human error (mislabeling or other 499 sampling problem) they may indicate the presence in this interval of "zoophycos" or

- 500 the remnants of downward-burrowing macrofauna (as was suggested by (Lougheed 501 et al., 2017)). By consuming and later excreting sedimentary material, these worms

502 are able to move 'younger' sedimentary components deeper in the sediment column, 503 though if this is the cause, the self-consistency of our ¹⁴C measurements in this

504 reworked interval (where microfossil and wood ¹⁴C ages suggest an undisturbed 505 sample) is surprising.

506

507 3.5 The stable isotopic composition of oxygen (δ^{18} O) and carbon (δ^{13} C)

508 The epifaunal benthic foraminifera (*P. ariminensis*) δ^{18} O and δ^{13} C measurements in

- 509 Figure 7 uses new and published data from LPAZ-21P (Herguera et al., 2010), but on
- 510 our wood-constrained age model. As previously reported, intermediate depth δ^{13} C
- 511 shows little variability between the Last Glacial Maximum (LGM) and Holocene at
- 512 the depth of this core (624 m; (Herguera et al., 2010)). Benthic foraminifera δ^{18} O has
- similar magnitude of change to benthic δ^{18} of for the nearby Undercurrent core sites 513

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529 (Figure 7 in (Lindsay et al., 2016)), although the <u>Undercurrent benthic</u> δ^{18} O increase 530 to Holocene values <u>may lag the Gulf site values (compare (Lindsay et al., 2016) with</u> 531 Figure 7).

532 533 **4.0 Discu**

533 4.0 Discussion 534 Based on the work presented here, the trend towards an extreme lowering of 535 intermediate-depth benthic for a Δ^{14} C in the subtropical northeastern 536 Pacific (the California Undercurrent site in Figures 1, 2, and 5) (Lindsay et al., 2015; 537 Marchitto et al., 2007) cannot be explained by species biases, bioturbation, or poor 538 age model controls (Figure 5). This statement is supported by our ¹⁴C 539 measurements of the epifaunal benthic foraminifera *P. ariminensis*—a species 540 known to provide the best record of seawater carbon at the sediment-water 541 interface (Keigwin, 2002)—and several commonly used infaunal benthic 542 foraminifera from sediment cores "upstream" of the canonical record of these 543 extreme Δ^{14} C observations (Figures 1 and 5). Our measurements indicate that even though the potential variability between infaunal and the preferred epifaunal 544 species' ¹⁴C ages is relatively large (several hundred years; Table 3), the average ¹⁴C 545 546 age difference at foraminifera abundance maxima is <100 years, and the overall 547 trend towards extremely low Δ^{14} C during the deglaciation cannot be explained by 548 bioturbation and persists regardless of species, 549 550 4.1 Comparing Gulf and Undercurrent site deglacial records 551 Our Gulf sediment core observations indicate that the mixed-species Δ^{14} C 552 measurements from the Undercurrent sites shown in Figures 1 and 5 are largely 553 accurate, although the higher values that form the middle of this 'W' shaped 554 anomaly (from ≈15- to 13-kyr BP) are not obviously reproduced by any of the 4 555 mono-species benthic foraminifera Δ^{14} C. It is possible that this and other some smaller-scale features of a mixed benthic Δ^{14} C record reflect the bias of a particular 556 557 species and/or the influence of bioturbation in our lower sedimentation rate sites. For example, the benthic foraminifera *T. bradyi* is a possible suspect for biasing 558 559 mixed benthic Δ^{14} C measurements because it is relatively large, dense, and sometimes has large deviations to younger ¹⁴C ages than the other species (Figure 560 561 5). Nevertheless, the overall agreement between the independently derived 562 Undercurrent and Gulf records lend credence to the methods used to construct the 563 age model by Marchitto et al., (2007) and tested by Lindsay et al., (2016). We should 564 note that we cannot explain the large offset between the records from 30-to-25-kyr 565 BP, although this comparison only includes one observation from the Undercurrent 566 sites. 567

568 The similar Δ^{14} C trends at both Undercurrent and Gulf sites despite sedimentation

- 569 rate differences and sediment core hiatus lends additional support for the
- 570 robustness of the Δ^{14} C trends (Lindsay et al., 2016) and against events such as the
- 571 large-scale—and far-fetched—redeposition of sand-sized sedimentary components.
- 572 In principle, the circulation of bottom waters from the Gulf to the Undercurrent
- 573 sediment core sites could allow for redeposition of benthic foraminifera with much
 - 11

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- 585 older ¹⁴C ages, but a much larger reworked component (and hence much older
- 586 benthic foraminifera ¹⁴C ages) would logically be expected at the "upstream" Gulf
- 587 sites. In fact, sedimentary redeposition should be amplified at the lower
- 588 sedimentation rate Gulf site, but significantly lower benthic foraminifera Δ^{14} C is not
- observed for any of the species at the Gulf sites.
- 590
- 591 These findings allow us to now focus our questions on two potential explanations
- 592 for the extreme depletions of benthic foraminifera Δ^{14} C observed during the
- 593 deglaciation: (1) it is a diagenetic signal imparted onto both epifaunal and infaunal 594 foraminifera after burial or (2) it reflects a real change in seawater Δ^{14} C during the
- for a for a fit or (2) it reflects a real change in seawater Δ^{14} C during the deglaciation.
- 595 (596

597 **4.2 Can diagenesis explain the low deglacial** Δ^{14} **C**?

598 Investigating the potential for diagenetic alteration of benthic foraminifera Δ^{14} C, we

- are not concerned about the newly observed coupling between carbonate
- dissolution and precipitation (Subhas et al., 2017), which only involves a few
- 601 monolayers of surface carbonate. Instead, producing the extreme Δ^{14} C lowering
- 602 observed at Undercurrent and Gulf sites (Figure 5) and other sites around the globe
- 603 (Bryan et al., 2010; Stott et al., 2009; Thornalley et al., 2011) requires the 604 precipitation of depleted ¹⁴C on or within the foraminifera test is required.
- 605
- 606 This authigenic calcium carbonate formation and foraminifera ¹⁴C content has been
- 607 examined in several ways. For example, benthic foraminifera from the eastern
- 608 equatorial Pacific give, <u>some</u> of the lowest observed deglacial Δ^{14} C values (-609‰),
- 609 but Scanning Electron Microscope images show no authigenic carbonate on benthic
- 610 or planktic foraminifera (Stott et al., 2009). Calcium carbonate overgrowth (via the
- 611 conversion of CaCO₃ to CaSO₄ (gypsum)) was observed in Santa Barbara Basin
- sediments (Magana et al., 2010), but would not influence the ¹⁴C content of the
- 613 microfossil. What's more, extreme ¹⁴C depletions of mixed benthic foraminifera
- 614 from this and other sites were found to be biased by *Pyrgo* spp., which are
- 615 <u>inexplicably depleted in ¹⁴C (Ezat et al., 2017)</u>. Other work suggests *younger-than-*616 *expected* ¹⁴C ages from the precipitation of carbonate onto foraminifera tests after
- 617 core recovery (Skinner et al., 2010). Cook et al., (2011) observed anomalously low
- for a minifera Δ^{14} C, high δ^{18} O, and low δ^{13} C was consistent with authigenic carbonate
- 610 precipitation from methane. Wycech et al., (2016) also compared the 14 C ages of
- translucent and opaque mono-specific planktic foraminifera from the same
- 621 sediment horizons and found the opaque foraminifera (thought to contain
- 622 authigenic carbonate) had 14 C ages more than 10,000 years older than the
- 623 translucent tests.
- 624

625 Neither the Gulf nor the Undercurrent site benthic foraminifera measurements

- 626 display the telltale signs of simultaneous Δ^{14} C, δ^{18} O, and δ^{13} C anomalies seen by
- 627 Cook et al., (2011) (see Figure 7). What's more, the planktic Δ^{14} C values from the
- 628 Undercurrent site do not show anomalous depletion during the deglaciation
- 629 (Lindsay et al., 2015), which is expected for post-depositional alteration / authigenic

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- 637 carbonate formation. It is possible that a completely different process of authigenic
- 638 carbonate formation is occurring in the subtropical eastern Pacific, but we cannot
- elaborate on what this mechanism might be. It is possible that authigenic carbonates

are removed from the foraminiferal test during the 10% acid leaching pre-treatment

641 at KCCAMS (see Methods), although selected pre-treatment tests did not

642 significantly alter the ¹⁴C ages. This pretreatment was not used in the Wycech et al.,

- 643 (2016) comparisons, but will be examined in our future studies.
- 644
- Finally, given the near identical deglacial Δ^{14} C trends at the Undercurrent and Gulf
- sites despite very different sedimentation rates (20-30 cm kyr⁻¹ at the Undercurrent
- 647 versus 1-to-5 cm kyr⁻¹ at the Gulf; Figure 3) it would be surprising if the same
- 648 depleted Δ^{14} C trends were of diagenetic origin. This is because a faster
- 649 sedimentation rate will decrease the potential for authigenic mineralization by
- decreasing the exposure time of the foraminifera. This reduction in exposure time
- 651 would apply to both the microfossil's exposure at the sediment-water interface and 652 at sediment depths favorable to authigenic carbonate precipitation. Thus, while the
- 652 at sediment depths favorable to authigenic carbonate precipitation. Thus, while the 653 potential influence of authigenic carbonate on the primary foraminifera record is an
- 654 important area of research that deserves further study, the similarity of the
- 655 Undercurrent and Gulf records argues against contamination from authigenic
- 656 carbonate precipitation as the major influence on these benthic foraminifera Δ^{14} C 657 values.
- 658

659 5.0 Conclusions

660 If the extreme deglacial depletion of benthic foraminifera $\Delta^{14}C$ at these northeastern 661 Pacific sites cannot be explained by species or habitat bias, bioturbation, or poor age 662 model control, the remaining explanation is that they reflect a change in seawater 663 DIC Δ^{14} C. Looking to other proxy systems, deep-sea coral Δ^{14} C in the North Atlantic 664 and Southern Ocean-archives with excellent age model control and different 665 diagenetic influences—also display depleted deglacial Δ^{14} C during the deglaciation (Adkins et al., 1998; Burke and Robinson, 2012; Chen et al., 2015; Robinson et al., 666 **2005).** However, the deep-sea coral Δ^{14} C depletion have a different timing and are 667 668 not as extreme as observed for the Gulf of California and California Undercurrent 669 sites (Figure 5E). 670

671 <u>A</u> leading candidate among the potential explanations <u>for these and other</u>

672 <u>intermediate depth records (Bryan et al., 2010) is the deep-sea sequestration and</u>

flushing of carbon through the intermediate depth ocean (Basak et al., 2010; Du et
al., 2018; Lindsay et al., 2016; Marchitto et al., 2007). This interpretation is plausibly

- 675 consistent with ¹⁴C records from only a few sites, such as the deep Southern Ocean
- 676 (Barker et al., 2010; Skinner et al., 2010) and deep Nordic Seas (Thornalley et al.,

677 2015). However, using an 18-box geochemical ocean-atmosphere model to simulate

- 678 glacial-interglacial ocean circulation and carbon cycling, Hain et al., (2011) argue
- 679 that matching the observed Δ^{14} C depletions in the intermediate depth, Northern
- 680 <u>Hemisphere sites requires unrealistic changes in ocean chemistry (e.g., lower</u>
- 681 surface ocean alkalinity) and ocean dynamics (i.e., mixing). <u>Specifically, to</u>

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- 702 appropriately "age" deep-sea ¹⁴C requires deep-sea anoxia, which is not observed. 703 Furthermore, the release of this deep-sea ¹⁴C to intermediate depths would 704 dissipate much quicker than the several thousand year anomaly shown in Figure 5E. 705 706 An alternative explanation involves the addition of ¹⁴C-depleted carbon via mid-707 ocean ridge (MOR) volcanism (Ronge et al., 2016), which is indirectly supported by 708 evidence for increased MOR activity (Lund, 2013; Middleton et al., 2016; Tolstoy, 709 <u>2015</u>), The locations and depths of the extreme benthic foraminifera Δ^{14} C lowering 710 are also suggestive of a MOR influence, given their proximity to the East Pacific Rise 711 / Gulf of California (Marchitto et al., 2007; Ronge et al., 2016; Stott et al., 2009; this 712 study), the Red Sea (Bryan et al., 2010), and Mid-Atlantic Ridge (Thornalley et al., 713 2011). However, this hypothesis of enhanced carbon flux from seafloor volcanism 714 must also explain the many intermediate-depth sites that do not show anomalous 715 deglacial Δ^{14} C depletions (Broecker & Clark, 2010; Cléroux et al., 2011; De Pol-Holz et al., 2010), Furthermore, this proposed carbon addition must have been associated 716 717 with an alkalinity addition, without which the increased seawater CO₂ 718 concentrations and therefore lower seawater pH would have caused a global-scale 719 carbonate dissolution event (Lindsay et al., 2016; Stott and Timmermann, 2011). 720 721 In summary, our work strongly suggests that at least for the Gulf of California and 722 adjacent Pacific sites, the foraminifera Δ^{14} C proxy records real ¹⁴C changes in 723 deglacial intermediate depth seawater DIC, but the question of what caused those 724 changes remains open. Careful examination to confirm or disprove the fidelity of the 725 benthic foraminifera Δ^{14} C on a case by case basis will be a critical part of building a 726 reliable body of data to identify the controls on glacial-interglacial marine carbon 727 cycling. 728 729 Acknowledgments: C. Bertrand, A. Hangsterfer (SIO Core Repository), H. Martinez, 730 N. Shammas, M. Ayad, M. Rudresh, A. De la Rosa, J. Troncoso, J. DeLine, J. Sanchez, C. 731 Manlapid, M. Chan, as well as T. Marchitto and two anonymous reviewers. 732 733 **References:** 734 Addison, J. A., Finney, B. P., Jaeger, J. M., Stoner, J. S., Norris, R. D. and Hangsterfer, A.: 735 Integrating satellite observations and modern climate measurements with the 736 recent sedimentary record: An example from Southeast Alaska: Modern SE Alaska 737 Fjord Sediment Records, J. Geophys. Res. Oceans, 118(7), 3444-3461, 738 doi:10.1002/jgrc.20243, 2013.
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956 Figure 2. Maps of sediment core sites (diamonds; see Table 1) and ocean circulation

957 (arrows: solid = surface; dashed = near seafloor). The foraminifera radiocarbon

958 measurements in Figure 1 are from core sites at the red diamond (Marchitto et al.,

2007; Lindsay et al., 2016). See Table 1 for details on site locations. Note that the

960 subsurface Mexican Coastal Current (MCC) flows between 200 to \approx 700 m and feeds

 $961 \qquad {\rm subsurface\ water\ into\ both\ the\ Gulf\ of\ California\ and\ California\ Undercurrent}$

962 (Gómez-Valdivia et al., 2015)—waters that bathe both core sites.

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calendar age [kyr BP]	Deleted: (t
Figure 3. (A) Sediment core depth versus calendar age. Age model constraints are	Patrick Raft
	Deleted: (1
based on wood ¹⁴ C (squares and diamonds), stratigraphic correlation ("X"; see (D)),	Patrick Rafte
and U. peregrina ¹⁴ C corrected for reservoir age (circles). (B) Sedimentation rate	Deleted: t
versus calendar age. (C), The ¹⁴ C age of atmospheric CO ₂ , for a minifera, wood, and	Deleted: (t BP)
rejected wood (see legend) versus calendar age_for <u>ET97-7T (diamonds) and LPAZ-</u>	Patrick Rafte
21P/ LPAZ-21PG (squares). See Figure 1 and Table 1 for locations, (D) Ca/Al for	Deleted: sit
	Patrick Raft
E197-71 (pink) and LPAZ-21P (black) was measured using X-Ray Fluorescence (see	Deleted: ,
Methods). Lower Ca/Al for the uppermost sediment (beginning at the arrows) is	Patrick Raft
coincident with loss of calcium carbonate microfossils and an overall darkening of	Patrick Raft
-	Deleted: (s
sediments at these and other sites in the region (van Geen et al., 2003). We use this	Patrick Rafte
stratigraphic feature to tie the age model for both sites (dashed arrow between	Deleted:)
"V"a) (E) Examples of wood found within and imput some LDAZ 21D (and easile)	Patrick Raft
<u>A SJ. [E]</u> Examples of wood found within sediment core LPAZ-21P <u>[see scale]</u> .	Deleted: B

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(Key et al., 2004).

997 **Figure 5.** The ¹⁴C isotopic composition (corrected for decay as Δ^{14} C) for Gulf of

998 California benthic foraminifera mono-species (A-D) and mixed species (D) are

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1000 from the California Undercurrent sediment core site (orange) (Lindsay et al., 2015;

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1003

- all Gulf benthic foraminifera (see Figure 3 legend) is shown in (E) alongside 1004
- 1005 atmospheric Δ^{14} C (grey) (Reimer et al., 2013) and California Undercurrent site Δ^{14} C
- 1006 (orange). Modern Δ^{14} C near the depth of the Gulf and Pacific sites is about -173%

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1012 **Figure 6**: Comparing Gulf of California *U. peregrina* Δ^{14} C with anomalous values

1013 based on the Bayesian calendar age (circle) based on sediment depth and the wood-

1014 constrained calendar age (square). If this anomaly was not the result of human error

- 1015 (mislabeling of the sample's depth), then this may suggest the influence of
- 1016 macrofauna. See text for more details.





1018Figure 7. From top to bottom: atmospheric carbon dioxide (CO2) (blue; same as1019Figure 1), atmospheric CO2 Δ^{14} C (grey; same as Figure 1), mixed and mono-species

1020 benthic for aminifera $\Delta^{14}C$ from the California Undercurrent site (red) (Lindsay et al.,

1021 2015; Marchitto et al., 2007), all mono-species benthic for aminifera Δ^{14} C from near

1022 the mouth of the Gulf of California (black; this study), sedimentation rate of LPAZ-

1023 21P (see Figure 3), benthic for aminifera *P. ariminensis* δ^{13} C (pink) and δ^{18} O (green)

- 1024 from this study and Herguera et al., (2010).
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Patrick Rafter 9/19/2018 2:13 PM Deleted: Figure 6



- 1028 Table 1. Latitude, longitude, depth below modern sea surface, and modern
- 1029 dissolved inorganic carbon (DIC) Δ^{14} C (26) at the sediment-seawater interface for
- 1030 sediment cores discussed in this study.

Table 1	latitude	longitude [°W]	depth [m]	modern DIC	
	[°N]			$\Delta^{14}\text{C}$ [‰] at	
				this depth	
LPAZ-21P / LPAZ-21PG	22.9	109.5	624	-148	
ET97-7T	22.9	109.5	640	-148	
MV99-MC19/GC31/PC08	23.5	111.6	705	-148	

1032 **Table 2.** <u>The difference between benthic foraminifera and concurrent wood 14C</u>

4).

1033 1034	ages for all measu	rements ("ALL") and	only at abi	indance ma	axima (see l	figure 4).
1001		[The difference between <i>P.</i> ariminensis - <u>wood</u> [¹⁴ C years]		The difference between <u>U.</u>		
			ALL	abundance maxima	ALL	abundance maxima	
		AVERAGE	2346	<u>2488</u>	<u>2309</u>	<u>2697</u>	
		STDEV	<u>1599</u>	<u>1791</u>	<u>1063</u>	<u>1117</u>	
		n	14	<u>,11</u>	<u>13</u>	<u>6</u> ,	
1035		L					
1036 1037 1038	Table 3. Comparison between benthic foraminifera ¹⁴ C ages for all measurements ("ALL") and only at abundance maxima (see Figure 4).						
		The difference between P. ariminensis - U. peregrina [¹⁴ C years]		<u>The difference between P.</u> ariminensis - T. bradyi [¹⁴ C years]		The difference between P. ariminensis - Bolivina spp. [¹⁴ C years]	
		ALL	abundance maxima	ALL	abundance maxima	ALL	abundance maxima
	AVERAGE	-104	10	826	35	-857	-1407
	STDEV	<u>759</u>	<u>861</u>	1484	<u>1125</u>	939	<u>597</u>
	n	<u>42</u>	<u>8</u>	<u>7</u>	<u>4</u>	<u>11</u>	<u>2</u>

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