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## **New insights into the Holocene development history of a Pacific, low-lying coral reef island: Takapoto Atoll, French Polynesia**

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1 **New insights into the Holocene development history of a Pacific, low-lying coral reef island: Takapoto**  
2 **Atoll, French Polynesia**

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15 **Highlights**

16 – Initiation of low-lying islets from Takapoto Atoll (French Polynesia) started not prior 2,300 yr BP from  
17 isolated depocentres.

18 – Development of atoll islets occurred mainly throughout a sea-level fall between 2,600 yr BP and the last 500  
19 years.

20 – Over the last 2,000 years, in northwest Tuamotu islands, cyclone activity was probably more intense from the  
21 11th to 19th century.

22 **Abstract**

23 Low-lying atoll islands are known to be made up of unconsolidated, coral-rich, detritus, together with high  
24 amounts of foraminifera, derived from both outer-reef and lagoonal environments. While regarded as highly  
25 vulnerable to ongoing global changes, these islands are poorly constrained in term of developement history.  
26 Herein is presented a detailed chronostratigraphic study of Tuamotu atoll islands (French Polynesia, south  
27 central Pacific) based on analyses of sedimentary sequences through seven excavations along two transects  
28 across both windward and leeward rim areas around Takapoto Atoll. The island accretionary chronology is  
29 supported by radiometric dating of 62 coral and molluscan clasts. The sequences range between 3.80 m and  
30 1.20 m in thickness, from the oceanic shoreline lagoonwards. Four lithofacies were identified from sediment  
31 composition and texture: a coral (pocilloporid)-rich, gravel-supported, preferentially located in the outermost rim  
32 areas; a coral-rich, gravelly sand-supported, locally interbedded with gravel-supported units; a foraminifera  
33 (amphisteginid)-rich, sand-dominated, mainly located at the central and innermost rim settings; and an organic-  
34 rich, sand facies atop of some sequences. A model of atoll islet formation is drawn up in relation to mid to late  
35 Holocene sea-level changes. The foundations of islets (motus), namely *conglomerate platforms*, started to form  
36 with deposition of patchy, rubble spreads over the upper reef-rim surfaces from ca 4,500 yr BP as sea level was  
37 about 0.80 m above its present mean level. On these platforms, islets started to accrete not before ca 2,300 yr BP,  
38 from isolated depocentres located midway between outer-reef and lagoon margins. At that time, sea level at  
39 about +0.60 m above present mean sea level was starting to slowly decrease to its present position. The major  
40 growth phases occurred in a context of continued sea-level fall. Islets continued to accrete through concentric  
41 ridges mainly until the last 300 years. Accretion was dominantly driven by low-frequency, high-energy wave-  
42 surge events. From dating of coral clasts, a number of one to two events by century were identified as having  
43 apparently contributed to island formation at Takapoto. Regionally predicted increase in the rates of sea-level  
44 rise may have negative impacts on such islands since these have evolved under conditions of falling sea level.

45 *Keywords:* Holocene, southern tropical Pacific, Tuamotu islands, U-Th dating, atoll-island accretion.

## 46 1. Introduction

47 Atolls are mid-ocean, subcircular to elongate coral reefs. The emergent part of the atoll, so-called *atoll reef rim*,  
48 is usually covered by dominantly detrital, unconsolidated islets with low elevations, usually less than 5 m in  
49 French Polynesia (Duvat et al., 2017) and small spatial extent (a few dozen to hundred square kilometres).

50 As emphasized by the IPCC (Nurse et al., 2014), such low-lying reef islands are probably among the most  
51 sensitive and vulnerable lands to the impacts of climate change, especially to future sea-level rise and increasing  
52 storm intensity. The dynamics and habitability of atoll islands in the face of the future climatic constraints is  
53 therefore of major concern as many atolls are inhabited (Dickinson, 2009; Storlazzi et al., 2015, 2018, East et al.,  
54 2018; Kench et al., 2018; Beetham and Kench, 2018).

55 Understanding the vulnerability and expecting the trajectories of habitable atoll territories can come inevitably  
56 through detailed historical reconstructions of controls, modes and timings of atoll island development (East et  
57 al., 2018; Montaggioni et al., 2018). While special attention has been paid to drivers and modalities of atoll  
58 shoreline adjustments in response to the rise in sea level over the last century (Aslam and Kench, 2017; Duvat et  
59 al., 2017; Kench et al., 2015, 2018), atoll-island morphodynamic responses to environmental changes at the  
60 millennial scale are poorly documented. Available radiochronologically constrained reconstructions of atoll  
61 island formation indicate that there are significant interregional differences (Perry et al., 2011) and probably  
62 intraregional ones (East et al., 2018), particularly in French Polynesia (Hallmann et al., 2018; Montaggioni et al.,  
63 2018).

64 However, detailed studies on how and when atoll islands have formed in the region are essentially non-existent.  
65 A preliminary study on the mode and timing of atoll island development in French Polynesia was recently  
66 published (Montaggioni et al., 2018). It was based on the chronostratigraphic analysis of one single windward,  
67 south-eastern site at Takapoto Atoll, in the north-western part of the Tuamotu Archipelago. From an ocean-  
68 facing, 4 m-deep excavation through a coral-rubble ridge and uranium-series dating of 21 coral clasts, the  
69 successive island accretionary stages were identified. The outer part of the island appeared to be composed of  
70 three gravelly sand-supported to gravel dominated units that have started to accrete by approximately 1,000 yr  
71 BP as sea level was about +0.40 m above present mean sea level (pmsl). The ocean-facing ridge rests on an  
72 indurated conglomerate platform, the top surface of which is at present culminating at about +0.50 m. The  
73 platform is presumed to have deposited and cemented from 2,000 to around 1,000 yr BP during the time of sea

74 level drop from +0.60 m to +0.40 m, according to the sea-level curve by [Hallmann et al. \(2018\)](#). Additional  
75 dating of surficial coral clasts revealed that, along the south-eastern side of Takapoto, islets tend to initiate and  
76 accrete from the inner rim parts oceanwards.

77 However, this study did not permit to wholly understand the processes of atoll island deposition. At first glance,  
78 there is no reason to support the idea that modes and timings of islet development are similar between windward  
79 and leeward atoll sides, since there are marked differences between both settings in water-energy regimes,  
80 related sediment supplies and rim to foreereef-slope morphologies as well ([Montaggioni et al., 2019](#)).

81 The aim of the present paper is to provide detailed stratigraphic analyses of islands from Takapoto Atoll, on  
82 windward, south-eastern and leeward, south-western parts. Island stratigraphy is delineated from the  
83 chronostratigraphy analysis of seven excavations through ocean- to lagoon-facing sites, based on uranium-series  
84 dating of 61 coral clasts and accelerator mass spectrometry radiocarbon dating of one molluscan shell sample.  
85 These new datasets allow the conceptual model of atoll-rim island development previously outlined from  
86 Takapoto Atoll ([Montaggioni et al., 2018](#)) to be improved. Critical episodes and depositional modes of island  
87 accretion are identified and interpreted in relation to Holocene sea level fluctuations.

## 88 **2. Environmental setting**

### 89 *2.1. Atoll location and morphology*

90 Located in the central south Pacific, the Tuamotu Archipelago is comprised of 77 atolls and extends over  
91 1500 km along W–NW to E–SE oriented volcanic chains. Takapoto Atoll is sited in the north-western portion of  
92 the Tuamotu, between 14°33'–14°43' south latitude and 145°08'–145°16' west longitude ([Fig. 1A](#)). It  
93 belongs to a specific group of actively subsiding atolls on the Tuamotu Plateau ([Dickinson, 2004](#); [Montaggioni](#)  
94 [et al., 2019](#)). About 17 km long and 5.5 km wide, elliptical in shape, Takapoto is elongated along a SW–NE  
95 direction, and covers a total surface area of 74 km<sup>2</sup> ([Fig. 1B](#)). The almost continuous, low-lying, atoll rim, about  
96 23 km<sup>2</sup> in total areal coverage, approximates 350 m in width, and entirely encloses a lagoon deeper than 45 m  
97 ([Chevalier et al., 1979](#); [Salvat, 1981](#); [Salvat and Richard, 1985](#)). The rim is covered by individual islets, known  
98 as *motus* in the Polynesian Pacific, reaching 4 m in maximum elevation above present mean sea level (pmsl).  
99 Passes are totally missing. The reef islets are elongate or crescent-shaped, usually composed of unlithified coral  
100 rubble, mixed with skeletal sands and, on the north-western and north-eastern atoll zones, separated by inter-

101 islet, shallow channels – so-called *hoas* –, shoaling locally at low tide and allowing water exchange between the  
102 open sea and the lagoon at high tide. Islets are usually bordered by shingle ridges along the ocean-facing side of  
103 the atoll rim. Transverse profiles across both sides of the atoll show similar topographies with a seaward  
104 protruding relief (i.e. a ridge) changing into flat to gently dipping benches lagoonwards. Essentially in the  
105 middle parts of the windward rim, there are locally shallow swales and ponds. Islets rest usually on coarse-  
106 grained, firmly cemented skeletal sheets, forming the so-called antecedent *conglomerate pavements* or  
107 *conglomerate platforms*, standing 0.30 m to up to 0.60 m above pmsl (Montaggioni and Pirazzoli, 1984;  
108 Pirazzoli and Montaggioni, 1986, 1988; Montaggioni et al., 2018). Previously published radiometric dating of  
109 conglomerates at Takapoto revealed that these have deposited between  $6,609 \pm 55$  and not earlier than  $1,019 \pm 4$   
110 yr BP (Montaggioni et al., 2018), prior to be cemented within phreatic and vadose marine zones during a period  
111 of higher than present sea level (Montaggioni and Pirazzoli, 1984).

112 The outermost parts of the atoll rim are fringed by a living coral reef tract. This comprises a reef-flat zone, about  
113 100 to less than 50 m wide, less than 1 m deep at low tide. The reef flat is followed seawards by a spur-and-  
114 groove system sloping down to the depth of around 10 m and capped by an algal ridge, 0.20–0.50 m high at its  
115 inner border, especially at the windward, eastern settings (Chevalier et al., 1979; Bouchon, 1983; Salvat and  
116 Richard, 1985; Kühlman and Chevalier, 1986). This system ends either into a gently or steeply dipping foreslope  
117 to depths greater than 35 m depending on the location (Montaggioni et al., 2019). The atoll islets are known to  
118 be supplied mainly with coral detritus from communities living on adjacent reef-flats and upper forereef zones to  
119 depths of about 20 m (Harmelin-Vivien, 1994; Harmelin-Vivien and Laboute, 1986) and from lagoonal deposits  
120 in their innermost portions (Adjas, 1988). The relevant coral communities are dominated by robust-branching  
121 *Pocillopora* and massive *Porites* (Bouchon, 1983; Kühmann and Chevalier, 1986; Montaggioni et al., 2019).

## 122 2.2. Climate

123 The climate in the north-western Tuamotu region is of tropical type. The warm, rainy, austral summer lasts from  
124 November to April and the relatively cooler and dryer, austral winter from May to October. Air temperature  
125 varies between 23 °C and 30 °C. Rainfall approximates 1500 mm/year. The tide regime is microtidal and semi-  
126 diurnal, averaging 0.5 m in amplitude to a maximum of 0.70 m at spring tide.

127 The regional climate system is both driven by the trade-winds and by El Niño-Southern Oscillation (ENSO)  
128 which regulates tropical to extra-tropical storms (Andréfouët et al., 2012). Takapoto Atoll experiences the effects

129 of trade-winds, blowing from the E–NE sectors for 70 % of the year and from the SE for 20 %. In the austral  
130 winter, the sea conditions are driven by strong trade-winds and southern swells resulting in a high-energy wave  
131 regime. Periods of low wave heights (around 1.5 m) and calm occur between periods of moderate to high swells  
132 (2.5 m). During the austral summer, the wave regime is typified by low wave heights ([Andréfouët et al., 2012](#)).  
133 Trade-winds are significantly less active and generate moderate-energy wave conditions, locally disturbed by  
134 high-energy events initiated either by ENSO-related cyclones or by storms originating from northern latitudes.  
135 Higher amplitude waves (up to 3.75 m) can be generated by three event types: high easterlies winds, western  
136 transient storms and distant cyclones ([Andréfouët et al., 2012](#)). The cyclonic season usually extends from  
137 November to April, with a large annual variability mainly related to ENSO. The eastward migration of warmer  
138 sea surface temperatures during El Niño episodes promotes the displacement of tropical storms further east into  
139 the the Tuamotu region. The cyclone track pattern in French Polynesia is typified by a tapering channel between  
140 the Society and the Austral Islands through which 70 % of the cyclone tracks pass ([Larrue and Chiron, 2010](#)).

141 Events of extreme wave hazard are poorly documented in the Tuamotu region. [Lau et al. \(2016\)](#) provided a  
142 comprehensive survey of recorded cyclones and their effects in historical times. A total of about 24 cyclones are  
143 known from the Tuamotu for the past 192 years between 1822 and 2014. The north-western Tuamotu islands  
144 were occasionally visited by tropical storms and cyclones (4–10 per century; [Dupon, 1987](#)) with maximum wind  
145 gusts up to 150 km/h and swells higher than 6 m. Since the beginning of the 20th century, Takapoto has been hit  
146 by four cyclones ([Duvat et al., 2017](#) and references therein). Over periods of several centuries, the number of  
147 cyclonic events in the northwestern Tuamotu have probably not exceeded 2–3 per century ([Canavesio,](#)  
148 [pers.com.](#)). Gaps of longer than 100 years are not uncommon between extreme wave events. However, such  
149 events seem to have been of greater magnitude during the past than during the last century ([Lau et al., 2016](#)).  
150 While the cyclonic hazard in the region is typified by a very low frequency of events, it displays active phases  
151 mainly in relation with ENSO episodes, during which several cyclonic events can occur within short time  
152 intervals. Cyclone hazard records reveal a 50-year return period for wave exceeding 12 m high ([Canavesio,](#)  
153 [2014](#)).

154 Little is known about the effects of cyclones and storms in shaping atoll morphology. In 1906, on Anaa Atoll,  
155 cyclone-generated waves have removed the western side of the island over a distance of more than 300 m.  
156 [Canavesio \(2014\)](#) estimated that these waves have reached heights ranging between 15.5 m and 18.5 m. From  
157 1926 to 2010, a total of 50 cyclones were registered in French Polynesia, but only those of 1982–1983 and  
158 1997–1998 resulted in severe disturbances fore-reef coral communities at Takapoto ([Harmelin-Vivien and](#)

159 [Laboute, 1986](#)). During Cyclone Orama, in February 1983, the village was flooded by 4 m to 5 m high waves.  
160 [Laboute \(1985\)](#) pointed out that about 50 to 100 % of the living fore-reef coral communities were destroyed  
161 along the eastern side of the atoll at that time.

162 As for the cyclone activity, little information is available on the frequency and effects of tsunamis in the  
163 Tuamotu ([Etienne, 2012](#)). The available data suggest that, since the 16th century, the Tuamotu islands were  
164 affected by less than ten tsunamis generating 0.3 m to 1.9 m-high waves ([Lau et al., 2016](#)). Based on numerical  
165 modeling and direct observations, the Tuamotu region seems to have not been significantly affected by tsunami  
166 waves compared to high volcanic French Polynesian islands ([Sladen et al., 2007](#)).

167 Reconstruction of absolute sea-level changes in the tropical Pacific over a 60-year period (1950–2009) indicated  
168 that sea level rose by  $2.5 \pm 0.5$  mm/yr, a value higher than the mean global absolute sea-level rise (1.2 to  
169 1.8 mm/yr) estimated for the 20th century ([Becker et al., 2012](#)). For the next decades, models predict an  
170 acceleration of sea-level rise in the north-western Tuamotu atolls, with rates greater than 8 mm/yr ([Botella,](#)  
171 [2015](#)).

### 172 **3. Materials and methods.**

#### 173 *3.1. Field work*

174 Topography surveys were conducted along two transects, respectively across the south-eastern and south-  
175 western sides of the reef rim ([Figs. 1B, 1C and 2](#)). Behind a 100-m wide reef-flat zone, the south-eastern transect  
176 extends over 330 m, from the ocean-facing shoreline to the lagoonal border ([Figs. 1C and 2](#)), between  
177  $S14^{\circ}40'42''$ – $W145^{\circ}12'50''$  and  $S14^{\circ}40'41''$ – $W145^{\circ}12'57''$ . Behind a 60-m wide reef-flat zone, the south-  
178 western transect extends over 370 m inland ([Figs. 1D and 3](#)), between  $S14^{\circ}41'08''$ – $W145^{\circ}15'32''$  and  
179  $S14^{\circ}41'14''$  and  $W145^{\circ}15'20''$ . Levelling was undertaken using a conventional automatic level. Along the  
180 transect, each reference point was positioned using DGPS coordinates. Rim elevations were established by  
181 reference to present mean sea level, assuming a conservative error of  $\pm 0.10$  m. The island surfaces are densely  
182 covered by coconut plantations.

183 Island topography on south-eastern, windward and south-western, leeward sides are comparable. Alongside the  
184 ocean, both transects exhibit unconsolidated rubble ridges, running parallel to the shoreline, with ocean-facing



185 steep ( $30^{\circ}$ – $45^{\circ}$ ) scarps. Ridges culminate at elevations of about 4.10 m and 3.30 m above pmsl at the eastern and  
186 western settings respectively. Behind the ridges, there are flat-topped benches, spreading out over 200 m  
187 lagoonwards and culminating at mean heights of about 1.5 m to 1.80 m. The benches end into  $20$ – $10^{\circ}$  sloping,  
188 beaches, less than 20 m wide, lagoon side.

189 Vertical excavations using backhoe were dug in both transects from top surface to underlying conglomerate  
190 surfaces in order to determine island subsurface stratigraphy. Starting from outer ridges inwards, surveys were  
191 conducted, at the south-eastern, windward atoll side, from four excavations, successively labelled A, B, C and E  
192 (Fig. 2), and at the south-western, leeward side, from three others F, G, and H (Fig. 3). Excavation location was  
193 defined using a GPS positioned at the surface. Field grain-size analysis of coarser detrital material was  
194 performed using the Udden-Wentworth classification (Terry and Goff, 2014) as measured along the longest axis  
195 from photographed square-metre quadrats. Coral pebbles and coarse-grained were collected for radiometric  
196 dating at all excavated sites. Taxonomic identification of dated coral and molluscan specimens was made at the  
197 generic level.

### 198 3.2. Radiometric dating procedures.

199 In order to determine island chronostratigraphy and accretion history, a total of 62 samples, labelled SAT –  
200 according to B. Salvat, collector – were collected along the walls and at the bottom of the excavations. Only one  
201 sample composed of sand-sized molluscan shelly debris (SAT 97A2) was dated using the AMS radiocarbon  
202 method at the LMC 14 – Laboratoire de mesure du carbone 14 –, ARTEMIS National Facility at Gif-sur-Yvette,  
203 France. A radiocarbon age of  $2,725 \pm 30$  was returned. Calibration using the IntCal13 and Marine13 radiocarbon  
204 calibration programme (Reimer et al., 2013) yielded a calibrated age of  $2,447 \pm 127$  with a two sigma error  
205 range.

206 For U/Th analysis purposes, millimetric pieces of coral clasts were cut using a micro saw in order to select the  
207 most clean and pristine parts. These pieces were rinsed with mQ water and ultrasonicated several time.

208 After adding a triple  $^{229}\text{Th}$   $^{233}\text{U}$ – $^{236}\text{U}$  spike in a Teflon beaker, samples (from 150 to 350 mg) were dissolved  
209 with diluted HCl. The U-Th separation and purification were performed after coprecipitation with  $\text{Fe}(\text{OH})_3$ , on  
210 0.6 ml columns filled with U-TEVA and pre-filter resins, in nitric media – see Pons-Branchu et al., 2014 for  
211 details. The U and Th isotopic compositions were analyzed at the *Laboratoire des Sciences du Climat* (LSCE,

212 France), on a Multi-Collector inductively coupled plasma source mass spectrometer (MC-ICPMS) Thermo  
213 Scientific™ Neptune<sup>Plus</sup> fitted with a desolvating introduction system (aridus II) and a jet interface. For mass  
214 fractionation correction, we used an exponential mass fractionation law – normalized to natural  $^{238}\text{U}/^{235}\text{U}$   
215 isotopic ratio –and standard–sample bracketing. More details on the analytical procedure (chemistry and MC-  
216 ICPMS analysis) can be found in [Pons-Branchu et al. \(2014\)](#). After corrections for peak tailing, hydrate  
217 interference and chemical blanks,  $^{230}\text{Th}/^{234}\text{U}$  ages were calculated ([Table 1](#)) from measured atomic ratios through  
218 iterative age estimation using the  $^{230}\text{Th}$ ,  $^{234}\text{U}$  and  $^{238}\text{U}$  decay constants of [Cheng et al. \(2013\)](#) and [Jaffey et al.](#)  
219 [\(1971\)](#).

### 220 *3.3. Establishing island chronology.*

221 The use of U/Th measurements from displaced skeletal material (corals, molluscs, foraminifera) for  
222 reconstructing depositional histories of atoll islands were discussed by [Woodroffe et al. \(1999, 2007\)](#), [Kench et](#)  
223 [al. \(2014\)](#) and [Montaggioni et al. \(2018\)](#). An indefinite time interval (tens to hundreds of years) is postulated to  
224 separate the time of death of a given organism from the time of final deposition and stabilisation of its skeletal  
225 fragments. Coral clasts may have experienced successive cycles of displacement, reworking and  
226 re-sedimentation. This is clearly evidenced by some age inversions in the stratigraphic sections. Island  
227 chronologies have therefore to be regarded as relative, not absolute. However, consistency of island chronologies  
228 is ensured by the fact that most dated samples occupy a stratigraphic position within the excavations which is  
229 usually consistent with their age ([Figs. 4 and 5](#)). Samples tend to be younger closer to the surface. In a given  
230 stratigraphic section, the youngest ages obtained are regarded as closer to the time of definitive stabilisation of  
231 the relevant island section.

## 232 **4. Results**

### 233 *4.1. Lithostratigraphy*

234 All excavations terminated 0.30–0.50 m above pmsl on a firmly cemented, composite surface, composed of  
235 gravel-sized, coral clasts embedded within a sandy matrix and identified as the underlying conglomerate  
236 platform. Locally, this surface is inundated by the water table at levels higher than of about 0.10 m (excavations  
237 C, E and G) to 0.40 m (excavation H). The thicknesses of the overlying, unconsolidated deposits are relatively

238 comparable within windward and leeward sites, according to their position along the transects. The ocean-facing,  
239 windward rubble-ridge sequence (excavation A) is 3.80 m thick (Figs. 2 and 6), while the thickness of the  
240 leeward-ridge one (excavation F) does not exceed 3 m (Figs. 3 and 7). The sedimentary sequences from the  
241 innermost sites range between 1.20 m and 1.50 m thick (Fig. 8). Except in the windward, outer-ridge sequence  
242 that contain sediment layers of about 2 m thick, other sequences are composed of layers averaging 0.20 m to  
243 0.30 m in thickness (Fig. 9). Grain-size decreases from the outermost deposits lagoonwards. Gravel-dominated  
244 facies laterally grades into gravelly, sand-supported, then in sand-dominated facies.

245 Sediment composition and texture are highly consistent between windward and leeward sides. Gravels, including  
246 cobbles and pebbles, are dominantly composed of coral pocilloporids, associated with acroporids and faviids,  
247 and low amounts of molluscan shells and coralline algal debris. Sandy fractions contain locally up to 80 % of  
248 benthic foraminifera. The remaining sand grains come mostly from coral, molluscs and algae. Foraminiferal  
249 detritus are almost exclusively composed of *Amphistegina lobifera*, associated with *Marginopora vertebralis*.  
250 Subordinate forms include *Sorites*, *Cymbaloporetta*, *Amphistegina lessonii* and miliolids.

251 Four major lithofacies were delineated, primarily based on textural characteristics.

252 1– Gravel-dominated facies.

253 It is divided into two subfacies as distinguished by its clast-supported attributes: gravel-supported and sand-  
254 supported. Both facies were reported from both atoll sides. Throughout the studied sites, amounts of gravel-sized  
255 sediments were markedly higher on the windward than the leeward rim sites. The gravel-supported subfacies is  
256 common within all windward holes at different stratigraphic levels (Fig. 9A), to 270 m back from the oceanic  
257 shoreline. By contrast, it seems to occur on the leeward coast only in excavation F (Figs. 9B, 9C) where it is  
258 most prevalent and at top of excavation G (Fig. 9D), up to 150 m behind the oceanic shoreline. However, this  
259 does not imply non-deposition of gravels further inland. The second sand-supported, gravelly subfacies is largely  
260 dominant over the gravel-supported one, especially within the south-eastern, windward areas, representing about  
261 90 % of the total sediment volume in excavations A, B and C (Fig. 9D).

262 Longest axis of coral gravels ranges between 300 mm (fine boulder) and less than 5 mm (fine pebble) with mean  
263 values of 100 to less than 10 mm. Along the windward atoll side, the gravel sizes tend to decrease lagoonwards.  
264 The mean size varies between 50 and 10 mm in the two outermost sites (excavations A, B) to reach 15 and less  
265 than 10 mm in the two innermost (excavations C, E). A similar size-decreasing trend was observed along the

266 leeward island parts. Gravelly grains are 120 mm in mean size at the ocean-facing site (excavation F), but are  
267 sized at an average of 40 and 3 mm in the innermost holes (excavations G, H) respectively. Surprisingly, the  
268 biggest gravels, 300 mm in maximum length, were found in the leeward, ocean-facing shingle ridge (excavation  
269 F).

270 The thickness of gravel-dominated stratigraphic units is consistent from site to site, averaging 0.30 to 0.40 m.  
271 Grading occurs usually in each unit, with a fining-upward trend. The units are usually separated by erosional,  
272 locally lithified surfaces as observed within the outermost, leeward site (excavation F).

### 273 2– Sand-dominated facies.

274 Sandy sediments were deposited mostly in the innermost island areas at both windward and leeward settings,  
275 within excavations C, E, G and H (Figs. 10A, 10B, 10C). Sands are usually coarse-to medium-graded (1–0.25  
276 mm in mean size) and well to moderately sorted as mostly composed of larger foraminiferal tests, together with  
277 coral and molluscan detritus. Proportions of sand-supported, gravel-sized grains vary locally. As a whole, their  
278 proportions tend to increase upwards in the stratigraphic cross-sections. In sand-dominated sequences  
279 (excavations E and H), foraminifera-rich layers, about 10–20 mm thick, are distributed in the form of fining-  
280 upward, graded-bedding units and alternate with coralgal-rich beds of similar thickness (Fig. 10D).

### 281 3– Organic-rich, sand facies.

282 This facies relates to the development of an organic-rich, brown to black-coloured, root-bearing horizon at the  
283 uppermost parts of most sedimentary sequences, mainly at the expense of sand-dominated deposits (Figs. 8B,  
284 8D, 10A, 10B, 11). It is missing from excavations B and F, the top of which consists exclusively of gravel-  
285 supported material. Its thickness is relatively constant from one sequence to another at both atoll sides, ranging  
286 between 0.3 m and 0.50 m, except atop of hole A where it does not exceed 0.10 m. Sands were primarily coarse-  
287 sized, poorly sorted and supporting coral clasts as long as 10 to 50 mm.

## 288 4.2. Chronostratigraphy

289 Corrected ages, expressed as years before 2018 or 2019 (yr BP), range between  $70 \pm 10$  yr BP for Sample SAT  
290 77A (excavation F) and  $6.629 \pm 38$  yr BP for Sample SAT 74 (excavation A) (Table 1). The initial uranium  
291 isotopic composition ( $\delta^{234}\text{U}_i$ ) range within the modern marine composition ( $146.86 \pm 0.1$  ‰ Andersen et al.,

292 2010) within the  $\pm 5\%$  interval usually used as criterion for age reliability, except 3 samples from excavation B  
293 (SAT 53A, 60A and 119A) that display values slightly lower (between  $136.0 \pm 1.9$  and  $139.2 \pm 1.9$ ).

294 Samples from the basal conglomerate platform returned ages ranging from  $6,629 \pm 38$  yr BP (SAT 74A) to  
295  $2,257 \pm 8$  yr BP (SAT 101A). The youngest ages at base of the overlying unconsolidated sediments within  
296 windward and leeward sites vary between and  $2,358 \pm 8$  yr BP (SAT 93B) and  $676 \pm 13$  yr BP (SAT 73B). At a  
297 given site, these are wholly younger than those of conglomerate pavements. In the uppermost stratigraphic  
298 sections, ages vary from  $2,531 \pm 53$  yr BP (SAT 96A) to  $70 \pm 10$  yr BP (SAT 77A).

299 Within most of the stratigraphic columns, ages tend to decrease from base to top and accordingly appear to be  
300 stratigraphically consistent (Figs. 4 and 5). In the windward and leeward outer-ridge sequences (excavations A  
301 and F), ages decrease from  $636 \pm 7$  yr BP (SAT 73A) to  $156 \pm 12$  yr BP (SAT 68A) and from  $1,130 \pm 10$  yr BP  
302 (SAT 86B) to  $70 \pm 10$  yr BP (SAT 77A) respectively. Similarly, within holes through the plateaus behind the  
303 outer ridges, ages range from  $1,660 \pm 60$  yr BP (SAT 57B) to  $1,280 \pm 13$  yr BP (SAT 52A) in hole B, from  
304  $2,340 \pm 11$  yr BP (SAT 36B) in hole C, and from  $2,843 \pm 16$  yr BP (SAT 100A) to  $801 \pm 13$  yr BP (SAT 97A1)  
305 in hole H. Hole G is distinguished by the fact that the five dated samples returned ages clustered between  
306  $2,958 \pm 17$  yr BP (SAT 91B) and  $2,358 \pm 8$  yr BP (SAT 93B). Such a narrow age range may express either a  
307 rapid accretion of this island part, within a 400 year-long interval or a continuous supply from a same sediment  
308 source. The average time lag between base and top of each sequence can be estimated as follows: 500 years in  
309 hole A, 400 years in hole B, 960 years in hole C, 500 years in hole E, 1,000 years in hole F, 600 years in hole G  
310 and 1,100 years in hole H.

311 The oldest deposits in both atoll sides were encountered in excavations from the mid rim-parts. Ages range, in  
312 hole C, from  $2,635 \pm 12$  yr BP (SAT 34B) to  $2,411 \pm 15$  yr BP (SAT 34A) and, in hole G, from  $2,958 \pm 17$  yr BP  
313 (SAT 91B) to  $2,358 \pm 8$  yr BP (SAT 93B). By contrast, the youngest dates from the two transects were reported  
314 from the outer-ridge sections, varying between  $636 \pm 7$  yr BP (SAT 73A) and  $156 \pm 12$  yr BP (SAT 68A) at the  
315 windward side (excavation A) and  $1,130 \pm 10$  yr BP (SAT 86B) and  $70 \pm 10$  yr BP (SAT 77A) at the leeward  
316 side (excavation F). As a summary, across both rim transects, ages tend to progressively decrease from the  
317 central excavated sites (C and G) toward the lagoon margin and the ocean respectively.

318 **5. Discussion**

319 *5.1. Age of deposition of conglomerate pavements*

320 Ages of coral clasts trapped into conglomerate pavements vary widely from  $6,629 \pm 38$  yr BP (SAT 74A) to  
321  $2,600 \pm 20$  yr BP (SAT 60A) at the windward setting and from  $4,683 \pm 21$  yr BP (SAT 94A) to  $2,257 \pm 8$  yr BP  
322 (SAT 101A) at the leeward one, expressing difference in age of about 4,000 and 2,500 years respectively (Table  
323 1; Figs. 2, 3, 6 and 7). Such age discrepancies in basal conglomerate platforms appear to be a common feature in  
324 coral islands as reported, for instance, from the Marshall Islands (Kench et al., 2014). At Takapoto, basal  
325 conglomeratic material previously extracted from other windard sites provided similar age offsets (Montaggioni  
326 and Pirazzoli, 1984). Thus, previous U/Th dating of conglomerates underlying a shingle ridge sitting about 130  
327 m north of the presently studied windward ridge (excavation A) provided ages of 1,391 yr BP to 1,019 yr BP  
328 (Montaggioni et al., 2018). This may indicate that coral material accumulated in a same narrow area have been  
329 supplied from a same adjacent stock containing detritus reworked over periods of several centuries prior to be  
330 deposited and stabilized. An alternative explanation is that deposition of conglomerate clasts is far from having  
331 been synchronous throughout the rim and has been rather patchy, originally resulting in the development of  
332 isolated, small cells to discontinuous spreads, finally more or less merged as observed at present. Sediment may  
333 have been provided by sources applied at different times during the Holocene sea level course. This is in  
334 agreement with previous dating of basal rubbles or conglomerates from low-lying islands throughout the Pacific,  
335 confirming their deposition mostly during the mid to late Holocene (Chivas et al., 1986; Hayne and Chappell,  
336 2001; Yu et al., 2012; Kench et al., 2014; Montaggioni et al., 2018). According to good coherency of age  
337 distribution versus elevation as observed in the different island stratigraphic sequences from both the present  
338 study and the previous one (Montaggioni et al., 2018), youngest ages of coral clasts are postulated to be close to  
339 time of deposition and represent maximum ages of deposition.

340 *5.2. Age and mode of island development.*

341 Assuming that ages of coral-clast production trapped into conglomerate pavements is very close to that of  
342 conglomerate formation, deposition of conglomerates on which islets have settled, would occur within a short  
343 interval, between around 2,600 yr BP and 2,200 yr BP on both rim sites, according to their youngest ages  
344 ( $2,257 \pm 8$  yr BP, SAT 101A;  $2,600 \pm 20$  yr BP, SAT 60A). Islets started to shape relatively coevally from

345 windward to leeward places. This is supported by ages of the lowermost, youngest deposits in some stratigraphic  
346 sequences:  $2,340 \pm 10$  yr BP (SAT 36B) in hole C,  $2,843 \pm 16$  yr BP (SAT 100A) in hole H,  $2,358 \pm 10$  yr BP  
347 (SAT 93B) in hole G. The outermost, ocean-facing parts of islets seem to have begun to growth later,  
348 presumably from 1,100 - 1,000 yr BP in accordance with ages recorded at base of holes A ( $636 \pm 7$  yr BP; SAT  
349 73A) and F ( $1,130 \pm 10$  yr BP; SAT 86B). Age distributional patterns (Figs. 2, 3, 6 and 7) revealed clearly that  
350 the oldest sections at windward and leeward settings are those located in the central parts of the rim (holes C and  
351 G). This gives evidence that islets began to accrete from distinct, nodal locations, interpreted as depocentres,  
352 located approximately midway between the ocean-facing beach and lagoon margins, at around 200 and 150 m  
353 from the beach, respectively on the windward, eastern and leeward, western sites. From the initial depocentres,  
354 proto-islets have presumably continued to develop laterally and both lagoonwards and oceanwards (Figs. 6, 7  
355 and 12). Spaces between the depocentres have probably functioned as zones of water exchange, i.e. paleo-hoas.  
356 The final phase of island accretion is believed to relate to infilling of remaining spaces between the outer margin  
357 of the depocentres and the innermost parts of the reef-flat zone. The mode of island development was identical  
358 on both rim sides as illustrated by isochron distribution (Figs. 6, 7 and 12). However, there is no direct evidence  
359 that the entire atoll-island areas were built from an amalgamation of a series of neighboring, isolated islets and,  
360 similarly, that there was formerly a crenulated shoreline with alternating motus and hoas, with gradual infilling  
361 of hoas, since, at present, the island-rim is prominently bounded by a continuous stretch of a linear shoreline.  
362 The proposed accretionary island model is based on observations of the present-day topographic status of a  
363 number of nearby atoll islands (for instance, Ahe, Manihi). These are composed mainly of a series of small,  
364 isolated islets, still separated by functioning hoas. This status may represent an intermediate, immature stage of  
365 atoll-island development. In addition, assuming that islet accretion result predominantly from cyclone-generated  
366 deposition, every deposit can be spatially restricted, as controlled by the path of the generating cyclone and  
367 sustainability of sediment sources.

368 Islet depocentres were initiated at around 2,300–2,200 yr BP, as expressed by the youngest ages at base of  
369 excavations C ( $2,340 \pm 10$  yr BP; SAT 36B) and G ( $2,358 \pm 8$ ; SAT 93B). Accretion of the depocentres would  
370 have operated throughout approximately 800 years, between 2,300 and 1,500 yr BP. From stabilization time of  
371 the depocentres, the development of the main islet parts was complete within about one millennium. The  
372 windward, outer shingle ridge would have formed in about 500 years, close to the growth time (700 years) of the  
373 outer shingle ridge rising at 130 m further north (Montaggioni et al., 2018). In addition, age comparison between  
374 the uppermost parts of outer-ridge sequences (holes A and F) and of innermost ones (holes E and H) gives

375 support to the idea that ocean-facing reliefs, dated from 193 to 70 yr BP at top, experience permanently active  
376 reshaping while lagoonward margins may have remained relatively stable since at least the last 500 years.

377 Lateral accretion rates occurred at varying rates along the outer and inner parts of both sides, starting from the  
378 central depocentres. The windward, outer rubble ridge developed oceanwards at rates of about 10–15 cm/yr  
379 while not higher than 5 cm/yr at the leeward setting. Along both windward and leeward sides, the inner areas  
380 would accrete lagoonwards at rates less than 5 cm/yr. These values clearly take into account episodes of  
381 erosional and reworking events since major depositional episodes are known to have occurred through  
382 instantaneous, low-frequency wave-surge events (see below).

### 383 *5.3. Frequency of island-shaping, high-energy wave events.*

384 Assuming that island shaping result from deposition of coral clasts mainly derived from upper forereef and reef-  
385 flat populations hit by winter storms and cyclones (Bourrouilh-Le Jan and Talandier, 1985; Harmelin-Vivien and  
386 Laboute, 1986) and partly from lagoonal areas (Adjas, 1988), attempt can be made to link dated samples to a  
387 given extreme hazard events, especially for the last 2,000 year-period (common era, CE), using the recently  
388 completed database of cyclone activity in French Polynesia (Laurent and Varney, 2014; Lau et al., 2016;  
389 Canavesio et al., 2018). From the U/Th age database provided herein, were identified a total of 25 events, taking  
390 into account possible age overlapping between samples as identified by U/Th error range (Table 2). These events  
391 are time distributed as follows: only one event from the 1st, 3th, 5th, 4th, 6th, 7th, 11th, 18th, and 20th centuries,  
392 two events from the 8th, 13th, 14th, 15th, and 16th centuries, and three events from the 9th and 19th centuries.  
393 These findings agree with the fact that cyclone frequency was relatively high in the north Tuamotu from the 11th  
394 century, with an average of two extreme wave events per century (Toomey et al., 2013; Montaggioni et al.,  
395 2018; Etienne et al., in preparation). The most striking feature relates to age deposition of ocean- and lagoon-  
396 facing island areas respectively in relation to wave-surge events (Fig.13). At windward and leeward sites as well,  
397 deposition occurred closer to lagoon margins (Excavations B, C, E and H) dominantly between the 1st to 12th  
398 centuries. Sediments were mostly composed of sands. By contrast, deposition along outer rim margins  
399 (Excavations A and F) took place later, between the 9th and 20th centuries. Sediments were gravel-dominated.  
400 In addition, this last episode was coeval with deposition of a number of megaclasts in the Tuamotu (Lau et al.,  
401 2016; Canavesio et al., 2018). This may confirm not only an increase in cyclone frequency, but also may reflect  
402 an increase in cyclone intensity since the 11th century, resulting in an increasing transport capacity of wave



403 surges.

404 Sample SAT 99B dated back to  $53 \pm 9.5$  CE may have been generated by the same hazard event that has  
405 displaced the mega-boulder dated from 54 CE at Kauehi Atoll in north-west Tuamotu (Canavesio et al., 2018).  
406 Intense storminess was reported by Nunn (2007) and Toomey et al. (2013) in the central south Pacific over the  
407 11th to 15th centuries as recorded by deposition of megaclasts by about 1270, 1300, 1330, 1420–1430 CE at  
408 Makemo Atoll, central Tuamotu (Lau et al., 2016). The ages of Samples SAT 71B ( $1269 \pm 16$ ), SAT 73A  
409 ( $1320 \pm 12.5$ ), SAT 74 ( $1344 \pm 12.5$  CE) encompass this period of high storm activity. Sample SAT 81A dated  
410 at  $1566 \pm 5.5$  CE is coeval of two megaclasts deposited on the north-eastern coast of Takapoto (Etienne et al., in  
411 preparation). The three wave-surge events recognized in the 19th century, based on Samples SAT 68A  
412 ( $1864 \pm 11.5$ ), SAT 77B ( $1856 \pm 4.5$ ) and SAT 68B ( $1826 \pm 10$  CE), may be related to cyclones that occurred in  
413 1822, 1825, 1877-1878 CE (Lau et al., 2016). These events were also identified by Canavesio et al. (2018) in the  
414 central Tuamotu (Marokau and Hikueru Atolls). Sample SAT 77A with an age of  $1948 \pm 9.5$  CE may have been  
415 supplied by the January 1958 event, the only registered in the Tuamotu since 1903 for the first half of the 20th  
416 century.

417 Going back into the first millennium before Jesus Christ (BC), a number of 11 distinct hazard events were  
418 apparently registered. The frequency ranges around 1 to 3 events per century: one over the 10th (940 BC, SAT  
419 91B), the 9th (825 BC, SAT 100A), the 7th (620 BC, SAT 34 B), the 3rd (240 BC, SAT 101A) and the second  
420 (120 BC, SAT 99A), two or three over the 8th (790–770 BC, SAT 53A, 55A, 57A; 740 BC, SAT 52B), the 6th  
421 (590–580 BC, SAT 50A, 55B, 60A; 510 BC, SAT 53B, 96A), and the 4th (390–380 BC, SAT 34A, 93A; 340–  
422 350 BC, SAT 91A) centuries. Although, the number of hazard events counted as from simple analysis of the  
423 number of clast occurrences can be biased due to random sampling, frequency of high-energy events recorded  
424 from the 10th to 2nd centuries BC is quite consistent with that calculated from the CE interval. Accordingly, as a  
425 summary, the present study is assumed to confirm that high-energy events would occur in the north Tuamotu  
426 over the last 3,000 years at an average frequency of one to two per century with a recurrence time of 50 to 100  
427 years. More especially, the increase in cyclone intensity from the 11th century deserves to be emphasized.

#### 428 *5.4. Conceptual model of atoll-island development*

429 Based on a previous chronostratigraphic analysis of one windward, outer shingle ridge excavation at Takapoto,

430 [Montaggioni et al. \(2018\)](#) postulated that the relevant motu was not emergent prior to about 1,000 yr BP. This  
431 assumption remains in line with the present study. However, new records from the seven additional excavations  
432 lead to improve the previous atoll-island development model in relation to the mid to late Holocene sea-level  
433 oscillations ([Fig. 14](#)).

434 In western French Polynesia, the sea-level course over the last 7,000 years is relatively well constrained from  
435 dating of reef cores and elevated micro-atolls, respectively by [Bard et al. \(1996\)](#) and [Hallmann et al. \(2018\)](#).  
436 Previous sea-level reconstructions come from petrographical examination of conglomerate platforms, especially  
437 at Takapoto ([Montaggioni and Pirazzoli, 1984](#)), together with dating of elevated coral heads ([Pirazzoli and](#)  
438 [Montaggioni, 1986, 1988](#)). Thus, it appears that, at around 7,000 yr BP, sea level was approximately 10 m  
439 below pmsl ([Bard et al., 1996](#)). At that time, the late Pleistocene reef surfaces at Takapoto are assumed to have  
440 been close to sea level, resulting in colonization by coral communities ([Fig. 14A](#)). Sea level outpassed its present  
441 position by about 6,000–5,500 yr BP in the Tuamotu ([Hallmann et al., 2018](#)) and, especially at Takapoto  
442 ([Montaggioni and Pirazzoli, 1984; Pirazzoli and Montaggioni, 1986, 1988](#)). As a result of upward accretion over  
443 the mid-Holocene, the top of the reef rim was then at depths of about 5–6 m below pmsl ([Fig. 14B](#)). Sea level  
444 continued to rise up to elevations of +0.80 m to +1 m from 5,000 to 4,000 yr BP ([Pirazzoli and Montaggioni,](#)  
445 [1988; Hallmann et al., 2018](#)). Assuming a mean vertical accretion of 4–5 mm/yr ([Montaggioni, 2005](#)), reef-rim  
446 surfaces are thought to have stabilized close to pmsl after a 1,000–1,500 year-long vertical accretion, at about  
447 5,000–4,500 yr BP. High intensity, wave-surge events probably started to supply rim surfaces with significant  
448 quantities of coral clasts. From that time, sea level began to drop progressively ([Hallmann et al., 1988](#)). From  
449 3,000 to 1,500 yr BP, sea level dropped from about +0.70 m to +0.50 m relative to pmsl ([Pirazzoli and](#)  
450 [Montaggioni, 1986, 1988; Hallmann et al., 2018](#)). According to their youngest ages within the test areas,  
451 conglomerate platforms would ended up forming not earlier than 2,300 yr BP, probably as patchily distributed  
452 deposits at the outset ([Fig. 14C](#)). Conglomerate cementation was interpreted to have occurred within vadose to  
453 phreatic zones, presumably from 2,300 to less than 1,000 yr BP according to location, as sea level was slightly  
454 higher than present ([Montaggioni and Pirazzoli, 1984](#)), between +0.60 m to +0.30 m. From 1,500 to 1,000 yr BP,  
455 sea level dropped regularly toward its present position ([Fig. 14D](#)). Correlatively, coral gravels continued to  
456 accumulate over conglomerate beds, forming depocentres. These extended laterally forming discontinuous islets.  
457 From 1,000 to 500 yr BP, islets develop dominantly oceanwards to finally form an almost continuous island  
458 ([Fig. 14E](#)). The present configuration of the atoll island was acquired over the last three centuries ([Fig. 14F](#)).

459 The degree of exposure of each respective rim side to wave surges, has apparently controlled distances to which  
460 deposits were transported from the outer reef margins and the lagoonal slopes. According to the transport  
461 capacity of waves (Presto et al., 2006), most coral clasts appear to have been first trapped at respective distances  
462 of about 200 m on the south-eastern, windward side and to 150 m on the south-western, leeward side prior to  
463 stabilize. As a result, detrital deposits are postulated to have begun to develop in the form of small islets  
464 (depo-centres), subcircular to elongated, as soon as 2,300–2,000 yr BP. Located initially closer to the lagoon  
465 border than to the oceanic coastline, these are regarded to have continued to spread concentrically both  
466 oceanwards and lagoonwards during the lowering sea level over the past 1,500 years (Figs. 13D, 13E). Islet  
467 extension to lagoon margins seem to have been achieved between about 1,000 and 500 yr BP, while ocean-  
468 facing shingle ridges approached the modern oceanic coastline not earlier than 200–100 yr BP (Fig. 13F).  
469 Unconsolidated sections of islets have started to develop when sea level was some 0.60–0.50 m above pmsl  
470 while conglomeratic foundations were still partly submerged. Consequently, at Takapoto and possibly, in other  
471 subsiding north Tuamotu atolls, islands are regarded as having mostly developed during a time of falling sea  
472 level.

473 The source of the material extending islets to lagoonward remains questionable, due to the lack of identifiable  
474 biogenic tracers exclusively confined to lagoonal environments. For instance, compositional analysis by Adjas  
475 (1988) revealed that, at Takapoto, sediments of reef flats and nearby beaches contain about 15% to up to 50% of  
476 foraminifera respectively, and those from lagoonal talus and bottoms, about 20%. In all of the studied atoll sites,  
477 the foraminiferal assemblages are similarly dominated by *Amphistegina* and *Marginopora*, thus making difficult  
478 the sediment sources to be identified. It is hypothesized that cyclones are able to remove and redeposit most  
479 sand-graded bioclasts derived from both ocean-facing and lagoon-facing environments in any atoll-rim zone  
480 through overwash and run-up processes. During strong cyclones, the water level in the open ocean like that in  
481 the lagoon can rapidly rise several metres above pmsl, and thus, approaching waves come onshore at both rim  
482 sides as rising turbulent surges loaded with bioclastic sandy grains. Owing to their respective form (subspheric  
483 and disk-shaped), *Amphistegina* and *Marginopora* tests have low settling velocity and high hydrodynamic  
484 stability, thereby able to experience grain size selection and to be moved by suspension far from their production  
485 areas (Montaggioni and Venec-Peyré, 1993). However, the dominance of foraminiferal tests (locally, up to 80%)  
486 over other bioclasts in the sedimentary sequences close to the lagoon margins may suggest that the relevant  
487 material came mostly from lagoonal deposits in which foraminifera is known to represent locally about 20% of  
488 the total sand fraction (Adjas, 1988). In this view, the extension of the inner shoreline towards the lagoon would

489 be chiefly driven by sediment supply from nearby lagoonal bottoms.

490 The island accretionary model presented herein refers to the “central core” model defined by [Woodroffe et al.](#)  
491 [\(1999\)](#) in which island accretion starts from depocentres (i.e. central cores) and extends both oceanwards and  
492 lagoonwards through time. This model is also in total agreement with [Dickinson’s](#) claim [\(2004\)](#), indicating that  
493 coral-reef island formation was promoted by gradual sea level fall. Similarly, the present scenario is closely  
494 linked to works by [McLean and Woodroffe \(1994\)](#), [Richmond \(1992\)](#), [Woodroffe et al. \(1999\)](#). These authors  
495 suggested the presence of hard basements close to or at sea level as a prerequisite for island formation. By  
496 contrast, in other tropical Indian and Pacific areas, differing models of low-lying, coral island development were  
497 described, in which main accretion occurred during marine transgressive to high-stand periods ([Kench et al.,](#)  
498 [2005, 2014; East et al., 2018](#)). In any case, long-term atoll-island stability would be governed by sea level  
499 changes. As formed in different sea-level contexts, i.e. transgressive, regressive or at higher than present,  
500 stabilized sea-level, islands will be going to respond differentially to the predicted sea-level rise. Those accreted  
501 during marine regressive events may be altered by rising sea levels, especially if sea level is expected to rise at  
502 rates up to 8 mm/yr ([Botella, 2015](#)), storminess to increase in intensity and vertical reef-growth rates to not  
503 exceed 4-5 mm/yr on average ([Perry et al., 2018](#)) in the next decades.

## 504 **6. Conclusions**

505 From chronostratigraphic analysis of seven excavations across two transects from the south-eastern, windward  
506 and south-western, leeward rim sides at Takapoto Atoll emerges a number of highlights relating to the history of  
507 atoll-island development in the north-western Tuamotu.

508 Storminess, especially cyclone activity, appears to be the major control of island formation, as demonstrated by  
509 textural and compositional patterns of the motus. Island stratigraphy is typified by a decreasing grain-size trend  
510 from the outer border lagoonwards. Gravel-dominated deposits grade laterally into gravelly, sand-supported to  
511 sand-dominated sediments as expressing a decreasing transport capacity of wave surges inwards. Dominant  
512 gravel components include pocilloporid corals, mostly derived from the adjacent, upper forereef zone. Sand-  
513 sized grains are prominently composed of foraminifera (amphisteginids, mainly), regarded as derived from open-  
514 sea environments and lagoonal bottoms as well. Distinct depositional sequences are composed of units, to 2 m  
515 thick at the windward, outer island margin, but not exceeding 0.40 m at other settings. Most sequences exhibit a  
516 fining-upward, graded bedding.

517 Based on 62 radiometric ages of skeletal material and preserved stratigraphic characteristics of the excavated  
518 deposits, the history of atoll-island development is reconstructed in relation to mid to late Holocene sea-level  
519 changes. The basal conglomerate pavements on which motus have settled began to form prior to about 2,600 yr  
520 BP over pre-existing reef flat surfaces as sea level was stabilized at about +0.80 m above pmsl. While deposition  
521 of conglomerates in the making occurred mainly during a period of high still-stand relative to present, the main  
522 phases of island development took place in a context of sea-level drop from about 2,300 yr BP to present. From  
523 about 1,500 yr BP, on both rim sides, islands started to growth from subcircular to elongate, partly emerging,  
524 patchily distributed depocentres (islets). They continued to spread out concentrically, reaching lagoon margins as  
525 soon as 1,000 yr BP. Over the last centuries, islets extended mainly oceanwards to form continuous islands. The  
526 dataset gives sufficient evidence to believe that this evolutionary scenario may be appropriate for explaining  
527 accretionary histories of other subsiding, northern Tuamotu atolls. However, this model would have to be tested  
528 in nearby atolls, especially those experiencing active uplifting, including Rangiroa, Tikehau, Mataiva and  
529 Tikehau Atolls ([Montaggioni, 1985](#)).

530 Dating of coral clasts revealed that, in the north Tuamotu, over the last 3,000 years, high-energy wave events  
531 occurred at an average frequency of one to two per century with a recurrence time of 50 to 100 years. This puts in  
532 light the critical role of low-frequency, high-energy events in island shaping, especially in ocean-facing areas.  
533 However, a rapid rise in sea level could be an additional key factor in the future behaviour of atoll islands. Of  
534 great concern is how islands formed in a context of sea-level fall will respond to a sea-level predicted to  
535 regionally rise at rates of about 8 mm/yr in the next future, assuming rates of reef vertical accretion averaging 4–  
536 5 mm/yr and increasing cyclone intensity.

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544 A, B, C and D are located on parcel A 510 of the land register (Terre Ohavana, owner Faarii Norbert Tetu

545 husband of Kaua Tevaha Tegahhe known as Denise). Excavations F and G are located on parcel A. 348 of the  
546 land register (Terre Orohoe, owner "successsion Teamanaha in Manake - F.O.). Excavation H is located on  
547 parcel A 356 of the land register (Owner French Polynesia, by default). Field work and sampling have been  
548 conducted from the end of February to early March 2018 by BS and AA. U/Th and AMS radiocarbon dating  
549 were performed by EPB and AD. AMS radiocarbon of Sample SAT 97A2 was performed by the French  
550 National facility Artemis LMC14 (LSCE (CNRS–CEA/UVSQ)-IRD-IRSN-MC) Saclay, France. The  
551 corresponding author, LFM, was in charge of interpreting the data and drafting the article in collaboration with  
552 allhis co-authors. BS and AA provided field pictures. Figures were conceived by LFM and BM-G.  
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## 708 **Table and Figure captions**

709 **Table 1.** Uranium/Thorium data of coral samples from Takapoto Atoll. Are given successively laboratory  
710 sample codes, field sample (SAT) numbers, uranium and thorium contents, isotopic composition with statistical  
711 errors (two standard deviations of the mean) and ages.  $\delta^{234}\text{U}_m = (\{^{234}\text{U}/^{238}\text{U}\}_{\text{measured}}/\{^{234}\text{U}/^{238}\text{U}\}_{\text{equilibrium}} - 1) \times$   
712  $1000$  , with  $^{234}\text{U}/^{238}\text{U}_{\text{equilibrium}} = 54.89 \times 10^{-6}$  (molar ratio. Cheng et al., 2013).  $\delta^{234}\text{U}_i$  is the  $\delta^{234}\text{U}$  at initial time  
713 (using U/Th ages). Ages are expressed in years BP (Before Present), relative to the year of sample analysis (2019  
714 for samples from 7813 and 2018 from the other samples) and are corrected for detrital content using a  
715  $^{230}\text{Th}/^{232}\text{Th}$  isotopic ratio =  $.7 \pm 50\%$ . For sample Exc. B - SAT 55 B, “e” is for external part and “I” is for  
716 internal part.

717 **Table 2.** Selection of dated coral samples, younger than 2,000 yr BP, with ages expressed in calendar years of  
718 the common era (CE).

719 **Fig. 1.** A) Location map of Takapoto Atoll in the Tuamotu Archipelago (French Polynesia, central Pacific). B)  
720 Te Fenua map of Takapoto Atoll showing location of the two studied areas, labelled as SE (south-east) and SW  
721 (south-west). C–D) Aerial views of both rim sides of Takapoto Atoll, showing location of the seven excavation  
722 sites from the SE and SW profiles respectively: south-eastern (see Figure 2) and south-western (see Figure 3)  
723 profiles.

724 **Fig. 2.** South-eastern, windward profile, with location and lithostratigraphy of excavations A, B, C, and E (see  
725 [Figs. 9, 10 and 11](#) for close-up views). Are also given location and radiometric age of coral samples (SAT)  
726 collected within each excavation – see [Table 1](#) for details of dates. Ages are expressed in years BP.

727 **Fig. 3.** South-western, leeward profile, with location and lithostratigraphy of excavations F, G and H (see [Figs.](#)  
728 [8, 9, 10 and 11](#) for close-up views). Are also given location and radiometric age of coral samples (SAT)  
729 collected within each excavation – see [Table 1](#) for details of dates. Ages are expressed in years BP.

730 **Fig. 4.** Plot of U/Th dated coral samples versus their respective stratigraphic location at the south-eastern,  
731 windward excavation sites (see [Figs. 1C and 2](#) for sample location). Ages are expressed in years BP. Note trends  
732 in decreasing ages from base to top. The numbers refer to field SAT samples (see [Table 1](#) for details of dates).

733 **Fig. 5.** Plot of U/Th dated coral samples versus their respective stratigraphic location at the south-western,  
734 leeward excavation sites (see [Fig. 1D and 3](#) for sample location). Ages are expressed in years BP. Note trends in  
735 decreasing ages from base to top. The numbers refer to field SAT samples (see [Table 1](#) for details of dates).

736 **Fig. 6.** Cross-section of the south-eastern, windward rim profile, with location of excavations A, B, C, and E.  
737 The numbers within each excavation refer to ages of the dated samples as positioned according to their  
738 stratigraphic level. Elevations are given relative to surfaces of the underlying conglomerate platforms. The  
739 dashed lines relate to accretion isochrons (years BP) based on the dated intervals within excavations. WT: water  
740 table level.

741 **Fig. 7.** Cross-section of the south-western, leeward rim profile, with location of excavations F, G and H. The  
742 numbers within each excavation refer to ages of the dated samples as positioned according to their stratigraphic  
743 level. Elevations are given relative to surfaces of the underlying conglomerate platforms. The dashed lines relate  
744 to accretion isochrons (years BP) based on the dated intervals within excavations. WT: water table level.

745 **Fig. 8.** Views of the stratigraphic sequences from both windward and leeward excavations. A) Excavation B  
746 (windward side): the uppermost 0.50 m are of gravel-supported facies while the 1 m-thick, lower section is  
747 composed of sand-supported, gravels. The cavity floor with the label is the top surface of the underlying  
748 conglomerate platform. B) Excavation C (windward side): the sequence is overtopped by a 0.25 m-thick,  
749 organic-rich unit. To depth of 0.60 m, sand is dominating. Below, the facies is sand-supported, gravelly. The  
750 conglomeratic floor is drowned under the water table. C) Excavation E (windward side): an about, 0.30 m-thick,

751 organic-rich layer caps the sequence (1.50 m in total thickness). Sediments are sand-dominated. The  
752 conglomeratic basement is inundated. D) Excavation G (leeward side): below the gravelly top surface and a  
753 0.50 m-thick, organic-rich unit, appears a bed, about 0.90 m-thick, composed prominently of foraminifera-rich  
754 sands. The basal conglomerate pavement is flooded by the water table.

755 **Fig. 9.** Gravel-dominated facies from both windward and leeward rim sites. The stick is decimetre-calibrated. A)  
756 Close-up of Excavation B (windward side), showing the stratigraphic sequence from top to 1.10 m deep. The top  
757 0.40 m bed is gravel-supported, while the lower 0.80 m layer is of sand-supported, gravel facies. B) Close-up of  
758 Excavation F (leeward side), showing the uppermost section (0.60 m-thick) composed of sand-supported gravels.  
759 The lower 0.10 m-thick layer is of gravel-supported facies. C) Close-up of Excavation F (leeward side), showing  
760 the section from 1.0 to 2.0 m below top surface. It exhibits three superimposed, fining-upward, gravel-supported  
761 units, ranging each from 0.30 to 0.40 m in thickness. D) Close-up of Excavation A (windward side), showing  
762 successively from top downhole: a 0.10 m-thick, organic-rich layer, a 0.30 m-thick gravel-supported unit, and a  
763 sand-supported, gravel unit.

764 **Fig. 10.** Sand-dominated facies from both windward and leeward rim sites.

765 The stick is decimetre-calibrated. A) Close-up of Excavation C (windward side), showing sand-dominated facies  
766 at depths of 0.83 to 1.20 m beneath top surface of the sequence. Locally, just below the stick, the sediment is  
767 partly lithified as a caliche crust. B) Close-up of Excavation G (leeward side), showing a sand-dominated bed  
768 overtopped by a brown-coloured, organic-and root-rich layer, about 0.50 m in thickness. The top surface of the  
769 section is covered by gravel-dominated horizon. C) Close-up of Excavation H (leeward side) showing a sand-  
770 dominated section, enriched in organic matter at its upper 0.25 m portion. D) Close-up of Excavation E  
771 (windward side), showing alternations of foraminifera-rich and coralgall laminations, ranging between 10 and  
772 20 mm in thickness.

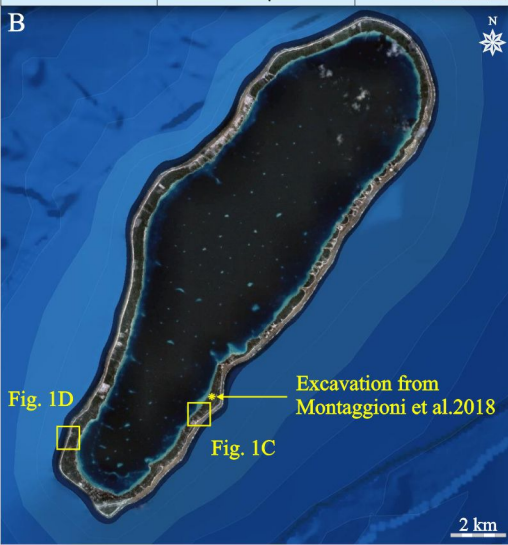
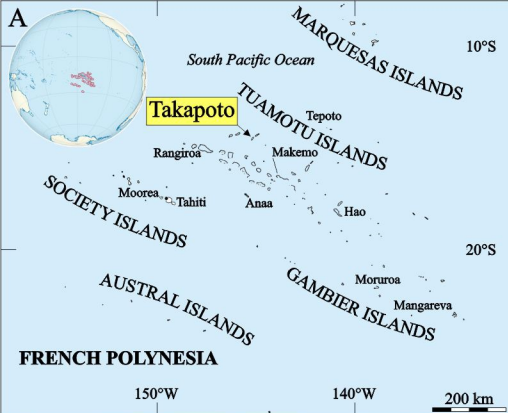
773 **Fig. 11.** Organic-rich, sandy facies. Close-up of Excavation H (leeward side), showing an about 0.25 m-thick,  
774 black-coloured, organic-rich bed, capping a sand-graded unit. The stick is decimetre-calibrated.

775 **Fig. 12.** Planimetric reconstruction of the south-eastern, windward atoll rim, showing successive island-accretion  
776 phases over the past 1,500 years. Isochrons delineate the changing aerial extent of islets through time, from  
777 1,500 yr BP to present. Initial depocentres are contained within the 2,000 yr-BP time-line clusters. Between  
778 adjacent depocentres, prior to be infilled, spaces are believed to have been first bare of significant detrital

779 volumes and thus to have served as channels of water exchange between the open ocean and the lagoon, similar  
780 to modern hoas. Islets extended to lagoon margins as soon as 1,000 yr BP, while they approached the modern  
781 ocean-facing shoreline not prior to about 500 yr BP.

782 **Fig. 13.** Age distribution of identified wave-surge events throughout the last 2,000 years, based on U/Th dating  
783 of coral gravels. For both windward and leeward rim sides, the blue dots refer to deposition of sand-dominated  
784 samples, inner island areas; the red dots refer to deposition of gravel-dominated samples, outer island areas. The  
785 ages of events identified herein are compared with those respectively reported by [Lau et al., 2016](#) (crosses) and  
786 [Canavesio et al., 2018](#) (open circles) for the same time span.

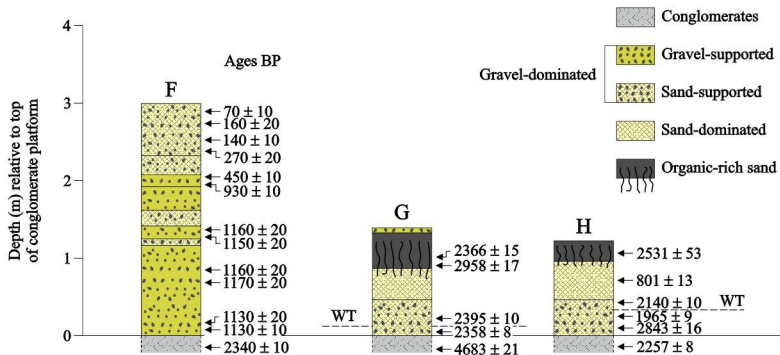
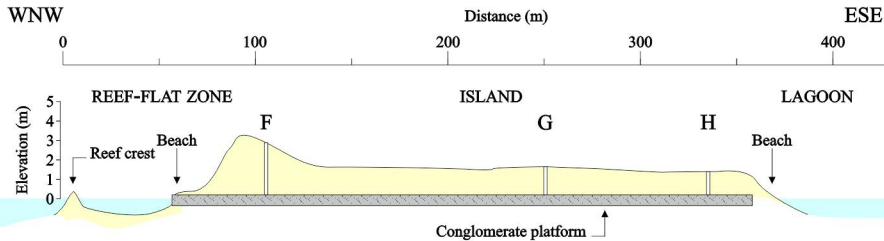
787 **Fig. 14.** Conceptual evolutionary model of rim-island development at Takapoto Atoll. A) At around 7,000 yr BP,  
788 as sea level was approximately  $-10$  m below present mean sea level (pmsl), the reef pile of late Pleistocene age  
789 culminated close to sea level. Coral communities started to colonize newly available substrates, while wave-  
790 surge events began to move coral fragments upslope to reef top. B) From 6,000 to 5,000 yr BP, while sea level  
791 rose to an elevation of about  $+0.80$  m to  $+1.00$  m above pmsl, the reef pile developed upwards, resulting in  
792 deposition of a 4–5 m-thick, mid-Holocene unit, but remained still submerged at depths of  $-5$  m to  $-6$  m relative  
793 to pmsl. The reef-rim top caught up with sea level during the late Holocene, by approximately 3000 yr BP. From  
794 5,000 to 3,000 yr BP, sea level dropped by 0.10 m. Correlatively, reef aggradation continued to operate and to  
795 deposit a few metre-thick, late Holocene unit. C) From 3,000 to 1,500 yr BP, sea level continued to fall down.  
796 Coral clasts extracted from proximal upper reef slopes were deposited across the reef-rim areas and along the  
797 lagoonal slopes. These deposits were the nuclei of basal conglomerate platforms. D) From 1,500 to 1,000 yr BP,  
798 sea level dropped regularly toward its present position promoting cementation of conglomeratic basements.  
799 Correlatively, coral gravels continued to accumulate over conglomerate beds, forming depocentres. These  
800 extended laterally, predominantly lagoonwards, forming discontinuous islets. E) From 1,000 to 500 yr BP, islets  
801 develop dominantly oceanwards to finally form almost continuous islands. F) The present configuration of the  
802 atoll island was acquired over the last centuries.

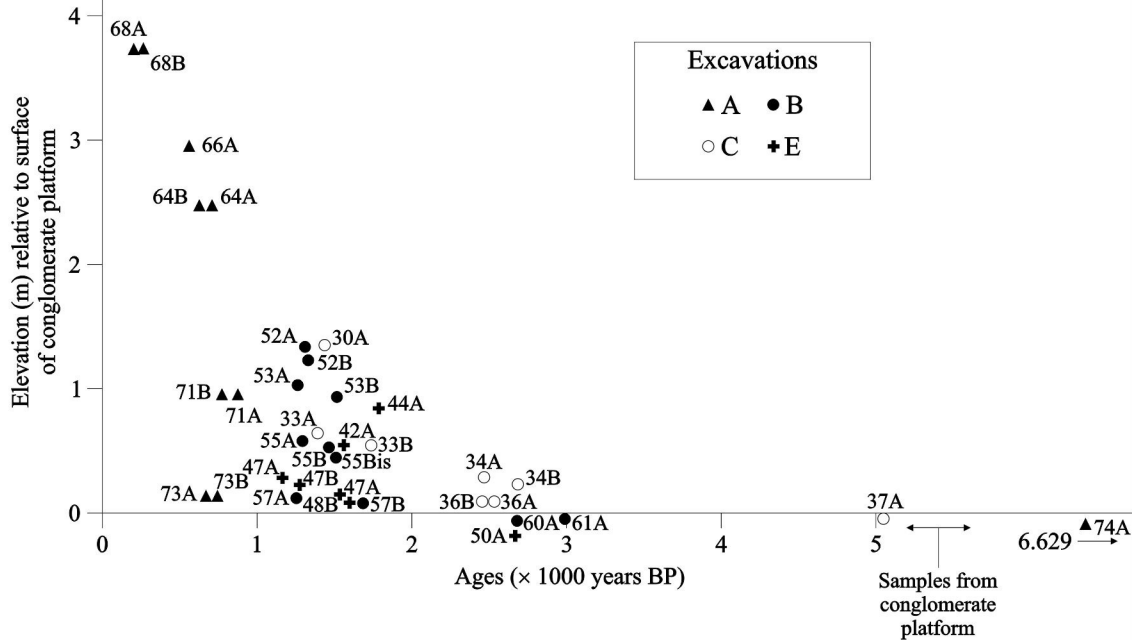




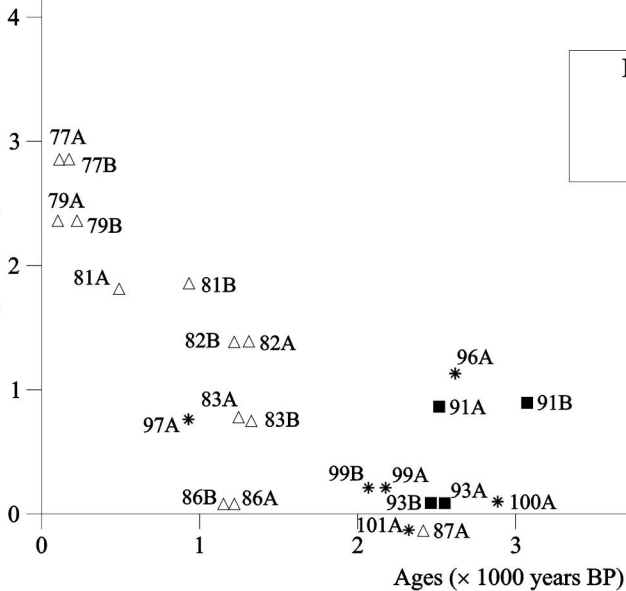


# SOUTH-WEST, LEEWARD SIDE



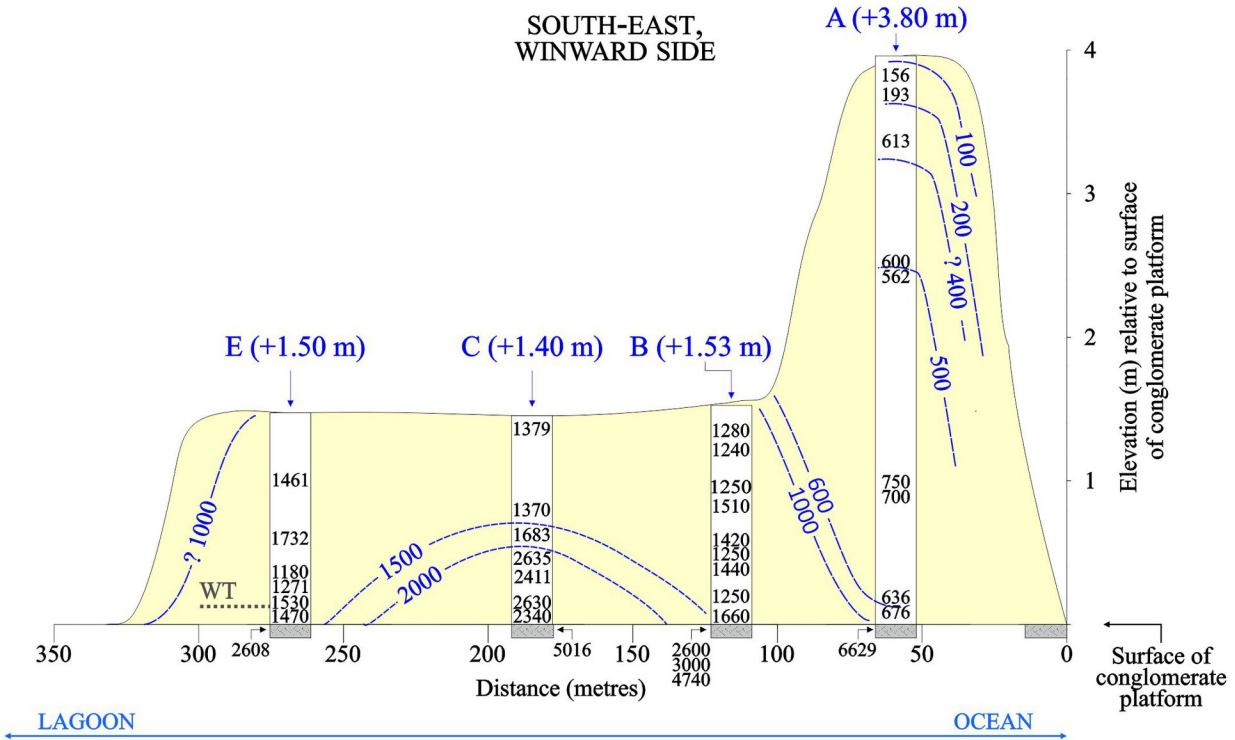


Elevation (m) relative to surface  
of conglomerate platform

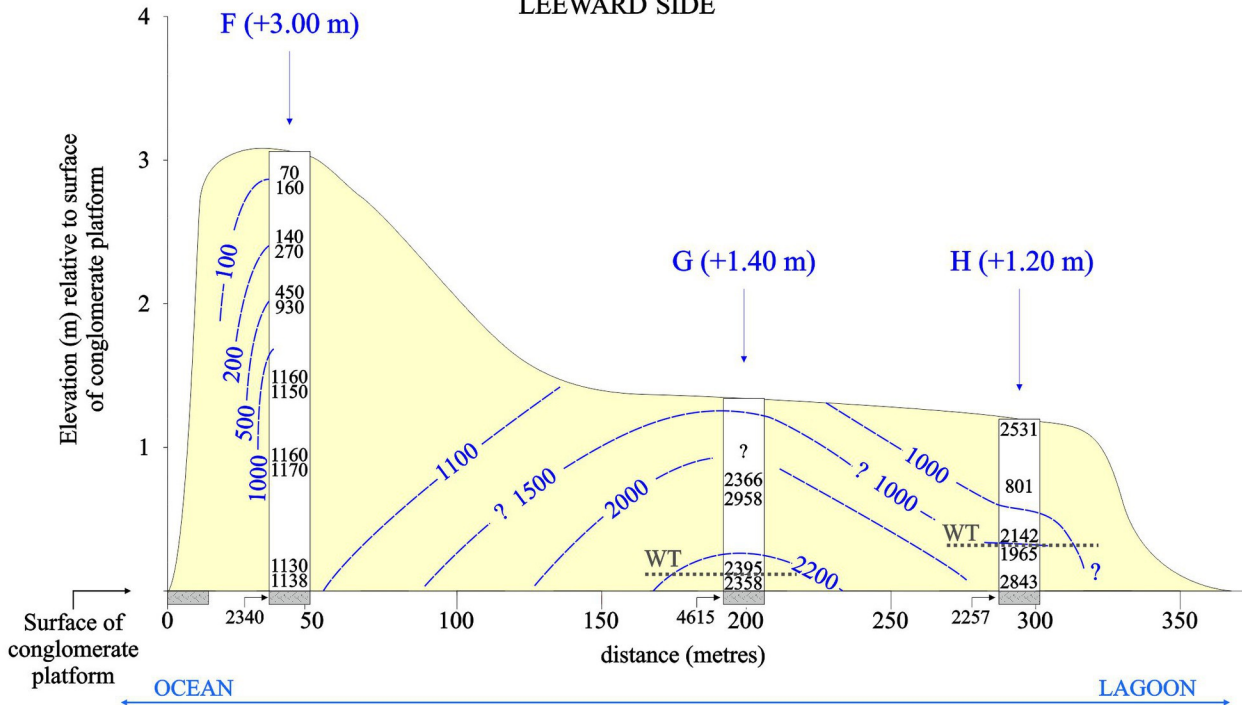


←  
Samples from  
conglomerate  
platform

SOUTH-EAST,  
WINWARD SIDE

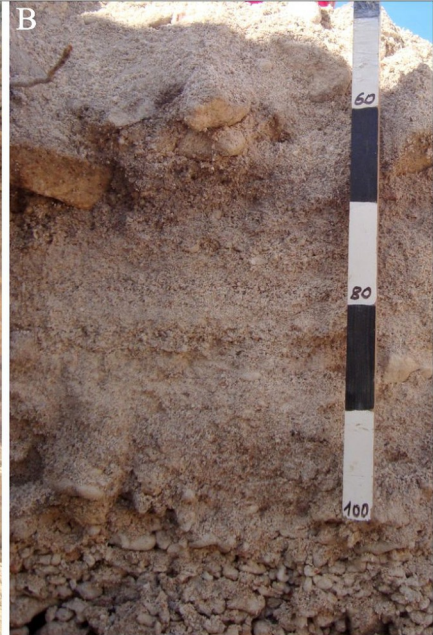


# SOUTH-WEST, LEEWARD SIDE

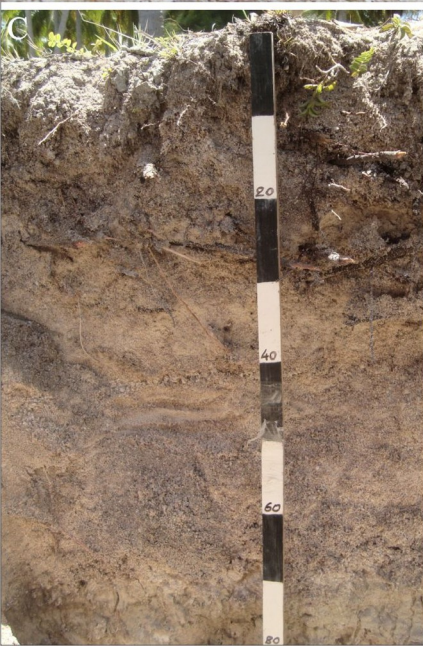




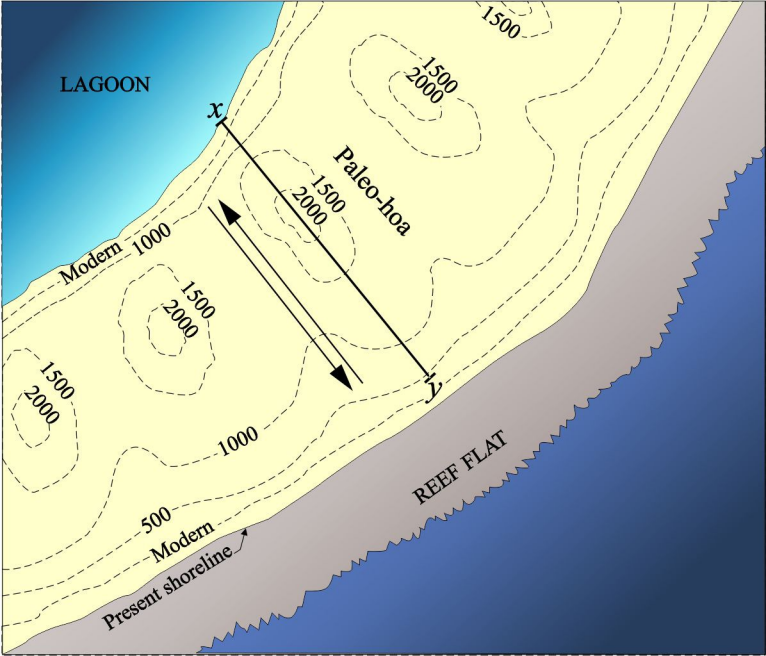


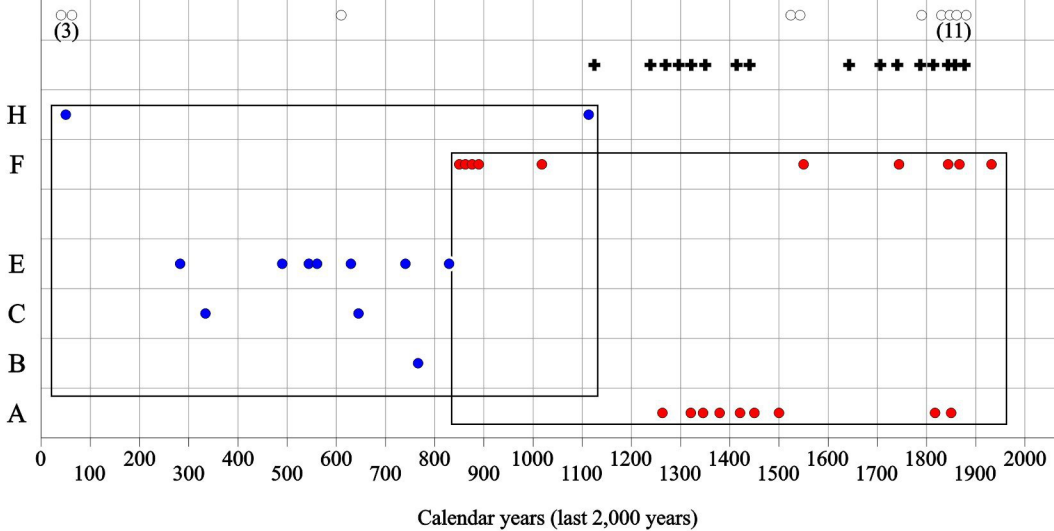


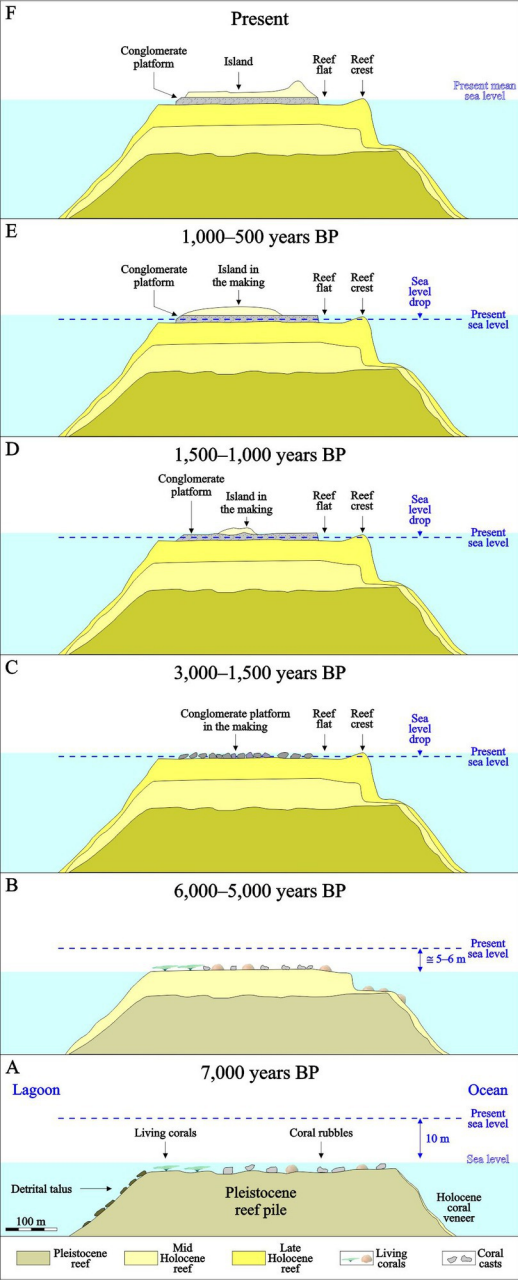














Codes	Samples	[ <sup>238</sup> U] ppm	[ <sup>232</sup> Th] ppb	δ <sup>234</sup> U <sub>m</sub> (‰)	( <sup>230</sup> Th/ <sup>238</sup> U)	( <sup>230</sup> Th/ <sup>232</sup> Th)	δ <sup>234</sup> U <sub>i</sub> (‰)	Ages Cor yr BP
<b>Excavation A</b>								
7813	Exc. A – SAT 64 A	2.240 ± 0.018	0.133 ± 0.001	145.3 ± 1.8	0.00641 ± 0.00008	310.4 ± 4.2	145.5 ± 1.8	600 ± 16
7814	Exc. A – SAT 64 B	2.621 ± 0.021	0.149 ± 0.001	147.1 ± 1.7	0.00601 ± 0.00007	324.2 ± 3.8	147.3 ± 1.7	562 ± 14
7815	Exc. A – SAT 66 A	2.492 ± 0.020	0.115 ± 0.001	147.9 ± 1.3	0.00548 ± 0.00006	364.0 ± 4.3	148.1 ± 1.3	513 ± 12
7816	Exc. A – SAT 68 A	2.237 ± 0.018	0.124 ± 0.001	146.1 ± 1.3	0.00175 ± 0.00005	97.1 ± 3.0	146.2 ± 1.3	156 ± 12
7860	Exc. A – SAT 68 B	2.793 ± 0.022	0.149 ± 0.001	146.2 ± 1.3	0.00214 ± 0.00005	123.0 ± 2.6	146.3 ± 1.3	193 ± 10
7861	Exc. A – SAT 71 A	2.660 ± 0.021	0.194 ± 0.002	145.2 ± 1.5	0.00800 ± 0.00007	335.1 ± 3.1	145.5 ± 1.5	750 ± 16
7862	Exc. A – SAT 71 B	2.564 ± 0.021	0.118 ± 0.001	146.2 ± 1.2	0.00742 ± 0.00007	491.5 ± 4.6	146.5 ± 1.2	700 ± 13
7863	Exc. A – SAT 73 A	3.268 ± 0.026	0.093 ± 0.001	145.6 ± 1.4	0.00671 ± 0.00003	724.5 ± 3.7	145.9 ± 1.4	636 ± 7
7864	Exc. A – SAT 73 B	2.395 ± 0.019	0.114 ± 0.001	148.2 ± 1.4	0.00718 ± 0.00007	461.3 ± 4.3	148.5 ± 1.4	676 ± 13
7865	Exc. A – SAT 74	2.492 ± 0.020	0.162 ± 0.001	145.2 ± 1.2	0.06767 ± 0.00024	3180.8 ± 11.2	147.9 ± 1.2	6629 ± 38
<b>Excavation B</b>								
7725	Exc. B – SAT 52 A	2.703 ± 0.022	0.0398 ± 0.0003	145.0 ± 0.7	0.01298 ± 0.00011	2690.8 ± 22.2	145.5 ± 0.7	1243 ± 12
7726	Exc. B – SAT 52 B	3.095 ± 0.025	0.051 ± 0.001	139.4 ± 1.8	0.01327 ± 0.00009	2474.6 ± 17.7	139.9 ± 1.8	1276 ± 13
7727	Exc. B – SAT 53 A	2.545 ± 0.021	0.0326 ± 0.0003	135.5 ± 1.9	0.01292 ± 0.00010	3086.6 ± 23.4	136.0 ± 1.9	1247 ± 13
7728	Exc. B – SAT 53 B	2.593 ± 0.021	0.0355 ± 0.0003	143.0 ± 1.5	0.01577 ± 0.00011	3526.5 ± 25.2	143.6 ± 1.6	1515 ± 15
7729	Exc. B – SAT 55 A	2.257 ± 0.018	0.0414 ± 0.0004	142.8 ± 1.5	0.01307 ± 0.00014	2189.0 ± 22.9	143.3 ± 1.5	1253 ± 17
7730	Exc. B – SAT 55 Bi	2.283 ± 0.022	0.0425 ± 0.0004	141.2 ± 3.9	0.01480 ± 0.00013	2435.4 ± 22.0	141.8 ± 4.0	1422 ± 20
7731	Exc. B – SAT 55 Be	4.032 ± 0.033	0.0474 ± 0.0004	140.7 ± 2.2	0.01499 ± 0.00009	3900.2 ± 24.0	141.2 ± 2.2	1442 ± 13
7732	Exc. B – SAT 57 A	2.575 ± 0.021	0.0350 ± 0.0003	141.6 ± 1.5	0.01306 ± 0.00011	2954.8 ± 24.1	142.1 ± 1.5	1254 ± 14
7733	Exc. B – SAT 57 B	2.486 ± 0.020	0.827 ± 0.007	144.2 ± 1.7	0.01799 ± 0.00022	166.4 ± 2.0	144.9 ± 1.8	1658 ± 60
7734	Exc. B – SAT 60 A	2.583 ± 0.021	0.113 ± 0.001	137.1 ± 1.9	0.02687 ± 0.00015	1873.7 ± 10.8	138.1 ± 1.9	2601 ± 25
7735	Exc. B – SAT 61 A	2.752 ± 0.022	0.0448 ± 0.0004	145.6 ± 1.8	0.03113 ± 0.00016	5873.7 ± 30.4	146.8 ± 1.8	3004 ± 23
7736	Exc. B – SAT 119 A	2.255 ± 0.018	1.285 ± 0.010	137.4 ± 1.9	0.04962 ± 0.00025	265.6 ± 1.4	139.2 ± 1.9	4743 ± 95
<b>Excavation C</b>								
7802	Exc. E – SAT 30 A	2.574 ± 0.021	0.093 ± 0.001	146.5 ± 0.8	0.01447 ± 0.00009	1228.6 ± 7.2	147.1 ± 0.8	1379 ± 13
7803	Exc. C – SAT 33 A	2.872 ± 0.023	0.0524 ± 0.0004	145.7 ± 0.7	0.01433 ± 0.00010	2406.9 ± 11.6	146.2 ± 0.7	1370 ± 12
7804	Exc. C – SAT 33 B	2.655 ± 0.021	0.0507 ± 0.0004	142.9 ± 1.9	0.01752 ± 0.00011	2826.3 ± 12.8	143.6 ± 1.9	1683 ± 16
7805	Exc. C – SAT 34 A	2.817 ± 0.023	0.0555 ± 0.0004	145.4 ± 1.6	0.02506 ± 0.00009	3887.9 ± 8.3	146.4 ± 1.6	2411 ± 15
7806	Exc. C – SAT 34 B	3.100 ± 0.025	0.0278 ± 0.0002	145.0 ± 1.5	0.02733 ± 0.00008	9347.1 ± 18.8	146.1 ± 1.5	2635 ± 12
7773	Exc. C – SAT 36 A	2.766 ± 0.022	0.0094 ± 0.0001	145.9 ± 1.2	0.02447 ± 0.00006	21947.5 ± 52.3	146.9 ± 1.2	2356 ± 8
7774	Exc. C – SAT 36 B	2.570 ± 0.021	0.0159 ± 0.0001	143.6 ± 1.2	0.02423 ± 0.00008	11909.7 ± 39.5	144.5 ± 1.2	2337 ± 11
7807	Exc. C – SAT 37 A	2.475 ± 0.020	0.079 ± 0.001	144.1 ± 0.8	0.05147 ± 0.00013	4951.8 ± 12.0	146.1 ± 0.8	5016 ± 19
<b>Excavation E</b>								
7797	Exc. E – SAT 42 A	2.830 ± 0.023	0.042 ± 0.0003	146.2 ± 1.0	0.01527 ± 0.00006	3116.5 ± 12.1	146.8 ± 1.0	1461 ± 9
7798	Exc. E – SAT 44 A	0.532 ± 0.004	0.074 ± 0.001	144.7 ± 0.9	0.01832 ± 0.00033	406.3 ± 7.2	145.4 ± 0.9	1732 ± 48
7799	Exc. E – SAT 47 A	2.606 ± 0.021	0.045 ± 0.0004	144.7 ± 1.1	0.01233 ± 0.00006	2180.8 ± 8.4	145.2 ± 1.1	1180 ± 10
7800	Exc. E – SAT 47 B	2.726 ± 0.022	0.052 ± 0.0004	144.9 ± 1.9	0.01329 ± 0.00005	2157.0 ± 6.6	145.4 ± 1.9	1271 ± 9
7775	Exc. E – SAT 48 A	2.681 ± 0.021	0.019 ± 0.0002	143.7 ± 1.6	0.01587 ± 0.00005	6844.1 ± 23.7	144.3 ± 1.6	1525 ± 8
7776	Exc. E – SAT 48 B	2.520 ± 0.020	0.018 ± 0.0001	145.1 ± 1.0	0.01531 ± 0.00008	6635.4 ± 33.2	145.7 ± 1.0	1469 ± 9
7801	Exc. E – SAT 50 A	2.788 ± 0.022	0.044 ± 0.0004	145.1 ± 0.9	0.02707 ± 0.00007	5266.9 ± 13.2	146.2 ± 0.9	2608 ± 11
<b>Excavation F</b>								
7759	Exc. F – SAT 77 A	2.178 ± 0.017	0.087 ± 0.001	145.9 ± 0.9	0.00083 ± 0.00005	63.0 ± 3.9	146.0 ± 0.9	71 ± 10
7760	Exc. F – SAT 77 B	2.918 ± 0.023	0.011 ± 0.0001	146.6 ± 1.5	0.00171 ± 0.00004	1334.5 ± 30.7	146.7 ± 1.5	163 ± 5
7761	Exc. F – SAT 79 A	2.690 ± 0.022	0.048 ± 0.0004	145.2 ± 1.6	0.00146 ± 0.00005	249.9 ± 9.3	145.2 ± 1.6	136 ± 7
7762	Exc. F – SAT 79 B	2.326 ± 0.019	0.293 ± 0.002	145.0 ± 1.5	0.00306 ± 0.00009	74.1 ± 2.2	145.1 ± 1.5	266 ± 23
7763	Exc. F – SAT 81 B	2.698 ± 0.022	0.041 ± 0.0003	145.2 ± 1.5	0.00977 ± 0.00010	1969.0 ± 19.3	145.6 ± 1.5	933 ± 12
7764	Exc. F – SAT 81 A	2.765 ± 0.022	0.042 ± 0.0003	144.1 ± 0.9	0.00477 ± 0.00004	945.3 ± 7.3	144.3 ± 0.9	453 ± 6
7765	Exc. F – SAT 82 A	2.440 ± 0.020	0.173 ± 0.001	144.5 ± 0.7	0.01224 ± 0.00007	526.6 ± 3.0	145.0 ± 0.7	1159 ± 15
7766	Exc. F – SAT 82 B	2.438 ± 0.020	0.177 ± 0.001	142.6 ± 3.0	0.01208 ± 0.00008	505.6 ± 3.2	143.0 ± 3.0	1146 ± 19
7767	Exc. F – SAT 83 A	2.627 ± 0.021	0.144 ± 0.001	144.0 ± 2.6	0.01226 ± 0.00006	673.9 ± 3.5	144.5 ± 2.6	1165 ± 15
7768	Exc. F – SAT 83 B	3.272 ± 0.026	0.220 ± 0.002	143.0 ± 1.7	0.01231 ± 0.00006	546.4 ± 2.6	143.4 ± 1.7	1167 ± 15
7769	Exc. F – SAT 86 A	2.497 ± 0.020	0.281 ± 0.002	143.4 ± 1.9	0.01207 ± 0.00007	323.3 ± 2.0	143.9 ± 1.9	1135 ± 22
7770	Exc. F – SAT 86 B	2.479 ± 0.020	0.018 ± 0.0001	147.4 ± 0.9	0.01183 ± 0.00007	4973.6 ± 28.9	147.8 ± 0.9	1131 ± 8
7771	Exc. F – SAT 87 A	3.991 ± 0.032	0.021 ± 0.0002	144.0 ± 1.0	0.02431 ± 0.00006	13765.3 ± 32.8	145.0 ± 1.0	2344 ± 8
<b>Excavation G</b>								
7793	Exc. G – SAT 91 A	2.858 ± 0.023	0.114 ± 0.001	145.3 ± 1.3	0.02463 ± 0.00007	1891.1 ± 3.8	146.3 ± 1.3	2366 ± 15
7794	Exc. G – SAT 91 B	4.149 ± 0.034	0.170 ± 0.001	146.5 ± 1.6	0.03074 ± 0.00008	2301.1 ± 5.0	147.8 ± 1.6	2958 ± 17
7795	Exc. G – SAT 93 A	2.733 ± 0.022	0.034 ± 0.0003	145.5 ± 0.8	0.02488 ± 0.00006	6043.1 ± 15.4	146.5 ± 0.8	2395 ± 10
7796	Exc. G – SAT 93 B	2.692 ± 0.022	0.029 ± 0.0002	145.3 ± 1.0	0.02449 ± 0.00005	7059.2 ± 15.0	146.2 ± 1.0	2358 ± 8
7748	Exc. H – SAT 94 a	2.177 ± 0.017	0.105 ± 0.001	142.8 ± 1.3	0.04811 ± 0.00010	3064.5 ± 6.5	144.7 ± 1.3	4683 ± 21
<b>Excavation H</b>								
7747	Exc. H – SAT 96 A	2.091 ± 0.017	0.735 ± 0.006	143.8 ± 0.9	0.02699 ± 0.00013	235.8 ± 1.2	144.9 ± 0.9	2531 ± 53
7746	Exc. H – SAT 97 A	3.059 ± 0.025	0.115 ± 0.001	145.2 ± 0.9	0.00845 ± 0.00008	690.6 ± 6.9	145.5 ± 0.9	801 ± 13
7808	Exc. H – SAT 99 B	3.342 ± 0.027	0.046 ± 0.0004	144.2 ± 1.0	0.02043 ± 0.00006	4488.5 ± 13.6	145.0 ± 1.0	1965 ± 9
7809	Exc. H – SAT 99 A	2.330 ± 0.019	0.041 ± 0.0003	146.4 ± 0.7	0.02229 ± 0.00007	3905.9 ± 12.8	147.2 ± 0.7	2140 ± 10
7810	Exc. H – SAT 100A	2.978 ± 0.024	0.125 ± 0.001	144.5 ± 1.1	0.02952 ± 0.00009	2158.3 ± 6.3	145.7 ± 1.1	2843 ± 16
7811	Exc. H – SAT 101A	5.029 ± 0.041	0.068 ± 0.001	143.5 ± 0.7	0.02342 ± 0.00006	5339.0 ± 13.2	144.4 ± 0.7	2257 ± 8

Windward sites		Leeward sites	
<b>Excavation A</b>		<b>Excavation F</b>	
SAT 64A	1419 ± 16	SAT 77A	1948 ± 9.5
SAT 64B	1457 ± 14	SAT 77B	1856 ± 4.5
SAT 66A	1506 ± 12	SAT 79A	1882 ± 7
SAT 68A	1864 ± 11.5	SAT 79B	1753 ± 22.5
SAT 68B	1826 ± 10	SAT 81A	1566 ± 5.5
SAT 71A	1269 ± 16	SAT 81B	1085 ± 12
SAT 71B	1320 ± 12.5	SAT 82A	859 ± 15
SAT 73A	1383 ± 7	SAT 82B	873 ± 18.5
SAT 73B	1344 ± 12.5	SAT 83A	854 ± 14.5
<b>Excavation B</b>		SAT 83B	851 ± 15
SAT 52A	776 ± 12.5	SAT 86A	884 ± 21.5
<b>Excavation C</b>		SAT 86B	888 ± 8.5
SAT 33A	648 ± 12	<b>Excavation H</b>	
SAT 33B	336 ± 15.5	SAT 97A	1217 ± 13
<b>Excavation E</b>		SAT 99B	53 ± 9.5
SAT 30A	639 ± 13		
SAT 42A	557 ± 9		
SAT 44A	286 ± 48		
SAT 47A	839 ± 9.5		
SAT 47B	747 ± 9		
SAT 48A	493 ± 8		
SAT 48B	550 ± 9.5		