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1 **Reef-rim structure and building history, Rangiroa an uplifted atoll, French Polynesia:**
2 **the role of morphotectonics and extreme marine hazard events**

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11 **Highlights**

- 12 – North of Rangiroa Atoll, due to a former uplift, the top of the Miocene carbonate
13 basement peaks at depths of less than 10 m beneath the modern reef-rim surface.
14 – Unusual, extreme marine hazard events are likely to have contributed to ~~were essential~~
15 ~~drivers of~~ early atoll rim-island accretion.
16 – Island accretion started by about 6,000 calendar years, 3,500 years before it did in
17 nearby subsiding atolls.

18 **Abstract**

19 Reconstructing the responses of low-lying, atoll-rim islands to future environmental changes
20 due to global warming requires a robust knowledge of the building history of reef rims
21 through time. In the northwest of Tuamotu Archipelago, atolls have experienced opposite
22 vertical motions (uplift *versus* subsidence) in response to differential tectonic constraints
23 undergone by the underlying oceanic crust. As a result, during Pleistocene high sea levels,
24 some atolls remained emerged whereas others remained flooded. Based on two electrical
25 resistivity tomography profiles across the northern rim-island of the uplifted Rangiroa Atoll
26 and on U/Th dating of corals clasts collected from unconsolidated sand-rubble deposits within
27 two wells through the same island area, the internal structure of the atoll-rim and its mode and
28 timing of building are tentatively reconstructed. The irregularly shaped, upper boundary of the
29 basal resistive unit is interpreted as residual, pinnacle-shaped reliefs of Miocene age. At the

30 seaward rim side, the uppermost highly resistive layers, an about 5 m-thick, were assumed to
31 be reef-related, partly consolidated material emplaced during the Holocene. Thicker resistive
32 layers that infill cavities in the Miocene basement, in the central part of the atoll rim, refer to
33 the fresh water lense in porous, more or less consolidated material (phosphorites?)
34 presumably emplaced during the Mio-Pliocene. In northern Rangiroa, the age of the oldest
35 coral clasts trapped into the atoll-rim islands ranges between about 11,000 and 8,000 calendar
36 years when sea level was approximately 60 to 20 m below its present position. This implies
37 that coral-clast supply from the adjacent forereef slopes was triggered by extreme wave-surge
38 events (presumably, tsunamis generated by island flank failures). The earliest island initiation
39 phase is thought to start by approximately 6,000 cal. yr and to be achieved by about 3,000 cal.
40 yr. By contrast, on the nearby subsiding Takapoto Atoll, the rim island began to initiate not
41 earlier than 2,500 cal. yr. At Rangiroa, morphotectonics is assumed to have played a major
42 role in controlling the internal rim architecture and, associated to extreme marine hazard
43 events, to have promoted the earlier settlement of low-lying, rim islands through an earlier
44 infilling of accommodation space as compared to nearby subsiding atolls.

45 **Keywords**

46 Atoll rim

47 Tectonics

48 Extreme hazard events

49 Rangiroa

50 Tuamotu

51 French Polynesia

52 **Introduction**

53 Sea-level rise and increasing storm intensity, due to ongoing climate change, are regarded as
54 risking of opening high-water energy windows across low-lying island coasts, especially
55 across tropical atolls (IPCC, 2019). The emergent, uppermost parts of atoll rims consist of
56 low-lying coral-reef islands, usually composed prominently of loose coral rubble deposits in
57 the form of small, continuous or scattered islets (*motu* in Polynesian language), usually less
58 than 5–6 m in maximum elevation, mostly resting on firmly cemented, underlying
59 conglomerate platforms (Biribo and Woodroffe, 2011; Montaggioni, 2011). Nowadays, atoll
60 islands are receiving increased attention because the combination of sea-level rise and

61 extreme hazard events is likely to cause future irreversible damage to them, thus precluding
62 any human occupation (Storlazzi et al., 2015, 2018). Recent observations indicated **showed**
63 that atoll islands are experiencing various evolutionary patterns, including stability, erosion
64 and accretion (Kench et al., 2018; Duvat et al., 2020). This suggests that, over the next
65 centuries to millennia, atoll islands should respond differentially to the future sea-level rise,
66 projected to elevations of metres (Clark et al., 2016; IPCC, 2019).

67 Reconstructing detailed histories of atoll-rim building is a prerequisite to better understand
68 atoll-island behaviours when faced with environmental changes at a millennial scale (East et
69 al., 2018; Montaggioni et al., 2018, 2019a). Previous studies in a number of reef sites in the
70 Indo-Pacific province revealed that rim-island development has started not before 5,000–
71 4,800 cal. yr and continued until 2,800-2,500 cal. yr in both the Western Indian Ocean
72 (Maldives: Kench et al., 2005; East et al., 2018) and the western and central Pacific – northern
73 Great Barrier Reef of Australia: Kench et al., 2012; Marshall Islands: Kench et al., 2014.
74 Low-lying, rim-island development has been interpreted as resulting from the interplay
75 between reef growth and the rate of sea-level changes over the last few thousands years
76 (Pirazzoli and Montaggioni, 1986; Richmond, 1992; Dickinson, 1999; Woodroffe et al., 1999;
77 Kench et al., 2005; Woodroffe, 2005; Barry et al., 2007; Kench et al., 2014 a, b; Perry et al.,
78 2011; East et al., 2018; Montaggioni et al., 2018, 2019a). Low-lying reef islands have been
79 capable of accreting under various eustatic regimes. Their development has occurred either
80 during a rise in sea level and sea-stands higher than the present (McLean et al., 1978; Stoddart
81 et al., 1978; Woodroffe and Morrisson, 2001; Kench et al., 2014a,b; Yamano et al., 2014;
82 East et al., 2018) or later, during a post-highstand sea-level fall (Woodroffe et al., 1999;
83 Dickinson, 2009; Kench et al., 2014 a,b; Yasukochi et al., 2014; Montaggioni et al., 2018,
84 2019a).

85 In northwest Tuamotu (French Polynesia, central south Pacific), apart from subsiding atolls
86 (Takapoto, Takaroa, Ahe, Manihi), there are also several uplifted atolls. These form a
87 continuous belt composed of Makatea, Mataiva, Tikehau, Rangiroa, Kaukura, typified by
88 exposed, partly dolomitized limestones of Miocene age (Delesalle, 1985; Harmelin-Vivien,
89 1985; Montaggioni, 1985; Ricard, 1985). This island belt is facing the northwest sides of
90 Tahiti and Moorea Islands in the Society Archipelago. Uplifting was thought to have been
91 caused either by a lithospheric flexure in response to volcanic loading generated by nearby
92 Tahiti-Moorea volcanoes (McNutt and Menard, 1978; Lambeck, 1981) or by an underlying
93 asthenospheric bump in relation to the Society hotspot swell (Menard, 1973; Crough, 1983)
94 during the early Pleistocene (Montaggioni, 1989; Montaggioni and Camoin, 1997). As a

95 consequence, even during most episodes of mid Pleistocene to Holocene high sea stands,
96 these atolls occurred as high rising reliefs. At those times, coral communities have grown in
97 the form of apron reefs plastered against their submarine flanks, as currently observed on the
98 nearby high carbonate Makatea Island (Montaggioni, 1985; Montaggioni and Camoin, 1997).
99 This accounts for the absence of exposed Pleistocene reef units capping the atoll rims. Only, a
100 few meter-thick mid to late Holocene reef deposits are overlying the Mio-early Pleistocene
101 rim surfaces (Rougerie et al., 1997). By contrast, as shown on the nearby subsiding Takapoto
102 Atoll, during the mid to late high sea stands Pleistocene, the top reef surfaces stage
103 (Montaggioni et al., 2019b) were regularly submerged, thus resulting in the overlaying of a
104 number of successive reef generations (Montaggioni et al., 2019b).

105 While sea level reached its present position by about 6,000 years BP, on Takapoto, the
106 Holocene reef unit in the making reached the position of present sea level not prior to 3,000
107 cal. yr. The initiation of modern, low-lying rim-islands started approximately 2,500 years ago,
108 as sea level was about 0.60–0.30 m above present sea level (Montaggioni, 2018, 2019a).

109 Using Rangiroa as a representative test area for uplifted atolls, the objectives of the present
110 study are to: (1) reconstruct the internal structure of the upper parts of the uplifted atoll-rim
111 pile, based on electrical resistivity tomography; (2) to test the hypothesis that, during the
112 Holocene, these atoll-rim surfaces have served as substrates for earlier initiation and
113 emplacement of low-lying rim islands as compared to subsiding atolls in the northern
114 Tuamotu. The neighbouring Takapoto Atoll will be used as a dipstick of subsiding atolls; (3)
115 demonstrate that morphotectonics and extreme marine hazard events in the considered region
116 have played a major role in atoll-rim development in addition to changes in accommodation
117 space.

118 **Environmental setting**

119 Rangiroa Atoll is located in the northwestern part of the Tuamotu Archipelago, between
120 latitude 14°59'–15°19' south and longitude 148°00'–147°10' west, approximately 200 km
121 northeast of Tahiti (Fig. 1A). Reaching 7 m in maximum elevation (Duvat et al., 2020), the
122 atoll is 80 km long, aligned along a WNW–ESE main axis, and 33 km in its widest part. The
123 total atoll area is about 1,000 km². The lagoon is 35 m to 55 m deep in its deepest parts. The
124 reef rim is larger in the northern sector (750–1100 m) than in the western and southern ones
125 (300–600 m). About 30 % of the total atoll-rim surfaces are occupied by islands, composed of
126 a series of gravelly to sandy islets (Fig. 1B), locally resting on a subhorizontal, cemented

127 conglomerate platforms, less than 1m-thick on average. The outer parts of the atoll rim
128 consists of a reef-flat zone ranging from 50 to 200 m in width and is locally bounded
129 seawards by a raised outer edge with a well-developed (10–20 m wide) algal ridge (Stoddart,
130 1969). Scuba diving surveys off Avatoru village (B. Martin-Garin, pers. observ.) revealed that
131 the upper forereef zone consists of a spur-and-groove system, extending over 100 m
132 oceanwards, from sea surface to about 8–9 m below pmsl. This system ends on an upper,
133 gently dipping terrace, up to 50 m wide, ranging between 9 m and 11 m in depth. This terrace
134 is followed downslope by a drop-off extending to a depth of 60 m. A lower terrace, about
135 50 m in maximum width, develops between 60 m and 62 m deep and ends on a subvertical
136 wall falling to depths greater than 100 m (Fig. 2).

137 The reef-flat surfaces are colonized by small *Porites* and *Acropora* colonies, not exceeding
138 10 % in cover rate (Ricard, 1985). Long-term coral monitoring from a selected forereef area,
139 i.e. the upper terrace, at 10.5–11 m deep off Avatoru village – 14°56'46'' south; 147°41'62''
140 west – indicated that the total coral cover rate has varied between 31 % and 52 % from year to
141 year over the last two decades. The dominant coral forms are branching *Pocillopora* (22 to
142 27 %) and massive *Porites* (9 to 12 %), together with *Montipora* (0 to 14 %) and *Acropora* (0
143 to 6 %) – data courtesy by Service d'observation national CORAIL, CRIOBE, Moorea Island,
144 French Polynesia.

145 Along the southern outer reef rim, are found deeply pitted and dolomitized, pinnacle-shaped
146 limestones, up to 3 m in height (Fig. 3). These pinnacles, referred to as *feo* by Polynesians,
147 were interpreted as remnants of formerly uplifted reef-related frameworks of late Neogene to
148 Pleistocene age (Vahrenkamp and Ginsburg in Ricard, 1985), demonstrated to be of late
149 Miocene age from paleontological records (Montaggioni, 1989; Montaggioni and Camoin
150 1997).

151 As for the other northwestern Tuamotu atolls, Rangiroa is influenced by the southeast trade-
152 winds, blowing from the ENE sectors for 70 % of the year and for 20 % from the SE sector.
153 In the austral winter (May to October), 2.5-m high swells with long periods (> 10 s) are
154 generated by strong trade winds. During the austral summer (November to April), trade
155 winds are less active and generate a moderate hydrodynamic regime, locally determined by
156 storm events initiated by ENSO-related cyclones or by storms originating from northern
157 latitudes (Andréfoüet et al., 2012). Cyclones come usually from the northeastern and
158 northwestern sectors, with a frequency of one to three events per century (Dupon, 1987;
159 Gabrié and Salvat, 1985; Larrue and Chiron, 2010). The rim islands suffer occasional damage
160 due to cyclone activity. For instance, the 1983 cyclonic events have resulted in significant

161 shore disturbance and reshaping, including strong reworking of sandy beaches and deposition
162 of new shingle ridges along the northern and western, ocean-facing shorelines (Ricard, 1985).
163 Tides are a twice-daily regime and microtidal, averaging 0.20 m in amplitude and reaching a
164 maximum of 0.50 m at spring tide. In northern Rangiroa, historical tsunamis are known to
165 have usually generated only low-frequency and low-amplitude (1–2 m-high) swells (Sladen et
166 al. 2007).

167 **Materials and methods**

168 **Electrical resistivity tomography (ERT)**

169 ERT is a geophysical imaging technique, based on measurements of electrical resistivity in
170 subsurface rocks (Schroot and Sass, 2008) using direct current. In reef systems, in absence of
171 clay, resistivity depends on limestone lithology, more specifically, on the degrees of
172 cementation and porosity, on water content and salinity (Comte et al., 2010; Join et al., 2011).
173 Resistivity therefore is a reliable tool used to discriminate: i) high resistivity, cemented
174 limestones from low resistivity, porous and aquifer limestones; ii) low resistivity, saline
175 intrusions from medium resistivity, fresh water lenses. Nevertheless, lithological and fluid
176 effects may interfere, thus leading to undetermination (Schrott and Sass, 2008; Youssef et al.,
177 2012; Carrière et al., 2013). In the northern part of Rangiroa atoll-rim, close to Avatoru
178 village, ERT was used to characterize subsurface rock heterogeneities and the salt-water/fresh-
179 water interface geometry.

180 Two 2D cross-island profiles oriented perpendicular to the shoreline were surveyed using a
181 multi-electrode system in dipole-dipole (DD) and Wenner-Schlumberger (WSR) array
182 configuration (Fig. 1C). The electrode arrays were spaced 10 m apart for lengths of 790 m
183 (P1) and 860 m (P3) respectively. The reached maximum investigation depth was about
184 150 m. These profiles have followed gentle island topography from the ocean-facing
185 shoreline to the lagoon border. The electrodes were hammered into the loose soil and surficial
186 island deposits and seawater was used to enhance electrode contact resistances, all of which
187 were checked to be of same order between a $0.5 \Omega \cdot \text{m}$ to $3.0 \text{ K}\Omega$. A Syscal Pro[®] resistivity-
188 meter with multinodes, system of 250 W power from Iris Instrument was applied to collect
189 the resistivity data. With 96–99 % (WSR) to 85–94 % (DD) data usable after screening, the
190 data are considered to be of good quality. Measured resistivity were inverted using
191 Res2Dinv[®] software from Geotomography using the blocky option (Loke et al., 2003). This

192 option lies on mean square regularization minimizing the sum of the absolute values of the
193 data misfit. It is applied to the model roughness filter, resulting in a better accommodation of
194 high resistivity contrasts and data outliers and tending to produce models consisting of areas
195 with piecewise constant resistivity (Farquharson and Oldenburg, 1998; Loke et al., 2003) with
196 a better resolution of discontinuities (Seaton and Burbey, 2003).

197 Inversion of surface tomography data is an illposed problem and different resistivity model
198 obtained as a result of inversion may satisfy the same dataset with a given RMS misfit. The
199 presented resistivity images are one solution among many possible solutions; but using the
200 blocky option applied to the combined DD and WSR dataset, these images present a reliable
201 determination of underground geometry. With the 10-m electrode spacings, modeled cells are
202 typically representative of plurimetric-wide heterogeneities at shallow and mid depths to up to
203 tens of metres deeper.

204 **Coral sampling and radiometric dating procedures**

205 Coral samples were collected from two water wells dug through the northern parts of the
206 island (Fig. 1C). Well 1 is located close to Avatoru village, at a distance of about 200 m
207 behind the outer coastline. Well 2 is located on Vaineate site at a distance of about 300 m
208 from the coastline, backward the runway. The well entrances (island surface) are at elevations
209 ranging from 2–2.3 m (Well 1) to 1.5–1.6 m (Well 2) above present sea level (pmsl) (Fig. 4).
210 Sampling was carried out randomly along the internal walls. These consist of a mixture of
211 skeletal sands and gravels, with some coral cobbles and pebbles (Fig. 5). In Well 1, samples
212 were taken at depths of 1.5 m (Sample Rangiroa 1-1) and 2 m (Sample Rangiroa 1-2)
213 respectively beneath the island surface along the southern and northeastern wall sections. The
214 bottom of the well is occupied by an indurated conglomerate platform, about 0.30 m high
215 above pmsl. In Well 2, Samples Rangiroa 2-1 and 2-2 were taken respectively at depths of
216 1.5 m and 1 m beneath the island surface along two opposite wall sections. The bottom of
217 Well 2 is made up of loosely consolidated gravelly-sand material (Fig. 5). As a supplement,
218 given that surficial deposits at the vicinity of the wells were reworked during excavation
219 works, a third sample (Sample Rangiroa Défense) was extracted from the top surface of an
220 old quarry located close to the city hall of Avatoru, in order to estimate the average age of
221 deposition of the uppermost layers in the considered rim islet. As demonstrated in a number
222 of previous studies (see Montaggioni et al., 2018, 2019a and references herein), radiometric
223 dating of coral clasts from atoll rim excavations and drillholes can be used to attempt

224 reconstructing the mode and timing of reef islet accretion.

225 Uranium-thorium dating was carried out on coral samples. They were gently crushed and the
226 cleanest parts were selected for analysis. A few hundreds of milligrams were dissolved in
227 dilute HCl. U and Th analyses were done after chemical separation at BRGM (Orléans, France)
228 on a Neptune MC-ICPMS mass spectrometer. Details on chemical separation and mass
229 spectrometry can be found in Innocent et al. (2005) and Millot et al. (2011). Results are
230 reported in Table 1.

231 All but one samples display uranium contents close to 3 $\mu\text{g/g}$ (Fig. 6A), which is known to
232 constitute the average value of living corals (Edwards et al., 1987). Thus, this strongly
233 suggests that the samples with lower uranium contents were not affected by any early
234 cementation or secondary recrystallization, despite their early to mid Holocene ages. Only the
235 Rangiroa Défense sample displays higher U contents (Table 1, Fig. 6B).

236 Thorium concentrations are very low, ranging from $< 1 \text{ ng/g}$ to 28 ng/g for Sample 1-1
237 (Table 1). Sample Rangiroa 1-1 and, to a lesser extent, Sample Rangiroa 2-1 emphasize the
238 occurrence of minute amounts of detrital Th. Uranium activity ratios are similar to the
239 present-day seawater value within uncertainty (Chen et al., 1986) (Table 1, Fig. 6B).

240 Ages have been calculated from $^{230}\text{Th}/^{234}\text{U}$ ratios. As corals are of young age, the effect of the
241 decay of excess ^{234}U can be neglected. Conversely, calculated ages should be corrected for the
242 initial ^{230}Th of detrital origin. Calculations have been done with a $^{230}\text{Th}/^{232}\text{Th}$ activity ratio of
243 0.78, corresponding to a ^{238}U decay chain at secular equilibrium, and to an elemental Th/U
244 ratio of 4, typical of the value of the average outcropping continental crust. The correction
245 effet remains very slight.

246 Ages are expressed in calendar years relative to the year of sample analysis (2018) during
247 which uranium-thorium dating were conducted.

248 **Results and discussion**

249 **Resistivity imaging the internal structure of the upper parts of the atoll-rim pile**

250 Geophysical results are interpreted in terms of types of depositional environments through
251 *resistivity units*, i.e. relatively resistive (Rn) or conductive (Cn). These units are defined as
252 areas of uniform resistivity, showing a high gradient of resistivity towards neighbouring units.
253 The limits between resistivity units refer to as *discontinuities* and are defined at the maximum

254 gradient of resistivity between areas of uniform resistivity. These resistivity units can relate to
255 varying geological features, including sedimentary layers, lenses, rocky blocks of varying
256 lithological and mineralogical composition, or varying hydrological features (aquifers, fresh
257 water lenses, salted intrusion) affecting a same carbonate formation. Accordingly, limits
258 between the resistivity units may be those delineating different geological features, between
259 bodies of different lithology within a same formation or those indicative of tectonic features
260 such as faults, fractures or unconformity surfaces and fresh/saline water interface as well.

261 Different interpretations can be proposed for a same resistivity unit. It is also possible that
262 some geological features, due to their limited thickness and extension and/or limited or no
263 resistivity contrast, cannot be detected and imaged by ERT and, as such, are not expressed in
264 resistivity images. The various resistivity units as defined in P1 and P3 tomographies are
265 presented in [Table 2](#) and [Figures 7A and 7B](#). Resistivity variations are presented as color-
266 countered images of subsurface resistivity variations. For the two profiles, high resistivity–
267 low conductivity zones were delineated by purple-red while low resistivity–high conductivity
268 zones by blue-green. Transitional conditions were identified by yellow to brown colors.

269 The two 2D cross-island electrical resistivity profiles (P1, P3) image the internal structure of
270 the upper parts of the atoll-rim pile to maximum depths of about 150 m ([Fig. 7A, 7B](#)). The
271 inversion-derived resistivity models show significant variations in resistivity from the ocean
272 side to the lagoon, especially near and beneath the atoll-rim surface. At depth, there is a
273 resistive basement R3 ($90\text{--}240 \Omega \cdot \text{m}$) at the seaward side. R3 has more upward resistive
274 columnar extensions (R3', R3'' with $240 < p < 700 \Omega \cdot \text{m}$) in irregular, indented contact with
275 the overlying conductive layers C3 and C3'. At the same rim side, resistivity unit R4 ranges
276 from about $90 \Omega \cdot \text{m}$ to up to $700 \Omega \cdot \text{m}$ over a 200 m (P1) or a 450 m (P3) distances inwards,
277 close to the island surface ([Fig. 7A, B](#)). Red to brown-coloured R4 forms 5-10 m-thick,
278 horizontal, plate-shaped structures. In P1, between surface to depths of about 30 m, shallow
279 (R2) and less shallow (R1) resistive units ($100 < p < 250 \Omega \cdot \text{m}$) are covering the central,
280 upper part of the atoll-rim pile. Lagoonwards, resistivity are markedly lower, varying from
281 about 100 to less than $1 \Omega \cdot \text{m}$ from the surface to several tens of meters. The very
282 conductive, blue cover C4 ($0.3 < p < 5 \Omega \cdot \text{m}$) extends more deeply beneath the atoll surface,
283 through more (C4'') or less conductive (C4') dark green intrusion, over an even less
284 conductive, light green basement C5 ($20 < p < 60 \Omega \cdot \text{m}$) ([Fig. 7A, B](#)).

285 **Geological and hydrological interpretation of resistivity imagery**

286 The geological interpretation of the overall resistivity variations (Table 2, Fig. 7C) is mainly
287 qualitative and based on field observations and partial knowledge of the development history
288 of Rangiroa and nearby atolls (see Delesalle, 1985; Montaggioni, 1985, 1989; Ricard, 1985;
289 Montaggioni and Camoin, 1997; Montaggioni et al., 2019a,b)

290 The uppermost, most resistive bed (R4), averaging 5-6 m-thick and extending over about
291 450 m from the shoreline landwards is interpreted as related to Holocene deposits (Fig. 7C).
292 In the absence of local drilling investigations, the nature of R4 could be identified by analogy
293 with deposits penetrated through rim-island areas from the nearby atolls of Mataiva and
294 Tikehau, given the latter have proven to follow a geological evolution similar to that of
295 Rangiroa (Delesalle, 1985; Harmelin-Vivien, 1985; Ricard, 1985). Reef drilling in both atolls
296 revealed that the limestone basement is directly covered by unconsolidated to partly
297 consolidated rubble-sand material of postglacial to Holocene age. Local induration is
298 presumably due to the fact that the lower parts of the Holocene deposits are standing below
299 the water table, in the phreatic zone, thus favoring intergranular cementation. On Mataiva,
300 Holocene deposits are 4 to 6 m-thick at rim-island sites (Delesalle, 1985; Pirazzoli and
301 Montaggioni, 1986). On Tikehau, the atoll rim is covered with Holocene detritus, less than 5
302 m-thick (Rougerie et al., 1997). Accordingly, in northern Rangiroa, at the studied rim sites, an
303 expected 5 to 6-m thickness of Holocene sediments is in good agreement with those from the
304 two neighbouring atolls. It is noteworthy that, on these three atolls, there is no evidence of
305 exposed or buried Pleistocene highstand reef units beneath the Holocene deposits.

306 In addition, at Rangiroa, along the studied seaward face, there are isolated R4 elements with
307 highest resistivity that may be regarded as isolated, cemented megaclasts trapped into the
308 Holocene deposits. Numerous megaclasts, i.e. pieces of spurs extracted from the uppermost
309 forereef zone, about 10-15 m³ on average, are exposed on the reef-flat zone, at the northern
310 end of the atoll (Ricard, 1985) and some of them are likely to be buried locally. Less resistive,
311 scattered features (R1, R2) are found centered beneath the middle part of the atoll rim from
312 the subsurface to depths of 30 m. These could be reworked remains of the limestone basement
313 found deeper (Fig. 7C). Indeed, more internally, between approximately 10 m and deeper than
314 120 m, there are high cohesive, pinnacle-shaped structures (R3), regarded as residual, firmly
315 indurated limestone reliefs (Fig. 7C). These reliefs are similar to *feo* restricted along the
316 southern, outer rim (Fig. 3) and to those found in the neighbouring atolls of Mataiva, Tikehau

317 and Kaukura. In a lack of conclusive dating, an early Miocene age for these *feo* is most likely
318 by analogy with similar biostratigraphically dated rock occurrences on the nearby high
319 carbonate island of Makatea (Montaggioni, 1985; Montaggioni et al., 1985; Montaggioni,
320 1989; Montaggioni and Camoin, 1997). Differences in elevation of about 20-30 m between
321 the remnants of dolomitized limestones present in the south and their expected, subsurface
322 counterparts in the north are thought to be due to a more severe karstic alteration in the
323 northern parts of the carbonate pile during successive periods of emergence. The strict
324 location of *feo* along the southern, outer reef-flat zones cannot be explained as resulting of a
325 northward tilting of the atoll and a subsequent differential uplift, since, on nearby uplifted
326 atolls (Mataiva, Tikehau, Kaukura), *feo* are distributed randomly from south to north.
327 Differential sub-aerial erosion between south and north of Rangiroa may have been generated
328 locally by fracture networks, known to develop parallel to some reef-front lines on the
329 northern Tuamotu atolls (Chevalier et al., 1968, Faure and Laboute, 1986; Montaggioni et al.,
330 2019b).

331 The conductive C1, C3 anomalies mostly located above R3 structures might refer to porous,
332 poorly consolidated deposits. These are infilling karstic cavities within the Miocene
333 limestones (Fig. 7C). On nearby Makatea and Mataiva Atolls, karst cavities are known to be
334 infilled by sand-grained phosphatic material (Obellianne, 1963; Montaggioni, 1985; Trichet
335 and Fikri, 1997) regarded to be Mio-Pliocene (Montaggioni, 1989; Montaggioni and Camoin,
336 1997) rather than mid Pleistocene (Aharon and Veeh, 1984). Similar sandy phosphorites
337 might be present directly beneath the Holocene unit at Rangiroa. Shallow to deep, more or
338 less conductive features (C4, C4', C4'') southwards close to or at lagoon sites, probably result
339 from dense saline intrusion in more or less permeable deposits (Fig. 7A, B). These deposits
340 may be phosphates, at least in part, covered by Holocene material (Fig. 7C).

341 **Validity of U/Th dating from removed coral material**

342 The value of U/Th measurements from removed skeletal material used as proxies for defining
343 the timing of building of low-lying, atoll-rim islands has been previously debated thoroughly
344 by Woodroffe et al. (1999, 2007), Kench et al. (2014a, b), and Montaggioni et al. (2018,
345 2019a). It has been suggested that time intervals separating the time of death of a given
346 organism from the time of deposition and final stabilisation of the relevant skeleton could
347 range from tens to hundreds of years as clearly evidenced by age inversions in the
348 stratigraphic sections. Consequently, reconstruction of island chronology should be

349 considered as relative rather than absolute. The coral-clast samples with mean ages relative to
350 all dated samples can serve to estimate the mean date in terms of deposition. By contrast, the
351 ages of youngest samples usually found close to the upper parts of wells produce estimates of
352 the time at which the main vertical island accretion phase has ended.

353 **Chronology of rim-island accretion**

354 U/Th dating of the pebble-sized coral clasts from the well sections excavated through the
355 northern part of Rangiroa provides ages ranging between $11,546 \pm 131$ and $3,098 \pm 57$ yr BP
356 (Table 1, Fig. 5). This means that the oldest coral clasts were moved from the adjacent
357 foreslopes along which coral populations were growing and projected onto the upper atoll-rim
358 surfaces while Rangiroa was an emergent carbonate island, initially at about 35–40 m high.
359 Taking into account possible storage and reworking of clasts before incorporation into rim-
360 island deposits and based on their mean ages, rim-island development is expected to have
361 started by approximately 6,000 cal. yr. At that time, sea level was close to its present position
362 (Figs. 8, 10).

363 **The role of morphotectonics in the contrasting atoll-island building histories**

364 As the other nearby uplifted atolls, Rangiroa is considered to have experienced uplifting,
365 probably at the beginning of the Quaternary (Montaggioni, 1989; Montaggioni and Camoin,
366 1997). Uplift has resulted at present in the emergence of remnants of the Miocene limestones
367 in its southern part or located at depths of less than 10 m below the modern rim surface in its
368 northern part. Otherwise, there is no evidence of exposed last interglacial reefs at Rangiroa
369 while this reef generation is assumed to have developed between +9 to +6 m above present
370 sea level between 128 to 116 ka (Kopp et al., 2009; Dutton and Lambeck, 2012; Murray-
371 Wallace and Woodroffe, 2014). This indicates that the relevant reefs are currently submerged,
372 which means that the uplifting effects have ended at least since the last interglacial times and
373 Rangiroa is now subsiding. This may be due to the fact that the lithospheric bulge generated
374 by the loading of Tahiti and Moorea volcanoes is experiencing an active deflation or Rangiroa
375 is at present situated at a distance long enough to escape the bumping effects of the Society
376 hotspot swell. Consequently, thermal subsidence of the underlying oceanic crust has taken up
377 its course as it did prior to the uplifting event, according to the standard cooling plate model
378 (Parsons and Sclater, 1977; McNutt and Menard, 1978; Marty and Cazenave, 1989). Despite
379 relatively recent subsidence resumption, the Miocene pile appears to have acted as a shoal-

380 water or emergent morphosystem throughout the Pleistocene to Holocene, thus usually
381 leading to coral growth in the form of apron to fringing reefs along the submarine flanks of
382 the atoll. By contrast, the atolls further to the northeast, including Takapoto, have been
383 continuously subsiding since the cessation of volcanic activity (Talandier and Okal, 1987),
384 likely to the Eocene times (Ito et al., 1995), thus permitting the vertical stacking of successive
385 Pleistocene high-stand reefs over the atoll rim (Montaggioni et al., 2019b).

386 The contrasting geodynamical history of Rangiroa and Takapoto Atolls would partly explain
387 the contrasting development history of their respective rim islands. In northern Rangiroa,
388 despite the limited number of dated samples, the provided ages clearly indicate that rim-island
389 accretion may have started not later than 6,000 cal. yr, according to the mean ages of the
390 dated samples. Assuming a mean vertical reef accretion rate of 4-5 mm/yr over the mid
391 Holocene (Dullo, 2005; Montaggioni, 2005), the accommodation space created by the
392 postglacial rising sea level was totally infilled by 6,000 cal. yr, at the time when sea level
393 reached its present position. This resulted in the formation of reef-flat surfaces at sea level.
394 These surfaces have served as depocenters for island initiation. The main accretional phase is
395 likely to have occurred between 6,000 and about 3,000 cal. yr (Figs. 8, 10).

396 At Takapoto, a dataset of 80 radiometrically dated coral samples were obtained from 8
397 excavations dug through the windward, southeast and leeward, southwest part of the island
398 (Montaggioni et al., 2018, 2019a). Except for one basal sample dated $7,705 \pm 120$ cal. yr, the
399 remaining 79 samples (98.75 % of total sampling) yielded ages not exceeding $2,958 \pm 17$ cal.
400 yr (Fig. 9). This means that the emplacement of the island deposits at Takapoto occurred
401 during the late Holocene, at a time of relative sea-level fall in the region (Pirazzoli and
402 Montaggioni, 1988; Rashid et al., 2014; Halmann et al., 2018, 2020). From 8,000 to 6,000 cal.
403 yr, contrary to Rangiroa, the rim at Takapoto was submerged at depths of about 5-6 m relative
404 to present, thus delaying the initiation of island building (Fig. 11).

405 **The role of unusual marine hazard events in the timing of rim-island building at**

406 **Rangiroa**

407 Coral detritus is likely to have derived from the adjacent foreslopes as observed in nearby
408 atolls (Hamelin-Vivien and Laboute, 1986; Montaggioni et al., 2018). Extraction of living
409 coral colonies from outer reef slopes and subsequent projection onto emergent rim surfaces
410 are known to be common processes triggered by severe cyclone hits (Harmelin-Vivien and
411 Laboute, 1986; Harmelin-Vivien, 1994). In addition, as mentioned above, reef megaclasts

412 (*cyclopean blocks*) are found in great number on Rangiroa, resting on the reef-flat zone,
413 especially along the northern area, most exposed to cyclones (Stoddart, 1969; Bourrouilh-Le
414 Jan and Talandier, 1985; Ricard, 1985). Similarly, several atolls within the French Polynesian
415 realm exhibit similar features (Etienne, 2012; Toomey et al., 2013; Lau et al., 2016). Given
416 the scarcity and low magnitude of tsunami events hitting coasts in the Tuamotu, the motion of
417 reef megaclasts was usually interpreted as triggered by high intensity cyclones (Canavesio,
418 2014; Canavesio et al., 2018). However, the most striking feature at Rangiroa is that pebble-
419 sized coral clasts dated at about 11,500 to 8,700 cal. yr have been extracted from the adjacent
420 forereef slope when sea level was between 55 and 40 m below present.

421 Two alternative scenarios could be invoked for explaining the incorporation of early
422 Holocene coral fragments into atoll-island deposits: step-by-step transport with transient
423 deposition on terraces located at mid-depth prior to be removed upwards; single-stroke
424 transport upwards and deposition along the margins of the atoll-rim tops prior to be removed
425 inwards. Along the forereef slopes in front of Avatoru village, there are two terraces,
426 respectively at depths of 8–11 m and 60–62 m. Assuming that the upper terrace has served as
427 a transient depositional zone for coral detritus of early Holocene age prior to be deposited at
428 the atoll-rim top, the relevant coral colonies have necessarily jumped approximately 45 to
429 30 m from their life space. These coral detritus are expected to have been stored on the outer
430 borders of the atoll rim and occasionally displaced inwards to contribute to the accretion of
431 basal conglomerates and island deposits.

432 Cyclone-generated surge impacts on foreslopes demonstrated to be efficient at depths not
433 exceeding 20 m. From these depths, broken colonies can be displaced upslope to atoll-top
434 surfaces (Harmelin-Vivien and Laboute, 1986; Harmelin-Vivien, 1994). Consequently,
435 whatever the scenario invoked, cyclones cannot have been originally involved in the
436 extraction of the oldest coral colonies at present trapped into the studied island sites. The most
437 likely explanation is that the moving force able to transport coral clasts at unusual elevations
438 were paroxysmal wave surges, maybe generated by occasional tsunamis known to be of very
439 low-frequency when compared to cyclones (Lau et al., 2016).

440 Similar hazard events have been described in a number of other tropical locations. Coral
441 clasts, ranging in size from pebbles to blocks, deposited at unusual heights (10–40 m), not
442 related to high sea stands, were found occasionally along tropical volcanic coasts, as on
443 Mauritius and Rodrigues Islands, Western Indian Ocean (Montaggioni, 1978). Their
444 uncalibrated radiocarbon ages range from around 6,000 to 3,700 yr BP. Especially, an
445 isolated, overturned, massive *Porites* head, about 2 m³ in volume, was encountered at the

446 elevation of 40 m above pmsl at Gunner's Quoin Island, 8 km north of Mauritius. Its age is
447 $5,730 \pm 120$ uncalibrated yr BP (Montaggioni, 1978). At that time, sea level was about 5–6 m
448 below pmsl (Camoin et al., 2001). This indicates that the removed *Porites* colonies has
449 experienced a 45 m-high jump at least, prior to be deposited. Similarly, Paris et al. (2013)
450 mentioned a 0.20–0.45 m-thick, mixed pebble- to block-sized coral-volcaniclastic
451 conglomerates, $4,425 \pm 35$ calibrated yr BP old at 10–15 m above pmsl on the southern coast
452 of Mauritius. Although it could be deemed inappropriate to compare the transport and
453 deposition conditions of pebble- and megablock-sized material, throwing of differently sized
454 clasts from coral communities living at several tens of meters is likely to require extreme
455 wave heights, irrespective of hydrodynamical processes invoked. As demonstrated from
456 several volcanic islands, including the Society, although there would have no statistic
457 correlation between sea-level rise and volcano flank collapses, 25–30 % of the identified
458 submarine landslides were demonstrated to have been coeval of rapid (> 5 mm/yr) sea-level
459 rise (Paris et al., 2013). Flank collapse records from Cape Verde Islands (Atlantic Ocean)
460 revealed that landslide-generated tsunamis may occur at a frequency of one to three every ten
461 thousands years (Paris et al., 2013).

462 Several flank collapse events have been identified from high volcanic islands in French
463 Polynesia as from Tahiti and Austral Islands (Clouard and Bonneville, 2003, 2004; Clouard et
464 al., 2001) and from Tuamotu atolls as Takapoto (Montaggioni et al., 2019b). Such processes
465 might easily explain displacement of coral gravels and pebbles to unusual altitudes as
466 observed in northern Rangiroa.

467 **Comparative models of low-lying, rim island development**

468 In French Polynesia, from 12,000 cal. yr, sea level rose from a depth of about 60 m relative to
469 present, at a mean rate of 10 mm/yr (Bard et al., 1996). It reached and overpassed its present
470 position by 6,000 cal. yr (Pirazzoli and Montaggioni, 1988; Bard et al., 1996, 2010; Hallmann
471 et al., 2018, 2020) (Fig. 8). On the basis of the electrical resistivity tomography profiles from
472 northern Rangiroa and by analogy with the nearby uplifted Mataiva and Tikehau Atolls, the
473 upper, partly indurated atoll-rim units, about 5 m-thick, were tentatively attributed to the reef
474 unit emplaced during the course of the rising sea level. On the subsiding northwest Tuamotu
475 atolls, including Takapoto, according to the mean vertical coral-reef accretion rate (4–
476 5 mm/yr) estimated for early to mid Holocene (e.g. Dullo, 2005; Montaggioni, 2005; Hubbard
477 and Dullo, 2016; Perry et al., 2018; Gischler and Hudson, 2019), the rate of the rising sea

478 level is most likely to have been too rapid to allow coral growth maintaining pace with sea
479 level. This resulted in the opening of a wider accommodation space. Indeed, the MIS 5e reef
480 tract, that is expected to underlie the modern atoll-rim (Montaggioni et al., 2019b), would
481 have been submerged under about 10 m of water by 7,000 cal.yr..

482 Unlike Takapoto, since the mid Holocene, most areas of the Rangiroa atoll-rim remained
483 emerged or close to sea surface, as indicated by the occurrence of emergent, up to 3 m-high
484 *feo* in the south (Fig. 3) and by electrical resistivity profiles showing similar geomorphic
485 features beneath the atoll-rim surface in the north-east (Fig. 7). In northern Rangiroa, when
486 sea level was approximately 50 to 30 m below pmsl, coral detritus have been extracted from
487 adjacent forereef slopes. The oldest extracted coral clasts were dated from the early Holocene
488 (Samples Rangiroa 1.1 and 2.1: $11,546 \pm 131$ and $8,769 \pm 205$ cal. yr, respectively). During
489 the 11,000–9,000 cal. yr interval, the atoll-rim top was situated at elevations changing from
490 about 40–45 to 30–35 m. In spite of its high rise, Rangiroa, at least in the northeast, is
491 believed to have been clast-supplied by exceptionally high-amplitude, tsunami-generated
492 surges. Coral clasts may have been originally trapped along the outer borders of the exposed
493 atoll rim. By 8,000 cal. yr, the atoll-rim surfaces culminated at about 15 m above sea level
494 (Fig. 10A). Based on the mean ages of coral clasts found in wells (Table 1), clast deposition is
495 thought to have given rise to incipient depocenters by about 6,000 cal. yr (Fig. 10B) as sea
496 level reached its present position. At that time, older coral clasts were removed occasionally
497 inland to participate in island building. The main phase of island building was achieved
498 presumably by about 3,000 cal. yr, as suggested by the age of the youngest coral specimen
499 (Sample Rangiroa Défense: $3,098 \pm 57$ cal. yr) during a relative sea-level drop (Fig. 10C).

500 The neighbouring subsiding atolls, such as Takapoto, were emerged at elevations of around 9-
501 10 m above pmsl, respectively by 8,000 cal.yr (Fig. 11A). The emergence episode resulted in
502 deposition of the coral sample dated at $7,705 \pm 120$ cal. yr, found at the lowermost part of the
503 southeast, island sequence (Montaggioni, et al., 2018). At that time, the atoll-rim top was
504 capped with a MIS 5e reef unit (Montaggioni et al., 2019b). Later, this reef terrace was
505 recolonized by coral populations and as such, was regularly depth-decreasing in response to
506 infilling accommodation space by early to mid Holocene coral growth (Fig. 11B). Island
507 initiation appears to have started only after the final emplacement of the modern reef flats, not
508 before 2,500 cal. yr. Islands have continued accreting until about 1,500 cal. yr at a time when
509 sea level was falling down to its present position (Figs. 8, 11C).

510 Over the last 3,000 years in north Rangiroa and over the last 1,500 years at Takapoto
511 (Montaggioni et al., 2019a), rim islands are likely to have continuously extended from the
512 initial depocentres seawards and lagoonwards owing to cyclone activity, resulting in the
513 present-day island physiography (Fig. 12).

514 **Conclusions**

515 Reconstruction of the internal atoll-rim structure and recent building history of rim islands in
516 the northern areas of the uplifted Rangiroa Atoll permits to gain the following new findings:

- 517 1– The uppermost, a few metres-thick, high resistive anomalies within the rim pile were
518 assumed to be Holocene reef-related deposits, composed of partly consolidated rubble
519 and sands, probably trapping isolated megaclasts. The other, irregularly shaped, high
520 resistive anomalies found at depth were thought to be dolomitized remnants of the
521 Miocene carbonate pile. The lower resistive material, which infills cavities within the
522 pile, is interpreted as unconsolidated, sandy, porous phosphates, presumably Pliocene
523 in age.
- 524 2– Coral-clast supply resulting in rim-island initiation started at a time when Rangiroa
525 was raised at elevations of several ten meters above sea level. Only paroxysmal hazard
526 events, such as tsunamis generated by island flank collapses, may explain clast
527 deposition at unusually high elevations.
- 528 3– Differential vertical motions – uplift followed by subsidence resumption versus
529 continuous subsidence – have given rise to different insular morphosystems in the
530 northwest Tuamotu Archipelago. These have contributed to drive the timing and mode
531 of rim-island building through controlling the width of opened accommodation spaces.
532 During the early Holocene, accommodation space was about 5 m-wide at Rangiroa
533 and 10 m-wide at Takapoto. Accordingly, island initiation in northern Rangiroa
534 appears to have happened out of phase with that in nearby subsiding atolls as
535 Takapoto. The combination of long-term emergence due to uplift and of unusual surge
536 regime has resulted in a markedly earlier island settlement as soon as the early
537 Holocene. Earliest supply of coral detritus to the rim top surfaces seems to have
538 started prior to 11,000 cal. yr, at least 4,000 years earlier than at Takapoto. The main
539 episode of island development is likely to have occurred during episodes of rising sea
540 level, from about 6,000 to 3,000 cal. yr.

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788 tomography in Saudi Arabia. *Journal of Geophysics and Engineering* 9, 655–663.
- 789 Table 1. Uranium and thorium concentrations in coral samples from the north-eastern rim-
790 island, Rangiroa Atoll. Are given successively, laboratory sample codes, uranium and thorium
791 contents, isotopic composition with statistical errors reported as 2 phi and non-corrected and
792 corrected ages. Total blanks were 18 pg for U and 82 pg for Th.

793 Table 2. Attempt at interpretation of resistivity data in terms of geological and hydrological
794 features, north-eastern rim-island, Rangiroa Atoll.

795 Figure 1. A: Location map of the northwestern Tuamotu Atolls in French Polynesia (central
796 south Pacific). B: Map of Rangiroa Atoll showing location of the studied northern areas. C:
797 Aerial view of the studied northern areas at Rangiroa showing location of the two well sites –
798 Well 1 and Well 2 – of U/Th dated Sample Défense and of two electrical resistivity profiles –
799 P1 and P3.

800 Figure 2. Bathymetric profile along the forereef slope in front of Taputa, northeast of
801 Rangiroa, showing the successive geomorphic feature from surface to –60 m depth.

802 Figure 3. General view of exposed, about 3 m-high, dolomitized remnants of Miocene
803 limestone pinnacles (*feo*) expected to be Miocene in age. These are peaking through the outer
804 reef-flat zone; in the background of the picture, on the left, appear two vegetated atoll
805 islets and, on the right, the wave-breaking, reef-crest zone. Photograph courtesy by Philippe
806 Bacchet.

807 Figure 4. Internal view of Well 1 and Well 2 showing the walls from which coral clasts were
808 collected, northern Rangiroa. Photographs by Aurélie Maspataud.

809 Figure 5. Sections of Well 1 (2.0–2.30 m deep) and Well 2 (1.5–1.6 m deep) northern
810 Rangiroa, showing location of U/Th–dated coral clasts collected along the internal walls. The
811 two logs shown for each well relate to the opposite well sides of each site.

812 Figure 6. Uranium isotope characteristics of dated coral samples. A: Comparison between
813 uranium contents and the average value of living corals (blue line). Analytical uncertainties
814 are smaller than the sizes of the symbols. B: Uranium activity ratios for the analyzed coral
815 samples. The blue line represents the seawater value, the dotted lines relate to uncertainties on
816 the average value.

817 Figure 7. Electrical resistivity tomography (ERT) profiles, close to Avatoru Village, northern
818 Rangiroa (see Fig. 1C for location of the two profiles). (A) Interpreted N–S Profile P1. B:
819 Interpreted N–S Profile P3. C: Conceptual geological model of the internal structure of the
820 uppermost carbonate pile based on both interpreted ERT profiles. FWL = Fresh Water Lens.

821 Figure 8. Comparing periods of coral-clast supply for rim-island accretion between Rangiroa
822 and Takapoto Atolls, relative to the course of sea level over the last 12,000 years. The relative
823 sea-level curve is based on data from Pirazzoli and Montaggioni (1988), Bard et al. (1996,
824 2010) and Hallmann et al. (2018, 2020).

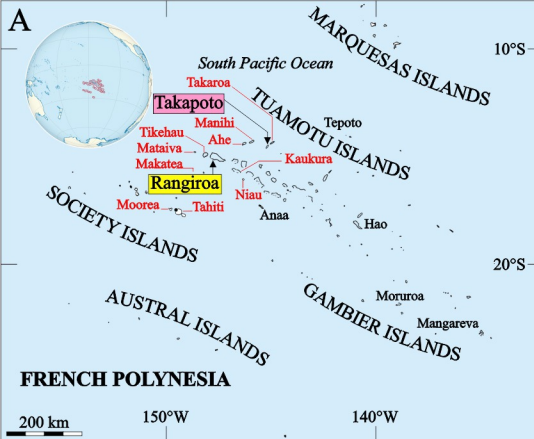
825 Figure 9. Plotted U/Th ages of the five coral clasts *versus* elevation – relative to present mean
826 sea level – collected in Well 1 and Well 2 (northern Rangiroa) compared with the U/Th age-
827 elevation cluster of the 79 coral samples collected from the eight holes excavated through
828 southeastern and south-western island sites at Takapoto Atoll (Montaggioni et al., 2018,
829 2019a). Note that among the 80 dated coral samples at Takapoto, only one sample (dated at
830 $7,705 \pm 120$ cal. yr) from the base of an excavation site is outside of the cluster.

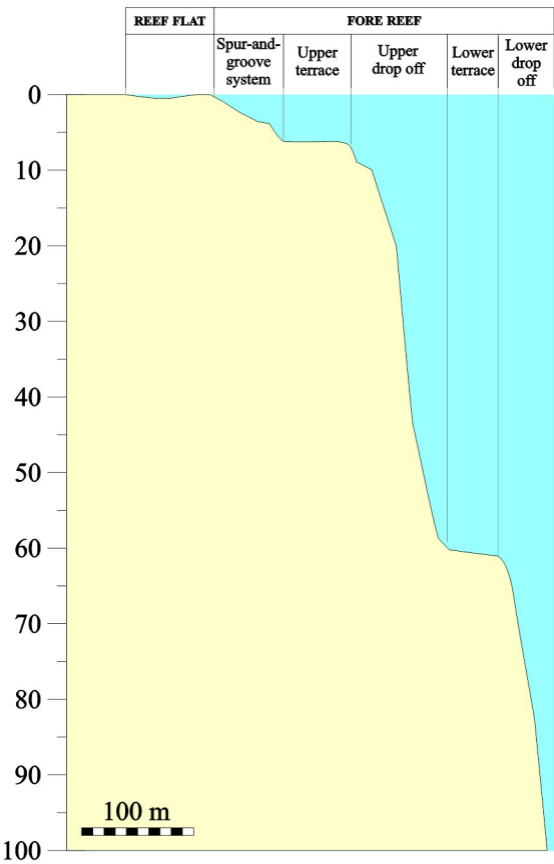
831 Figure 10. Northern Rangiroa Atoll: conceptual model of rim-island accretion from 8,000 to
832 3,500 cal. yr. A: 8,000 cal. yr: the top of the Miocene-Pleistocene carbonate pile culminated at
833 an elevation of about 15 m above sea level and was clast-supplied by extreme wave-surge
834 events. B: 6,000 cal. yr: sea level reached and outpassed its present position, thus flooded the
835 carbonate pile. The Holocene unit develops in the form of an about 5 m-thick bed. Coral-clast
836 deposition resulted in the formation of depocentres mainly composed of skeletal sands and
837 gravels. C: 3,000 cal. yr: sea level was falling down. The rim-island initiation phase was
838 achieved and islets continued to accrete laterally and vertically.

839 Figure 11. Takapoto Atoll: conceptual model of rim-island development from 8,000 to 1,500
840 cal. yr – adapted from Montaggioni et al., 2018, 2019a. A: 8,000 cal. yr: the top of the
841 carbonate pile – late Pleistocene in age – culminated at an approximate elevation of 9–10 m.
842 B: 6,000 cal. yr: during the sea-level rise, from 8,000 to 6,000 cal. yr, the available
843 accommodation space thus created was partly infilled by mid Holocene coral-reef growth. C:
844 2,500–1,500 cal. yr: from 6,000 to 5,000 cal. yr, during the final course of the rising sea level,
845 the remaining accommodation space was totally infilled by late Holocene coral growth. From
846 2,500 cal. yr, coral clasts derived from the adjacent forereef zones were deposited onto the
847 reef-flat surface thus created, resulting in the formation of indurated conglomerates and then
848 unconsolidated gravelly to sandy rim-islets. The 2,500–1,500 cal. yr interval relates to the
849 phase of rim-island initiation.

850 Figure 12. Conceptual mapping of the northern areas at Rangiroa atoll and of the southeastern
851 area at Takapoto atoll, showing successive rim-island accretion phases. Isochrons delineate

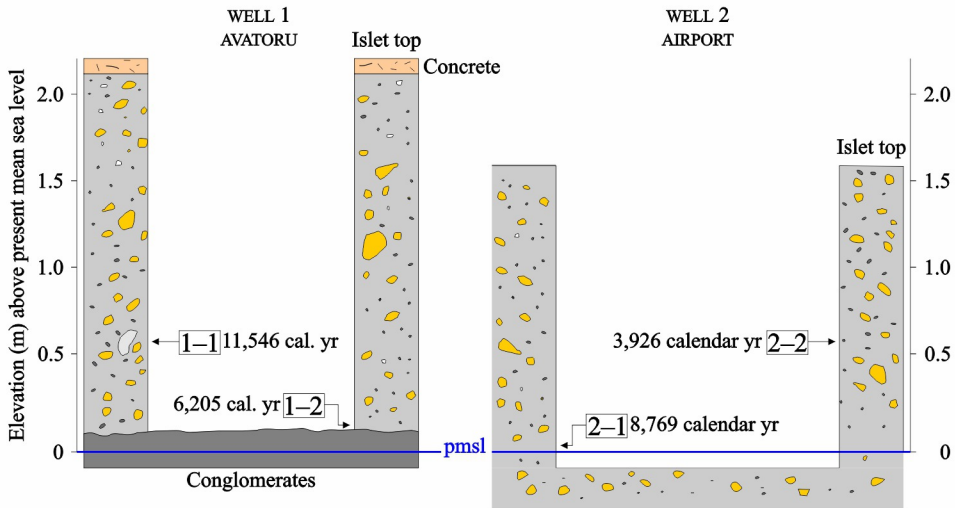
852 the changing aerial extent of islets through time. A: Rangiroa: island accretion from 6,000 cal.
853 yr to present. The development of initial depocentres occurred within the 6,000–3,000 cal. yr
854 time-lines. From about 3,000 cal. yr to present, the islets accreted laterally to vertically to
855 result in the modern island morphology. B: Cross section along the X–Y axis in Figure 12A.
856 C: Takapoto: adapted from Figure 12 in Montaggioni et al. (2019a). This shows the timing of
857 the rim-island development at Takapoto.











WELL 1
AVATORU

Islet top

Concrete

WELL 2
AIRPORT

Islet top

Elevation (m) above present mean sea level

2.0
1.5
1.0
0.5
0

2.0
1.5
1.0
0.5
0

1-1 11,546 cal. yr

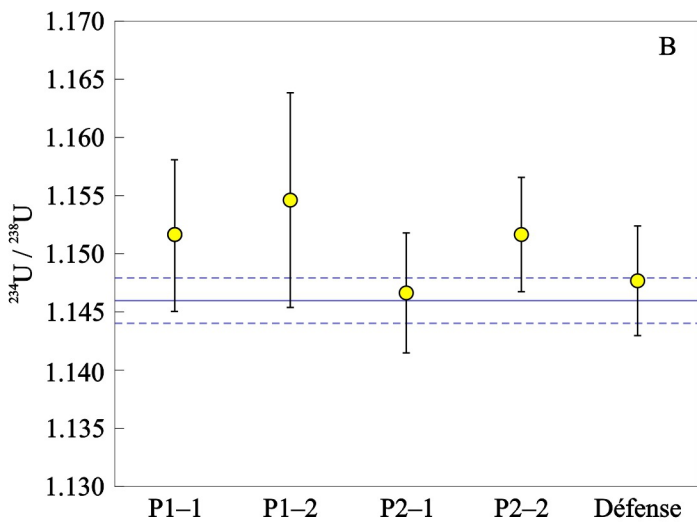
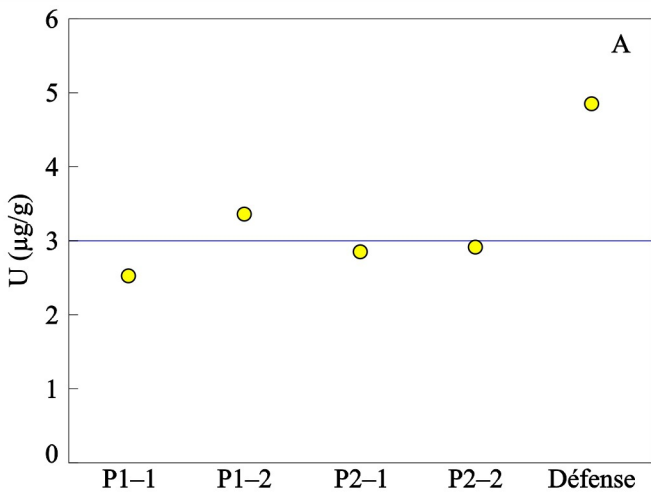
6,205 cal. yr 1-2

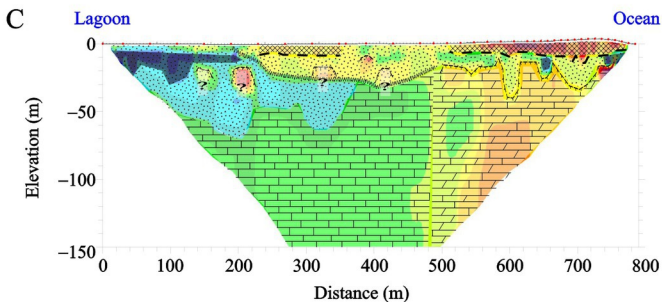
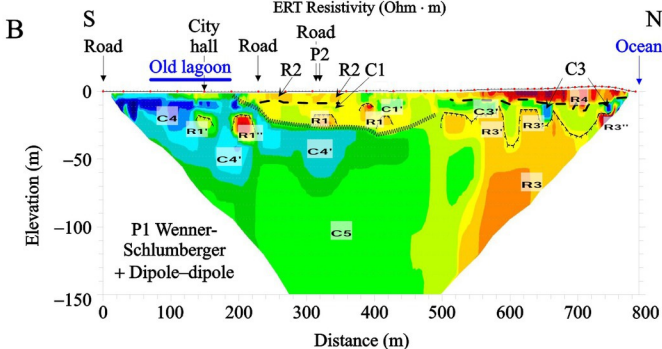
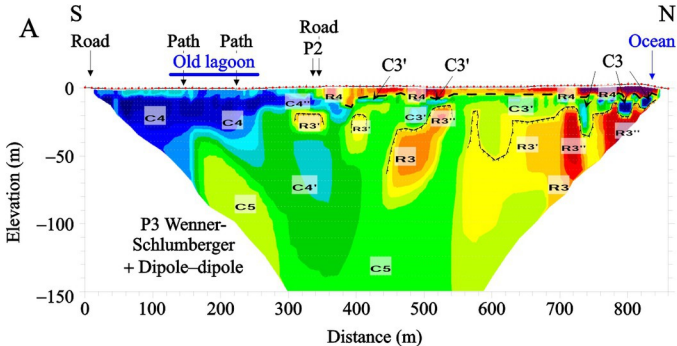
3,926 calendar yr 2-2

2-1 8,769 calendar yr

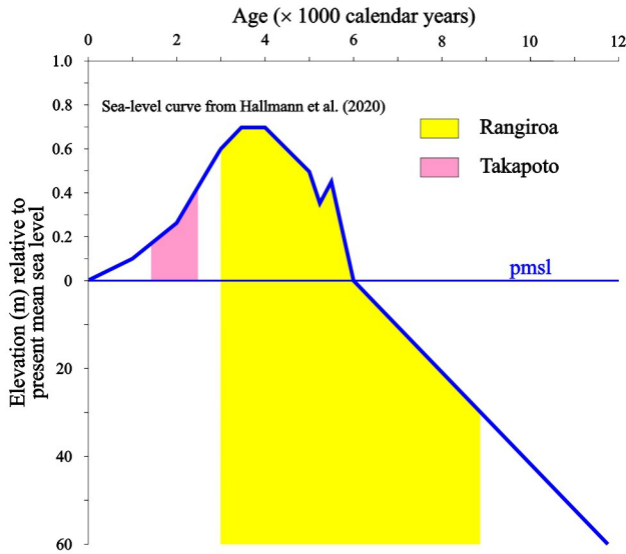
Conglomerates

pmsl

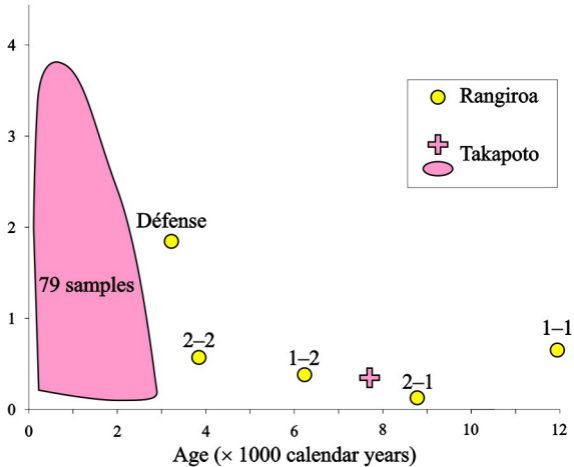




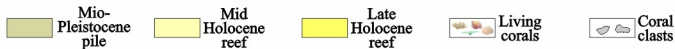
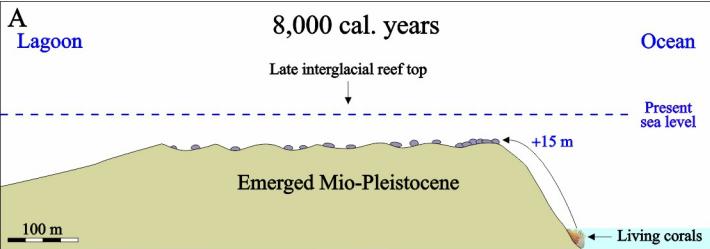
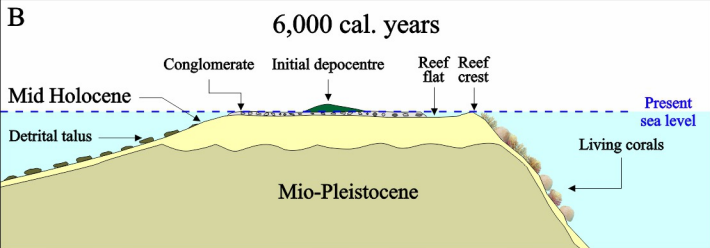
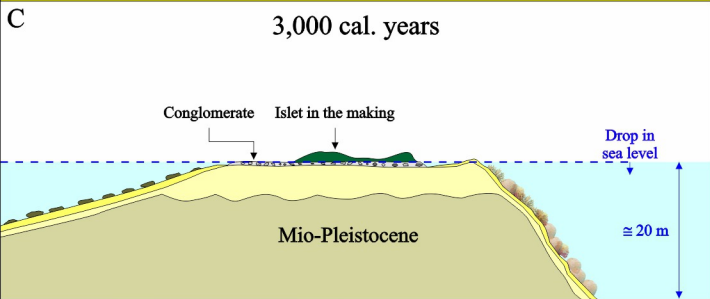
- | | | | | | |
|-----|--|-----|---|-------|--|
| --- | Lower boundary of Holocene deposits | TTT | Upper boundary of Miocene limestones | ~~~~~ | FWL base |
| | Holocene deposits, partly indurated | | Pinnacle shaped firmly cemented Miocene limestones? | | Less cemented, more fissured Miocene limestones? |
| | Holocene to Pliocene more or less consolidated, porous sediments | | High energy storm block or isolated pinnacles? | | |
| | High permeability saline intrusion | | | | |



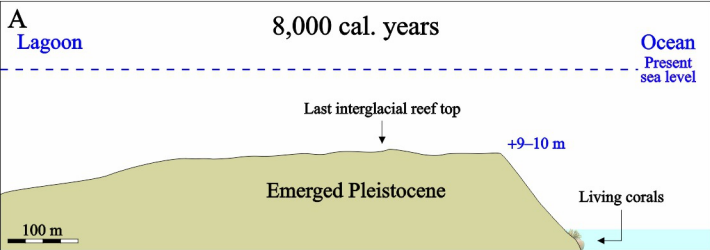
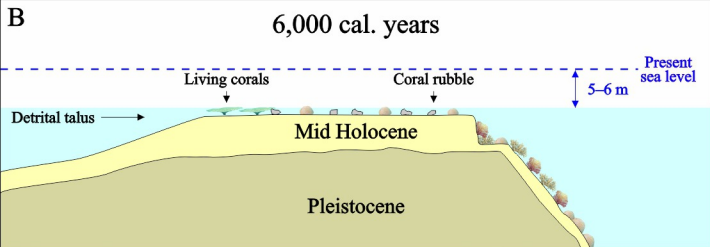
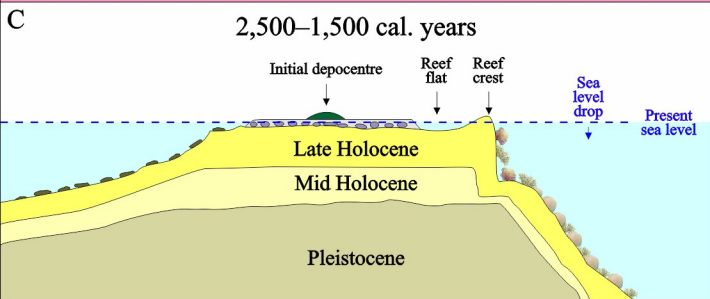
Elevation (m) relative to present mean sea level



RANGIROA



TAKAPOTO



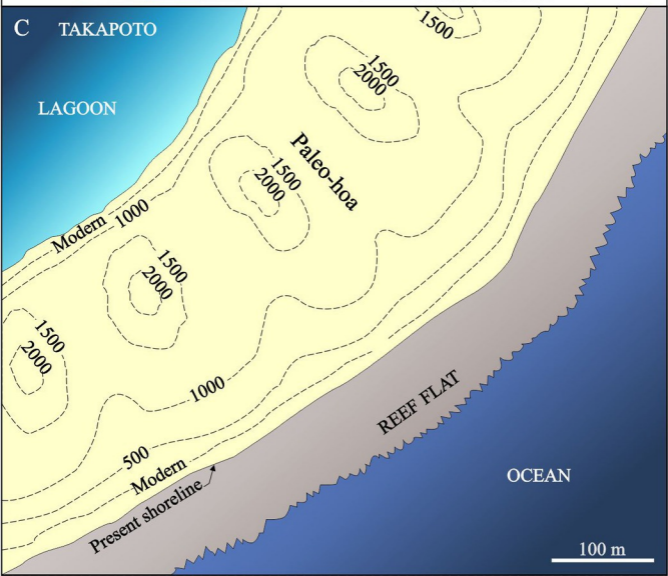
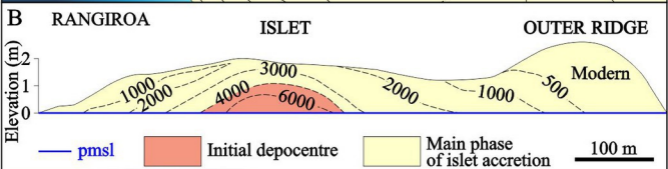
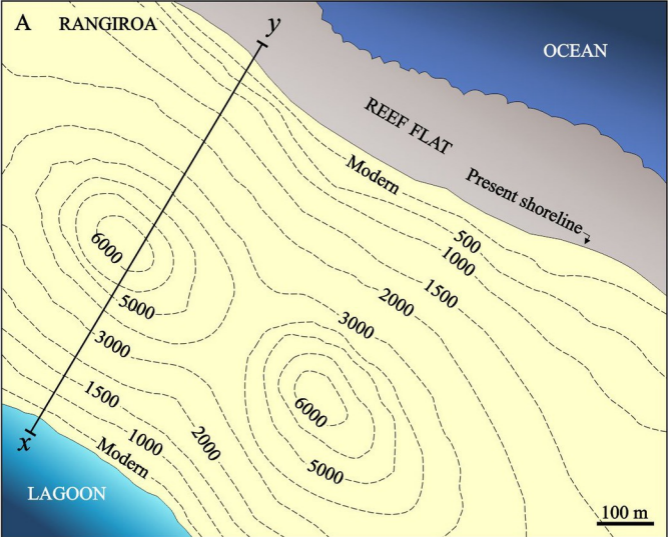
Pleistocene reef

Mid Holocene reef

Late Holocene reef

Living corals

Coral clasts



Resistivity units		Possible geological and hydrological features	Remarks
R3, R3', R3''	Resistive units at the seaward side of the atoll-rim pile ($90 < \rho < 500 \Omega \cdot m$) with upward columnar extensions.	Miocene cemented and karstified limestone basement, possibly dolomitized.	
R4	Resistive ($90 < \rho < 700 \Omega \cdot m$) cover at the seaward side of the atoll-rim pile.	Postglacial to Holocene deposits – sand-rubble sheets, conglomerate platforms, isolated megaclasts (?).	Because of the large (10 m) electrode spacing, possible intercalated fresh water lens may be not observed.
R1, R2	Shallow (R2) or deeper (R1) resistive ($90 < \rho < 250 \Omega \cdot m$) cover in the central part of the atoll-rim pile	More or less consolidated sediments bathed by fresh to saline water. With C1, C1' these zones constitute the fresh water lens.	Deeper resistive units (R1) may also correspond to the top of karstified Miocene limestones. Lack of freshwater lens in P3 tomography is explained by its proximity to the pass which favours saline intrusion.
C4, (C4', C4'')	Conductive ($0.3 < \rho < 5 \Omega \cdot m$) cover (C4) at the lagoon side of the atoll-rim pile; less conductive ($5 < \rho < 15 \Omega \cdot m$) extension (C4', C4'') intruding the atoll-rim subsurface.	Large saline intrusion in more or less hydraulically conductive sediments.	C4 may refer to porous, Holocene material. C4' and C4'' may refer to large karstic zones within the Miocene basement infilled with porous phosphatic deposits of Pliocene (?) age.
C3, C3'	More (C3 $0.3 < \rho < 10 \Omega \cdot m$) or less intense (C3', $10 < \rho < 60 \Omega \cdot m$) isolated conductive anomaly.	Isolated saline intrusion, intercalated, porous, weakly consolidated deposits invaded by saline water.	Karstic galleries running into Miocene limestones may be filled with saline water and/or hydraulically conductive sediments, electrically conductive phosphatic deposits of Pliocene (?) age.
C1, C1'	Intercalated conductive layer ($20 < \rho < 60 \Omega \cdot m$)	Intercalated freshwater and/or more or less salty (C1') aquifer	
C5	Intermediate resistivity basement ($20 < \rho < 60 \Omega \cdot m$)	Possibly fissures/fractures in Miocene limestone basement.	The reason why internal and external atoll-island substratum presents contrasted resistivity remains a question: differential nature or state of sediments: rubble <i>versus</i> sand (?) cementation (?) dolomitization (?)