

# Morphology of fore-reef slopes and terraces, Takapoto Atoll (Tuamotu Archipelago, French Polynesia, central Pacific): The tectonic, sea-level and coral-growth control

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- 1 Morphology of fore-reef slopes and terraces, Takapoto
- 2 Atoll (Tuamotu Archipelago, French Polynesia, central
- 3 **Pacific): the tectonic, sea-level and coral-growth control**
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# 25 Abstract

26 A dataset of 41 bathymetric profiles detected by satelline 27 imagery and echo-sounding to a maximum depth of 38 m along 28 the fore-reef slopes of Takapoto Atoll (Tuamotu Plateau, 29 French Polynesia, central Pacific) were qualitatively and 30 quantitatively analyzed in order to identify the main 31 geomorphological scuba-diving features. In addition, investigations from a selected site resulted in defining coral 32 33 composition and cover rate. Six distinct fore-reef sectors were morphologically differentiated on the basis of seaward 34 35 extension and slope gradient. Only the north end, and a 36 restricted area of the mid-south-east side extend seawards over 37 an average distance of 150 m, with a relatively low gradient 38  $(23^{\circ}-38^{\circ})$ . Most of the outer-slope areas are narrow (less than 39 100 m on average) and steep (average slope equals to  $45^{\circ}$  to up 40 to 70°). Geomorphic features include spur-and-groove systems, 41 sub-horizontal to gently dipping terraces (23-45 m wide) 42 ending seawards in vertical steps (<10 m high) and drop-offs 43 (> 10 m high), outer-reef crest-like reliefs (0.5 m-1.5 m high), 44 pinnacles (2 m–17 m high), coral heads (< 2 m high), trenchs 45 and concave scars. The recognized seven terrace levels occur at the respective depths of about -5 m, -10 m, -15 m, -20 m, 46 -24 m, -30.5 m and -38 m. Based on comparison with 47

48 subsurface chronostratigraphy of drilled reef sequences from 49 some other Pacific atolls, the terraces are interpreted as 50 remnants of reef tracts formed during Pleistocene interglacial, 51 high sea-stands, respectively during MIS substage 5e (about 52 -125 ka), MIS substages 7a (about -195 ka), 7c (about -210 53 ka), 7e (about -240 ka) and 9e (-330 ka). After depth 54 correction of ground lowering during periods of emergence and 55 subsidence effects, terrace elevations were expected to indicate 56 eustatic sea-level positions at each identified high sea-stand, at 57 approximately 7 m (MIS 5e) and 2.2 m (MIS 7a) above present 58 sea level and 9.5 m (MIS 7c), 11 m (MIS 7e) and 8.6 m (MIS 59 9e) below present sea level. During the post-glacial sea-level 60 rise, from about 9.5 ky, the studied portions of fore-reef slopes 61 were re-flooded. It was assumed that coralgal deposits in the 62 form of thin veneers, coral heads, outer-reef crest-like reliefs 63 and pinnacles have simply overlapped pre-existing structures. 64 Locally, the fore-reef zones are carved by trenchs, i.e. incipient 65 detachment faults, and scars, i.e. imprints of former landslides. 66 Similarly, some drop-offs may be regarded as fault walls. The 67 prevailing direction of faulting-collapsing surfaces is 68 consistent with the SW-NE orientation of the main axis of the 69 atoll and submarine ridges rising up from the north-western 70 floor of the Tuamotu Plateau. Analysis of the composition and 71 distribution of coral communities to -30 m depth revealed 72 high, downslope-increasing coral coverage (24 % to 67 % on

average) and the sharp replacement of robust-encrusting *Pocillopora* by sub-massive to plate-like *Porites* from depths
greater than -10 m. Significant inter-regional differences were
detected with atolls in west Pacific, probably due to local
ecological constraints.

## 78 Highlights

- A detailed survey of morphological features of upper forereef slopes from a Pacific atoll is provided for the first time,
- 81 using satellite-based records.
- Five submerged terrace levels among the seven detected are
  regarded as related to distinct Pleistocene high sea stands
  are identified.
- At a large scale, the morphogenetic evolution of the atoll
  fore-reef slopes is mainly controlled by SW–NE trending
  regional-scale, tectonic structures.
- At a small scale, living coral communities with low
  diversity, but high cover contribute significantly to atoll
  fore-reef shaping.
- 91 Keywords: submerged terraces, fore-reef slopes, Pleistocene92 high stands, atoll, central Pacific.

#### 93 1 Introduction

94 Coral reefs, typical ecosystems of many tropical coastlines, are 95 known to be reliable indicators of climate, environmental (see 96 Montaggioni and Braithwaite, 2009; Phinney et al., 2013 for 97 reviews) and relative sea-level changes (see reviews by 98 Montaggioni and Braithwaite, 2009; Murray-Wallace and 99 Woodroffe, 2014; Woodroffe and Webster, 2014; Camoin and 100 Webster, 2015). Intensive submarine exploration has given 101 evidence that reefs have developed at times of lower sea levels, 102 and at present located along continental and island shelves at 103 different depths. A number of submerged reefs were described 104 in the Pacific Ocean (Australia: Abbey et al., 2011; Webster et 105 al., 2009; Linklater et al., 2015 - French Polynesia: 106 Montaggioni et al., 1987; Cabioch et al., 2008; Camoin et al., 107 2012; Seard et al., 2013 - Hawaii: Faichney et al., 2009, 2010 108 and references herein - Papua New Guinea: Webster et al., 109 2004b; Ryukyus: Arai et al., 2016), in the Indian Ocean (Dullo 110 et al., 1998; Rovere et al., 2018; and references herein) and the 111 western Atlantic (Lightly et al., 1978; James and Ginsburg, 112 1979; Blanchon et al., 2002; Khanna et al., 2017; and 113 references herein). Submerged reefs have proven to provide 114 valuable information on relative sea-level and tectonic histories 115 (Webster et al., 2004a,b, 2006; Cabioch et al., 2008; Faichney 116 et al., 2010; Abbey et al., 2011; Rovere et al., 2018) and sub-117 aerial erosional patterns as well (Purdy and Winterer, 2001).

118 The origin of submerged reefs and associated topographic 119 anomalies - terraces, breaks-in-slope, pinnacles and steps, has 120 been intensively discussed (Hopley, 2006; Beaman et al., 2008; 121 Abbey et al., 2011; Rovere et al., 2018). Reef tracts were 122 speculated to form during either the last deglacial sea-level rise 123 (-20 ka to -8 ka) or early, during late to mid-Pleistocene 124 variations of sea level. They may be multi-generational, 125 resulting from stacked successive growth and erosional 126 episodes over several cycles of submergence and sub-aerial 127 exposure, finally overlain by last deglacial deposits. Especially, 128 terraces are interpretated to be constructional in origin or to 129 have been shaped by erosive wave action during sea-level sea-130 stands lower than present. Similarly, steps may result from 131 seaward accretional processes during stillstands, step and drop-132 off recession during low stands or faulting. Contrary to shelf 133 slopes of continents and high volcanic islands, those of atolls 134 have been little explored. Earlier bathymetric surveys using 135 single beam echo-sounding have been conducted from the end 136 of the forties on a number of Pacific atolls (Ladd et al., 1970; 137 Winterer, 1976; Smith et al., 1994; Wong et al., 1999). 138 Recently, investigations using shallow-water multibeam 139 mapping, multispectral satellite-, optical- and acoustic-based 140 imagery off several atolls from Pacific US overseas territories, 141 provided new detailed insights into shelf morphology (for 142 instance, see Poppenga et al., 2018). In French Polynesia,

143 shallow-water (0 to -30 m) bathymetric investigations were 144 initiated at Moruroa (Chevalier et al. 1968).. At Takapoto, the 145 first underwater surveys were carried out by Kühlmann and 146 Chevalier (1986). A series of terraces and breaks-in-slope occur 147 at different depths to about -40 m downslope. From satellite-148 derived near-shore bathymetry, Collin et al. (2018) provided 149 the first high-resolution outer-slope morphometry of the eastern 150 side of Takapoto.

151 In addition to geomorphology, the characterisation of coral 152 communities living along the upper fore-reef slopes is an 153 important step in terms of paleo-water depth reconstructions. 154 The earlier works on the compositional and distributional 155 patterns of coral communities at Takapoto were carried out by 156 Chevalier and Denizot (1979), Kühlmann (1982), Bouchon 157 (1983) and Kühlmann and Chevalier (1986).

In this study, are presented both morphological and biological
datasets from the foreslopes of Takapoto Atoll in the Tuamotu
Archipelago (French Polynesia, south-central Pacific). Analysis
of satellite-based datasets gains insight into the detailed spatial
distribution of submerged geomorphic features. Scuba-diving
investigations reveal richness and cover rate of coral
populations.

The aims of this study are to: (1) identify the main geomorphic
features present on the shelf slopes and quantitatively describe
their morphology; (2) define the depth distributional trends of

168 these features, especially those of terraces; (3) explore 169 scenarios of their possible nature, mode and timing of 170 formation, based on chronostratigraphic comparisons with 171 other atoll sites; (4) determine the main depth-related 172 compositional and distributional attributes of coral 173 communities.

# 174 2 Environmental setting

# 175 2.1 Geological background

176 French Polynesia lies in the south-central Pacific and extends 177 over about 5 500 000 km<sup>2</sup>, from 134°28'W to 154°40'W and 178 from 7°50'S to 27°S (Fig. 1a). Its sea floor includes a broad 179 zone, the so-called 'Pacific Superswell' which is 250 to about 180 1000 m shallower compared to the depth predicted for its age 181 by classical seafloor subsidence models (McNutt and Fischer, 182 1987; McNutt, 1998; Adam et al., 2014). It is typified by a 183 great number of volcanoes, aseismic volcanic plateaus and 184 seamounts, aligned along south-east to north-west linear 185 (N115°E) trends, consistent with the predicted direction of 186 absolute motion of the Pacific plate (Duncan and Clague, 187 1985). By contrast, the underlying oceanic crust exhibits 188 structural features, including south-west to north-east-oriented, 189 transform faults and magnetic lineations (Patriat et al., 2002) 190 and volcanic ridges (Jordahl et al, 2004), and thus, oblique to 191 the hot-spot-generated island trails (Ito et al., 1995).

192 The Tuamotu Plateau, part of the oceanic superswell, 193 encompasses an area of approximately 1500 km long and 800 194 km large (Fig. 1b). It does not exceed 2000 m in bathymetry 195 and is composed of basaltic flows, postulated to have erupted 196 near the East Pacific spreading centre. The plateau is known to 197 be aged of 70 (Okal and Cazenave, 1985) to less than 50 198 million years (Schlanger et al., 1984).

199 Accretion of the north-west atoll-bearing volcanoes is 200 attributed to the passage of two hotspots 50-30 million years 201 ago as they migrated beneath the Pacific plate. However, the 202 morphology and orientation of a number of linear volcanic 203 features onto the plateau were controlled by tectonic structures 204 of the underlying lithosphere. (Ito et al., 1995). Carbonate 205 deposition over the oldest volcanoes is likely to have begun as 206 early as 49 million years (Jackson and Schlanger, 1976).

# 207 2.2 Location of the study area.

208 Located between 14°33'S-14°43'S and 145°08'W-145°16'W, 209 Takapoto Atoll rises from the northwestern portion of the 210 Tuamotu Plateau (Fig. 1b). Its total surface area is 74 km<sup>2</sup>, 211 about 17 km long and 5.5 km wide. The atoll is elongate, 212 oriented NE-SW, with an approximately 350 m wide rim 213 enclosing a -45 m-deep lagoon. The outer part of the atoll rim 214 is a living reef system, subdivided into three zones, from the sea inwards (Chevalier et al., 1979; Salvat, 1981; Salvat and 215

216 Richard, 1985; Laboute, 1985; Kühlmann and Chevalier, 1986; 217 Montaggioni, 1981, personal observation). The outer reef zone 218 comprises a spur-and-groove system, extending downwards to 219 about 6-10 m, followed by sub-horizontal to gently sloping 220 terraces to depths of 10-15 m, previously interpreted as the top 221 of the last interglacial high-stand reef (Montaggioni et al., 222 2018). Below this, low gradient to sub-vertical slopes are 223 developing to depths greater than 60 m. The emergent, 224 innermost parts of the spurs are capped by an algal crest, about 225 20 m wide, reaching 0.20 m to 0.50 m above low tide level.

226 The climate in the northern Tuamotu is tropical, warm and 227 humid. The rainy, austral summer lasts from November to 228 April and the relatively cooler, and dryer, austral winter from 229 May to October. Air temperatures vary between 23 °C and 230 30 °C. Annual rainfall averages 1500 mm. Tides are a twice 231 daily regime and microtidal, 0.5 m in average amplitude and 232 0.70 m in maximum at spring tide. As in all Tuamotu islands, 233 Takapoto is influenced by the south-east trade-winds, blowing 234 from the ENE sectors for 70 % of the year and for 20 % from 235 the SE sector. In the austral winter, 2.5-m high swells are 236 generated by strong trade-winds. During the austral summer, 237 trade-winds are significantly less active and generate moderate-238 energy wave conditions, locally disturbed by storm events 239 initiated either by ENSO-related cyclones or by storms originating from northern latitudes (Andréfoüet et al., 2012). 240

The eastward migration of warmer sea surface temperatures
during ENSO episodes promotes the displacement of tropical
storms further east into the Tuamotu region (Larrue and
Chiron, 2010).

245 Little is known about frequency of extreme wave hazards, i.e. 246 tropical cyclone- and tsunami-generated. Over periods of 247 several centuries, the number of cyclonic events has probably 248 not exceeded 2-3 per century. The effects of cyclones and 249 storms in shaping atoll morphology at the long-term scale is 250 poorly documented (Montaggioni et al., 2018) onto atoll 251 surfaces (Harmelin-Vivien and Laboute, 1986). Similarly, there 252 is little information about the frequency of tsunami occurrences 253 in the Tuamotu. Based on numerical modelling and direct 254 observations, the Tuamotu islands seem not to have 255 significantly suffered from tsunami impacts compared to some 256 high-volcanic islands in French Polynesia (Sladen et al., 2007).

# 257 **3** Methods and data

### 258 3.1 Acquisition and analysis of geomorphic data

Pleiades-1 satellite imagery was collected over Takapoto Atoll
on September, 22 2016 at 20 h 01 min 03 sec (UTC). Orbiting at
694 km altitude, Pleiades-1 sensor provides four spectral
wavebands (blue: 430 nm–550 nm, green: 490 nm–610 nm,
red: 600 nm–720 nm, and infrared: 750 nm–950 nm) at 2 m
pixel size. The processed imagery totaled 72 294 672 pixels in

265 the form of 9759 lines and 7408 columns. Given the sun-266 sensor-scene trigonometry, a geometric correction was 267 necessary to project multispectral imagery in UTM 6 South 268 within RGPF local datum. For the sake of standardization and 269 further comparison, a radiometric correction was carried out. It 270 firstly converted top-of-atmosphere (TOA) digital number into 271 TOA radiance using calibration factors, secondly TOA 272 radiance into down-of-atmosphere (DOA) radiance by 273 compensating for atmosphere absorption, and thirdly DOA 274 radiance into DOA reflectance by sun irradiance normalization. 275 In parallel, a sonar campaign, aiming at calibrating-validating a 276 depth model, was conducted, from September, 25 to 26, 2016, 277 to acquire water depth soundings over both lagoon and ocean 278 parts (Fig. 2a). Fieldwork week was close enough to imagery 279 date to be confident with an absence of bathymetric 280 disturbances between two periods. An array of 276 082 281 geolocated measurements was compiled across 104.4 km over 282 16 h 44 min recordings. The dataset ranged from 0.54 m to 283 180.85 m with an average of 9.90 m  $\pm$  10.02 m. The sonar 284 device, installed on a fishboat, was a 200 kHz echosounder 285 Lowrance HD7 leveraging a 10 Hz GPS unit. Water level 286 driven by tide was corrected using the nearest French Marine 287 gauge in Rangiroa atoll.

The bathymetry has been extracted based on the optical law,showing that electro-magnetic radiation is absorbed by water in

respect to the wavelength. Pleiades-1 infrared waveband
enabled to discriminate land from sea areas, owing to the strong
water absorption of the infrared. Three remaining visible
Pleiades-1 wavebands (blue, green and red) were used to
elucidate the bathymetry based on the ratio transform (Stumpf
et al., 2003):

296 
$$Z = a_1 \left( \frac{\ln(R_w(\lambda_i) - R_\infty(\lambda_i))}{\ln(R_w(\lambda_j) - R_\infty(\lambda_j))} \right) - a_0$$
(1)

where  $a_0$  is the intercept for a null water depth (0 m),  $a_1$  is the modeled slope converting the ratio to absolute bathymetry,  $R_w$ is the DOA reflectance related to the waveband  $\lambda_i$ , and  $R_\infty$  is the DOA reflectance above no-bottom water. Both intercept and slope stemmed from soundings, whose values were re-adjusted by an offset linked with the tide level observed at the satellite collection time.

304 А very strong agreement between waterborne sonar 305 observations and spaceborne modeled depths was reached  $(R^2 = 0.95, RMSE = 0.17 m, see Collin et al. 2018 for more$ 306 307 details). Since the model accuracy declined with depth, a 308 truncature at 38 m was applied. The formula, underlying the 309 model, was thereafter implemented to every pixel, in order to 310 build a digital depth model spanning the entire scene captured 311 by the satellite.

Finally, a set of 41 bathymetric profiles was selected (Fig. 2b)and visually inspected to define the type and spatial distribution

314 of morphological features imaged on the atoll shelf slopes. 315 Especially, criteria used to define terraces include the 316 identification of flat-topped to low-gradient surfaces and major 317 breaks-in-slope across the island shelves. The geomorphic 318 features are classified according to their sizes, from larger-scale 319 (hectometres to kilometres) to finer-scale (metres to 320 decametres). The geomorphological classification used in this 321 study is adapted from previously published descriptions and in 322 common usage (see Beaman et al., 2008 and Addey et al., 2011 323 for reviews). Table 1 and figures 2b and 3 present the different 324 geomorphic features.

325 Shelf-slope inclination and size, elevation and width of the 326 different geomorphic features were manually measured from 327 the recorded transects. To measure terrace width, slope 328 extension and inclination, and graphically compare the depth 329 ranges of the successive terrace levels, positive reliefs, such as 330 pinnacles and coral heads, were masked.

331 3.2 Acquisition and analysis of biologic data

The study site is located at the south end of the atoll, close to the village of Fakatopatere and profile T23. Digital images of the quadrats were acquired using a SLR Nikon D300s body camera with aquatica housing and equipped with a Nikkor 15 mm (AF 15 mm f/2.8) lens and two SB 105 Nikonos strobes. Pictures were taken at -5 m, -10 m, -15 m, -20 m, -25 m, and

338 -30 m depth running downslope. At each depth site, 4 pictures 339 were taken perpendicular to the bottom surface with a 340 frequency of 1 picture every 30 seconds by a scuba diver 341 swimming at low speed (1 m per 5 sec). Reef bottom to camera 342 lens distance was approximately 5 m. Digital pictures were 343 processed on computer screen using the point intercept method 344 (50 points-picture). Frequency of coral/non-coral substrate was 345 assessed on each picture by identifying the benthic category 346 present under each point. Except in some cases, coral taxa were 347 identified at the genus level. Amount of living coral cover was 348 obtained by calculating the proportion of points occupied by 349 living coral colonies against the total number of points in a 350 given processed surface area.

#### 351 4 Results

# 352 4.1 Morphometry of fore-reef features.

353 Visual examination of the 41 bathymetric profiles (T1 to T41)
354 revealed significant variability in distribution, shape and size of
355 fore-reef features.

# 356 4.2 Gross morphology

357 Six morphologically distinct sectors can be delineated around
358 the atoll, based on seaward extension and mean slope gradients
359 of the bathymetric profiles (Figs. 4 and 5).

The north-end sector (T1 to T5) appears to be the widest with deepest points at 30 m to 36 m, at a distance of 143 m to 190 m from the modern reef-crest line (Fig.4a and 5a). It has relatively gently dipping slopes (23° to 38°) and numerous sub-horizontal terraces, 7 m to 45 m wide. Usually, terraces terminate in steps, 1.80 m to 10 m high. There is a prominent line of pinnacles, with elevations of 2.70 m to 17 m.

The eastern sector (T11 to T16) exhibits steeply dipping slopes (45°–58°) punctuated by narrow (less than 15 m) terraces ending in steps, 2 m to 15 m high (Figs. 4b and 5b). The deepest points are at 30 m to 37 m, 80 m to 110 m far from the modern reef-crest line. Pinnacles are usually rare or scattered, and not exceed 3.50 m in average elevation. Coral heads are occasional.

The south-end sector (T19 to T25) is characterized by steeply dipping slopes (45°–65°) frequently ending in vertical dropoffs (Figs. 4c and 5c). The lowest depths recorded range between 26 m to 36 m, at the distance of 70 m to 135 m from the modern reef-crest line. Terrace width varies between 3 m and 15 m. Step height ranges from 2 m to 17 m. Pinnacles are absent or uncommon.

The north-western sector (T31 to T41) exhibits a gradient of
45° to up to 70°. The deepest points recorded range between
6 m and 24 m, at 80 m to 105 m far from the reef front line.

There are successive, narrow terraces (2 m–15 m wide) and low steps (1.80 m–12 m). Pinnacles and coral heads are occasional.

386 The steepest foreslopes are located in the north-eastern and 387 south-western sectors of the atoll (T6 to T10 and T26 to T30, 388 respectively) (Fig. 4e and 5e). The mean slope angle varies 389 between  $64^{\circ}$  and up to  $75^{\circ}$  (Fig. 6). Along the north-eastern 390 margin, the base of the profiles does not exceed depths of 26 m 391 to 36 m, at the distance of 40 m to 55 m from the modern reef-392 crest line. Along the south-western side, the deepest detected 393 isobath ranges between 9.5 m and 14 m only, at a distance of 394 40 m-50 m from the modern outer reef-crest line. In both 395 sectors, the slope is interrupted by narrow terraces, usually less 396 than 7 m wide ending in low steps and drop-offs, ranging from 397 2 m to 15 m in elevation. The height of pinnacles does not 398 exceed 8.5 m. Coral heads are common.

There is locally an atypical zone at the mid-south-eastern side (T17, T18) along which a gently dipping  $(25^{\circ}-35^{\circ})$  slope ends in drop-offs not higher than 7 m (Fig. 4a and 5e). The zone between the reef crest and the 38 m isobath extends for a length of 120 m to 210 m. Pinnacles are common, with heights of 2 m to 4.80 m.

405 *4.3 Terrace levels.* 

406 The morphology of the Takapoto outer-reef slopes is typified407 by several sets (or levels) of terraces. These lie at relatively

recurrent depths from the sea surface to about 38 m and have a
relatively spatial continuity. Seven morphologically distinct
levels of terrace (TL1 to TL7) were recognized (Fig. 7).

# 411 4.3.1 Terraces TL1

412 As in most of reef zones facing the open ocean, the outer reef 413 crest extends into a seaward dipping terrace, which is the top 414 surface of the spur-and-groove system (Fig. 8). Locally, this 415 terrace is missing or poorly developed, ending in abruptly 416 dipping  $(50^{\circ}-76^{\circ})$  or vertical drop-offs, especially along the 417 north-eastern, eastern (windward) and south-western (leeward) 418 sites. This means that the development of the spur-and-groove 419 system is not directly dependent upon the location and 420 orientation of the foreslopes, since locally lacking from both 421 some windward and leeward sectors. The main driving factor 422 seems to the slope angle; spurs and grooves are usually 423 restricted to more gently dipping slopes, irrespective of 424 exposure to winds and waves. At its seaward end, the depth of 425 TL1 edges range between 2 m and 7 m, with an average depth 426 of  $5.24 \text{ m} \pm 2.0 \text{ m}$ .

427 4.3.2 Terraces TL 2

428 This terrace, identified from 34 profiles, is found at the average 429 depth of 10.1 m  $\pm$  2.4 m (Figs. 6, 8). It is missing from narrow, 430 steeply dipping slopes and drop-offs (profiles T6 to T10, T22, T23, T27 to T30). The surfaces seem generally to have a
bumpy morphology generated by thick and widespread coral
layers or metre-high coral heads, locally oriented perpendicular
to the terrace margins. In most cases, the seaward margin of
TL2 ends in a steep break-in-slope. Another point to note is the
presence of outer reef-crest-like morphologies, less than 2 m
high, at the seaward margin of the terraces.

438 4.3.3 Terraces TL 3

On 28 profiles, a third set of terraces is identified at an average
depth of 14.7 m ± 3.8 m. These terraces are missing from a
number of transects because of local strong steepness (T4, T8,
T9, T10, T20, T26 to T33, T37, T39 to T41).

443 4.3.4 Terraces TL4

444 Another level of terraces is encountered at an average depth of 445 20.3 m  $\pm$  2.3 m on 20 out of the 41 profiles. Yet, the strong 446 steepness of the fore-reef slopes makes the mid-fore-reef zone 447 deeper than 20 m not accessible, as seen on T21 to T30, T33, 448 T34, T35, T36, T39 to T41. Despite high coral cover rate, the 449 occurrence of TL4 can be inferred from T17 to T20 based on 450 sharp changes in slope.

#### 451 4.3.5 Terraces TL5

- 452 The relevant terraces are found from 21 sites at an average 453 depth of  $-24 \text{ m} \pm 2 \text{ m}$ . These are missing from the transects T6, 454 T13 à T17, T26 to T41.
- 455 4.3.6 Terraces TL6
- These terraces are inferred from seven profiles showing gently shelving surfaces (T3, T11, T14 to T17, T20, and T23) and located at an average depth of  $30.5 \text{ m} \pm 3 \text{ m}$ .
- 459 4.3.7 Terraces TL7
- The deepest terrace recorded is at 38 m, only from T17 and T18. Examining patterns among profiles show similarities and contrasts in the number and width of terraces. In order to determine the number of terraces within a given width range, a frequency histogram was generated (Fig. 9). Among the 112 terraces identified from the 41 profiles, most have widths less than 20 m.
- 467 Furthermore, the width of terraces appears to be partly 468 correlated to the length of profiles (Fig. 10) which is slope-469 gradient dependent. Where profile lengths do not exceed 80 m, 470 most terrace widths are less than 8 m. On profiles as long as 471 100 m–110 m, a number of terraces can be as wide as 15 m to 472 20 m. The profiles longer than 130 m have one-quarter of their 473 terraces, 25 m to 45 m wide.

#### 474 4.4 Pinnacles

475 Steep-sided, high reliefs, found on terraces, were interpretated 476 as isolated pinnacles. These are widepread along gently 477 inclined slopes (profiles T1 to T6), but less common on steeply 478 dipping slopes. Their elevation and diameter range from about 479 2.30 m to 15 m and 2 m to 12 m respectively. However, it is 480 neccessary to remain cautious about inferring the possible 481 lateral extent of a pinnacle line from transects.

482 4.5 Drop-offs, trenchs, and scars

Drop-offs of 11 m to 13 m high are encountered at several shelf 483 484 locations (T13, T19, T21, T26, T27, T32, T37) at different 485 depth ranges, from -9 m to -35 m deep. Trenchs are observed 486 on profiles T24 and T31 (Fig. 5d), in the form of 6 m to 17 m-487 deep indentations, at depths of -6 to -12 m and -12.5 to -29.5488 m respectively. Concave scars, interpreted as collapsed margin 489 portions, are found at the south-eastern side and along the 490 western side of the atoll (Fig. 2a).

491 4.6 Quantitative assessment of coral communities

Living coral cover increases downslope from 24 %–25 % at
depths of -5 m and -10 m to 42 %, 55 %, 67 %, and 50 % at
depths of -15 m, -20 m, -25 m, and -30 m respectively (Table
2, Fig. 11). Robust-branching *Pocillopora* (mainly, *P. verrucosa*) is the dominant genus at the upper fore-reef

497 settings, representing 10 % to 26 % of coral coverage, from 498 -5 m to -10 m deep. At depths of -25 m to -30 m, 499 pocilloporids do not exceed 2 %-4 %. Sub-massive to plate-500 like Porites (P. rus) becomes the prominent coral form from 501 15 m deep, locally covering 50 % to up to 85 % of the 502 substrate. Other scleractinian corals belong to Acropora, 503 Porites cf. lobata, Leptastrea, and Montipora, each of them not 504 exceeding 2 % to 4 % of the total coral cover. It is noteworthy 505 that along steeply dipping slopes and drop-offs, modern coral 506 buildups have significantly re-shaped antecent substrate 507 morphology (Fig. 12)

### 508 **5** Discussion

# 509 5.1 Mode and timing of terrace formation

510 As pointed out by Rovere et al. (2018), in absence of 511 radiochronological constraints, the age and formational patterns 512 of marine terraces remain speculative. However, different 513 possible scenarios for their mode and timing of formation can 514 be discussed, especially since two processes, respectively 515 constructional or erosional, may have been involved in terrace 516 shaping, either prior to the last glacial maximum (-23 ka to 517 -20 ka-interval) over the past 300 ky or afterwards, during the 518 last deglaciation.

519 From a contructional point of view, most submerged terraces520 identified in this study, especially those from gently sloping

521 shelves (profiles T1 to T5, T17, T25, T35) may have developed 522 according to one of the two following models. First, these may 523 result from backstepping of reef bodies developed during the 524 last deglacial rising sea level or previous deglaciation times. In 525 these cases, reef-related terraces would have been generated by 526 punctuated sea-level jump events that have forced reef bodies 527 to drown and backstep upslope through time, rather than 528 develop upwards from a gradual and continuous sea-level rise. 529 Secondly, the terraces may have been shaped during one of 530 high sea-stands that have occurred over the late to mid-531 Pleistocene. In all scenarios, terraces represent the still visible, 532 outermost surfaces of reef edges of former reef tracts.

From an erosional point of view, submerged terraces may result
from marine planation during episodes of slowing in sea-level
rise or stillstands during the last deglaciation. In this scenario,
terraces would be wave-cut platforms, as suggested in the
Maldives for the last deglaciation (Rufin-Soler et al., 2013;
Green et al., 2014).

At Takapoto, as everywhere in French Polynesia, during the post-glacial transgressive phase, sea was at a level corresponding to the deepest isobath recorded in the profiles (-38 m) by -9.5 ka. Sea level continued to rise at a rapid and relatively constant rate of 10 mm  $\cdot$  y<sup>-1</sup> before reaching its present position by about -6 ka (Bard et al., 1996, 2010). Slowly rising sea level is known to provide the much-needed

546	accommodation space for enhanced vertical reef accretion
547	while lateral accretion is dependent of the relative time spent at
548	sea level. According to the mean vertical reef accretion rates
549	(4–5 mm $\cdot$ y <sup>-1</sup> ) estimated for the early Holocene (see Dullo,
550	2005; Montaggioni, 2005; Hubbard and Dullo, 2016; Gischler
551	and Hudson, 2019, for reviews), the rate of sea-level rise was
552	most likely too high to allow coral growth to maintain pace
553	with sea level or to prograde oceanwards. As observed on the
554	mid-shelf slopes at Tahiti (Seard et al., 2013), during the post-
555	glacial transgression, corals have rather built isolated, straight-
556	walled pinnacles or thin veeners covering the Pleistocene
557	antecedent topography than typical, flat-topped fringing reefs.
558	A similar scheme was described from Mayotte Island
559	(Comoros, Western Indian Ocean) by Dullo et al. (1998). By
560	analogy, at Takapoto, the major morphological characteristics
561	of the fore-reef slopes are assumed to dominantly reflect those
562	of the antecedent substrate upon which coral buildups have
563	grown more recently. Accordingly, the core of most terraced
564	structures is probably late to mid Pleistocene in age. The heigth
565	of steps is probably indicative of the thickness of the related
566	reef unit. Additionally, a sea-level rise at the rate of 10 mm $\cdot$ y <sup>-1</sup>
567	appears inappropriate to allow shelf slopes to be abrased or
568	excavated. Similarly, during the penultimate (from MIS 6b to
569	MIS 5e) and oldest (MIS 10 to MIS 9, MIS 8 to MIS 7)
570	deglaciation episodes, sea level rose at rates similar to or higher

571 than those recorded from the last deglaciation (Siddall et al., 572 2007), precluding any significant constructional, abrasional or 573 excavational event to have occurred. Accordingly, the 574 identified terraces and associated reef units were assumed to 575 have formed during high sea stands.

576 Some terraces possess outer crest-like reliefs of 0.5-1.5 m in 577 elevation and 3-6 m in width at the seaward margin (for 578 intance, see Fig. 5a, b). Given their specific location on top of 579 the outermost part of submerged reef edges, these features are 580 interpreted to be isolated coral heads or laterally extending, 581 continuous ridge-like, coralgal buildups developed at 582 windward, high-energy settings during the Holocene course of 583 sea-level. Contrary to most of pinnacles described along the 584 shelf slopes at Takapoto, their upward development would have 585 been drastically interrupted in response to the rapid sea-level 586 rise. In some way, these are « give-up » reefal features in the 587 sense of Neumann and Macintyre (1985). Morphologically 588 speaking, these buildups are similar to windward, high-energy, 589 coralline algal ridges (Adey, 1978, 1986; Montaggioni and 590 Braithwaite, 2009), typical of Pacific atoll rims (Chevalier et 591 al., 1969), particularly at Takapoto (Chevalier et al., 1979; 592 Chevalier and Salvat, 1976). Submerged terraces with raised 593 coralgal ridges at their outer extent are known from a number 594 of Pacific reef sites: Australian Great Barrier Reef (Beaman et 595 al., 2008; Abbey et al., 2011; Webster et al., 2018), Hawaii

(Webster, 2004a) and Papua New Guinea (Webster et al., 2004b, 2009), Ryukyu Islands (Arai et al., 2016) and the Marquesas (Cabioch et al., 2008). These terraces are thought primarily to be remnants of coralgal piles developed at the seaward margins of incipient fringing reefs during the postglacial times, but not capable of keeping pace with rising sea level.

603 At Takapoto, terraces TL2 exhibit locally low, coral-built 604 ridges oriented perpendicular to the reef-edge line and 605 alternating with elongated, sand-filled grooves, similar to 606 spurs-and-groove reliefs (Fig. 11b and Montaggioni, personal 607 observations, 1981). Accordingly, TL2 are regarded as outer-608 reef edge features. By analogy, the terraces identified 609 downslope (TL3 to TL7) may be also interpreted to be 610 remnants of paleo-reef-edge surfaces.

611 Along both gently inclined terraces and shelf slopes, pinnacles 612 are common (for instance, see Fig. 5a–f). These features were 613 also described on a number of submerged tropical shelves, 614 mostly on the Australian Great Barrier Reef where they are 615 usually associated with modern juvenile reefs (Hopley, 1982). 616 According to Abbey et al. (2011), during the last deglaciation, 617 terraces would not be ideal settings for extensive vertical coral 618 accretion, due to their narrowness. Similarly, at Takapoto, 619 during the final course of the rising sea level, from about 620 9.5 ka, and despite the subsequent increase in accommodation

621 space, coral growth was unable to produce, flat-topped,622 aggrading reefs.

# 623 5.2 Faulting and submarine landslides

624 The present data reveal that, at both windward and leeward 625 settings, except in its north extremity and mid-south-east, part 626 the Takapoto rim is bounded by steep fore-reef slopes, with gradients up to 45° or vertical submarine cliffs. There are no 627 628 significant differences in the overall fore-reef morphology 629 between windward and leeward sides of the atoll. The steepest 630 fore-reef slopes were found as well along the western, leeward 631 coast as the eastern, windward one (Figs.4 and 5). This 632 suggests that the swell regime from the east is not the main 633 driver of foreslope evolution.

634 The atoll seaward margins are nearly linear as opposed to most 635 of the curved high volcanic island margins found in the nearby 636 Society and Marquesas archipelagos, thereby suggesting 637 structural failure. Faulting control in shelf shaping is further 638 supported by both the presence of vertical drop-offs, higher 639 than 10 m, and trenchs, 6 m to 17 m deep, cutting through the 640 upper parts of the shelf slopes. The trenchs are considered to be 641 incipient, normal faults. Similar features were reported from 642 Tikehau (Faure and Laboute, 1984), and Moruroa (Chevelier et 643 al., 1969). The overall tectonic evolution of the Tuamotu 644 plateau, appears to be partly driven by extensional processes in

645 relation to major, regional fracture zones. The fault 646 distributional patterns of nearby, high-carbonate Makatea 647 Island (Montaggioni, 1985) are quite similar, oriented in a 648 south-west to north-east (35°N-50°E) direction. It is 649 noteworthy that the lagoons of Takapoto and other atolls of the 650 outer Northern most Tuamotu island-belt (Takaroa, Ahe, 651 Manihi, Raroia, Takume), together with that of southermost 652 Amanu atoll, are aligned according the same direction. These 653 atolls are superimposed upon ridges, that are expected to have 654 been formed from erupting fissures influenced by the 655 underlying lithosphere fractures (Jordahl et al., 2004). The 656 dominant fault system affecting the western and eastern shelf 657 slopes at Takapoto is clearly oriented parallell to the atoll and 658 ridge alignment. By contrast, the island shelves at the north 659 end, which developed outwards at right-angles to the SW-NE 660 fault system, have probably escaped large-scale collapsing, thus 661 explaining their unusual morphology, i.e. large seaward 662 development, high density of pinnacles and lack of high 663 escarpments.

Scars in the normally convex seaward margins of atolls and
reef barriers as well were usually interpretated as resulting from
submarine landslides generated by slope failure (Fairbridge,
1950; Keating, 1987, 1998; Keating and McGuire, 2000; Riyaz
and Park, 2008; Terry and Goff, 2012, 2017; Webster et al.,
2016; Poupardin et al., 2017; Puga-Bernabéu et al., 2017). As

emphazised by Terry and Goff (2017), submarine landslides
can significantly modify gross atoll morphology. In addition,
giant landslides can generate tsunamis (Webster et al., 2016)
and subsequent, partial submersion of atoll rims (Poupardin et
al., 2017). Although rare, especially in the Tuamotu (Sladen et
al. 2017), landslide-generated tsunamis can contribute to atoll
shaping and island formation.

# 677 5.3 Significance of terraces in terms of sea level

678 In absence of a chronological frame, as a first approximation, 679 the submerged terraces identified at Takapoto may refer to 680 higher or lower Pleistocene sea-stands relative to present sea 681 level. Hovewer, over the last 500,000 years, sea level during 682 interstadials and glacial, low stands were systematically at 683 depths greater than -30 m (see Murray-Wallace and 684 Woodroffe, 2014 for reviews), especially at atoll-subsiding 685 sites (Camoin et al., 2001). Accordingly, at Takapoto, all the 686 terrace sets were assumed to refer to interglacial, high-sea 687 stands.

688 Morphological and chronostratigraphical correlations between 689 Takapoto and some other atolls used as reference sites in the 690 Pacific can be attempted to help attributing a given terrace level 691 to a specific highstand. All reference cores used herein were 692 extracted from outer reef-flat settings (Fig. 13).

693	On Moruroa Atoll, there is an upper, gently sloping $(10^{\circ})$
694	terrace, about 60 m wide, extending from about $-4$ m to $-10$ m
695	deep. It is interrupted by a break-in-slope followed by a steeper
696	(25°) mid-shelf topography (Chevalier et al., 1969). Similar
697	morphologies were described from Enewetak and Bikini Atolls,
698	Marshall Islands (Tracey and Ladd, 1974), Tarawa, Gilbert
699	Islands (Marshall and Jacobsen, 1985) and Yongle Atoll, Xisha
700	Islands, South China Sea (Guozhong et al., 1990). The break-
701	in-slope at approximately -10 m deep was regarded as
702	superficially translating the presence of an unconformity, i.e.
703	subaerial exposure surface. This surface is encountered beneath
704	the modern outer reef-flat and reef-edge zones at depths of
705	-10 m to -14 m at Enewetak (Tracey and Ladd, 1974; Lincoln
706	and Schlanger, 1991; Ristvet et al., 1977; Szabo et al., 1985),
707	-8 m to -10 m at Bikini (Emery et al., 1954; Tracey and Ladd,
708	1974), -11 m to -17 m at Tarawa (Marshall and Jacobsen,
709	1985), and -16 m to -17.3 m at Yonge Atoll (Jian et al., 1997).
710	Uranium-series dating of coral material collected above and
711	below this unconformity revealed that this surface separates an
712	overlying Holocene reef unit not older than 9 ka, from a late
713	interglacial (MIS 5e) unit, dated at $-120 \text{ ka} \pm 10 \text{ ka}$ to
714	$-134$ ka $\pm$ 5 ka, as observed in Moruroa, Enewetak, Bikini, and
715	Tarawa (Fig. 13). The thickness of the Holocene reef sequences
716	ranges approximately between 12 m and 17 m. At Takapoto,
717	the uppermost reef unit, spur-shaped, approximates a maximun

718 thickness of 10 m. By analogy with the reference atolls, it is 719 considered to be Holocene in age, probably not older than 9 ka. 720 On the basis of morphological and structural similarities 721 between the upper parts of outer-edge zones among atolls, 722 terraces TL2 were though to be geomorphic analogs of the 723 unconformity surfaces atop of MIS 5e reef units. During the relevant high sea-level episode (-128 ka to -116 ka; Muhs, 724 725 2002), sea level was between 5.5 m to 9 m above psl (Dutton 726 and Lambeck, 2012). Based on statistical modelling, there 727 would have a 95 % confidence level that global sea level, 728 irrespective of local controls, peaked at 6.6 m above psl and a 729 67 % probability that sea level was higher than 8 m above psl 730 during MIS 5e, but it was unlikely to have been higher than 731 9.4 m (Kopp et al., 2009).

732 A second subaerial exposure surface was found in the same 733 reference cores at Moruroa, Enewetak, Bikini and Yongle, at 734 depths of -18 m to -22 m, -22 m to -23 m, -24 m to -27 m, 735 and 30 m respectively (Fig. 13). The reef sequence capped by 736 this surface yielded U-Th ages averaging -215 ka at Moruroa 737 (Camoin et al., 2001) thus indicating that the relevant reefs 738 have developed during the penultimate interglacial (MIS 7) 739 high stand. No date is available from other atoll sites. On these 740 atolls, the depth of the second unconformity relative to psl is 741 locally greater than that of terraces TL3 (14.7 m  $\pm$  3.8 m), but 742 closer to the level of terraces TL4 (20.3 m  $\pm$  2.3 m) and TL 5

743	$(24 \text{ m} \pm 2 \text{ m})$ . It is obvious that attempting to link the terraced
744	surfaces TL3, TL4, and TL5 to MIS 7 substages result in
745	significant uncertainties, in part, induced by differences in local
746	erosional and tectonic patterns (see sections 4 and 5 stage).
747	Among the reference atolls, the total thickness of reef units
748	deposited during the entire MIS 7 stage is similar, varying from
749	11 m to 15 m. At Takapoto, the thickness of the intervals
750	delineated by TL3-TL4, TL4-TL5, and TL5-TL6 range
751	between 5 m and 7 m only. Such thickness values appear to be
752	too low to account for the entire MIS 7 depositional history of
753	Takapoto when compared to other atoll sites and with regard to
754	the thermal subsidence constraints of the atoll (see section 5
755	below). On the contrary, integrating the whole TL3-TL6 depth
756	interval (average = 16 m) provides a greater reliance on
757	depositional patterns for the entire MIS 7 episode in the studied
758	area. Furthermore, while there is often an inability to
759	distinguish one substage to another within the penultimate and
760	older interglacials from cored reef sequences (Camoin et al.,
761	2001; Montaggioni et al., 2015), identification of distinct sea-
762	level pauses from a series of closely stepped terraces seems
763	achievable if assuming that terrace formation is the result of
764	successive backstepping events during successive high-stand
765	substages. Each terrace may correspond to the outer-edge
766	surface of one single backstepped reef tract as observed in a
767	number of reef provinces worldwide (Barbados: Fairbanks,

768	1979; the Marquesas: Cabioch et al., 2008 – Hawaii: Sanborn
769	et al., 2010 - Texas: Khann et al., 2017 - Great Barrier Reef,
770	Australia: Webster et al., 2018). Accordingly, the best
771	interpretative scenarios for TL3, TL4, and TL5 are the
772	following. These terraces may correlate respectively with MIS
773	7a (-201.5 ka to -189.7 ka), MIS 7c highstand (-217.2 ka to
774	-206 ka) and MIS 7e (-248.9 ka to -231 ka) (Figs.13 and 14).

775 Few coastal landforms referring to MIS 9 (-335.6 ka to 776 -316.8 ka), especially in reef provinces, are documented, most 777 likely due to lower preservation potential and reduced 778 accessibility (Murray-Wallace and Woodroffe, 2014). At 779 Moruroa, a third solution unconformity was recognized in 780 vertical cores between 29 m to 32 m below psl. It caps a 7-781 11 m thick, reef unit (Buigues, 1997). This unit is regarded as 782 the lateral equivalent of reef-margin deposits recovered from 783 oblique boreholes and dated at  $-332 \text{ ka} \pm 12 \text{ ka}$  (MIS 9e 784 substage) by Camoin et al., (2001). On Enewetak and Bikini, a 785 third unconformity was penetrated at 36.2-42.5 m (Ristvet et 786 al., 1977; Szabo et al., 1985), and at 49 m below psl (Tracey 787 and Ladd, 1974) respectively. In the latter site, a coral sample 788 from the underlying interval gave an age older than 400 ka, 789 apparently inconsistent with local stratigraphy. To maintain 790 consistency with the overall development history of Takapoto 791 submerged terraces, TL6 are approximated to refer to MIS 9e.

The belonging of terraces TL7 to a given MIS stage is facingconsiderable uncertainty and therefore is not discussed.

# 794 5.4 Effects of subaerial erosion

795 Another prerequisite to define a paleo-relative sea-level 796 position from given terrace levels is quantifying the impact of 797 subaerial erosion on the morphological evolution of terraces 798 during times of emergence. From estimates of the amount of 799 reef rocks destroyed over the last 120 ky, the rates of carbonate 800 ground lowering from some Pacific atolls and reliefs were thought to range between 0.011 mm  $\cdot$  y<sup>-1</sup> and 0.202 mm  $\cdot$  y<sup>-1</sup>, 801 with mean rates of  $0.11 \text{ mm} \cdot \text{y}^{-1}$  (Paulay and McEdward, 802 803 1990). These values are similar to those calculated  $(0.12 \text{ mm} \cdot \text{y}^{-1} \text{ on average})$  by Purdy and Winterer (2001) from 804 805 Enewetak Atoll for the same time span in response to local 806 rainfall regime. Since present-day annual rainfall at Takapoto is around 1500 mm  $\cdot$  y<sup>-1</sup>, quite similar to that recorded at 807 808 Enewetak (Purdy and Winterer, 2001), a mean value of  $0.12 \text{ mm} \cdot \text{y}^{-1}$  is taken as the maximum solution rate during 809 810 Pleistocene low sea stands in the north-western Tuamotu.

#### 811 5.5 Subsidence

812 In the Tuamotu, the thermal sinking rate of the underlying 813 oceanic crust is lower than the usual decaying exponential rate 814 (about 0.32 mm  $\cdot$  y<sup>-1</sup>–0.35 mm  $\cdot$  y<sup>-1</sup>: Menard, 1969; Korenaga

815 and Korenaga, 2008) as a function of increasing age as for most 816 of oceanic volcanic domains (Patriat et al., 2002). The Tuamotu 817 plateau. In relation to its age (47 to 55 million years old), the 818 Tuamotu plateau is considered to be near isostatic equilibrium 819 since it was emplaced (Patriat et al., 2002). Moreover, for the 820 north-western Tuamotu islands, earth dynamic topography 821 models predicted about 2–3 m fall since the last 125 ky, which 822 is included in the subsidence signal (Austermann et al., 2017).

823 Quantitative constraints on the possible rate of subsidence at 824 Takapoto can be provided on the basis of the following 825 assumptions: (1) subsidence is expected to approximate 826 linearity for the past 300 ky; (2) TL2- related reef unit formed 827 during MIS 5e high stand; (3) at that time, sea level peaked at 828 +7 m above psl (Rovere et al., 2016); (4) the rate of sub-aerial erosion averaged 0.12 mm  $\cdot$  y<sup>-1</sup>; (5) the time span during which 829 830 MIS 5e reef was exposed lasted 106.5 ky, from 116 ka to 831 9.5 ka, i.e. from the termination of the MIS 5e substage to the 832 time of re-flooding of the shelf slope from the deepest detected 833 isobath. As a result, the ground lowering of the TL2-related 834 reef pile during emergence can be estimated at around 12 m. If 835 correct, given TL2 is now at about 10 m deep, the subsidence 836 amplitude would be about 5 m. The calculated subsidence rate 837 is 0.047 mm  $\cdot$  y<sup>-1</sup> for the past 125 ky. This rate is in complete accord with that estimated (0.045 mm  $\cdot$  y^{-1}) from Pukapuka 838 839 and Rakahanga Atolls (Gray et al., 1992), the origin of which is
840 linked to the formation of the Manihiki Plateau as old as the 841 Tuamotu basement (Mahoney, 1987). Similar thermal 842 subsidence rates, around  $0.035 \text{ mm} \cdot \text{y}^{-1}$  to  $0.050 \text{ mm} \cdot \text{y}^{-1}$ 843 were inferred from other mid-plate low-lying carbonate islands 844 originated during the early Cenozoic (Schlanger et al., 1987; 845 Quinn, 1991; Gischler et al., 2008).

### 846 5.6 Identification of paleo-relative high sea-levels

847 Paleo-sea-level reconstructions over the last 300 ky were 848 attempted to be achieved on the basis of the vertical 849 distribution of terrace levels at Takapoto (Table 3). The rates of sub-aerial erosion  $(0.12 \text{ mm} \cdot \text{y}^{-1})$  and thermal subsidence 850  $(0.047 \text{ mm} \cdot \text{y}^{-1})$  previously determined were used in the 851 852 calculations, assuming that similar environmental and tectonic 853 conditions have prevailed during all considered high sea stands. 854 The position of a paleosea level at a given high stand (SL) was 855 calculated as follows: SL = S + E - TL where S is the product 856 of the amount of time during which a given terraced-reef tract 857 has subsided and of the subsidence rate, subsidence operating 858 as soon as reef growth has initiated; E is the produit of the 859 amount of time during which a given reef pile has been 860 emerged and undergone ground lowering and of the erosion 861 rate, considering that duration of emergence is the time interval 862 between the termination of a given high stand and the start of 863 the following re-flooding and subsequent overlapping by a new

reef generation. TL is the present depth at which a given terraceis found (Table 3).

866 Terraces TL3, as remains of MIS 7a reef surfaces, would have 867 suffered a ground lowering of 7.40 m and a drowning of 9.50 m 868 since they have formed, resulting in a deepening of -16.90 m 869 relative to their initial position. Based on its present location at 870 an average depth of  $14.70 \text{ m} \pm 3.8 \text{ m}$ , the paleo-sea level is 871 estimated to have been at 2.2 m  $\pm$  3.8 m above psl. Regarding 872 terraces TL4, as referred to MIS 7c, ground-lowering and 873 subsidence amplitudes were assessed to be 1.20 m and 9.60 m 874 respectively. The resultant drop did not exceed 10.80 m while 875 these features are found at present at  $-20.30 \text{ m} \pm 2.3 \text{ m}$ . This 876 means that the related past sea level was at  $9.50 \text{ m} \pm 2.3 \text{ m}$ 877 below psl. Two alternative scenarios can account for the 878 evolutionary history of MIS 7e reefs represented by terraces 879 TL5. In the case where this reef generation was overlapped by 880 younger MIS 7c reefs, the time of emergence has not exceeded 881 11 ky and the thickness of the reef pile released by solution 882 ranged around 1.30 m. If sea level was lower, MIS 7e reefs 883 may have remained exposed over 31 ky. Accordingly, ground 884 lowering of MIS 7e deposits would reach 3.70 m. In both 885 situations, subsidence was 10.30 m. The resulting terrace 886 deepening ranges between 13.0 m and 15.40 m. Given terraces 887 TL5 are now located at a depth of  $-24 \text{ m} \pm 2 \text{ m}$ , the MIS 7e sea 888 level may have been at approximately 11 m or  $8.60 \text{ m} \pm 2 \text{ m}$ 

below psl. The morphological evolution of reefs TL6 is summarized as follows. Sub-aerial erosion would have removed 9.20 m while sinking motion was 15.80 m in amplitude. Finally, terraces TL6 were deepened by 25 m. With respect to their present depth location, the corresponding reef tops were believed to have originally cropped out at a paleo-sea level between 5.80 m  $\pm$  3 m below psl.

896 The sea-level positions derived from fore-reef past 897 morphometry at Takapoto appear to be in good agreement with 898 some predicted on the basis of different proxies in different 899 seas (Fig. 14). Regarding the elevations at which sea level 900 peaked during the MIS 7 substages, reconstructions gave 901 evidence for only two prominent high sea levels, MIS 7a and 902 7e, close to or higher than present, between -12 m and +4 m 903 relative to psl. These findings are based on U/Th dating of 904 speleothems in Bahamian caves (Li et al., 1989; Lundberg and 905 Ford, 1994), open-system uranium-series ages (Thompson et 906 al., 2003; Thompson and Goldstein, 2005) and ESR ages 907 (Schellmann and Radtke, 2004) of corals collected from 908 uplifted reef terraces at Barbados, stratigraphic and radiometric 909 constraints in the Bahamas and Bermuda (Hearty and Kindler, 910 1995), paired Mg/Ca and oxygene isotope measurements of 911 planktonic foraminifera cooled in a core from the Cocos Ridge 912 (Lea et al., 2002), sea water oxygen isotope in the Red Sea 913 (Siddall et al., 2003) and coupling of the Red Sea sea-level

914 signal with Asian monsoon records (Grant et al., 2014). By 915 contrast, past sea-level reconstructions derived from oxygene 916 isotope analysis of speleothems (Bard et al., 2002; Dutton et 917 al., 2009) would indicate that sea level during the MIS 7 stage 918 maintained continuously below psl, at a depth of around -18 m. 919 Similar results, suggesting that paleo-sea level during the 920 penultimate interglacial stage has fluctuated between 10 m and 921 17 m below psl, were gained from the analysis of inclined reef 922 cores at Moruroa (Camoin et al., 2001). During the MIS 9 923 stage, sea level is inferred to have peaked at levels close to 924 present (Siddall et al., 2006; Rohling et al., 2009; Murray-925 Wallace and Woodroffe, 2014).

# 926 5.7 Comparison with the composition of coral communities I 927 in some other Tuamotu and Pacific atolls

928 Compositional and distributional patterns of corals along outer-929 reef slopes from atolls, are known to be controlled, not only by 930 bathymetry and water agitation, but also by reef orientation, 931 and slope gradient (Wells, 1956; Kühlmann, 1982; Bouchon, 932 1983; Faure and Laboute, 1984; Laboute, 1985; Kühlmann and 933 Chevalier, 1986; Maragos, 1994). At Takapoto, as observed in 934 both windward and leeward sides, Pocillopora remains 935 dominating within the upper -10 m to -15 m along gently 936 sloping spurs (TL1), and terraces TL2, while Porites achieves 937 prominence from -15 m to -30 m, along steeper to sub-vertical 938 slopes (Bouchon, 1983; Kühlmann and Chevalier, 1986).
939 Similar trends were reported from the nearby Tikehau Atoll
940 (Faure and Laboute, 1984).

941 Coral cover rates from other Pacific atolls are poorly 942 documented (Wells, 1954; Maragos, 1994). The only detailed, 943 quantitative coral censuses of seaward outer margins were 944 carried out on Mili and Rongelap Atolls (Marshall Islands, 945 central Pacific) at different depths between -5 m and -20 m 946 (Pinca et al., 2006). Porites is by far the most abundant genus 947 (14-62 %) in both leeward and windward sites. Surprisingly, 948 robust branching Pocillopora, 12 % to up to 20 % in cover 949 rates, are restricted to lagoons, apparently missing from open-950 sea environments. By contrast, on some other Marshall Islands 951 (Bikini, northern atolls), as on Takapoto, Pocillopora species 952 are amongst the most common outer-reef dwellers, especially 953 in the upper fore-reef parts (Wells, 1954; Maragos, 1994). 954 These observations indicate there can have marked, within-955 region to inter-regional differences in coral composition, 956 maybe due to. competitive interactions between coral groups 957 (Lenihan et al., 2011). Anyway, in the study areas, coral 958 growths contribute intensively to shaping of upper fore-reef 959 slopes to depths greater than 40 m.

960 The present study confirmed the reliability of robust-branching
961 *Pocillopora verrucosa* as a relative sea-level marker as
962 previously demonstrated in some Indo-Pacific reef sites

963 (Montaggioni and Faure, 1997; Montaggioni et al., 1997;
964 Cabioch et al., 1999; Camoin et al., 2001). Composite *P*.
965 *verrucosa*-dominated frameworks appeared to be restricted to
966 the 0–10 m depth range.

#### 967 6 Conclusions

968 Detailed geomorphological analysis of satellite-based 969 bathymetric profiles obtained from fore-reef zones all around 970 Takapoto Atoll, using spaceborne imagery, together with direct 971 underwater observations of fine-scale geomorphic features and 972 coral community composition, allows the following 973 conclusions to be drawn.

974 1. Six distinct fore-reef sectors were delineated based on 975 seaward extension to the detected slope depths and 976 mean slope gradients. The lowest gradient ( $< 30^{\circ}-35^{\circ}$ ) 977 and most extended (close to 200 m) sectors are situated 978 at the northern atoll end and along a short portion of the 979 mid-south-eastern side. It exhibits wide terraces and 980 low steps. The north-eastern sector displays highest 981 gradient (68° on average) and narrowest (90 m) slopes 982 and narrow terraces. The remaining eastern and north-983 western sectors, together with south-western and 984 southern ends have steep slopes ( $52^{\circ}$  to  $57^{\circ}$  on average), extending seawards over 90 m to 100 m on average, 985 986 with narrow terraces and high steps.

2. Among the described geomorphic features, of specific
988 interest are terraces, outer-reef crest-like reliefs
pinnacles, steps and drop-offs, scars and trenches to
reconstruct the development history of fore-reef zones.
991 Seven levels of submerged terraces were identified a
depths averaging -5 m, -10 m, -15 m, -20 m, -24 m
-30.5 m, and -38 m respectively. These range from
about 45 m to 2 m in width. The shallowest terrace level
refers to the present-day surfaces of spurs. In lack of
any radiometric dating, the deeper terrace levels were
postulated to be remnants of a series of Pleistocene reel
998 tracts, severely altered by sub-aerial erosion during
periods of emergence, and finally overlapped by cora
veneers during the post-glacial marine transgression
001 from about 9.5 ky to present. This scenario is in great
part based on comparisons with subsurface reet
003 chronostratigraphy from several Pacific atolls. The rates
004 of sub-aerial erosion and linear subsidence were
005 estimated at $0.12 \text{ mm} \cdot \text{y}^{-1}$ and $0.047 \text{ mm} \cdot \text{y}^{-2}$
respectively from comparisons with calculated surface
lowering of Pacific atolls and usually accepted sea-leve
position at 125 ka. After depth correction of ground
lowering and of subsidence effects, the interglacial high
sea-stands during which each reef tract has formed and
011 the position of the corresponding sea level were

- 1012 tentatively defined. The 10-m, 14.5m, 20-m, 24-m and
  1013 30.5-m terraces were expected to relate to the MIS 5e,
  1014 7a, 7c, 7e and 9e respectively, despite substantial
  1015 uncertainties on elevation estimates.
- 1016Outer reef crest-like features, less than 2 m high, occur1017frequently at the seaward edge of terraces. Similarly,1018steep-walled pinnacles are commun at different places1019and depths on terraces and slopes. Both were considered1020to be remains of coralgal buildups, unable to1021compensate with the post-glacial sea-level rise.
- 1022 Steps and drop-offs, a few metres to more than 15 m 1023 high, are presumably remains of the foreslopes of pre-1024 existing reef tracts or preserved scars of partially 1025 collapsed fore-reef slopes. Trenchs cutting the fore-reef 1026 zone were found locally and represent detachment 1027 fissures. The faces of the western and eastern fore-reef 1028 slopes are aligned in south-west to north-east direction, 1029 consistent with the main axis orientation of the atoll. 1030 This direction is that of atoll-bearing, submarine 1031 volcanic ridges discovered in the north-western part of 1032 the Tuamotu plateau, generated from and shaped by 1033 underlying lithospheric fractures.
- 1034 3. Compositional and distributional patterns of coral
  1035 populations at the study site are in agreement with
  1036 previous investigations in the Tuamotu atolls. Robust

1037 branching *Pocillopora* forms appear to be the main 1038 builders on the uppermost, gently dipping parts of fore-1039 reef zones, to the depth of about 10 m. This explains 1040 why this species is regarded as diagnostic in terms of 1041 paleo-bathymetry reconstruction. Pocilloporids are 1042 replaced by sub-massive to plate-shaped Porites, 1043 profusely growing from -15 m to -35 m deep at least. 1044 Concerning biogeographic distribution of corals across 1045 the central Pacific, there are noticeable differences 1046 between the Marshall and Tuamotu islands, probably 1047 controlled mainly by local ecological constraints. 1048 However, along upper fore-reef zones, coral growths 1049 appear to play a key role in controlling superficial 1050 morphogenesis.

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#### **1562 7 Table captions**

**Table 1.** Geomorphic features identified along the fore-reefslopes of Takapoto Atoll.

1565 **Table 2.** Coral cover rate at different depths along fore-reef

1566 slopes (-5 m, -10 m, -15 m, -20 m, -25 m, and -30 m), south

1567 end, Fakatopatere area, Takapoto Atoll.

**Table 3.** Depth distribution of terrace levels (TL3 to TL6)
identified from fore-reef slopes at Takapoto Atoll, and
interpreted in terms of paleo-sea level positions.

1571 The following parameters are given: time duration (ky) of MIS 1572 substage; duration (ky) during which terraces were exposed to 1573 sub-aerial erosion; time at which terraces were re-fooded by 1574 sea-level rise (ka); amplitude of subsidence and ground 1575 lowering (metres); resulting deepening (metres) of terraces; 1576 interpretative eustatic paleo-high sea stands.

## 1577 8 Figure captions

- 1578 **Fig. 1.** (a) Location map of Takapoto Atoll in the Tuamotu
- 1579 Archipelago (French Polynesia, Central Pacific). (b)
- 1580 Bathymetric and structural map of the northern area of the
- 1581 Tuamotu Plateau. Are specifically indicated the location of
- 1582 atolls (Manihi, Takaroa, Ahe, Raroia, Takume) whose major
- 1583 axis of elongation is oriented south-west-north-east, consistent
- 1584 with that of Takapoto and a number of nearby submarine

- 1585 volcanic ridges (SVR). Background map from Google Earth1586 Pro
- Fig. 2. Google Earth Pro aerial maps of Takapoto Atoll. (a)
  Location of water-depth sounding tracks along the eastern outer
  margin of the atoll and landslide-related scars. (b) Location of
  satellite-derived bathymetric profiles (T1 to T41) around the
  atoll fore-reef slope, running from the modern outer reef crest
  to the deepest detected toe. Colors refer to profile length.
- 1593 Fig. 3. Virtual bathymetric profile showing the different
- 1594 geomorphic features identified along the fore-reef slopes at
- 1595 Takapoto.
- 1596 Fig. 4. Plots of bathymetric profiles from the six fore-reef
- 1597 sectors delineated around the atoll, on the basis of profile
- 1598 length and gradient. See figure 2b for location of profiles.
- 1599 Fig. 5. Selected bathymetric profiles from each delineated fore-

1600 reef sector showing local geomorphic attributes. See figure 2b

1601 for location of profiles.

1602 Fig. 6. 3-D reconstruction of a portion of the WSW side at 1603 Takapoto Atoll, based on satellite imagery surveys. The image 1604 portion is lying between the profiles T26 and T27 – see figure 1605 2b for location of profiles. Successively, from inland 1606 oceanwards are shown: the atoll island, the reef flat zone 1607 bounded outwards by an algal ridge, the spur-and-groove

1608	system (terrace TL1), two identified terrace lines, TL2 and
1609	TL3, respectively at depths of about $-10 \text{ m}$ and $-14 \text{ m}$ , an
1610	expected terrace line TL4, at about -20 m ending into a drop-
1611	off about 15 m high.

1612 **Fig. 7.** Depth location of terraces identified from each

1613 bathymetric profile along the fore-reef slopes at Takapoto. A

total of 112 individual terraces, including 96 well-defined and

1615 16 expected, were counted. These are distributed among 7

1616 terrace levels, at recurrent depths of about -5 m, -10 m, -15 m,

1617 –20 m, –24 m, –30.5 m, and –38 m.

1618 **Fig. 8.** Google Earth Pro aerial view of a portion of the eastern

atoll margin, showing from the rim seawards, the outer reef-flat

1620 zone, algal reef crest, spur-and-groove system (terrace TL1),

1621 gently dipping terrace TL2 abruptly ending into dark waters.

1622 Fig. 9. Relative frequency and percentage of terraces plotted by

- 1623 width range, and calculated from 112 terraces identified from
- 1624 levels TL 2 to TL7.

1625 The histogram is left-skewed, expressing high frequency of

1626 terraces less than 15 m wide.

1627 Fig. 10. Plot of terrace width as a function of the detected1628 length of bathymetric profiles.

1629 Are plotted 112 terraces identified from levels TL2 to TL7.

- 1630 Fig. 11. Close-up pictures of coral communities at different
- 1631 depths from -5 m to -30 m, fore-reef slope, Fakatopatere area,
- south end of Takapoto.
- 1633 (a) –5 m depth: spur surface partly covered by robust branching
- 1634 Pocillopora (P. verrucosa).
- 1635 (b) -10 m depth: terrace colonized by coral head mostly
- 1636 composed of Pocillopora verrucosa, together with some
- 1637 branching, cluster-like *Pocillopora elegans*.
- 1638 (c) -15 m depth: up to 1 m, thick coral cover, mainly composed
- 1639 of plate-shaped to encrusting colonies of *Porites rus*.
- 1640 (d) -20 m depth: coral patch dominated by plate-like *Porites*
- 1641 *rus*.
- 1642 (e) and (f): -25 m and -30 m deep: drop-offs densely encrusted
- 1643 by plate-like *Porites rus*.
- 1644 **Fig. 12.** Wide-angle view of drop-offs between -28 m and
- 1645 –32 m, showing dense cover of *Porites rus*.
- 1646 Fig. 13. Depth ranges of terrace levels (TL1 to TL6) identified
- 1647 from fore-reef slopes at Takapoto, compared with stratigraphic
- 1648 position of surface unconformities in interpretative core
- 1649 sections from Moruroa, Enewetak, Bikini, Tarawa, and Yongle
- atolls. Absolute dates are indicated locally on the right side of
- 1651 Moruroa, Enewetak, and Tarawa cores.

- 1652 Fig. 14. Eustatic sea level curve for the last 350 ky (from Grant
- 1653 et al., 2014) with position of terrace levels (TL1 to TL6)
- 1654 identified from fore-reef slopes at Takapoto.
- 1655 Symbols for terrace levels: red coloured = present-day depth
- 1656 range; green coloured = former depth range after correction of
- 1657 subsidence and ground lowering.
- 1658 Correspondance between terrace levels and marine isotope
- 1659 stages: TL1 = MIS 1; TL2 = MIS 5e; TL3 = MIS 7a;
- 1660 TL4 = MIS 7c; TL5 = MIS 7e; TL6 = MIS 9e.

MARQUESAS ISLANDS a 10°S South Pacific Ocean TUAMOTU ISLANDS water Takapoto Rangiroa SOCIETY ISLANDS Noorea . Tahiti Ànaa Hao 20°S AUSTRAL ISLANDS GAMBIER ISLANDS Mangareva FRENCH POLYNESIA 150°W 140°W 200 km b STR SVR SVR Manihi Takaroa SVR Ahe Takapoto Mataiva Tikehau Takume Tuamotu Plateau Raroia 100 km



Lenght of fore-reef slopes (metres)










Reef flat	Algal reef Spur-and-groove crest system – TL1	TL2	Shelf slope
	Cart I		
	~		
145913132 63W			
14°41'51.06S			
0			
70.			
Ph. State			N
1 - Company			茶
			20 m













Marine isotope stages

Terrace levels

☐ Present depth location

☐ Initial depth location (after corrections for subsidence and ground-lowering)

Types	Definitions
Fore-reef zone	the area extending from the seaward margin of the atoll rim to the deepest detected isobath
Shelf slope	the area extending beyond the lowest limits of the spur-and-groove system $(-10 \text{ m deep on average})$ to the deepest detected isobaths
Reef edge	the outermost, top part of a reef tract
Spur-and-groove system	the uppermost part of a fore-reef zone formed by a series of parallel, linear ridges (spurs) alternating with narrow channels (grooves), oriented perpendicular to the reef-crest line and extending down to average depths of $-10$ m
Terrace	a relatively flat-topped or gently dipping surface, which is bounded seawards by a steeper descending slope or step and inwards by a steeper ascending slope
Outer-reef crest like-relief	about 1 m-high, strictly located to the seaward outer margin of a reef tract or terrace
Drop-off	a relatively high (up to 10 m), vertical surface facing the open sea
Step	a low (less than 10 m), steeply inclined to vertical surface, and usually located at the seaward end of a terrace
Pinnacle	an isolated, composite, tower-shaped relief up to 2 m high, both terraces and slopes
Coral head	a relief less than 2 m high, occasionally composed of one single large colonies, but usually composite in nature, located at different places on terraces and slopes
Trench	narrow, vertical cut deeply dissecting the fore-reef zone
Scar	bight-shaped indentations along the outer reef margin

Protogr	APPA HUMBER	.cropord	ephostren N	Jonipora P	ocilloporte Porites St	- hassive forms	orites rus	Sted Hime	on Programs
5M-01			2	22				24	
5M-02			2	22				24	
5M-06			4	22	2			26	24
5IVI-13		4		20		6		22	24
10M 04		4	2	14 20	4	U	2	20 24	
101v1-04 10M_07			Z	20	4	Q	Δ	24 22	
10M-11				26	4	0		22	25
15M-00	2			6		12		20	25
15M-01	2			6		46		20 52	
15M-03				10	2	48		60	
15M-16		2		14	4	14		34	42
20M-00				4	30	26	2	62	
20M-05				6		26	4	36	
20M-07				8	2	38		48	
20M-09				6		68		74	55
25M-00				4		50		54	
25M-01				4		70	6	80	
25M-04						88		88	
25M-06				2		44		46	67
30M-00						82		82	
30M-01				2		60		62	
30M-05				2		16	2	20	
30M-09				2		32	2	36	50



Terrace levels	Present depth (m)	Expected MIS stages	Time duration (ky)	Reflooding time (ka)	duration of emergence (ky)	Amplitude of ground lowering (m)	Amplitude of subsidence (m)	Deepening of terraces (m)	Past sea-level elevation (m)
TL3	$14.7\pm3.8$	7a	-201.5 to -189.7	128	61.7	7.4	9.5	16.9	$2.0 \pm 3.8$ apsl
TL4	$20.3\pm2.3$	7c	-217.2 to -206.0	196	10.0	1.2	9.6	10.8	$9.5 \pm 2.3$ bpsl
TL5 24.0 ±	$240 \pm 20$	$0 \pm 2.0$ 7e	-248.9 to -231.0	(1) 220	11.0	1.3	11.7	13.0	$11.0 \pm 2.0$ bpsl
	$24.0 \pm 2.0$			(2) 200	31.0	3.7	11.7	15.4	$8.6 \pm 2.0 \text{ bpsl}$
TL6	$30.5\pm3.0$	9	-335.6 to -316.8	240	76.8	9.2	15.8	25.0	$5.5\pm3.0$
Rate of sub-aerial erosion = 0.12 mm/y Rate of subsidence = 0.047 mm/y			<ul><li>(1) MIS 7e reef overlapped by MIS 7c reef</li><li>(2) No overlapping</li></ul>			apsl : above present sea-level bpsl : below present sea-level			