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

Alexander L. Thomas^{a,*}, Kazuhiko Fujita^b, Yasufumi Iryu^{c,1}, Edouard Bard^d,
Guy Cabioch^{e,†}, Gilbert Camoin^d, Julia E. Cole^f, Pierre Deschamps^d, Nicolas Durand^d,
Bruno Hamelin^d, Katrin Heindel^{g,2}, Gideon M. Henderson^a, Andrew J. Mason^a,
Hiroyuki Matsuda^h, Lucie Ménabréaz^d, Akitoshi Omoriⁱ, Terry Quinn^{j,3}, Saburo Sakai^k,
Tokiyuki Sato^l, Kaoru Sugihara^m, Yasunari Takahashi^c, Nicolas Thouveny^d,
Alexander W. Tudhopeⁿ, Jody Webster^{o,4}, Hildegard Westphal^{g,5}, Yusuke Yokoyama^{k,p,q},

* Corresponding Author: E-mail, alexct@earth.ox.ac.uk; Tel, +44 (0)1865 272047; Fax +44 (0)1865 272072

^a Department of Earth Sciences, Oxford University, South Parks Road, Oxford, OX1 3AN, UK

^b Department of Physics and Earth Sciences, University of the Ryukyus, Okinawa 903-0213, Japan

^c Institute of Geology and Paleontology, Graduate school of Science, Tohoku University, Sendai 980-8578, Japan

^d CEREGE (UMR 6635), Aix-Marseille Université, CNRS, IRD, Collège de France, Europole de l'Arbois, BP80, 13545 Aix-en-Provence, France

^e Research Unit "Paleotropique" Institut de Recherche pour le Développement BP A5 98848 Nouméa Cedex New Caledonia France

^f Geosciences Department University of Arizona 1040 East 4th Street Tucson AZ 85721 USA

^g MARUM, Department of Geosciences, University of Bremen, Leobener Strasse, 28359 Bremen, Germany

^h Department of Earth Sciences, Faculty of Science Kumamoto University 2-39-1, Kurokami Kumamoto 860-8555 Japan

ⁱ Institute of Geosciences, Shizuoka University, Shizuoka, 422-8529 Japan

^j College of Marine Science University of South Florida 140 7th Avenue South MSL 119 St. Petersburg FL 33711 USA

^k Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology, Yokosuka 237-0061, Japan

^l Institute of Applied Earth Sciences, Faculty of Engineering and Resource Science, Akita University, Japan

^m Earth System Science, Faculty of Science Fukuoka University 8-19-1, Nanakuma Jonan-ku, Fukuoka 814-0180 Japan

ⁿ School of GeoSciences, Grant Institute, University of Edinburgh, Kings Buildings, West Mains Road, Edinburgh EH9 3JW, Scotland, U.K.

^o School of Earth Sciences James Cook University of North Queensland Townsville QLD 4811 Australia

^p Atmosphere and Ocean Research Institute, 5-1-5, Kashinonoh, Kashima-shi, Chiba 277-8564 Japan

^q Department of Earth and Planetary Sciences, University of Tokyo, Tokyo 113-0033, Japan

¹ Now at: Nagoya University, Department of Earth and Planetary Sciences, Graduate School of Environmental Studies, Nagoya University, Nagoya 464-8601, Japan

² Now at Department for Geodynamics and Sedimentology, University of Vienna Althanstrasse 14, 1090 Vienna, Austria

³ Now at: Institute for Geophysics, Jackson School of Geosciences, The University of Texas at Austin, J.J. Pickle Research Campus, Bldg 196 (ROC), 10100 Burnet Rd. (R2200), Austin, TX 78758-4445, U.S.A.

⁴ Now at: School of Geosciences, The University of Sydney, NSW 2006, Australia

⁵ Now at: Leibniz Center for Tropical Marine Ecology, Fahrenheitstraße 6, 28359 Bremen, Germany

†. 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 mka^{-1} , with the most likely rate being close to the existing
60 minimum estimate of 0.25 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 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 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 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.,

137 2010). Most of the reef framework is therefore preserved in growth position. Hole IODP-310-
138 M0005D was drilled at 17° 45.9915'S 149° 33.0476'W in 59.63 m water-depth on the south-western
139 side of Tahiti, and reached down to 161.8 mbsl (meters below modern sea level, defined as lowest
140 astronomical tide). A total of 36 core sections were recovered from this hole (Fig. 1). Although the
141 conventional core recovery was 64.86% (Camoin et al. 2007), accounting for void space, 97.35% of
142 the available material was retrieved (Inwood et al., 2008).

143

144 The lithology of Hole IODP-310-M0005D is described in detail by Camoin et al. (2007) and the pre
145 last glacial sections are summarised by Fujita et al. (2010) and Iryu et al. (2010). Briefly the hole
146 consists of: The postglacial sequence of corallgal framestone and microbialite of cores 1R-6R, from
147 91.39 – 82.63 mbsl, which was deposited while sea level rose during the last deglaciation (the
148 chronology will be presented elsewhere Deschamps et al., In Revision, Camoin et al., In Revision).
149 An older sequence of corallgal framestone in cores 7R-8R; a rhodolith floatstone and grainstone in
150 cores 9R-15R; a sandy *Halimeda* floatstone, and packstone in cores 16R-20R; a further sequence of
151 corallgal framestone in cores 20R and 21R; a microbialite sequence in cores 21R-22R; a sequence of
152 sandy grainstones with massive *Porites* corals in cores 23R-28R; a thin sequence of corallgal
153 framestone in core 29R; a rhodolith coral floatstone in core 29R; a thick sequence of corallgal and
154 coral framestones and coral floatstones in cores 30R-35R; a coral floatstone sequence in cores 35R-
155 36R; and the base of the hole is marked by a sandy bioclastic grainstone at the base of core 36R
156 (Fig. 1a). Iryu et al. (2010) identify three distinct horizons within Hole IODP-310-M0005D which
157 represent erosional hiatuses, based on the presence of sharp contacts with evidence of carbonate
158 dissolution in the underlying unit. These unconformities are in cores 21R, 29R, and 36R (Fig. 1a).

159

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 Ω cm (Milli-Q) water. For U and Th analysis, samples were
165 weighed into Teflon beakers and spiked with a mixed ^{229}Th : ^{236}U spike ((Robinson et al., 2004a), with
166 0.006% ^{230}Th , 0.02% ^{238}U , 0.004% ^{235}U , and 39 ppt ^{234}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 HNO_3 to the sample immersed in Milli-Q water. Once dissolved, any
169 remaining organic material is removed by refluxing in hot 15N 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 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 μM) was used, incorporating NaEDTA (25 μM)
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 μm sieve (the scale of the theca is approximately 100 μm) 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}U and ^{230}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}Th : ^{230}Th : ^{232}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}U or ^{230}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 ± 15 mbsl) in sections 26R to 23R followed by a deepening upwards sequence in core sections
206 18R to 16R (from 45 ± 15 to 75 ± 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 ± 0.005 should follow the closed system evolution path (Fig. 2) as it ages: ($^{230}\text{Th}/^{238}\text{U}$)
218 increasing as ^{230}Th is produced from decay of ^{234}U , and ($^{234}\text{U}/^{238}\text{U}$) decreasing as initial excess ^{234}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}U - ^{230}Th decay chain (^{238}U , ^{234}Th , ^{234}Pa , ^{234}U , or ^{230}Th). Often the
225 gain/loss of ^{234}U and ^{230}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}U - ^{230}Th gain/loss has occurred. Data for multiple measurements of coral from

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

236

237 The partial dissolution of coral 23R illustrates that successive removal of surface material generally
238 moves the position of the coral towards the closed system age evolution line in
239 $(^{234}\text{U}/^{238}\text{U})$ - $(^{230}\text{Th}/^{238}\text{U})$ space (Fig. 4). This indicates that the sequential dissolution technique may
240 be useful in isolating portions of corals that have not been subject to open system behaviour, by
241 preferential removing the outer surfaces which have been potentially exposed to open system
242 behaviour through interaction of uranium and/or thorium isotopes between the coral and pore
243 fluid. However, the measured values of $(^{234}\text{U}/^{238}\text{U})$ and $(^{230}\text{Th}/^{238}\text{U})$ for partially dissolved sub
244 samples should not be considered more representative of a closed system, because removal of the
245 outer surface of the coral by partial dissolution is on such a small scale that there will have been
246 recoil exchange between the high ^{234}U and ^{230}Th exterior and the “unaltered” interior (Henderson et
247 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
248 calculate a conventional closed system age. Indeed, some of the leached sub-samples move away
249 from the closed system line, which may represent a more complex heterogeneous alteration of the
250 coral or an artefact of the leaching procedure. That the leached coral U-series data lie close to the
251 closed system evolution path, coupled with constraints based on our knowledge of the subsidence
252 rate of Tahiti and the history of global sea level, an approximation of the age of the coral can be
253 made.

254

255 *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 ± 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 ± 0.004 mka⁻¹. 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⁻¹ (LeRoy, 1994), using similar methodology. A lower, Holocene, subsidence rate of
263 0.15 mka⁻¹ 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⁻¹ 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⁻¹), 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}Th addition as well as the possibility of coupled ^{234}U - ^{230}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 mka^{-1} or 0.36 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 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 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 ± 1.0 and 133.7 ± 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

327 level was high during the MIS 5.5 highstand. Hypothesised ages, positions and hence paleo
328 water-depths of these cores are illustrated by open triangles in Fig. 3. Assuming a subsidence rate of
329 0.25 mka^{-1} the corals in M0005D-20R-2W were deposited at 84 mbsl. If the MIS 5.5 highstand was
330 ~ 8 mbsl (Kopp et al 2009) then the maximum water-depth that could have existed above these
331 corals was 94 m (including 2 m of subsidence from 133 ka to the time of the maximum highstand).
332 If core M0005D-16R is indeed MIS5.5 age then this would imply a water-depth of 83 m (16R is
333 11 m above 20R in the hole), which is in remarkably good agreement with the paleo water-depth
334 estimation of Fujita et al of 75 ± 15 m. This age constraint therefore indicates that both methods
335 for paleo water-depth estimation are sensitive to increasing water-depth and have accurately
336 recorded the sea level rise over the latter part of the penultimate deglaciation (Termination II).

337

338 Further comparisons between the age constraints and the paleo water-depth interpretations can be
339 made in the older sections of Hole M0005D. Iryu et al. (2010) suggest M0005D-23R to 24R,
340 characterized as a sandy bioclastic grainstone with massive *Porites* colonies, is representative of a
341 shallow water environment at the beginning of the penultimate deglaciation which is then
342 punctuated by a sea level reversal (Andrews et al., 2007; Esat et al., 1999; Siddall et al., 2006;
343 Thomas et al., 2009) from deeper water in M0005D-22R to 21R (characterised by bioclastic
344 packstones and microbialites with encrusting corals) back to shallow water in M0005D-21R to 20R
345 (coralgal framestone consisting of massive *Porites*). Fujita et al. (2010) also suggest M0005D-23R to
346 24R is shallow water deposit from the beginning of termination II, but has no data to constrain the
347 water-depth from M0005D 22R-21R. Ages of M0005D-23R to 24R are much older (MIS 9) than is
348 assumed by Fujita et al. (2010) and Iryu et al. (2010). Because there is no direct age control on the
349 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 ± 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 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 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 ~ 40 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 ~ 58 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 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 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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606

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 $((^{234}\text{U}/^{234}\text{U})_i)$, 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 $(^{234}\text{U}/^{234}\text{U})_i$ 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 ± 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 2σ uncertainties of the U-Th data of this study. The black arrow represents the direction
644 coupled addition of ^{234}U and ^{230}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 mka^{-1} and (B) 0.35 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 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 indicates 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	²³⁸ U ppm	2s	²³² Th ppb	2s	(²³⁰ Th/ ²³⁸ U)	2s	(²³⁴ U/ ²³⁸ U)	2s	(²³² Th/ ²³⁸ U)	2s
5D8146a2 ^a	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 ^a	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 ^b	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 ^b	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 ^c	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 ^c	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 ^c	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 ^d	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 ^d	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 ^d	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 ^d	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 ^d	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 ^d	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 ^d	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 ^c	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 ^c	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 ^c	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 ^c	30R-1W-119, 135	2.3745	0.0003	0.2373	0.0006	1.0541	0.0014	1.0541	0.0009	0.00003273	0.00000008

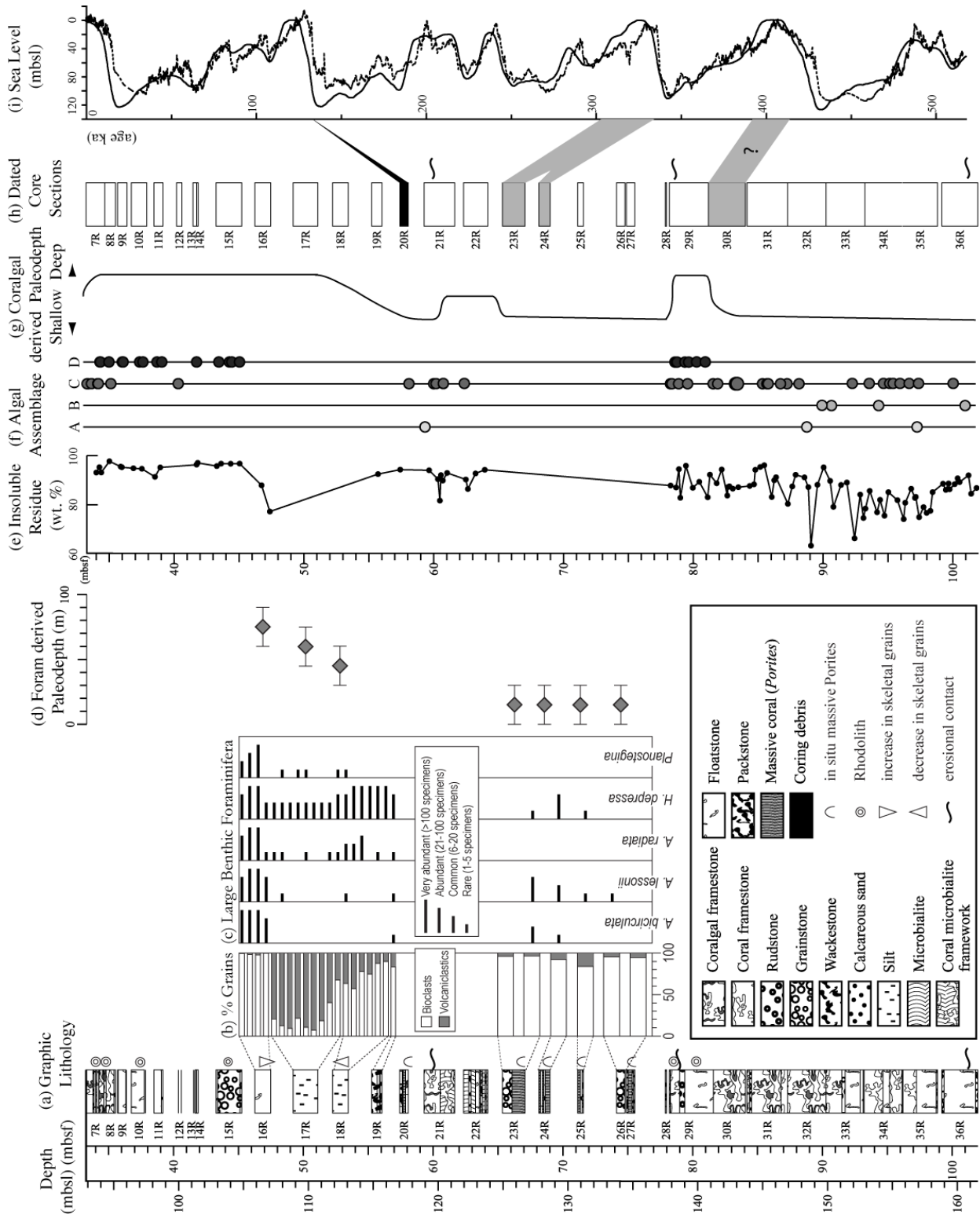
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668 **Table 2**

Sub-sample ID	mbsl	% Residue	Closed System Age			(234U/ 238U) _i	Open System Age			% calcite	2s
			ka BP	2s			ka BP	2s			
<i>5D8146a2^a</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^a</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^b</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^b</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 ^c	128.24	100%	472	15	1.261	0.011	379	8			
5D7198b ^c	128.24	100%	460	14	1.251	0.009	376	8			
5D7198c ^c	128.24	100%					502	18			
5D8256b1	128.02	100%	338	8	1.174	0.004	318	6	0.2%	0.2%	
5D23RTop_ac ^d	125.95	84%	340	4	1.1691	0.0021	324	4			
5D23RTop_ap ^d	125.95	89%	343	5	1.1640	0.0021	329	4			
5D23RTop_bc ^d	125.95	71%	342	5	1.1558	0.0022	334	4			
5D23RTop_bp ^d	125.95	56%	322	4	1.1547	0.0018	315	3			
5D23RTop_cc ^d	125.95	100%	324	4	1.1595	0.0019	315	3			
5D23RTop_cp ^d	125.95	65%	324	4	1.1532	0.0019	318	3			
5D23RTop_dp ^d	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 ^e	141.98	100%	503	20	1.25	0.01	409	9			
5D8668b ^c	141.98	84%					513	21	0.42%	0.04%	
5D8668c ^c	141.98	82%					507	21			
5D8668dp ^c	141.98	75%	432	9	1.183	0.003	399	7			

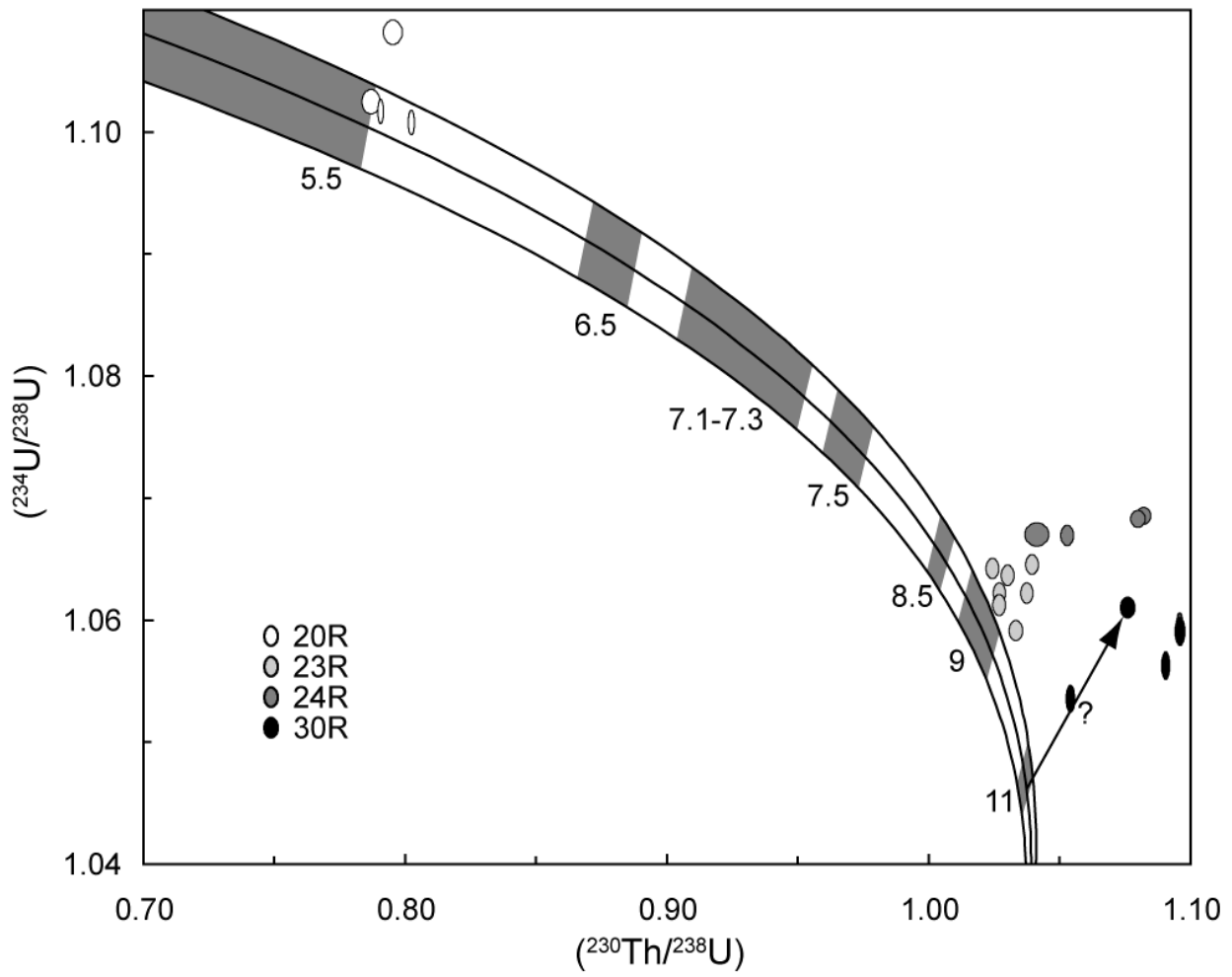
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670 Figure 1



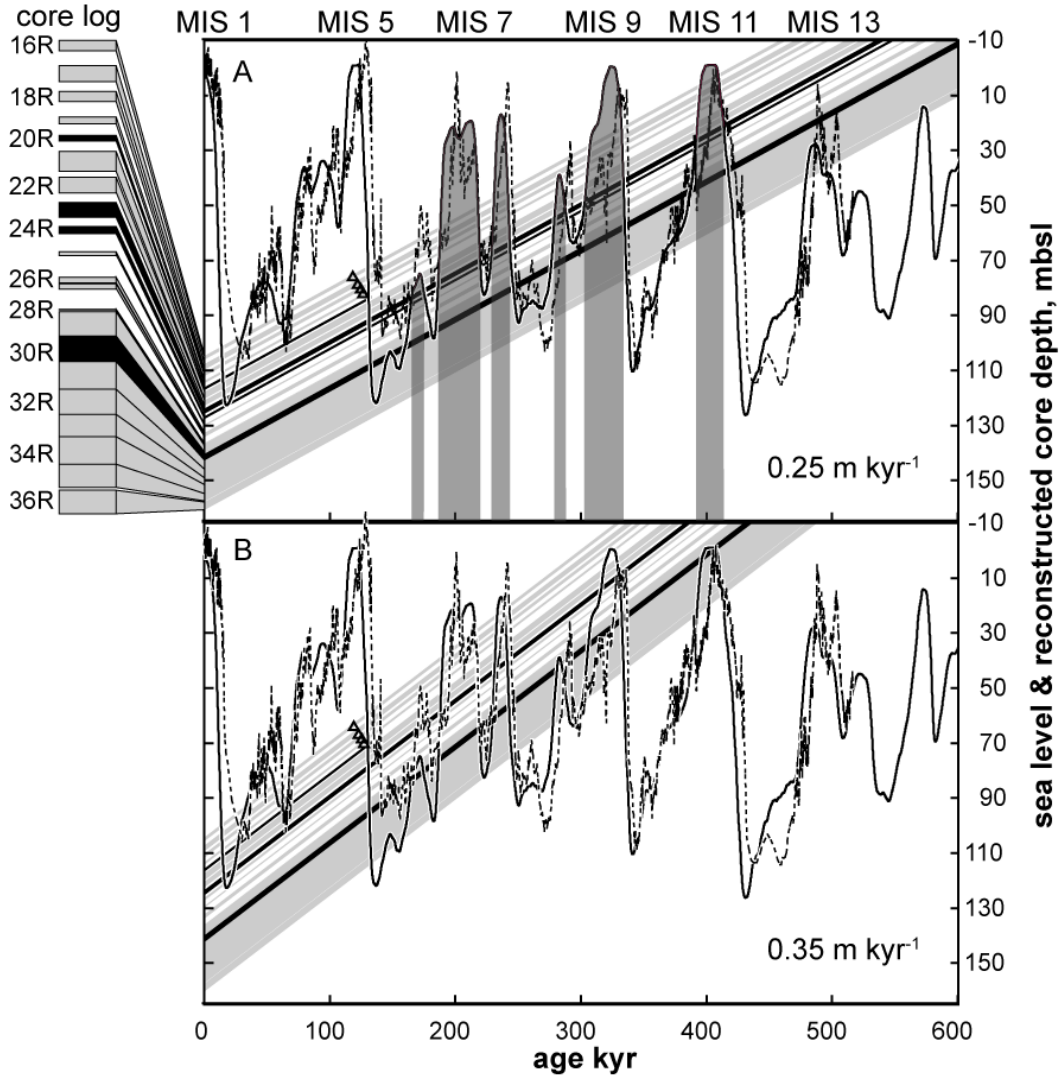
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672 Figure 2



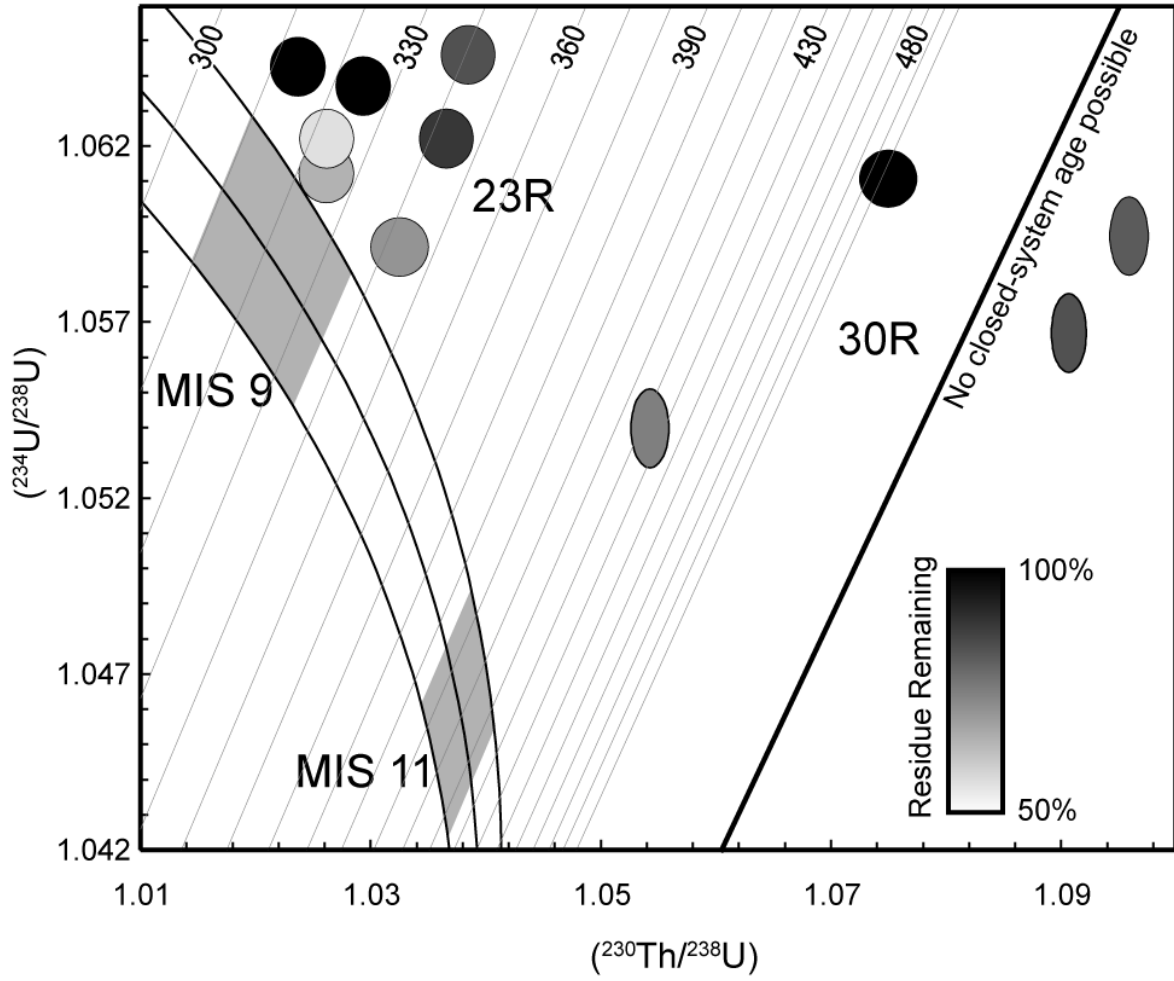
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674 Figure 3



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676 Figure 4



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