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# Assessing subsidence rates and paleo water-depths for Tahiti reefs using U-Th chronology of altered corals

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†. Deceased. Guy Cabioch passed away during the submission of this manuscript. We wish to recognize the contributions Guy made, not only to the IODP expedition to Tahiti, but also more widely as a carbonate geologist. His presence in the coral reef community will be missed.

45

46 **Abstract**

47

48 We present uranium-thorium chronology for a 102 m core through a Pleistocene reef at Tahiti  
49 (French Polynesia) sampled during IODP Expedition 310 “Tahiti Sea Level”. We employ total and  
50 partial dissolution procedures on the older coral samples to investigate the diagenetic overprint of  
51 the uranium-thorium system. Although alteration of the U-Th system cannot be robustly corrected,  
52 diagenetic trends in the U-Th data, combined with sea level and subsidence constraints for the  
53 growth of the corals enables the age of critical samples to be constrained to marine isotope stage 9.  
54 We use the ages of the corals, together with  $\delta^{18}\text{O}$  based sea-level histories, to provide maximum  
55 constraints on possible paleo water-depths. These depth constraints are then compared to  
56 independent depth estimates based on algal and foraminiferal assemblages, microbioerosion  
57 patterns, and sedimentary facies, confirming the accuracy of these paleo water-depth estimates. We  
58 also use the fact that corals could not have grown above sea level to place a maximum constraint on  
59 the subsidence rate of Tahiti to be  $0.39 \text{ mka}^{-1}$ , with the most likely rate being close to the existing  
60 minimum estimate of  $0.25 \text{ mka}^{-1}$ .

61

62

63 **Keywords:** paleo water-depth; Tahiti, IODP Expedition 310; island subsidence; coral; U-Th;  
64 open system.

65

## 65    **1 Introduction**

66

### 67    *1.1 Paleo water-depth reconstructions*

68

69    Estimation of the overlying depth of water is crucial for the reconstruction of past sea levels from  
70    geological deposits (typically coral reefs or marine sediments). Ideally a narrow range of possible  
71    paleo water-depth, coupled with accurate uplift/subsidence correction, can be combined with a  
72    chronological constraint to produce an accurate and precise sea level history. This approach has  
73    succeeded in producing archives of sea level from a variety of localities (Bard et al., 1996; Chappell  
74    and Polach, 1991; Peltier and Fairbanks, 2006). These records have benefited from relatively  
75    shallow paleo water-depths reducing the potential for uncertainty in the correction from water-  
76    depth estimate. Where water-depth was thought to be larger, however, accurately recording changes  
77    in sea level is more problematic. Also, producing a calibration of fossil assemblage to paleo water-  
78    depth involves the study of modern environments of deposition (Hopley, 1986, Montaggioni and  
79    Faure, 1995, Cabioch et al., 1999, Humblet et al., 2009, Hongo and Kayanne, 2010) or the  
80    examination of fossil material from locations, and times, for which past sea level is well constrained  
81    (Montaggioni, 2005). In addition, changes in water transparency, e.g. as an effect of changed trophic  
82    conditions, introduce a telescoping effect on biotic assemblages, in particular corals, used for the  
83    reconstruction of past sea levels (Heindel et al., 2009a, b). Changes of the water-depths at which  
84    assemblages are related through time will therefore also cause sea level estimates to be in error if the  
85    calibration is not appropriate.

86

87    Often estimates of paleo water-depth are made from material for which some age control already  
88    exists (eg Thomas et al., 2009), therefore some bias may be introduced from the expectation of how

89 sea level changed during the time that the material represents. Two recent papers (Fujita et al.,  
90 2010; Iryu et al., 2010) have made independent estimates of paleo water-depth (bathymetric ranges)  
91 from the same drill core through a carbonate reef, sampled during Integrated Ocean Drilling  
92 Program (IODP) Expedition 310 “Tahiti Sea Level”. These two sets of estimates are based on  
93 benthic foraminifera (Fujita et al., 2010) and non-geniculate coralline algal assemblages (Iryu et al.,  
94 2010), and were made without radiometric age control. The addition of age control provided by U-  
95 Th measurements of fossil corals from Hole IODP-310-M0005D, coupled with comparison to  
96 “known” sea level history, provided the opportunity to check both the robustness of these paleo  
97 water-depth estimates as well as their validity back in time. In addition paleo water-depth estimates  
98 may be assessed, from post-LGM (Last Glacial Maximum) material, where good chronological and  
99 sea level information was available, in an example where water depth was inferred from the basis of  
100 the photic levels recorded by microbioerosion patterns (Heindel et al. 2009a, b).

101

## 102 *1.2 Subsidence rate*

103

104 Volcanic islands emplaced onto oceanic lithosphere are typically found to be subsiding owing  
105 principally to the effect of mass loading of the island depressing the underlying oceanic lithosphere  
106 (Watts and Zhong, 2000), along with a small component of subsidence related to the cooling and  
107 thickening of the oceanic lithosphere itself. At Tahiti – on 74 Ma crust (Muller et al., 2008) – this  
108 secondary component equates to only  $0.0088 \text{ mka}^{-1}$  (Stein and Stein, 1992), the bulk of the  
109 subsidence resulting from the loading of the island during the main shield building phase of  
110 volcanism 1.4 - 0.87 Ma (Hildenbrand et al. 2004). Constraining this rate of subsidence is not only  
111 important for our understanding of crust-mantle dynamics (Moore, 1970; Courtney and White,  
112 1986; Zhong and Watts, 2002) but is also crucial for the accurate reconstruction of past sea levels

113 from relative sea level indicators on such ocean islands (Bard et al., 1996; Muhs et al., 2002; Szabo et  
114 al., 1994). Modern geodetic measurements (Fadil et al., 2010) of vertical island movement suffer  
115 from relatively short baselines and also form the potential of anthropogenically driven ground  
116 movement (Bird, 1993) biasing results. Geodetic measurements of subsidence at Tahiti typically  
117 have uncertainties that are of comparable size to the rate measured ( $0.3 \pm 0.4 \text{ mka}^{-1}$  (Fadil et al.,  
118 2010)). It is therefore advantageous to estimate subsidence over longer time periods, giving a time-  
119 averaged subsidence rate.

120

121 Previous estimates of long-term subsidence at Tahiti have provided minimum estimates based on  
122 radiometric dating of, now submerged, sub-aerial lava flows of  $0.21$  and  $0.25 \text{ mka}^{-1}$  (LeRoy, 1994;  
123 Bard et al., 1996). Short-term subsidence rate has been estimated from the position of Holocene  
124 shoreline deposits and is significantly lower at  $0.15 \text{ mka}^{-1}$  (Pirazzoli et al., 1985), although other  
125 higher Holocene estimates of  $0.3 - 0.4 \text{ mka}^{-1}$  (Montaggioni, 1988) have also been made. Large  
126 uncertainties of these Holocene estimates arise from the relatively short baselines of the  
127 measurements, amplifying uncertainties in paleo-sea level and water-depth used in subsidence rate  
128 calculations. Here we use the additional constraints provided by U-Th dating of much older fossil  
129 corals to provide a maximum estimate of subsidence rate to better constrain the history of the  
130 island.

131

### 132 *1.3 Core description*

133 More than 630 m of cores were recovered during IODP Expedition 310 (Expedition 310 Scientists,  
134 2007), and were described sedimentologically within the standardized procedure of the IODP  
135 onshore Science Party (Camoin et al., 2007). The deglacial coral reef framework is heavily encrusted  
136 by microbialites, in many cases preceded by coralline algal crusts (Seard et al., 2011; Westphal et al.,

2010). Most of the reef framework is therefore preserved in growth position. Hole IODP-310-M0005D was drilled at 17° 45.9915'S 149° 33.0476'W in 59.63 m water-depth on the south-western side of Tahiti, and reached down to 161.8 mbsl (meters below modern sea level, defined as lowest astronomical tide). A total of 36 core sections were recovered from this hole (Fig. 1). Although the conventional core recovery was 64.86% (Camoin et al. 2007), accounting for void space, 97.35% of the available material was retrieved (Inwood et al., 2008).

The lithology of Hole IODP-310-M0005D is described in detail by Camoin et al. (2007) and the pre last glacial sections are summarised by Fujita et al. (2010) and Iryu et al. (2010). Briefly the hole consists of: The postglacial sequence of corallgal framestone and microbialite of cores 1R-6R, from 91.39 – 82.63 mbsl, which was deposited while sea level rose during the last deglaciation (the chronology will be presented elsewhere Deschamps et al., In Revision, Camoin et al., In Revision). An older sequence of corallgal framestone in cores 7R-8R; a rhodolith floatstone and grainstone in cores 9R-15R; a sandy *Halimeda* floatstone, and packstone in cores 16R-20R; a further sequence of corallgal framestone in cores 20R and 21R; a microbialite sequence in cores 21R-22R; a sequence of sandy grainstones with massive *Porites* corals in cores 23R-28R; a thin sequence of corallgal framestone in core 29R; a rhodolith coral floatstone in core 29R; a thick sequence of corallgal and coral framestones and coral floatstones in cores 30R-35R; a coral floatstone sequence in cores 35R-36R; and the base of the hole is marked by a sandy bioclastic grainstone at the base of core 36R (Fig. 1a). Iryu et al. (2010) identify three distinct horizons within Hole IODP-310-M0005D which represent erosional hiatuses, based on the presence of sharp contacts with evidence of carbonate dissolution in the underlying unit. These unconformities are in cores 21R, 29R, and 36R (Fig. 1a).

## 160    **2. Analytical techniques**

161    Coral samples were identified as being pristine by visual, and thin section, inspection and by X-ray  
162    diffraction to ensure that they were primary aragonite (0.26% calcite detection limit). Approximately  
163    0.3 g sub-samples of coral were cut using a hand-held diamond wheel. These chips were then  
164    cleaned by ultra-sonication in 18 M $\Omega$ cm (Milli-Q) water. For U and Th analysis, samples were  
165    weighed into Teflon beakers and spiked with a mixed  $^{229}\text{Th}$ : $^{236}\text{U}$  spike ((Robinson et al., 2004a), with  
166    0.006%  $^{230}\text{Th}$ , 0.02%  $^{238}\text{U}$ , 0.004%  $^{235}\text{U}$ , and 39 ppt  $^{234}\text{U}$  impurities, and calibrated with the HU-1  
167    standard assuming the half lives and U:Th of Cheng et al. 2000). Total dissolution is achieved by  
168    drop-wise addition of 7.5N  $\text{HNO}_3$  to the sample immersed in Milli-Q water. Once dissolved, any  
169    remaining organic material is removed by refluxing in hot 15N  $\text{HNO}_3$  followed by an attack in cold  
170    aqua regia. The sample is converted to nitrate form by repeated drying and dissolution in  
171    15N  $\text{HNO}_3$  before being prepared for anion exchange chromatography to separate U and Th from  
172    the sample matrix and each other. The chromatographic separation followed the procedure of  
173    Thomas et al., (2006) with volumes scaled to accommodate 2 ml of resin.

174

175    To investigate the possibility that deviation from closed system of U and Th is localised to the  
176    surfaces of the coral, a leaching approach was taken. To ensure only the surfaces of the corals were  
177    leached, a weak acid attack with ascorbic acid (63  $\mu\text{M}$ ) was used, incorporating NaEDTA (25  $\mu\text{M}$ )  
178    to ensure leached Th was not reabsorbed to the remaining solids, following the procedure of  
179    Lomitschka and Mangini (1999), and varying the leaching time from 0.5 to 3 hours. Because the  
180    coral used for this partial leaching procedure was of the finely porous genus *Porites*, it was crushed  
181    and passed through a 106  $\mu\text{m}$  sieve (the scale of the theca is approximately 100  $\mu\text{m}$ ) so that all of  
182    the surfaces of the coral were equally subject to the acid leach. Chips of uncrushed coral were also  
183    subjected to the same leaching procedure to test the necessity of the crushing step. Once leached

184 samples were rinsed with Milli-Q water to remove any remaining leachate and NaEDTA, they were  
185 then prepared for U-Th analysis in the same way as for unleached samples. Measurement of U and  
186 Th from the leachate was not possible due to the difficulty in separating the leached Th and U from  
187 the EDTA complexing agent.

188

189 Measurement of U and Th isotopes was by Nu instruments MC-ICP-MS in static mode. U and Th  
190 isotopes were measured separately, with  $^{234}\text{U}$  and  $^{230}\text{Th}$  in an ion counter and all other isotopes in  
191 Faraday collectors. Machine biases were corrected for using CRM-145 (for uranium), and an in-  
192 house  $^{229}\text{Th}$ : $^{230}\text{Th}$ : $^{232}\text{Th}$  standard (for thorium) (Mason and Henderson 2010), bracketing each  
193 sample with 3 standard measurements to also assess instrumental reproducibility. For both U and Th  
194 measurements the  $^{234}\text{U}$  or  $^{230}\text{Th}$  concentration is matched to the standard's so that the intensity of  
195 the beam in the ion counter is equal, to negate any possible instrumental biases arising from non-  
196 linear collector responses.

197

### 198 **3. Results**

199

200 Uranium and thorium concentrations and isotope ratios are presented in Table 1, and calculated  
201 ages in Table 2. Details of the biological assemblages and inferred paleo-environments are presented  
202 in Fujita et al. (2010) (benthic foraminifera) and Iryu et al. (2010) (coralline algae). The results of  
203 these two studies are summarized in Fig. 1. The foraminiferal assemblages were analysed from core  
204 sections M0005D-26R to 16R and have been interpreted as a shallow water environment  
205 ( $15 \pm 15$  mbsl) in sections 26R to 23R followed by a deepening upwards sequence in core sections  
206 18R to 16R (from  $45 \pm 15$  to  $75 \pm 15$  mbsl) (Fig. 1d). Coralline algal assemblages from all of the pre-  
207 LGM sections have also been investigated (Iryu et al., 2010). The relative paleo water-depths

208 interpreted are shallow from section M0005D-36R to 30R, deep in section 29R, shallow in sections  
209 28R to 23R, deep in 22R and 21R, followed by a deepening upwards sequence from 21R to 17R,  
210 and then deep water from 17R to 7R (Fig. 1g).

211

## 212 **4. Discussion**

213

### 214 *4.1 Partial dissolution of coral to “remove” open system U-Th contamination*

215

216 A hypothetical coral sample that incorporated uranium from seawater with a ( $^{234}\text{U}/^{238}\text{U}$ ) of  
217  $1.146 \pm 0.005$  should follow the closed system evolution path (Fig. 2) as it ages: ( $^{230}\text{Th}/^{238}\text{U}$ )  
218 increasing as  $^{230}\text{Th}$  is produced from decay of  $^{234}\text{U}$ , and ( $^{234}\text{U}/^{238}\text{U}$ ) decreasing as initial excess  $^{234}\text{U}$   
219 incorporated from sea water, decays towards secular equilibrium ( $(^{234}\text{U}/^{238}\text{U}) = 1$ ). A range of  
220 potential seawater ( $^{234}\text{U}/^{238}\text{U}$ ) is considered due to the potential for subtle secular variation in the  
221 isotopic composition of uranium in seawater (Esat and Yokoyama 2006). Deviation from this path  
222 is observed for many fossil corals (e.g. compilation in Henderson (2002) because of open-system  
223 behaviour over the history of the fossil. This open system behaviour is the result of gain or loss of  
224 any of the isotopes in the  $^{238}\text{U}$ - $^{230}\text{Th}$  decay chain ( $^{238}\text{U}$ ,  $^{234}\text{Th}$ ,  $^{234}\text{Pa}$ ,  $^{234}\text{U}$ , or  $^{230}\text{Th}$ ). Often the  
225 gain/loss of  $^{234}\text{U}$  and  $^{230}\text{Th}$  during open system behaviour is coupled leading to linear arrays of data  
226 in ( $^{234}\text{U}/^{238}\text{U}$ )-( $^{230}\text{Th}/^{238}\text{U}$ ) space, for corals which are thought to be of similar age (Gallup et al.,  
227 1994). This coupled behaviour has been used to apply corrections to coral U-Th data, which fall  
228 away from the hypothetical closed-system evolution path, to calculate open-system ages (Scholz et  
229 al., 2004; Thompson et al., 2003; Villemant and Feuillet, 2003). These approaches of correcting for  
230 open-system behaviour rely on the data falling on a linear array and the assumption that a single  
231 type of coupled  $^{234}\text{U}$ - $^{230}\text{Th}$  gain/loss has occurred. Data for multiple measurements of coral from

core 24R (Table 1 and Fig. 2) indicate these criteria are not upheld (the measurements show enhanced elevation of  $^{230}\text{Th}/^{238}\text{U}$  without the associated elevated  $^{234}\text{U}/^{238}\text{U}$  typical of coupled addition), and therefore open system correction to these data will not necessarily yield more accurate ages.

The partial dissolution of coral 23R illustrates that successive removal of surface material generally moves the position of the coral towards the closed system age evolution line in  $(^{234}\text{U}/^{238}\text{U})$ - $(^{230}\text{Th}/^{238}\text{U})$  space (Fig. 4). This indicates that the sequential dissolution technique may be useful in isolating portions of corals that have not been subject to open system behaviour, by preferential removing the outer surfaces which have been potentially exposed to open system behaviour through interaction of uranium and/or thorium isotopes between the coral and pore fluid. However, the measured values of  $(^{234}\text{U}/^{238}\text{U})$  and  $(^{230}\text{Th}/^{238}\text{U})$  for partially dissolved sub samples should not be considered more representative of a closed system, because removal of the outer surface of the coral by partial dissolution is on such a small scale that there will have been recoil exchange between the high  $^{234}\text{U}$  and  $^{230}\text{Th}$  exterior and the “unaltered” interior (Henderson et al., 2001). The  $(^{234}\text{U}/^{238}\text{U})$  and  $(^{230}\text{Th}/^{238}\text{U})$  of the leached samples should not therefore be used to calculate a conventional closed system age. Indeed, some of the leached sub-samples move away from the closed system line, which may represent a more complex heterogeneous alteration of the coral or an artefact of the leaching procedure. That the leached coral U-series data lie close to the closed system evolution path, coupled with constraints based on our knowledge of the subsidence rate of Tahiti and the history of global sea level, an approximation of the age of the coral can be made.

#### 4.2 Refinement of the subsidence rate of Tahiti

256

257 A previous estimate of the subsidence rate of Tahiti has been made from a K-Ar age, of  
258  $549 \pm 11$  ka, on a now submerged lava flow, at 114 mbsl (Bard et al., 1996). This placed a minimum  
259 constraint on the subsidence rate of  $0.207 \pm 0.004$  mka<sup>-1</sup>. A faster rate being possible if the lava  
260 flow was emplaced substantially above sea level, and lower rate if the lava was emplaced during a  
261 period of sea level lowstand. This is in reasonable agreement with an earlier unpublished estimate of  
262  $0.25$  mka<sup>-1</sup> (LeRoy, 1994), using similar methodology. A lower, Holocene, subsidence rate of  
263  $0.15$  mka<sup>-1</sup> has been inferred from the elevation of corals and beach deposits on Tahiti relative to  
264 nearby ‘stable’ islands (Pirazzoli et al., 1985). This discrepancy between the longer and shorter  
265 timescale estimates is not unexpected. The subsidence rate due to the loading of an island on the  
266 oceanic lithosphere is time dependent, being most rapid at the time of loading and reducing with  
267 time (Watts and Zhong, 2000). In consideration of the longer timeframe, a minimum subsidence  
268 rate of  $0.25$  mka<sup>-1</sup> is assumed here, based on the expectation that subsidence rate in the Holocene is  
269 a minimum constraint on the rates further into the past. Also, that the ages of corals interpreted  
270 here are 100s of ka old, similar to the age from which this subsidence rate has been measured,  
271 makes this a suitable subsidence assumption.

272

273 Constraining the time that corals in M0005D could have grown is possible by considering that the  
274 corals could only have grown while sea level was above the position they were in – assuming the  
275 corals are found in growth position. Reconstructing the elevation of core M0005D back through  
276 time (using a subsidence rate of  $0.25$  mka<sup>-1</sup>), comparison with a continuous estimate of sea level  
277 (Bintanja and van de Wal, 2008), and the U-Th constraint that M0005D-20R was deposited during  
278 the MIS 6-5 transition (Table 2 and Fig. 3), indicates that the only times that core section

279 M0005D-23R would have been underwater, are: MIS 6.5; MIS 7; MIS 8.5; MIS 9 and MIS 11 (Fig.  
280 3a).

281

282 The U-series data for the partial leaching of sample 23R and the multiple measurements of corals  
283 from 24R suggests that both corals grew during MIS 9 (Fig. 2). Assuming – as seems reasonable –  
284 that seawater ( $^{234}\text{U}/^{238}\text{U}$ ) remained close to 1.146 (Henderson 2002; Robinson et al., 2004b), these  
285 corals appear to have undergone open system behaviour in which there was a significant amount of  
286  $^{230}\text{Th}$  addition as well as the possibility of coupled  $^{234}\text{U}$ - $^{230}\text{Th}$  addition. It is possible that seawater  
287 may have been higher during MIS 9, Andersen et al. 2010 suggest it may have been as high as 1.152.  
288 If this higher seawater ( $^{234}\text{U}/^{238}\text{U}$ ) is considered then it suggests this coral has undergone less  
289 open-system alteration and hence more confidence that this coral is of MIS 9 age.

290

291 An upper limit on the subsidence rate can be determined from this new age estimate: that these  
292 corals are of MIS 9 age. If the magnitude of the highstand during MIS 9 is inferred from  $\delta^{18}\text{O}$  based  
293 reconstructions of sea level as 0 mbsl at 325 ka (Bintanja and van de Wal, 2008) or 6 mbsl at 329 ka  
294 (Rohling et al., 2009), and the corals are assumed to have grown at sea level, then the subsidence  
295 rate would be  $0.39 \text{ mka}^{-1}$  or  $0.36 \text{ mka}^{-1}$  respectively. Uncertainty of the magnitude of the highstand  
296 of  $\pm 10 \text{ m}$  or in the timing of the highstand of  $\pm 10 \text{ ka}$  leads to uncertainty the subsidence rate of  
297  $0.03$  and  $0.01 \text{ mka}^{-1}$ , respectively. This is a maximum constraint of the subsidence rate because the  
298 corals may not have grown during the absolute maximal sea level highstand, instead growing while  
299 sea level was slightly lower as it rose (fell) to(from) the highstand and/or could, as is likely, have  
300 grown in a depth of water greater than zero. A paleo water-depth of 15 m, as has been suggested for  
301 these corals (Fujita et al., 2010), would reduce the maximum subsidence rate by  $0.045 \text{ mka}^{-1}$ . These  
302 new data therefore provide an absolute maximum constraint on subsidence, over the past 325 ka, of

303  $0.39 \pm 0.03 \text{ mka}^{-1}$ , although it is likely to have been lower, allowing for the depth of water that the  
304 corals grew under, and for the possibility that they did not grow at the sea level maximum.

305  
306 *4.3 Comparison of paleo water-depth estimates with sea level history and age constraints*

307  
308 The age constraints provided by U-Th dating can be used to assess water-depth estimates made  
309 from fossil assemblages (Fujita et al., 2010; Iryu et al., 2010). A coral from M0005D-20R-2W has  
310 yielded a robust U-Th age (Thomas et al 2009). This coral was broken into two fragments in the  
311 core. While the upper fragment (5D8146, Tables 1 and 2) has >1% calcite and the replicate U-Th  
312 ages do not agree, the lower fragment (5D8006, Tables 1 and 2) appears to be purely aragonite with  
313 replicate ages in agreement at  $133.6 \pm 1.0$  and  $133.7 \pm 0.4$  ka. Although the  $(^{234}\text{U}/^{238}\text{U})_i$  of this  
314 fragment indicates that there has been some open-system behaviour it is reasonable to assume that  
315 this coral grew at some time approximately 133-134 ka. The age of this coral, when compared to  
316 other sea level records for this interval (Andrews et al., 2007; Esat et al., 1999) and other corals  
317 from Tahiti from Hole M0019A-27R to 29R (Thomas et al., 2009) suggest this time was during a  
318 millennial scale lowstand which followed a brief period when sea level was higher, and preceded sea  
319 level rise towards the interglacial of MIS 5.5.

320  
321 Both Fujita et al. (2010) and Iryu et al. (2010) identify an increase of water-depth in the cores  
322 immediately above M0005D-20R (cores 19R-16R, Fig. 1), in the case of Fujita et al. from 45-75 m  
323 water depth. Although we cannot be certain as to the absolute age of these cores, they have been  
324 shown to record the Blake geomagnetic excursion (115-120 ka) (Menabreaz et al., 2009). These  
325 water-depth interpretations are, therefore, consistent with the rise in sea level during the  
326 penultimate glacial termination, and ultimately representing a deeper water environment while sea

level was high during the MIS 5.5 highstand. Hypothesised ages, positions and hence paleo water-depths of these cores are illustrated by open triangles in Fig. 3. Assuming a subsidence rate of  $0.25 \text{ mka}^{-1}$  the corals in M0005D-20R-2W were deposited at 84 mbsl. If the MIS 5.5 highstand was  $\sim 8 \text{ mbsl}$  (Kopp et al 2009) then the maximum water-depth that could have existed above these corals was 94 m (including 2 m of subsidence from 133 ka to the time of the maximum highstand). If core M0005D-16R is indeed MIS5.5 age then this would imply a water-depth of 83 m (16R is 11 m above 20R in the hole), which is in remarkably good agreement with the paleo water-depth estimation of Fujita et al of  $75 \pm 15 \text{ m}$ . This age constraint therefore indicates that both methods for paleo water-depth estimation are sensitive to increasing water-depth and have accurately recorded the sea level rise over the latter part of the penultimate deglaciation (Termination II).

Further comparisons between the age constraints and the paleo water-depth interpretations can be made in the older sections of Hole M0005D. Iryu et al. (2010) suggest M0005D-23R to 24R, characterized as a sandy bioclastic grainstone with massive *Porites* colonies, is representative of a shallow water environment at the beginning of the penultimate deglaciation which is then punctuated by a sea level reversal (Andrews et al., 2007; Esat et al., 1999; Siddall et al., 2006; Thomas et al., 2009) from deeper water in M0005D-22R to 21R (characterised by bioclastic packstones and microbiolites with encrusting corals) back to shallow water in M0005D-21R to 20R (coralgal framestone consisting of massive *Porites*). Fujita et al. (2010) also suggest M0005D-23R to 24R is shallow water deposit from the beginning of termination II, but has no data to constrain the water-depth from M0005D 22R-21R. Ages of M0005D-23R to 24R are much older (MIS 9) than is assumed by Fujita et al. (2010) and Iryu et al. (2010). Because there is no direct age control on the core sections 21R and 22R it is entirely possible that the age interpretation of Iryu et al. (2010) is

350 correct, although it is just as feasible that the material from these core sections was deposited during  
351 MIS 7 or 9.

352

353 The U-Th data combined with the minimum subsidence rate constraint has shown the  
354 M0005D-23R to 24R corals to be of MIS 9 age rather than from the early deglacial of the MIS 6-5  
355 transition. The paleo depth of these corals has been estimated as  $15 \pm 15$  m on the basis of  
356 foraminiferal assemblage (Fujita et al., 2010) and also “shallow” ( $< 20$  m water-depth) on the basis  
357 of nongenticulate coralline algae (Iryu et al., 2010). A constraint on the maximum possible paleo  
358 water-depth available for these corals to grow, based on a minimum subsidence rate of  $0.25 \text{ mka}^{-1}$   
359 and sea level history is 45 m (Fig. 3). The constraints on subsidence rate ( $0.25\text{-}0.39 \text{ mka}^{-1}$ ) are  
360 however loose enough for this estimate to be as shallow as zero (this is from the construction of the  
361 maximum subsidence rate being constrained by the criterion that these corals must have grown  
362 below sea level).

363

364 A coral from core M0005D-30R has been found to display considerable open system behaviour for  
365 U-Th such that an accurate age cannot be determined. It is however interesting to note that using  
366 an open-system correction (Thompson et al., 2003), assuming an initial seawater ( $^{234}\text{U}/^{238}\text{U}$ ) of  
367 1.146, the untreated coral and one of the leached aliquots appear to be of MIS 11 age, although  
368 when considering the scatter of the other leached aliquots it is not clear that such an open-system  
369 correction is merited (other sub-samples of the same coral suggest an older MIS 13 age (Table 2)).  
370 That section 30R is below 23R and 24R infers that it is indeed older than them but it could be that  
371 it is from some time in MIS 9 earlier than then, rather than necessarily being as old as MIS 11. The  
372 occurrence of erosional features in core sections between 24R and 30R (Fig. 1a and h, and Iryu et al.  
373 2010), however, suggest that there had been a fall in sea level between these to “dated” corals

374 (potentially during MIS 10). This stratigraphic control implies that the older interpretation of MIS  
375 11 for section 30R is more likely, although the possibility of millennial scale sea level variability  
376 during the MIS 9 highstand being responsible for the erosional features cannot be discounted. The  
377 only paleo water-depth estimates for sections 29R-36R are by Iryu et al. (2010), and are all  
378 “shallow” except for 29R which displays a rhodolith assemblage characteristic of “deep” water (>  
379 50 m water-depth). If the minimum subsidence rate of  $0.25 \text{ mka}^{-1}$  is considered, and it is assumed  
380 that core 29R is of MIS 11 age (based on a tenuous open-system age interpretation, and position  
381 below an unconformity assumed to represent MIS 10) then the maximum possible water-depth is  
382  $\sim 40 \text{ m}$  (Fig. 3). The shallow water depth inferred for 30R therefore may reflect lower sea level  
383 during the rise from MIS 12 to MIS 11. If, however, the corals from 29R are from MIS 9 then the  
384 maximum available water-depth is  $\sim 58 \text{ m}$ . Faster rates of subsidence would reduce these available  
385 water-depths, therefore if the corals from 29R are representative of deep water then the upper  
386 estimate of subsidence rate becomes less likely.

387

388 The robustness of paleo water depth reconstructions can also be assessed from cores covering the  
389 last deglaciation, where radiocarbon chronology, the elevation of the samples and knowledge of sea  
390 level during the deglaciation can be used to provide “known paleo-bathymetry” to test  
391 reconstructions. Here we investigate reconstructions based on microbioerosion patterns. Since light  
392 controls the occurrence of phototrophic endoliths, their traces left in corals from different water-  
393 depths (microbioerosion patterns) reflect different stages of illumination (photic zones), which can  
394 be used to reconstruct paleo water-depths (e.g. Vogel and Marincovich, 2004). At Tahiti, the  
395 microbioerosion patterns in Holocene corals sampled in cores from around 115 mbsl  
396 (M0024A-11R: 14800 cal. yr BP) to 55 mbsl (M0007B-11R: 9280 cal. yr BP) indicate increasing  
397 water-depths (deepening upwards), i.e. a decrease in light levels, which reflects the rising deglacial

398 sea level (Heindel et al., 2009b). For example at around 115 mbsl microbioerosion in the corals of  
399 core M0024A-11R indicates shallow euphotic to deep euphotic conditions, whereas  
400 microbioeroders in the immediately overlying red algal crusts and microbialites imply dysphotic  
401 conditions, ie. an increase in water-depth. In combination with calibrated AMS 14C ages, which  
402 indicate a significant time delay of ~600 years between coral growth and microbialite development  
403 (Seard et al., 2011), the significantly changing microbioerosion patterns in the different substrates  
404 next to each other reflect the rapid rise in sea level around Meltwater Pulse 1A (Bard et al., 1996;  
405 Heindel et al., 2009b). This expected finding therefore adds confidence to paleo water-depth  
406 reconstructions based on microbioerosional patterns. Although, as with all paleodepth  
407 reconstruction, care must be taken to consider the potential of other environmental factors that may  
408 influence the “water depth proxy”. For example the potential of water turbidity to condense photic  
409 zones and hence bias paleodepth estimates to deeper values (Heindel et al., 2009a, b).

410

411

## 412 **5. Conclusions**

413 Leaching of shallow water corals that display “open system” U-Th behaviour has the  
414 potential to remove U and Th added to the coral’s surface leaving a residue that is closer to a closed  
415 system, however the resulting residue may not be considered to be representative of a closed  
416 system.

417 A minimum subsidence rate constrains the possible ages of sections 23R and 24R to  
418 highstands MIS 6.5, 7, 8.5, 9, or 11, and the U-Th data further limits the possible age of corals from  
419 these sections to be MIS 9.

420 This extra age constraint places an absolute upper limit on the subsidence rate of 0.39  
421  $\text{mka}^{-1}$ , based on the criteria that the corals could not have grown above sea level. Estimates of paleo

422 water-depth for older corals suggest that this upper limit may be too high and a subsidence rate  
423 more similar to the minimum of  $0.25 \text{ mka}^{-1}$  may be more appropriate.

424 Comparison of constraints, provided by U-Th dating and subsidence rate, to estimates of  
425 paleo water-depths based on sedimentary facies and foraminiferal/algal/microbioeroding  
426 assemblages illustrate the accuracy of the paleo water-depth estimates in the absence of prior  
427 knowledge of the age and hence expected water-depth.

428

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437

437 **References**

438

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606 *Table Captions*  
607

608 **Table 1**

609 Uranium and thorium concentrations (expressed in mass per mass) and isotope ratios (expressed as  
610 activity ratios, using half lives according to Cheng et al. 2000). *Italics* denote data that have been  
611 previously published (Thomas et al., 2009). Uncertainties are based on the reproducibility of  
612 standard U and Th solutions, within a measurement session. Superscripts in sub-sample IDs denote  
613 where sub-samples have been taken from the same coral specimen.

614

615 **Table 2**

616 Sample context and calculated ages. Depth below present sea level in meters (mbsl) that the coral  
617 was cored from. % of sample remaining following partial dissolution (100%, represents total  
618 dissolution of sample, with no leaching procedure). Closed system age (before 1950 AD) and  
619 ( $^{234}\text{U}/^{238}\text{U}$ ) at time of coral growth ( $(^{234}\text{U}/^{238}\text{U})_i$ ), calculated using isoplot software (Ludwig, 2003)  
620 and the half lives of (Cheng et al., 2000). Open system ages are calculated using the approach of  
621 (Thompson et al., 2003) and assuming ( $^{234}\text{U}/^{238}\text{U}$ )<sub>i</sub> of modern seawater at 1.146 (Robinson et al.,  
622 2004a). *Italics* denote data that have been previously published (Thomas et al., 2009).

623

624

625 *Figure Captions*

626

627 **Figure 1**

628 Graphic log of the Pre-LGM sections of Hole IODP 310 M0005D (a), sedimentology (b and e),  
629 foraminifera (c) and nongeniculate coralline algal (f) assemblages with associated paleo water-depth  
630 interpretations (d and g respectively). Panels a-g are adapted from Fujita et al. (2010) and Iryu et al.  
631 (2010). Core sections on which the U-Th data provide age control (h) are illustrated in black  
632 (closed-system U-Th age) and grey (marine isotope stage inferred from combination of open-system  
633 U-Th data and minimum subsidence rate), erosional contacts from (a) are re-illustrated in (h). Sea  
634 level records based on continuous  $\delta^{18}\text{O}$  (i): solid line, (Bintanja and van de Wal, 2008) on the LR04  
635 timescale (Lisiecki and Raymo, 2005); dotted line (Rohling et al., 2009) on the EDC3 timescale  
636 (Parrenin et al., 2007).

637

638 **Figure 2**

639  $(^{234}\text{U}/^{238}\text{U})$  relationship with  $(^{230}\text{Th}/^{238}\text{U})$  over time for a hypothetical closed system coral that had  
640  $(^{234}\text{U}/^{238}\text{U})_i$  of  $1.146 \pm 0.005$  (grey band). Time is marked along the closed system band by marine  
641 isotope stages following the numbering system of (Martinson et al., 1987). The darker grey sections  
642 of the closed system band are the times when core section 23R was submerged (Fig. 3). Ellipses are  
643 the  $2\sigma$  uncertainties of the U-Th data of this study. The black arrow represents the direction  
644 coupled addition of  $^{234}\text{U}$  and  $^{230}\text{Th}$  would drive MIS 11 corals in a possible mode of open system  
645 alteration (Thompson et al., 2003).

646

647 **Figure 3**

648 Plot of core section reconstructed depth vs. age for (A)  $0.25 \text{ mka}^{-1}$  and (B)  $0.35 \text{ mka}^{-1}$ . Core sections  
649 are shown in grey and sections which have age control provided by U-Th are highlighted in black.  
650 Sea level history is shown as a black solid line (Bintanja and van de Wal, 2008) and black dotted line  
651 (Rohling et al., 2009). For the  $0.25 \text{ mka}^{-1}$  scenario the times when sea level was above the position  
652 of core section 23R (and hence the only times during which corals could grow) are illustrated by  
653 vertical grey bars. Open triangles highlight hypothesised ages and hence paleo water-depths of core  
654 sections M0005D-19R to 16R, that record increasing paleo water-depth during the penultimate  
655 deglaciation.

656 **Figure 4**

657 The MIS 9 portion of the closed system band from Fig. 2 with age isochrons (grey lines) marked  
658 every 10 ka (the isochrons represent where closed system samples would plot if they had exactly the  
659 same age but had different  $(^{234}\text{U}/^{238}\text{U})_i$  – an impossible scenario for corals which should all have the  
660 same  $(^{234}\text{U}/^{238}\text{U})_i$  because seawater should have homogenous uranium isotopes). The  $(^{234}\text{U}/^{238}\text{U})$  and  
661  $(^{230}\text{Th}/^{238}\text{U})$  are plotted for the sub-samples of corals 23R-2W-0, 37 cm and 30R-1W-119, 135 cm  
662 which had been subject to partial dissolution (ellipse size is analytical uncertainty). The darkness of  
663 the ellipses indication the amount of the initial sub-sample remained following leaching, lighter  
664 shades indicating greater dissolution.

665

666 **Table 1**

| Sub-sample ID            | IODP Sample ID<br>310-M0005D- | <sup>238</sup> U<br>ppm | 2s     | <sup>232</sup> Th<br>ppb | 2s      | ( <sup>230</sup> Th/<br><sup>238</sup> U) | 2s     | ( <sup>234</sup> U/<br><sup>238</sup> U) | 2s     | ( <sup>232</sup> Th/<br><sup>238</sup> U) | 2s          |
|--------------------------|-------------------------------|-------------------------|--------|--------------------------|---------|-------------------------------------------|--------|------------------------------------------|--------|-------------------------------------------|-------------|
| 5D8146a2 <sup>a</sup>    | 20R-2W-0, 21                  | 3.126                   | 0.004  | 0.194                    | 0.003   | 0.7866                                    | 0.0028 | 1.1024                                   | 0.0008 | 0.0000204                                 | 0.0000004   |
| 5D8146b <sup>a</sup>     | 20R-2W-0, 21                  | 2.9457                  | 0.0004 | 0.2445                   | 0.0004  | 0.8020                                    | 0.0009 | 1.1007                                   | 0.0008 | 0.00002717                                | 0.00000004  |
| 5D8006a2 <sup>b</sup>    | 20R-2W-14, 21                 | 2.736                   | 0.004  | 0.216                    | 0.004   | 0.7949                                    | 0.0029 | 1.1081                                   | 0.0008 | 0.0000259                                 | 0.0000005   |
| 5D8006c <sup>b</sup>     | 20R-2W-14, 21                 | 2.5690                  | 0.0008 | 0.08490                  | 0.00014 | 0.7902                                    | 0.0009 | 1.1016                                   | 0.0008 | 0.000010821                               | 0.000000018 |
| 5D7198a <sup>c</sup>     | 24R-1W-73, 87                 | 2.2911                  | 0.0004 | 0.04475                  | 0.00016 | 1.0810                                    | 0.0022 | 1.0686                                   | 0.0005 | 0.000006395                               | 0.000000024 |
| 5D7198b <sup>c</sup>     | 24R-1W-73, 87                 | 2.2922                  | 0.0003 | 0.04366                  | 0.00016 | 1.0787                                    | 0.0022 | 1.0684                                   | 0.0005 | 0.000006236                               | 0.000000023 |
| 5D7198c <sup>c</sup>     | 24R-1W-73, 87                 | 3.0441                  | 0.0004 | 1.4241                   | 0.0023  | 1.0960                                    | 0.0012 | 1.0600                                   | 0.0008 | 0.0001532                                 | 0.0000003   |
| 5D8256b1                 | 24R-1W-51, 85                 | 2.618                   | 0.003  | 0.477                    | 0.008   | 1.040                                     | 0.004  | 1.0671                                   | 0.0008 | 0.0000597                                 | 0.0000011   |
| 5D23RTop_ac <sup>d</sup> | 23R-2W-0, 37                  | 2.3190                  | 0.0003 | 0.0771                   | 0.0004  | 1.0383                                    | 0.0019 | 1.0646                                   | 0.0007 | 0.00001088                                | 0.00000005  |
| 5D23RTop_ap <sup>d</sup> | 23R-2W-0, 37                  | 1.9876                  | 0.0003 | 3.745                    | 0.018   | 1.0364                                    | 0.0019 | 1.0623                                   | 0.0007 | 0.000617                                  | 0.000003    |
| 5D23RTop_bc <sup>d</sup> | 23R-2W-0, 37                  | 2.5846                  | 0.0020 | 0.1563                   | 0.0007  | 1.0323                                    | 0.0021 | 1.0593                                   | 0.0007 | 0.00001980                                | 0.00000010  |
| 5D23RTop_bp <sup>d</sup> | 23R-2W-0, 37                  | 2.5651                  | 0.0009 | 3.290                    | 0.016   | 1.0259                                    | 0.0019 | 1.0623                                   | 0.0007 | 0.0004199                                 | 0.0000020   |
| 5D23RTop_cc <sup>d</sup> | 23R-2W-0, 37                  | 2.3938                  | 0.0009 | 0.161                    | 0.001   | 1.0291                                    | 0.0019 | 1.0638                                   | 0.0007 | 0.00002209                                | 0.00000011  |
| 5D23RTop_cp <sup>d</sup> | 23R-2W-0, 37                  | 2.6566                  | 0.0013 | 1.341                    | 0.006   | 1.0259                                    | 0.0020 | 1.0613                                   | 0.0007 | 0.0001653                                 | 0.0000008   |
| 5D23RTop_dp <sup>d</sup> | 23R-2W-0, 37                  | 2.4011                  | 0.0012 | 6.44                     | 0.03    | 1.0234                                    | 0.0020 | 1.0643                                   | 0.0007 | 0.0008782                                 | 0.0000042   |
| TFC 2                    | 24R-1W-27, 33                 | 2.2509                  | 0.0010 | 0.0688                   | 0.0003  | 1.0516                                    | 0.0020 | 1.0670                                   | 0.0007 | 0.00001000                                | 0.00000005  |
| TFC 3 <sup>e</sup>       | 30R-1W-119, 135               | 2.2092                  | 0.0012 | 0.1592                   | 0.0008  | 1.0748                                    | 0.0021 | 1.0611                                   | 0.0007 | 0.00002360                                | 0.00000011  |
| 5D8668b <sup>e</sup>     | 30R-1W-119, 135               | 2.3352                  | 0.0003 | 0.1449                   | 0.0003  | 1.0905                                    | 0.0013 | 1.0568                                   | 0.0009 | 0.00002031                                | 0.00000004  |
| 5D8668c <sup>e</sup>     | 30R-1W-119, 135               | 2.2480                  | 0.0003 | 0.1383                   | 0.0005  | 1.0958                                    | 0.0014 | 1.0595                                   | 0.0009 | 0.00002014                                | 0.00000007  |
| 5D8668dp <sup>e</sup>    | 30R-1W-119, 135               | 2.3745                  | 0.0003 | 0.2373                   | 0.0006  | 1.0541                                    | 0.0014 | 1.0541                                   | 0.0009 | 0.00003273                                | 0.00000008  |

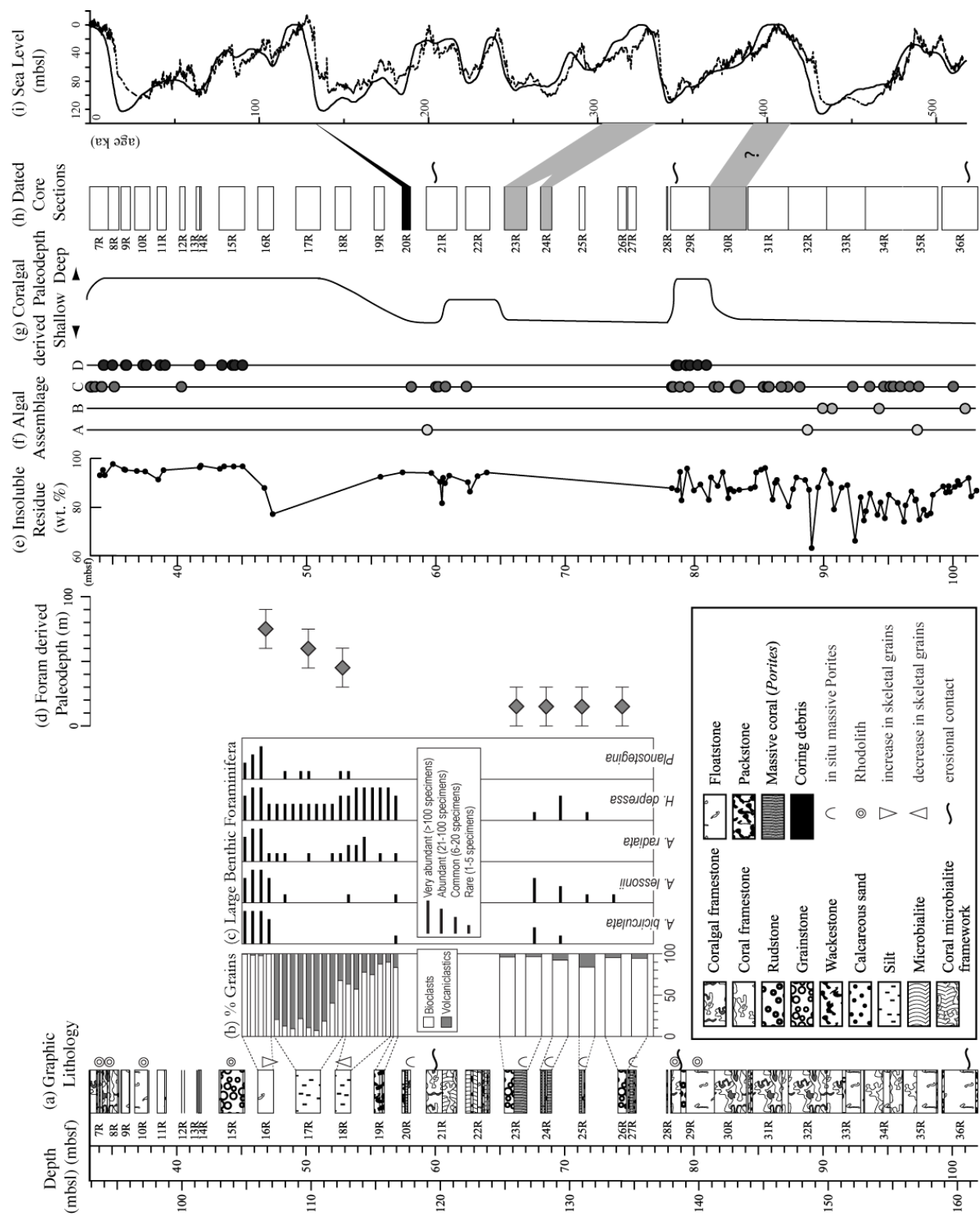
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668 **Table 2**

| Sub-sample ID               | mbsl          | %<br>Residue | Closed<br>System Age<br>ka BP | 2s         | ( <sup>234</sup> U/ <sup>238</sup> U) <sub>i</sub> | 2s            | Open<br>System Age<br>ka BP | 2s  | %<br>calcite | 2s          |
|-----------------------------|---------------|--------------|-------------------------------|------------|----------------------------------------------------|---------------|-----------------------------|-----|--------------|-------------|
| <i>5D8146a2<sup>a</sup></i> | <i>117.52</i> | <i>100%</i>  | <i>132.4</i>                  | <i>0.9</i> | <i>1.1489</i>                                      | <i>0.0012</i> | 130.7                       | 1.0 | <i>1.9%</i>  | <i>0.3%</i> |
| <i>5D8146b<sup>a</sup></i>  | <i>117.52</i> | <i>100%</i>  | <i>137.9</i>                  | <i>0.4</i> | <i>1.1487</i>                                      | <i>0.0011</i> | 136.3                       | 0.8 |              |             |
| <i>5D8006a2<sup>b</sup></i> | <i>117.66</i> | <i>100%</i>  | <i>133.6</i>                  | <i>1.0</i> | <i>1.1576</i>                                      | <i>0.0012</i> | 128.3                       | 1.1 | <i>0.3%</i>  | <i>0.2%</i> |
| <i>5D8006c<sup>b</sup></i>  | <i>117.66</i> | <i>100%</i>  | <i>133.7</i>                  | <i>0.4</i> | <i>1.1483</i>                                      | <i>0.0011</i> | 132.4                       | 0.7 |              |             |
| 5D7198a <sup>c</sup>        | 128.24        | 100%         | 472                           | 15         | 1.261                                              | 0.011         | 379                         | 8   |              |             |
| 5D7198b <sup>c</sup>        | 128.24        | 100%         | 460                           | 14         | 1.251                                              | 0.009         | 376                         | 8   |              |             |
| 5D7198c <sup>c</sup>        | 128.24        | 100%         |                               |            |                                                    |               | 502                         | 18  |              |             |
| 5D8256b1                    | 128.02        | 100%         | 338                           | 8          | 1.174                                              | 0.004         | 318                         | 6   | 0.2%         | 0.2%        |
| 5D23RTop_ac <sup>d</sup>    | 125.95        | 84%          | 340                           | 4          | 1.1691                                             | 0.0021        | 324                         | 4   |              |             |
| 5D23RTop_ap <sup>d</sup>    | 125.95        | 89%          | 343                           | 5          | 1.1640                                             | 0.0021        | 329                         | 4   |              |             |
| 5D23RTop_bc <sup>d</sup>    | 125.95        | 71%          | 342                           | 5          | 1.1558                                             | 0.0022        | 334                         | 4   |              |             |
| 5D23RTop_bp <sup>d</sup>    | 125.95        | 56%          | 322                           | 4          | 1.1547                                             | 0.0018        | 315                         | 3   |              |             |
| 5D23RTop_cc <sup>d</sup>    | 125.95        | 100%         | 324                           | 4          | 1.1595                                             | 0.0019        | 315                         | 3   |              |             |
| 5D23RTop_cp <sup>d</sup>    | 125.95        | 65%          | 324                           | 4          | 1.1532                                             | 0.0019        | 318                         | 3   |              |             |
| 5D23RTop_dp <sup>d</sup>    | 125.95        | 100%         | 313                           | 4          | 1.1558                                             | 0.0018        | 306                         | 3   |              |             |
| TFC 2                       | 127.78        | 100%         | 364                           | 6          | 1.1876                                             | 0.0028        | 334                         | 5   |              |             |
| TFC 3 <sup>e</sup>          | 141.98        | 100%         | 503                           | 20         | 1.25                                               | 0.01          | 409                         | 9   |              |             |
| 5D8668b <sup>c</sup>        | 141.98        | 84%          |                               |            |                                                    |               | 513                         | 21  | 0.42%        | 0.04%       |
| 5D8668c <sup>c</sup>        | 141.98        | 82%          |                               |            |                                                    |               | 507                         | 21  |              |             |
| 5D8668dp <sup>c</sup>       | 141.98        | 75%          | 432                           | 9          | 1.183                                              | 0.003         | 399                         | 7   |              |             |

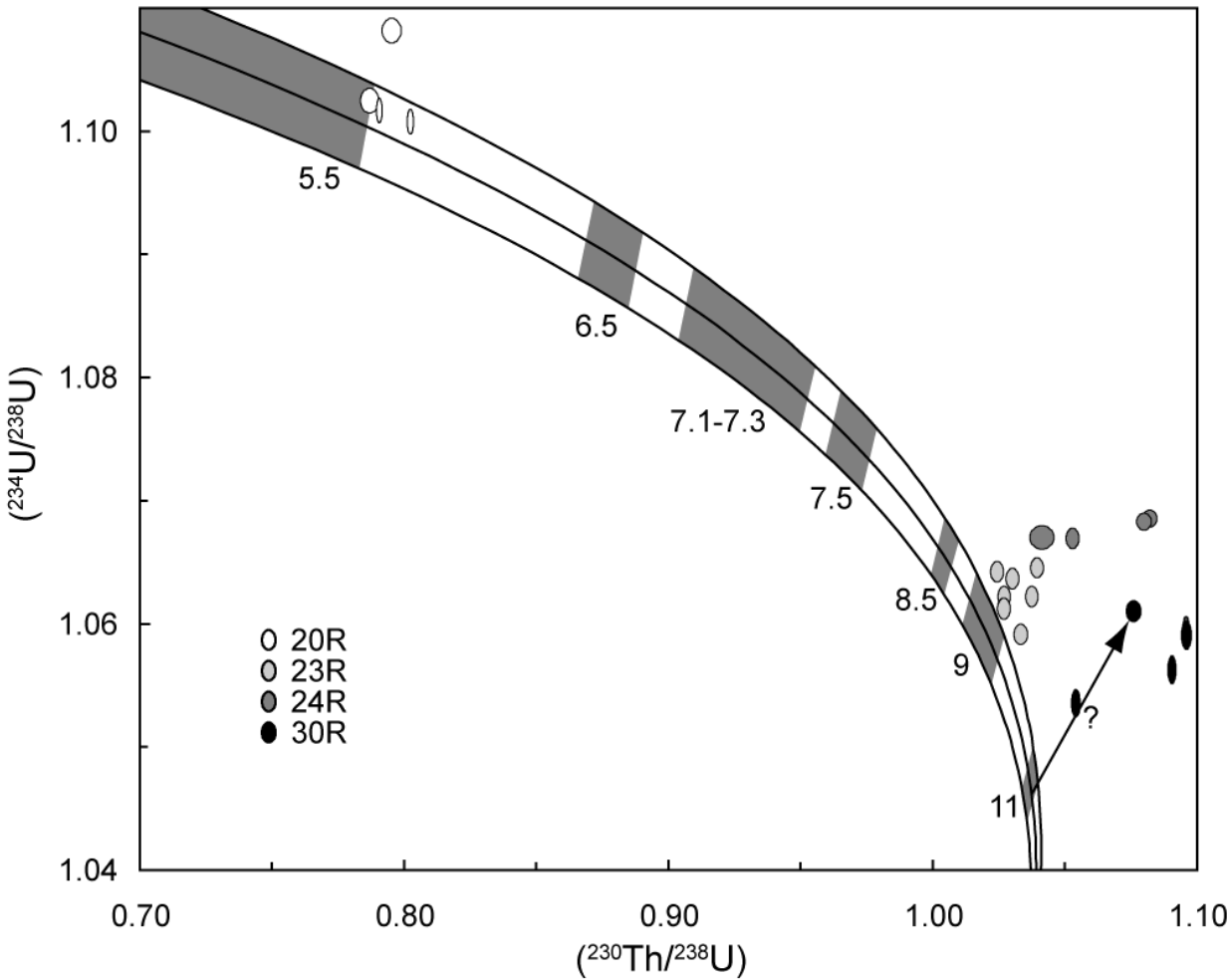
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670 Figure 1



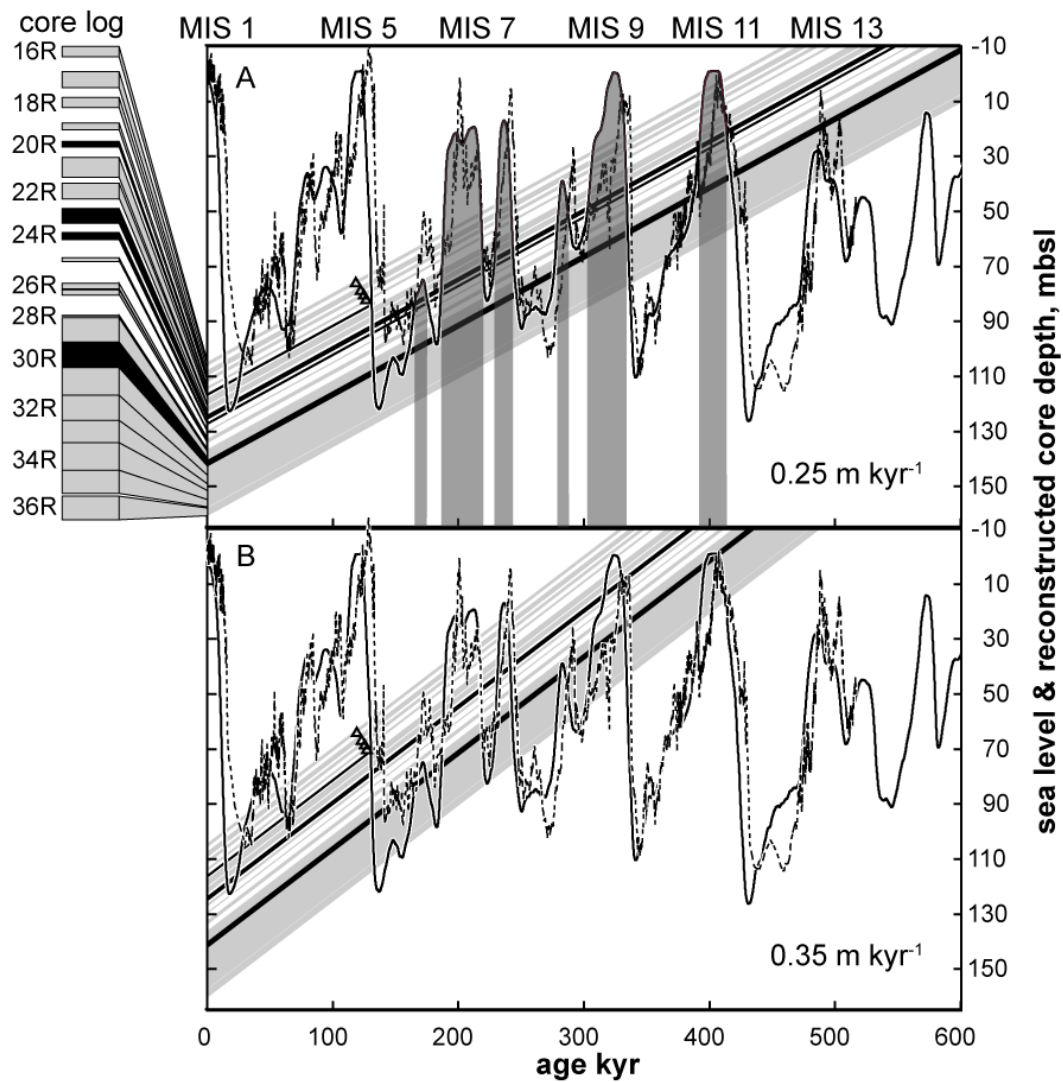
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672 Figure 2



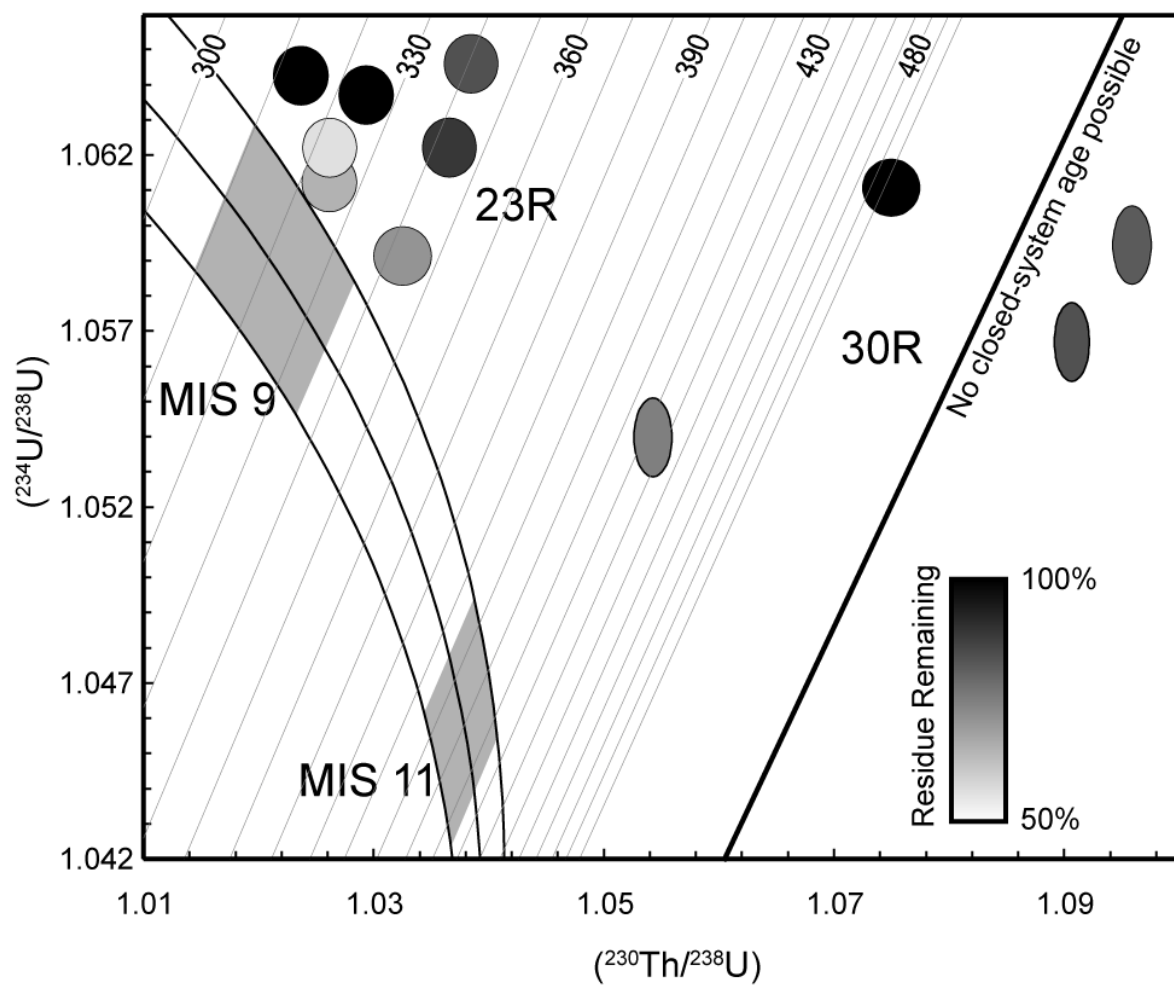
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674 Figure 3



675

676 Figure 4



677