



HAL
open science

Atoll islets reshaping processes induced by extreme cyclonic waves and calm weather. Evidence from two centuries of megablocks emergences and coral rubble displacements in Anaa, Rangiroa and Tikehau atolls (western Tuamotu archipelago - French Polynesia)

Remy Canavesio, Olivier Cohen, Edwige Pons-Branchu, Stephane Costa

► **To cite this version:**

Remy Canavesio, Olivier Cohen, Edwige Pons-Branchu, Stephane Costa. Atoll islets reshaping processes induced by extreme cyclonic waves and calm weather. Evidence from two centuries of megablocks emergences and coral rubble displacements in Anaa, Rangiroa and Tikehau atolls (western Tuamotu archipelago - French Polynesia). *Marine Geology*, 2023, 464, pp.107140. 10.1016/j.margeo.2023.107140 . hal-04198673

HAL Id: hal-04198673

<https://hal.science/hal-04198673v1>

Submitted on 13 Jan 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

1 **Atoll islets reshaping processes induced by extreme cyclonic waves and calm weather.**
2 **Evidence from two centuries of megablocks emergences and coral rubble displacements**
3 **in Anaa, Rangiroa and Tikehau atolls (western Tuamotu archipelago - French**
4 **Polynesia).**

5
6
7
8 **Communicating and first author:**

9 Canavesio Remy (remycanavesio@hotmail.fr)

10 Affiliations and adress:

11 CNRS-LETG Caen – Geophen (UMR 6564). Université de Caen Normandie (France)

12 CRIOBE CNRS-EPHE (USR 3278) Moorea 98729 (French Polynesia)

13 EASTCO. Université de la Polynésie française (French Polynesia)

14
15 **Other authors:**

16 Cohen Olivier (olivier.cohen@univ-littoral.fr)

17 Affiliations and adress:

18 Université du Littoral Côte d’Opale, Laboratoire d’Océanologie et de Géosciences, UMR

19 CNRS 8187 CNRS-ULille-ULCO-IRD, Av. Foch, 62930 Wimereux, France.

20
21 Pons-Branchu Edwige (edwige.pons-branchu@lsce.ipsl.fr)

22 Affiliations and adress:

23 LSCE/IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, 91198 Gif Sur Yvette (France)

24
25 Costa Stephane (stephane.costa@unicaen.fr)

26 Affiliations and adress:

27 Normandie Univ, UNICAEN, CNRS, IDEES, 14000 Caen, (France)

28
29
30 **Keywords**

31 Coral boulders – Storm surge – Tropical cyclone – Atoll rim – South Pacific – Megablocks

32
33 **Abstract**

34 Understanding the islets morphodynamics of polynesian atolls requires a study of their
35 evolution over several decades. These low-lying islands are exposed to highly variable
36 ocean/weather conditions, especially high energy events. This study is based on a diachronic
37 analysis of aerial photographs, in the field measurements and the U/Th dating of megablocks
38 in three atolls in the western part of the Tuamotu archipelago. It presents an investigation of
39 these dynamics from the 19th century until now. This period makes it possible to record the
40 movements of sediments accumulated during decades of calm weather but also to observe the
41 impact of moderate cyclones such as that of 1983. This article also highlights that exceptional
42 cyclones such as those of 1822 and 1906 can dislocate the coral reef and move up the famous
43 Rangiroa megablock whose volume has been significantly refined by photogrammetry at 369
44 m³. In Rangiroa and Anaa, we have identified three blocks weighting more than 500 tons that
45 were put in place by these cyclones.

1. Introduction

51 The morphology of the atolls is now well documented and their relative homogeneity among
52 archipelagos has made it possible to produce general descriptions that are valid on a global
53 scale (e.g. Hosking, 1991; Woodroffe and Biribo, 2011; Kench, 2014).

54 Alternatively the atoll morphodynamics remain poorly known despite the recent progress in
55 understanding their evolutionary patterns whether during the long period of their
56 establishment (Woodroffe & Biribo, 2011; Montaggioni et al., 2022) or in the contemporary
57 context of climate change (Duvat, 2019). The gradual rise in sea level and the expected
58 changes in tropical cyclones activity (Shaw et al., 2016) make this issue particularly
59 interesting for ecosystems and societies.

60 As modelling is still struggling to convincingly reproduce the interactions between the
61 components of this system to predict its evolution, we have decided to look back in time. As
62 extreme events have a specific impact on the islands (e.g. Stoddart and Walsh, 1992), we aim
63 to clearly distinguish the geomorphological dynamics produced by calm weather-marine
64 conditions from those produced by cyclones. In this paper, we focus on the displacement of
65 coral material in the western atolls of the Tuamotu archipelago (French Polynesia) during
66 recent decades both under normal (low energy) marine and weather conditions and during
67 High Energy Marine Inundations (HEMIs) caused by cyclones or tsunamis. In the coastal
68 environment, many geomorphological structures (ridges, megablocks etc.) result from
69 interactions with the ocean. Weather and sea conditions have a direct influence on these
70 structures. For example, on coral islands, the presence of megablocks on the reef flat is
71 interpreted as an evidence of the occurrence of at least one major HEMI in the past. The study
72 of these megablocks in coral environments (Bourrouilh and Talandier, 1985; Harmelin-
73 Vivien, 1994; Nott, 2001; Goff et al., 2004; Hyvernaud, 2009; Goto et al., 2009; Frohlich et
74 al., 2009; Goto et al., 2010; Etienne et al., 2011; Engel and May, 2012; Terry et al., 2013;
75 Gienko and Terry, 2014; Terry and Goff, 2014; Terry and Etienne, 2014; Etienne et al., 2014;
76 May et al., 2015; Terry et al., 2016; Lau et al., 2016; Canavesio et al., 2018) offers many
77 opportunities to identify the HEMIs of the past, when neither aerial photographs nor historical
78 archives were available. It is possible to determine the nature (cyclone or tsunami) of the
79 HEMI by studying the arrangement of the blocks on the reef (Goff et al., 2004; Frohlich et al.,
80 2009; Goto et al., 2010). The intensity of the HEMIs can also be inferred from the size of
81 these blocks (Goto et al., 2009; Etienne et al., 2014; May et al., 2015) which can be now
82 precisely estimated using photogrammetry (Gienko and Terry, 2014). Finally, the age of the
83 HEMI can be estimated by dating coral samples collected from these blocks (Lau et al., 2016;
84 Terry et al., 2016; Canavesio et al., 2018).

85 From a climatic perspective, the northwestern atolls of the Tuamotu archipelago are
86 homogeneous (Larrue and Chiron, 2010). They were the most impacted of all French
87 Polynesia by the intense 1983 tropical cyclones (Dupont, 1984; Bourrouilh and Talandier,
88 1985) and they have been mostly spared from extreme events since that time (Fig. 1). This
89 cyclone history makes it possible to analyse both the sedimentary transfers induced by a brief
90 intense event, but also to record the morphological changes accumulated over the last four
91 decades devoid of HEMIs.

92 In addition, the atolls of Anaa, Tikehau and Rangiroa are known to host coral blocks of
93 exceptional size on their north to northwest coasts whose origin has long remained
94 mysterious, (e.g. Messenger of Tahiti, 1854; Bourrouilh and Talandier, 1985; Hyvernaud,
95 2009; Etienne et al., 2014). These stretches of coast are the study sites of this paper where we
96 aim to (1) demonstrate that cyclonic HEMIs are -by far- the most important drive of atoll islet
97 reshaping; (2) reconstruct the main features of the morphoclimatic history of these islands

98 over the last two centuries; (3) identify how megablocks whose volume was supposed (e.g. ;
99 Bourrouilh and Talandier, 1985; Etienne et al., 2014) to exceeds 200 m³ (about 500 tons) are
100 placed on a reef ”.

101

102

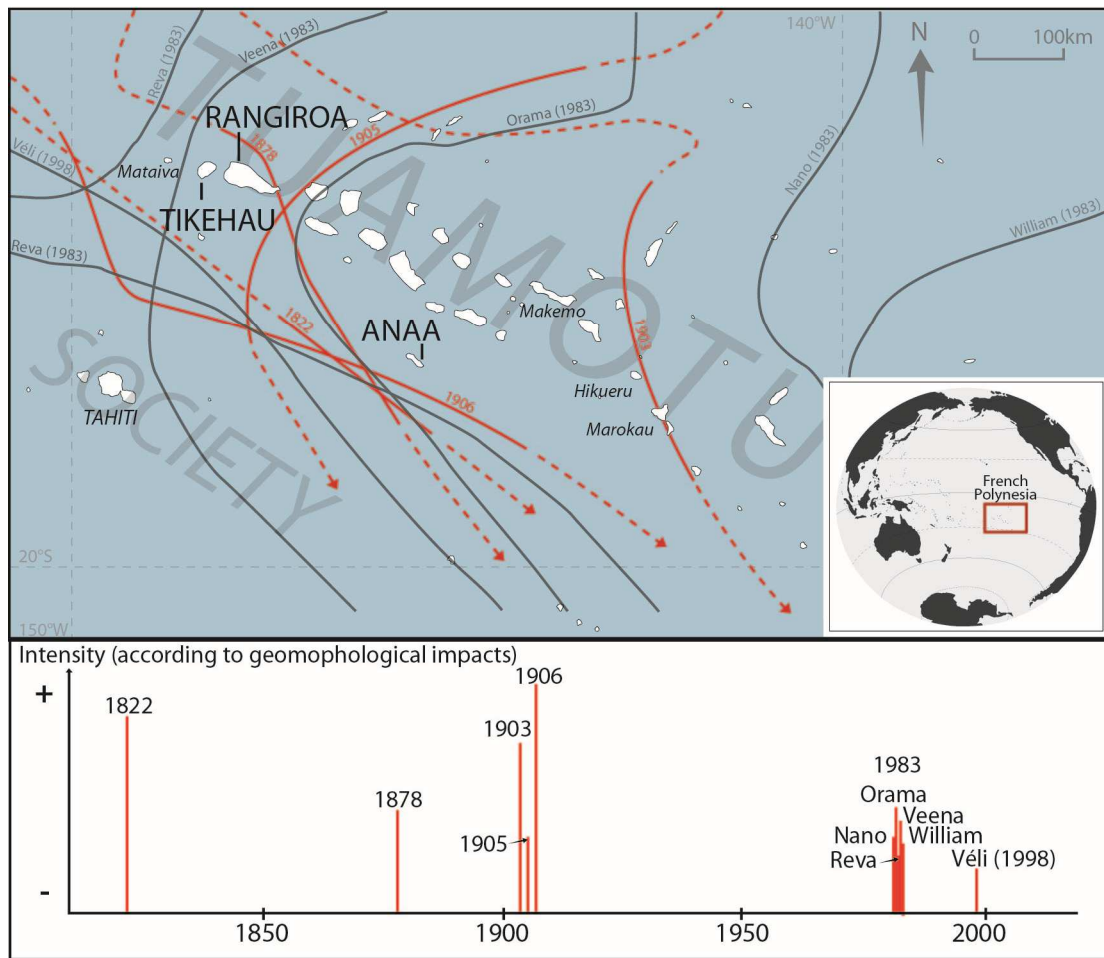
103

104 **2. Study areas and environmental settings**

105

106 **2.1. Study areas**

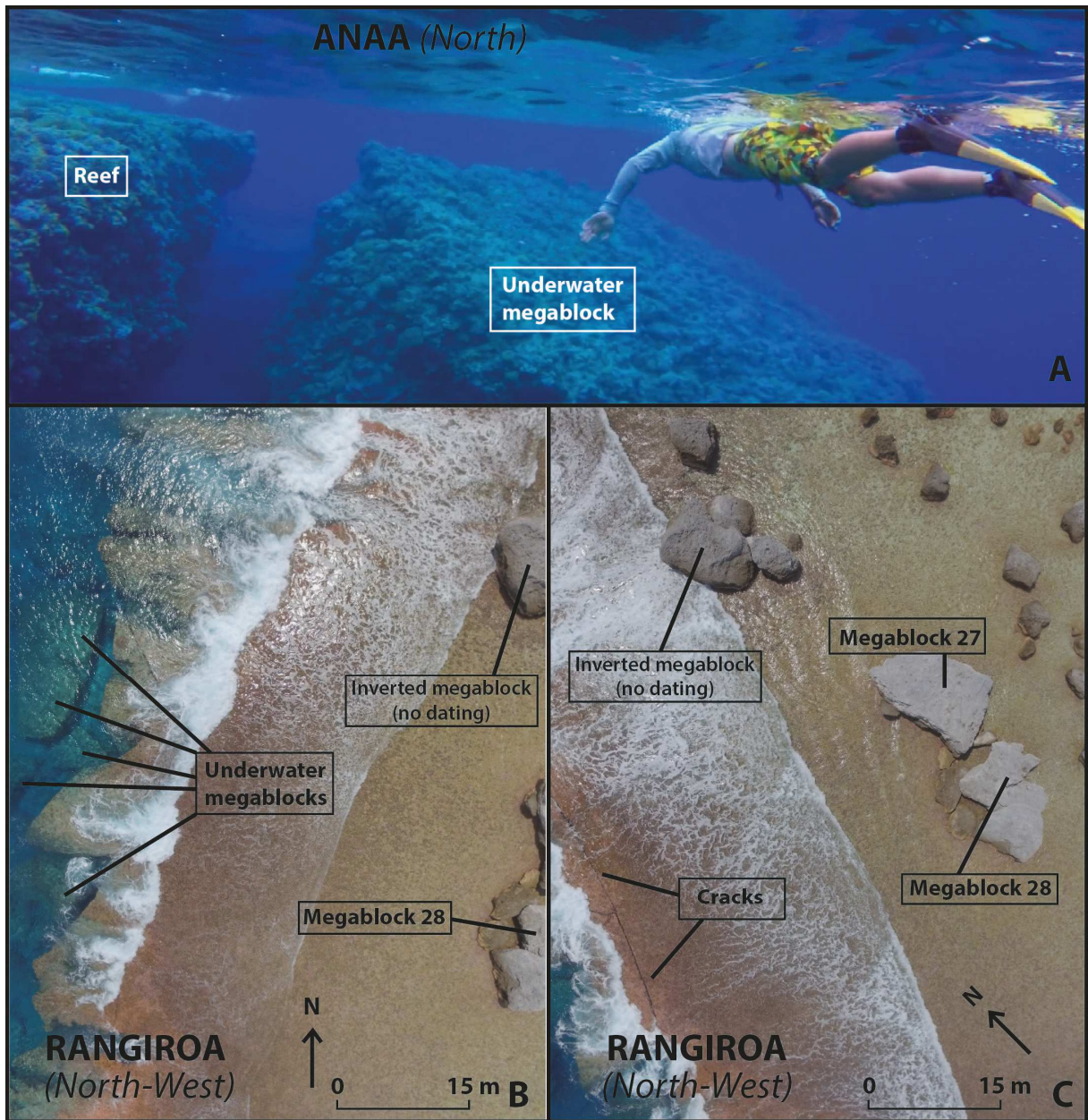
107 The Anaa, Rangiroa and Tikehau atolls are located in the northwestern part of the Tuamotu
108 archipelago, approximately 200 km northeast (Rangiroa and Tikehau) or east (Anaa) of Tahiti
109 (Fig. 1). These atolls are mostly between 1 and 5 meters above sea level, locally reaching a
110 maximum elevation of 12 m. The lagoons are 35 m to 55 m deep at Rangiroa and Tikehau
111 (Montaggioni et al., 2022) but only 3 m to 10 m deep at Anaa (personal observations). The
112 lagoons of Tikehau and Rangiroa are connected to the ocean by passes and many shallow
113 channels on the eastern, northern and western sectors. These passes and channels slow down
114 the filling of the lagoon induce by large distant swells coming from south or southwest
115 (Canavesio, 2019). Alternatively, the Anaa’s lagoon is devoid of passes and only connected to
116 the ocean by few shallow channels in the northern and northeastern sectors, but is partially
117 opened on the southern sector. For these reasons, Anaa’s lagoon is more affected by water
118 filling and with a water level higher than the oceanic level, even during usual swell
119 conditions. Since the average amplitude of the tides is 0.20 m (max 0.50 m) (Montaggioni et
120 al., 2022), lagoon water filling induced by swell is the main driver of lagoon level.
121



122
 123
 124
 125
 126
 127
 128
 129
 130
 131
 132
 133
 134
 135
 136
 137
 138
 139
 140
 141
 142
 143
 144

Fig. 1: Location of the study areas, trajectories of historical tropical cyclones (adapted from Canavesio, et al., 2018). Black lines are used for cyclones that occurred since satellite observations. Red lines are used for cyclones that occurred between 1822 and 1978. Old cyclones trajectories and intensity have been identified using crossed observations (coming from different islands) mainly found in archives and one the field. When the path was not precisely defined, it is shown in dashed lines.

Tikehau and Rangiroa have thinner reef rim (300 to 600 m) than Anaa where the reef rim can be more than 1500 m wide. In the northern sector of Rangiroa, reef rim can locally reach 1000 m. In the areas studied at Rangiroa and Tikehau (Fig. 1), islets have settled on quiet large atoll-rim surfaces. These islets are based on a cemented conglomerate platform covered with coral rubble and sand (planted with coconut trees). In the Anaa area studied, the cemented conglomerate platform is more fragmented and the vegetation is mainly composed of sparse endemic plants. The outer part of the atoll rim consists of an 80 to 150 m wide reef-flat zone scattered with a few to numerous coral boulders. As already demonstrated in the case of the northwest coast of Rangiroa (Bourrouilh and Talandier, 1985; Etienne et al., 2014) and Anaa (Etienne et al., 2014), the source of these megablocks is the upper fore-reef zone. Scuba diving surveys of the northwestern sectors of Anaa and Rangiroa (Fig. 2) revealed that the dislocated fore-reef zone (from 30 to 7 meters below sea level) was sprinkled of coral boulders of equal -to even larger- size.



145
146

147 Fig. 2: Dislocated upper fore-reef zone in the northwest of Anaa (A) and Rangiroa (B & C).
 148 On the underwater view of Anaa a seven meters deep crack separate the remaining reef (left)
 149 from a partially tilted megablock of several hundred cubic meters (right) (picture of Jacques
 150 Navarro-Rovira, November 2018). The UAV aerial photographs of the upper fore-reef of
 151 Rangiroa (northwestern area) show the dislocation of the reef and underwater megablocks
 152 (B). On picture “C”, linear narrow cracks are visible in the reef, about 60 meters seaward
 153 from boulder 27 (pictures “B” and “C”, R. Canavesio, April 2019). This is the first stage of
 154 the creation of new megablocks.

155
156
157

2.2. Environmental and climatic settings

158 In the Tuamotu archipelago, HEMIs are known to produce significant shore reshaping,
 159 including deposition and/or reworking of coral rubble ridges, changes in the location of sandy
 160 beaches and sometimes emergence or displacement of large coral boulders (e.g.; Dupont,

161 1984; Ricard, 1985; Harmelin-Vivien 1994). In this region of French Polynesia, tropical
162 cyclones are the most energetic source of HEMI (except hypothetical local tsunamis caused
163 by submarine landslides) as recent and historical far-field tsunamis are known to have
164 generated only low-amplitude (1–2 m-high) ocean elevation (Sladen et al., 2007).

165 In order to identify the HEMIs that impacted the west of the archipelago and to highlight
166 islets reshaping processes induced by both HEMIs and the usual oceanographic and
167 meteorological conditions, we combined the analysis of megablocks with the diachronic
168 analysis of aerial and satellite imagery. The Polynesian archives of Tahiti and the French
169 colonial archives located in Aix-en-Provence (France), were previously investigated to
170 identify the atolls offering the best potential for analysis.

171 This preliminary work allowed to determine the consequences of 1878, 1903, 1905 and 1906
172 cyclones. Cyclones of 1878 and 1905 appear to have generated rough but not exceptional
173 marine weather conditions. Conversely, the cyclone of 1903 has been shown to be the origin
174 of the deposition of large megablocks (up to 100 m³) on the Hikueru and Marokau flat
175 (Canavesio et al., 2018). But at the archipelago scale, the cyclone of 1906 appeared to be even
176 stronger due to its high speed of movement (up to 60 km/h) which led to amplification of the
177 swell (Canavesio, 2014) and despite a medium atmospheric intensity (the pressure was
178 measured by a vessel in the eye at 953 hPa when the 1906 cyclone was in the vicinity of
179 Anaa). According to us, it would be the one with the greatest capacity to generate a
180 catastrophic HEMI since the mid-nineteenth century.

181 In previously published papers, the death of 95 inhabitants during the submersion of Anaa in
182 1906 was linked with a huge swell whose significant height (Hs) was estimated between 15.5
183 m and 18.5 m (Canavesio, 2014), much higher than the known maximum in "recent" period
184 (modelled at 12 m -Orama- in 1983 at Anaa, Lecacheux et al., 2013). Its trajectory took it to
185 reach the Anaa atoll with full intensity¹ while violently impacting the northwest coasts of
186 Rangiroa, Tikehau, and Mataiva (Fig. 1). In addition, there is evidence from several atolls in
187 the Tuamotu Archipelago that this cyclone was able to cause significant geomorphological
188 changes. These impacts, also described in several archival documents, were transmitted
189 within the population and are sometimes reported today by the elders. Nevertheless, neither
190 elders nor archives do not make it possible to locate precisely the geomorphological impacts
191 induced by the cyclone of 1906.

192 Prior this series of cyclones, naval reports and explorers' texts also mention the existence of a
193 major cyclonic HEMI in 1822 on the west of the archipelago (notably at Anaa). In 1831, the
194 British missionary William Ellis (p. 306-307) testifies to the extensive destruction caused by a
195 submersion. In 1837, the French ethnologist Jacques-Antoine Moerenhout (p. 365) states that
196 this westerly gale (most likely a powerful cyclone) displaced huge stones inside the Anaa
197 Atoll. Finally, in 1854, the authors of "the Messenger of Tahiti" described in the northwest of
198 Anaa, limestone megablocks 20 to 25 feet high of likely marine origin. All these testimonies
199 from the nineteenth century and early twentieth suggest that the northwestern part of the
200 Tuamotu archipelago (and particularly the atoll of Anaa) could gather the cyclonic history
201 adapted to this study.

202 The western part of the archipelago is also interesting because of its more recent cyclonic
203 history. The Tuamotu archipelago suffered very extensive damages due to low frequency
204 tropical cyclone. According to the National Oceanic and Atmospheric Administration

¹ The pressure in the cyclone eye was measured by a boat at 953 hPa about 45 km offshore (in the west side) of Anaa. At this time the cyclone was moving to the southeast at about 45 km/h. This very fast movement strongly increases wave heights on the eastern side of the cyclone (Canavesio, 2014).

205 “hurricane world track” data base the archipelago experienced only 6 tropical cyclones² since
206 satellite monitoring began in 1978. In addition, this hurricane activity is very variable from
207 one year to year (Fig. 1). With 5 cyclones in 1983, this season is, by far, the most intense.
208 Once again, it was the northwest of the archipelago that was the most impacted. Finally, if
209 Tikehau, Rangiroa and Anaa (with Kaukura) experienced the strongest winds and sea
210 conditions in the archipelago in 1983, they experienced no catastrophic cyclonic HEMI since
211 this time. It was only in 1998 that the low energy tropical cyclone impacted the northwestern
212 shore of Tikehau during a high-energy distant swell coming from the north (Duvat, et al.,
213 2017). Therefore, over the past two centuries, this part of the archipelago has been affected by
214 several series of devastating cyclones but also by long periods of calm weather conducive to
215 the establishment of various geomorphological structures over the time.
216
217

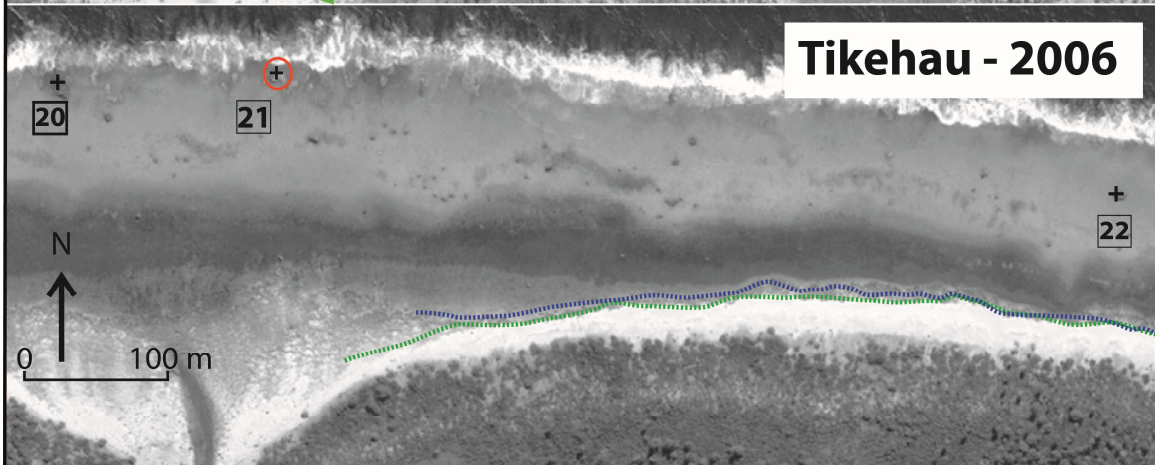
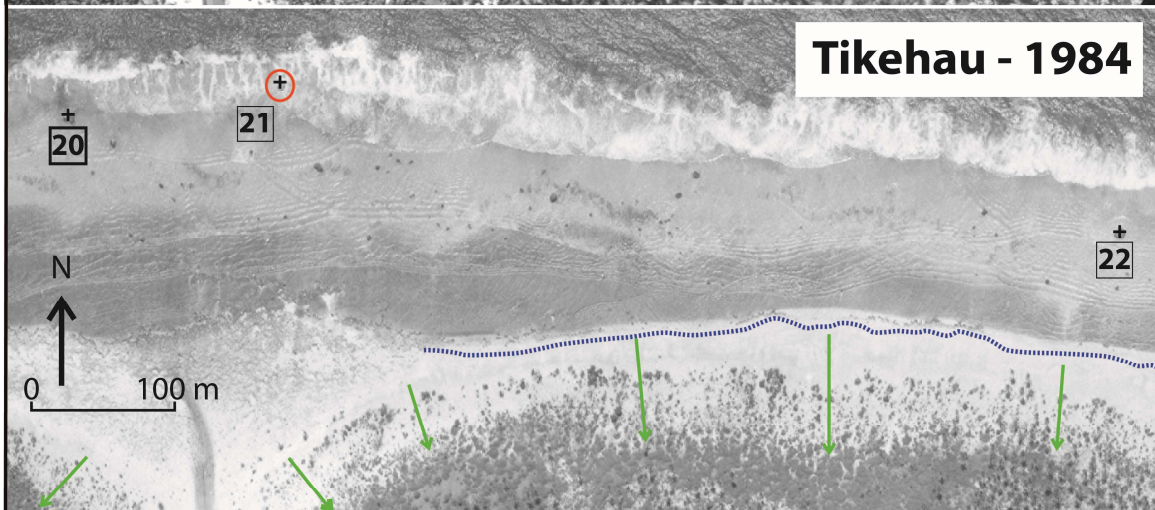
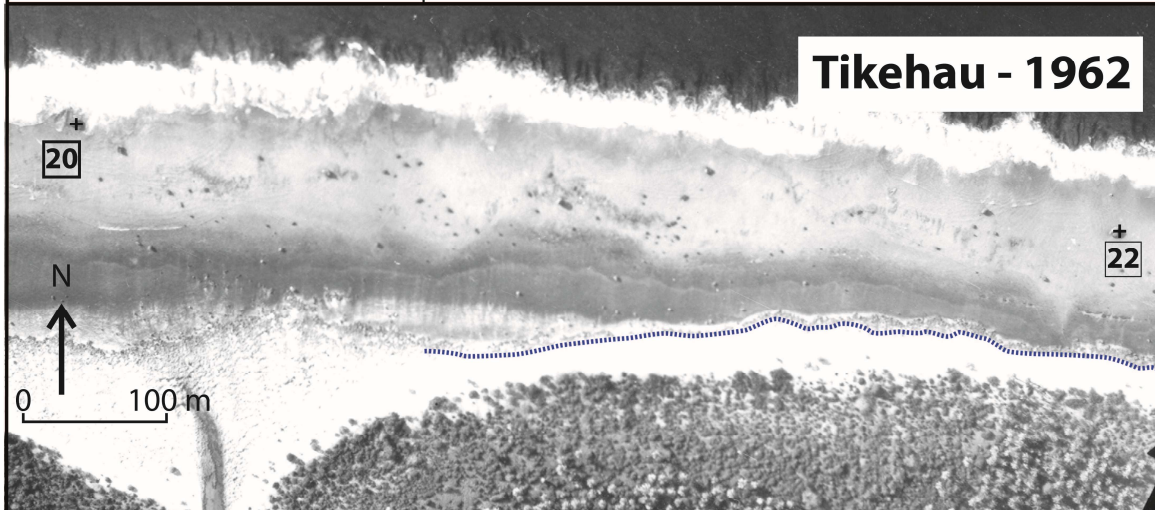
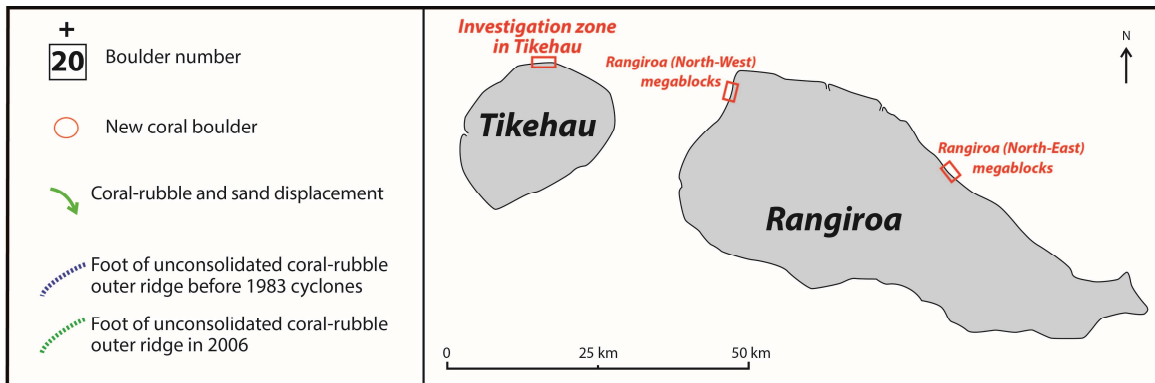
218 **3. Materials and methods**

219 **3.1. Megablocks measurement and dating**

221 Observation of aerial and satellite imagery shows that the Mataiva atoll is devoid of large
222 megablocks. Conversely, the north and northwest coasts of Tikehau (Fig. 3), Anaa (Fig. 4)
223 and Rangiroa (Fig. 5) are known for their important blocks fields of unknown origin.
224 Therefore, three field missions were organised between November 2017 and June 2019 to
225 analyse these blocks. We also took advantage of our trip to Rangiroa to analyze three
226 megablocks located in the northeast of the atoll. (Fig. 5). The dating method established by
227 Terry et al. (2013) and Terry & Etienne (2014) was used, for which we specified dating
228 reliability (Canavesio et al., 2018). We focused on the largest blocks expecting that some of
229 them could be connected with known HEMIs.

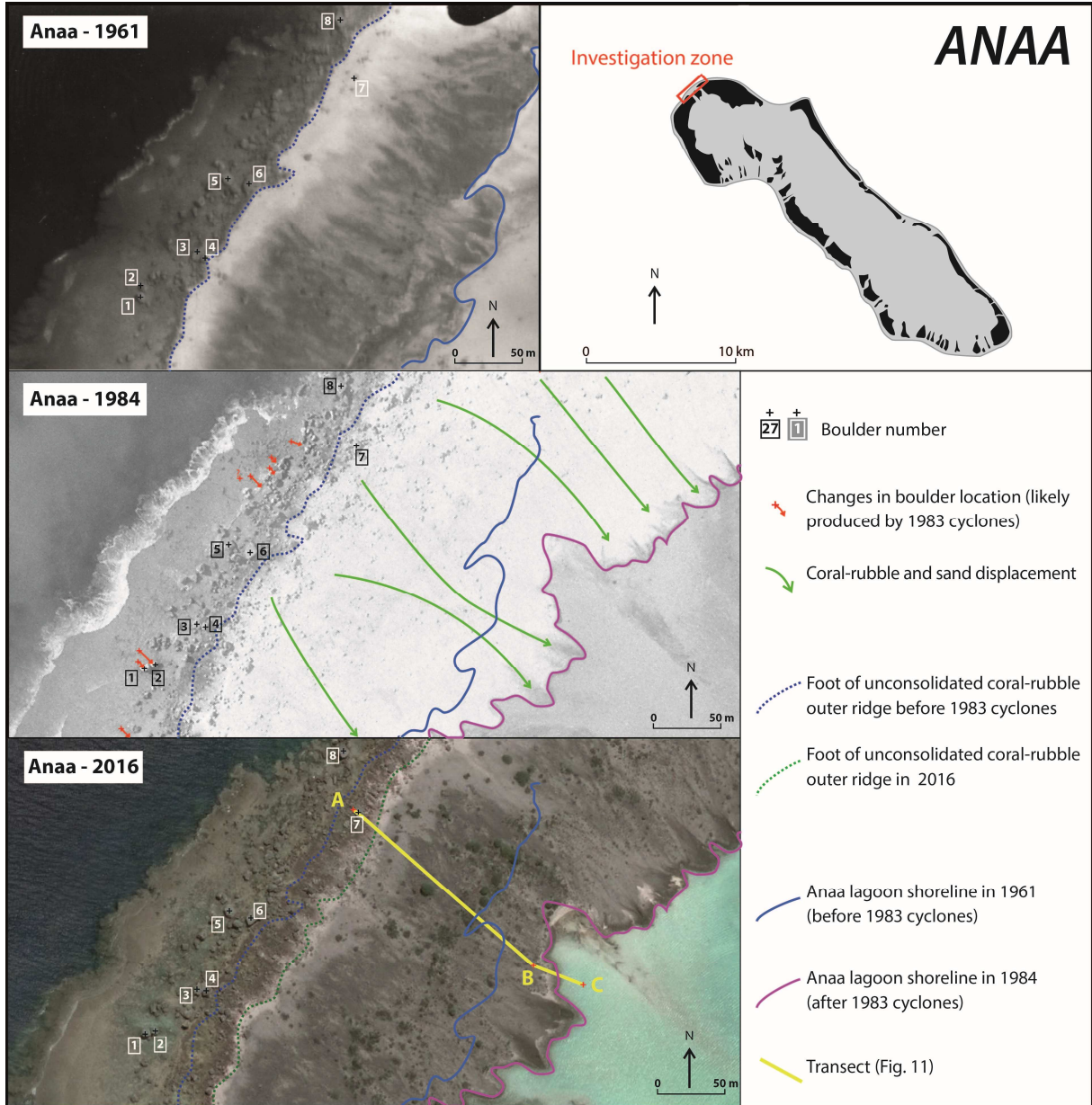
230 Due to the deep depth bathymetric context, and according to observations and modelling,
231 tropical cyclones and extremely distant swells are the only known natural hazards (with
232 hypothetical underwater landslides) capable of causing the establishment of megablocks in the
233 Tuamotu archipelago (Bourrouilh and Talandier, 1985; Etienne et al., 2014; Lau et al., 2016;
234 Canavesio et al., 2018). Indeed, peer-reviewed paper (Sladen et al., 2007) indicate that
235 tsunamis have never been able to generate run-ups greater than 1.8 m in this region. This
236 assertion is confirmed by the memories of the elders that we collected in a previous study
237 (Canavesio, 2017): the 1946 aleutian tsunami was the largest of the 20th century in the
238 archipelago, but only caused a 2 m rise in sea level near the western Makemo pass. Moreover,
239 in French Polynesia, as the distant swells (Andrefouët et al., 2012; Canavesio, 2019) powerful
240 enough to create megablocks come only from the south, so the megablocks positioned on the
241 west, north and east coasts of the archipelago are reliable markers of past cyclonic activity.
242

² Cyclones whose track has passed more than 150km from the islands of the archipelago have not been retained in this list.a



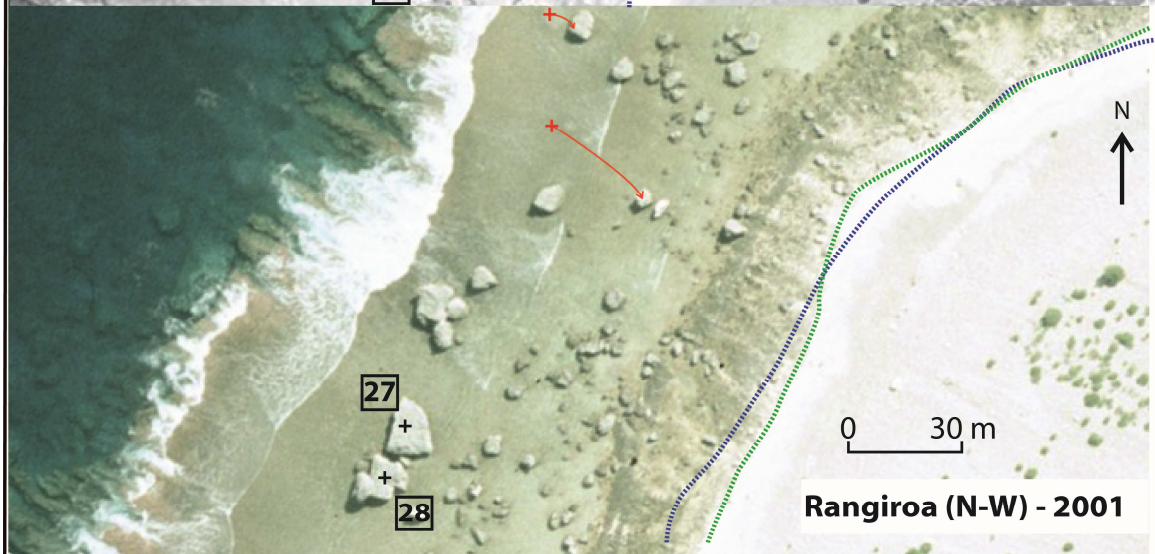
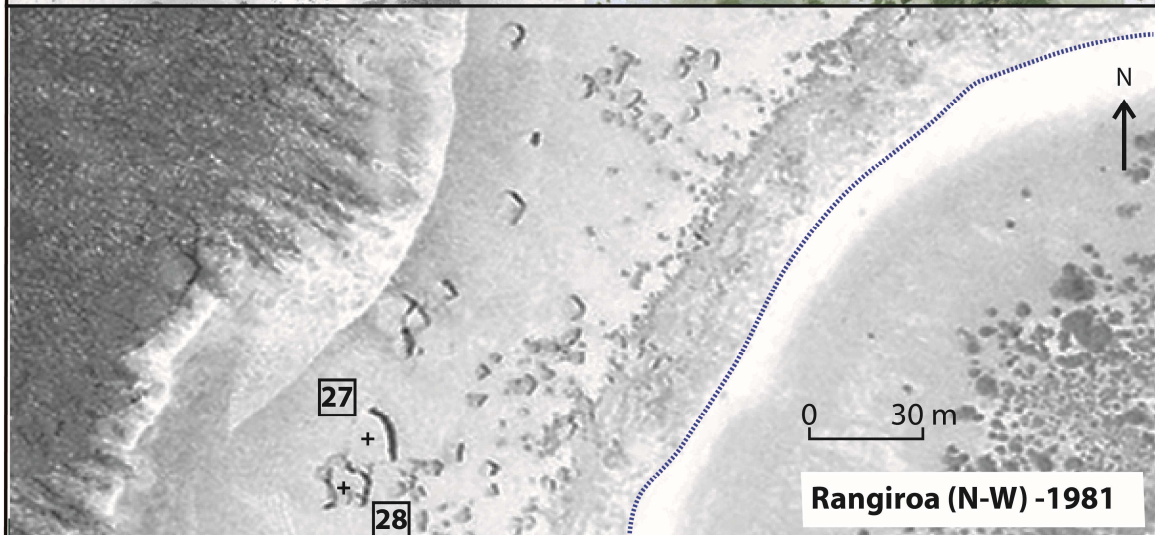
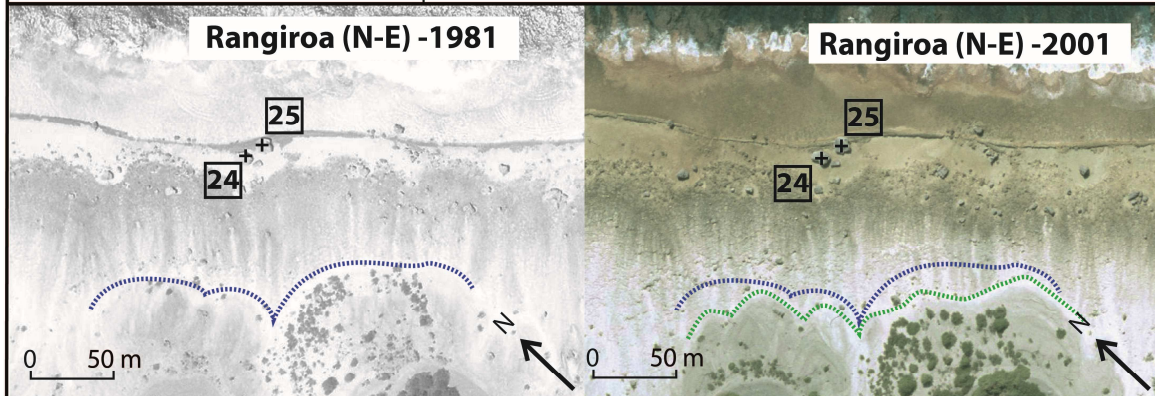
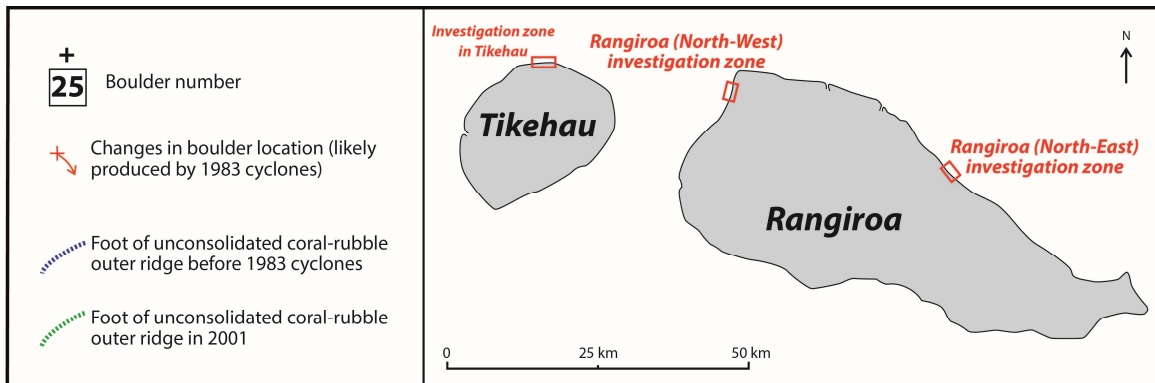
244
 245
 246
 247
 248
 249

Fig. 3: Location of Tikehau’s boulders field and aerial photographs before and after the cyclones of 1983. Block n°23 is not visible in this figure. It is located six hundred meters east of block n°22. No movement of boulders already in place has been identified at the site during the HEMIs but a new boulder (n°21) appeared.



250
 251
 252
 253
 254
 255
 256
 257

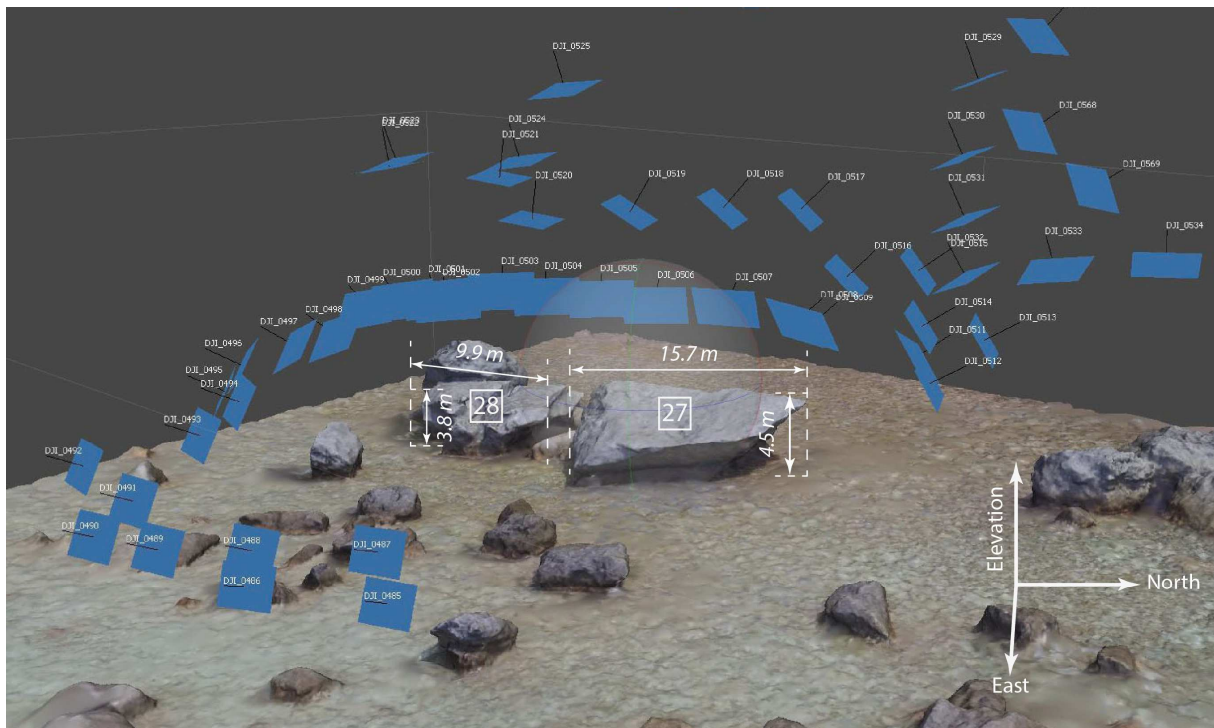
Fig. 4: Location of Anaa’s boulder field and aerial views before and after the cyclones of 1983. The boulder field has experienced some medium sized boulder movements (megablocks n°1 and n°2). The shoreline of the lagoon has changed considerably during the HEMIs of 1983. Due to incomplete aerial coverage before 1983, some parts of the study site (boulder n°9 to boulder n°19) are not visible in this figure.



259
260
261
262
263
264
265
266
267
268
269
270
271
272
273
274
275
276
277
278
279
280

Fig. 5: Location of the Rangiroa boulder field and aerial photos before and after the cyclones of 1983. The boulder field to the northwest of Rangiroa has experienced some moderate boulder movements. No boulder movement was identified at the northeast coast site.

The boulders were surveyed in the field by trying to exhaustively analyse the blocks whose surface was greater than 40m² on the Google Earth satellite imagery. As an exception, smaller blocks also have been studied, especially when the condition of the coral seemed particularly suitable for dating (block n°9 and n°17) or when we hypothesised that the megablock could have been put in place by 1983 cyclone (block n°21). Length, width and height were measured for six boulders in two different areas: 3 in the northwest of Anaa and 3 in the north of Tikehau. For the purpose of photogrammetric volumes calculation, low elevation aerial photographs were acquired using a DJI Phantom III UAV equipped with a GNSS and a 12 Mpix camera sensor for 22 other megablocks (16 at Anaa, 1 at Tikehau and 5 at Rangiroa). The UAV was manually piloted in order to fly over and around the blocks and to capture georeferenced images from all angles (Fig. 6). Photogrammetric processing was carried out using Agisoft Metashape 1.8. For each sector, a high-resolution Digital Elevation Model (5 cm per pixel) and a 3D mesh model were calculated. Block volumes were calculated using the 3D mesh model as upper surface and the average elevation of the reef-flat in the immediate vicinity of the blocks as ground level. The results of these volume measurements are summarised in a table (Fig. 7B).

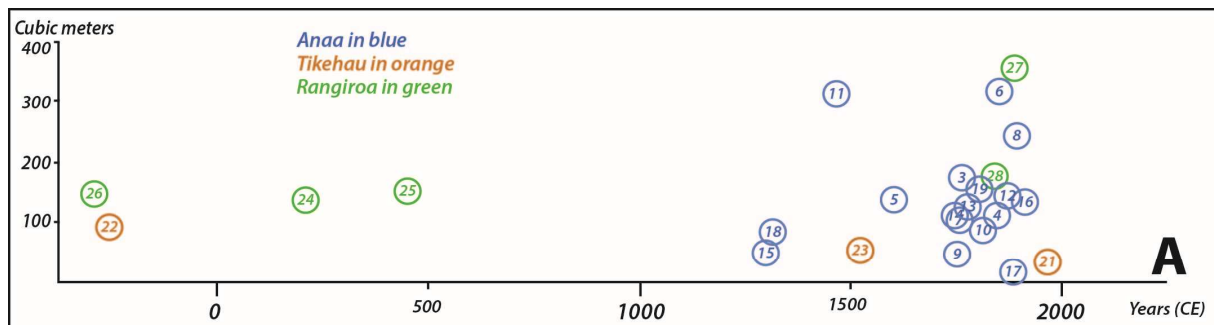


281
282
283
284
285
286
287
288
289

Fig. 6: Photogrammetric 3D model of megablocks on the Rangiroa northwest shore. The blue frames indicate the locations of the pictures shot with the UAV.

Coral samples were also collected from the most recent surfaces (the surface on which the coral "grew" when the block was still submerged) of 25 of these blocks (17 at Anaa, 3 at Tikehau and 5 at Rangiroa). U/Th dating of these samples (Fig. 2B) has been performed at the Laboratory of Climate and Environmental Sciences in Gif-sur-Yvette (France).

290 After adding a triple ^{229}Th ^{233}U - ^{236}U spike in a Teflon beaker, samples were dissolved
291 with diluted HCl. The U-Th separation and purification were performed after coprecipitation
292 with $\text{Fe}(\text{OH})_3$, on 0.6 ml columns filled with U-TEVA and pre-filter resins, in nitric media.
293 The U and Th isotopic compositions were analyzed at the Laboratoire des Sciences du Climat
294 (LSCE, France), on a Multi-Collector inductively coupled plasma source mass spectrometer
295 (MC-ICPMS) Thermo ScientificTM NeptunePlus fitted with a desolvating introduction
296 system (aridus II). For mass fractionation correction, we used an exponential mass
297 fractionation law (normalized to natural $^{238}\text{U}/^{235}\text{U}$ isotopic ratio) and standard / sample
298 bracketing. More details on the analytical procedure (chemistry and MC-ICPMS analysis) can
299 be found in Pons-Branchu et al. (2014). After corrections for peak tailing, hydrate interference
300 and chemical blanks, $^{230}\text{Th}/^{234}\text{U}$ ages were calculated from measured atomic ratios through
301 iterative age estimation using the ^{230}Th , ^{234}U and ^{238}U decay constants of Cheng et al.
302 (2013) and Jaffey et al. (1971). U/Th dating is very reliable but it may have a significant
303 sampling bias that can lead to an overestimation of the age of the blocks of more than a
304 century. Indeed, an inverted position expose dating age to a larger deviation because of
305 limited choice for sampling and fast coral alteration in proximity of soil / water (Canavesio,
306 2018). Luckily, most of the boulders were right way up. Except on one boulder (n°11) of
307 particular interest due to its exceptional size ($>300 \text{ m}^3$), it was decided not to perform samples
308 on inverted megablocks.



Block number	Sampling area & GNSS location	Measurement method In the field (a-, b-, c- axis) or photogrammetry	Volume ¹ (cubic meters)	Distance from reef edge (m)	Orientation	U-TH Corrected age (yr)	HEMI responsible for emergence (most likely in bold)
1	Anaa 17°20'4.56"S / 145°36'2.69"O	Photogrammetry	140	62	no data	no data	?
2	Anaa 17°20'4.38"S / 145°36'2.31"O	Photogrammetry	67	65	no data	no data	?
3	Anaa 17°20'3.33"S / 145°36'1.11"O	Photogrammetry	181	81	Right way up	1778 AD +/- 5	1822 1878 / 1906
4	Anaa 17°20'3.44"S / 145°36'1.02"O	Photogrammetry	105	88	Right way up	1848 AD +/- 2.5	1906 1878
5	Anaa 17°20'1.53"S / 145°36'0.44"O	Photogrammetry	141	65	Right way up	1609 AD +/- 8	?
6	Anaa 17°20'1.64"S / 145°35'59.93"O	Photogrammetry	314	77	Right way up	1831 AD +/- 12	1822 / 1906 1878
7	Anaa 17°19'58.93"S / 145°35'57.20"O	Photogrammetry	105	85	Right way up	1760 AD +/-5	1822 1878 / 1906
8	Anaa 17°19'57.54"S / 145°35'57.57"O	Photogrammetry	239	41	Right way up	1896 AD +/- 5	1906
9	Anaa 17°19'54.25"S / 145°35'53.38"O	Photogrammetry	47	98	Right way up	1756 AD +/- 9	1822 1878 / 1906
10	Anaa 17°19'53.69"S / 145°35'54.69"O	Photogrammetry	84	58	Right way up	1807 AD +/- 8	1822 1878 / 1906
11	Anaa 17°19'53.36"S / 145°35'54.32"O	Photogrammetry	311	64	Inverted	1474 AD +/- 23	?
12	Anaa 17°19'53.05"S / 145°35'54.57"O	Photogrammetry	149	54	Right way up	1879 AD +/- 12	1906 1878
13	Anaa 17°19'52.49"S / 145°35'52.63"O	Photogrammetry	115	77	Right way up	1759 AD +/- 7	1822 1878 / 1906
14	Anaa 17°19'52.36"S / 145°35'52.83"O	Photogrammetry	110	70	Right way up	1742 AD +/- 9	1822 1878 / 1906
15	Anaa 17°19'51.58"S / 145°35'52.79"O	Photogrammetry	55	52	Right way up	1312 AD +/-7	?
16	Anaa 17°19'51.21"S / 145°35'53.68"O	Photogrammetry	131	27	Right way up	1914 AD +/- 4	1983
17	Anaa 17°19'55.29"S / 145°35'44.23"O	In the field 6.4 x 2.8 x 1.2	15	289	Right way up	1883 AD +/- 5	1906 1878
18	Anaa 17°19'32.60"S / 145°35'19.11"O	In the field 6.1 x 5.2 x 3.9	87	95	Right way up	1326 AD +/- 20	?
19	Anaa 17°19'30.04"S / 145°35'15.66"O	In the field 8.3 x 6.3 x 4.3	157	66	Right way up	1809 AD +/-5	1822 1878 / 1906
20	Tikehau 14°54'12.18"S / 148° 9'13.82"O	In the field 7.1 x 6.2 x 1.6	70	37	Right way up	no data	?
21	Tikehau 14°54'11.96"S / 148° 9'8.90"O	In the field 4.5 x 4.3 x 1.9	37	36	Right way up	1973 AD +/- 4	1983
22	Tikehau 14°54'15.20"S / 148° 8'48.90"O	In the field 6.3x 6.6 x 2.3	96	67	Right way up	257 BC +/- 12	?
23	Tikehau 14°54'19.39"S / 148° 8'27.86"O	Photogrammetry	58	79	Right way up	1517 AD +/-5	?
24	Rangiroa (North coast) 15° 4'16.35"S / 147°31'22.18"O	Photogrammetry	144	71	Right way up	210 AD +/-12	?
25	Rangiroa (North coast) 15° 4'16.47"S / 147°31'21.72"O	Photogrammetry	162	62	Right way up	465 AD +/- 9	?
26	Rangiroa (North coast) 15° 4'45.52"S / 147°30'47.49"O	Photogrammetry	157	74	Right way up	281 BC +/-11	?
27	Rangiroa (North-West) 14°55'55.30"S / 147°51'27.84"O	Photogrammetry	369	59	Right way up	1894 AD +/-4.5	1906
28	Rangiroa (North-West) 14°55'55.69"S / 147°51'27.92"O	Photogrammetry	172	61	Right way up	1834 AD +/-3.5	1906

¹ Accurate measurements with the 3D models have demonstrated that the volumes of boulders are only a fraction of those estimated using rectangular geometry. In this study, a conservative value of 0.7 was used to minimize error in the estimation of volume for the megablocks measured in the field.

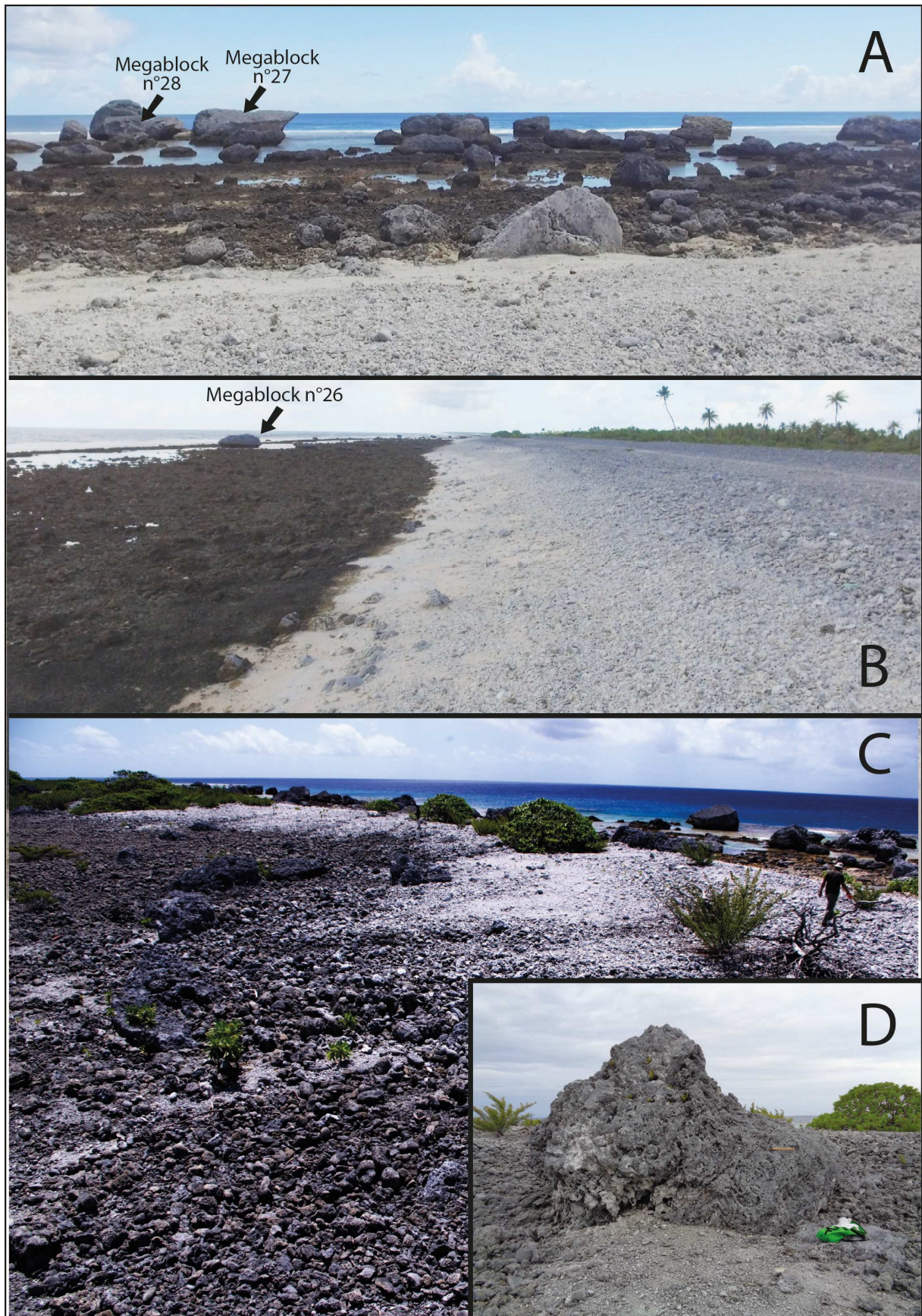
309
310
311

Fig. 7. A: Timeline showing coral samples U/Th ages and megablocks volumes. B: Table of megablocks features.

312
313

3.2. Aerial and satellite imagery analysis

314 The Tuamotu archipelago was mapped using aerial photographs in the early 1960s. These
315 images, which are of variable quality, make it possible to identify the main geomorphological
316 structures prior the 1983 cyclone season. The effects of the 1983 cyclones are most easily
317 seen as most of the atolls were photographed again in 1984 to assess the extent of the
318 destruction. Several more or less coordinated aerial photography campaigns were then carried
319 out. The Polynesian urban planning department gave us access to this database.
320



321
 322
 323
 324

Fig. 8: Figures 8A (Rangiroa NW) and 8B (Rangiroa NE) show that the unconsolidated coral-rubble outer ridge consists of much lighter coral material (because the ridge is recent) than the

325 reef flat. The boundary between the two structures is often very clear. It is this limit that is
326 referred to in this article as "foot of the unconsolidated coral-rubble ridge". An increase in
327 grain size (from sand to pebbles of about 200 mm in diameter) can be observed between the
328 foot of the outer ridge and its top. Photos 8B and 8C taken at the back of the ridge (Anaa
329 atoll) show darker coarse sediments (because older of several years). Photo 8C shows the
330 transport of slightly lighter sediments which were deposited at the top of the ridge. Photo 8D
331 shows an inverted megablock partially buried in these sediments.

332
333 The photographs were imported, rectified and georeferenced into a GIS software. Stable
334 identifiable landmarks such as plate fractures, highlights of the cemented conglomerate
335 platforms, and apparently immobile megablocks were used as ground control points for
336 georeferencing. Sedimentary movements have been identified, such as changes in the position
337 of coral blocks, lagoon shoreline shifts and moves of the coral-rubble outer ridge. The contact
338 zone between the reef flat and the ridge (referred to as "foot of unconsolidated coral-rubble
339 ridge" in figures "3", "4" and "5") is easy to identify on aerial images. The reef flat is still
340 dark in colour while the outer slopes of the coral-rubble ridge (composed of recently
341 deposited coral elements) are much lighter in colour (Fig. 8).

342 Due to the variable quality of aerial photographs, it has not always been possible to monitor
343 all areas over the entire period. Only the southernmost part of the Anaa blocks field offers a
344 complete coverage of aerial photos before 1983, in 1984 and in 2016 to allow such a
345 monitoring (from reef edge to lagoon) over a period of 55 years. The transect ABC (yellow
346 line on the Anaa 2016 photograph, Fig. 4) is the main basis for the model of atoll islets
347 reshaping presented in the discussion section (Fig. 11).

348 The distance between the megablocks and the reef edge has been measured on satellite
349 imagery on Google Earth (from 2006 to 2019). The blocks are clearly visible on the images
350 but the measurement remains approximate (+/- 5m). In fact, the edge of the flat is often
351 masked by waves.

352
353

354 **4. Results**

355 **4.1. Islet reshaping induced by 1983 cyclonic waves**

356 Reforecasts using both Wavewatch 3 (Lecacheux et al., 2013) and MIKE21 (Damlamian and
357 Kruger, 2013) wave models estimate that the maximum swell generated by the 1983 cyclones
358 was 12 m high at the northern tip of Anaa in February during Cyclone Orama. At Tikehau and
359 Rangiroa the maximum cyclonic swell would have been reached in April during cyclone
360 Veena (Hs between 8 and 10 m). For these two cyclones, the biggest swells came from a wide
361 northern sector, which means that they reached the study sites with maximum energy.

362 During these HEMIs megablocks movements were very limited although we could see on the
363 field that none of the dated blocks are cemented into the reef. According to the aerial imagery,
364 the investigated zone on the northeast coast of Rangiroa did not experience any visible block
365 movement during the whole period (Fig. 5). On the northwest coast of Rangiroa, a
366 displacement of two small blocks were observed to have moved to the southeast (Fig. 5).
367 These blocks have not been measured but, from their small size on aerial imagery (about 19
368 m² -for the largest- according to aerial pictures) they are likely less than 60 m³. The other
369 blocks in the area, including those measuring only a few tens of cubic meters, remained
370 stable. At Tikehau (Fig. 3), a block (n°21) estimated to be 37 m³ by field measurement was
371 set up on the flat. Its relatively modest size and its position on the edge of the reef (only 36 m
372 from the sea) indicate to moderate flow velocities. We also note that the blocks visible in
373 1962 (from about ten cubic meters to one hundred cubic meters for the largest) did not move

374 in 1983. In Anaa where the cyclonic swell was slightly stronger, the movement of the blocks
375 is also limited (Fig. 4). The main change is recorded at the southern end of the block field.
376 Block number 2, measured by photogrammetry at 67 m³, moved 20 m to the southeast. Block
377 number one (140 m³), which was close to number 1 in 1961, would have moved in the same
378 direction of about five meters. However, due to the coarse spatial resolution of the
379 photographs and possible rectifying errors, we cannot formally ensure that this block has
380 moved during the 1983 cyclone. If it did it right, it would be the largest block movement
381 recorded. To the northeast of the area covered by these aerial photographs, U/Th dating has
382 shown that a block (n° 16) has been set up by cyclone Orama. Indeed, coral from this boulder
383 has been dated from 1914 (+/- 4 years) which means that the block was set up by a HEMI
384 after the cyclone of 1906. Although its large dimensions (131 m³), it does not prove an
385 exceptional HEMI since it was deposited very close to the reef edge (Fig. 4 and Fig. 10).
386 Finally, in these three atolls, waves heights of 8 to 12 meters (Hs) induced by the 1983
387 cyclones had very limited effects on the megablocks since their volume exceeded ten cubic
388 meters. Based on this results, we confirm that the 1983 cyclones produced significantly lower
389 energy HEMIs than the events that produced the largest megablocks of the archipelago.
390 However, the shape of the islets was modified by the transport of finer materials (coral rubble,
391 sand), in accordance with the observations made in the field at this time (Dupont, 1984;
392 Ricard, 1985; Harmelin-Vivien 1994). At Tikehau, aerial photographs (Fig. 3) taken a year
393 after the cyclone show the spread of coral sediments in the coconut grove over several tens of
394 meters. These sediments, (20-250 mm in diameter) that had accumulated in the outer coral
395 rubble ridge over the previous decades, were carried away several hundred meters from the
396 reef edge during the 1983 cyclones, helping to raise the elevation of the central part of the
397 islet. Even if the aerial photographs do not make possible to estimate the heights, it can be
398 deduce that this complete submersion of the ridge (due to waves run-up) has the consequence
399 of reducing the elevation or even causing the complete disappearance of this coral rubble
400 ridge. Aerial photographs from 2006 at Tikehau (Fig. 3) and 2001 at Rangiroa (Fig. 5) show
401 that the toe of the coral-rubble ridge had not returned to its pre-cyclone position on these
402 dates.
403 At Anaa, where the islet was narrower, probably lower and where the swell was slightly
404 stronger, the reshaping was massive (Fig. 4). On the 1961 photo, the coral-rubble ridge is
405 clearly visible (light colours). A few large megablocks were barely emerging from this cluster
406 of coral sediments and it is likely that many smaller blocks were buried beneath the surface.
407 In 1984, these megablocks were partially exhumed by submersion which carried most of the
408 sediments that formed the corral ridge to the edge of the lagoon. This transfer of coral
409 sediments allowed the island to expand from a few tens of meters to more than one hundred
410 meters. We hypothesize that islet extension is smaller during extreme HEMIs as the 1906
411 cyclone due to sediment transfer further into the lagoon (Fig. 11).

412
413

4.2. Reshaping during low energy times (since 1983)

414 Since 1983, the areas studied have experienced mostly calm weather and sea conditions. The
415 most significant swell is that of February 1998 which peaked at 8 m at Mataiva (but less at
416 Tikehau, Rangiroa and Anaa which were further from the cyclone track). No megablock
417 movement was detected during these four decades. During this time, we have observed on the
418 aerial photographs the reconstruction of a coral-rubble ridge in place of the previous one that
419 was washed away in 1983. At Anaa, this result is the reburial of many boulders (Fig. 8D) that
420 were partially exhumed in 1983. Figure 4 shows that the progradation of this coral rubble
421 ridge towards the ocean has not yet reached the original position (about 50 meters difference
422 for the foot of the ridge between 1961 and 2016). A smaller gap can also be seen at Tikehau

423 and Rangiroa (both on the northwest and northeast sectors). It can be assumed that the
424 progradation is still ongoing and that the very outer position in 1961 was the result of a more
425 lasting accumulation (55 years), than the contemporary accumulation phase (33 years).
426 On the lagoon side, Anaa's islet shape has changed very little. However, the profile extracted
427 from the photogrammetric DEM (Fig. 11) shows a small sandy ridge at the edge of the
428 lagoon, likely formed during the cool season by waves associated with frequent southeasterly
429 winds. The existence of this low sandy ridge (a few tens of centimeters above the lagoon
430 water level) located on the lagoon shore of the islets has long been recognised. This is a
431 classic geomorphological feature in the atolls (e.g. Hosking, 1991; Kench, 2014).

432
433

4.3. Megablocks emergence induced by extreme HEMIs

434 The largest block measured (Fig. 7) is located on the northwest coast of Rangiroa. This block
435 (n°27) was previously estimated to be between 495 m³ (Etienne et al., 2014) and 750 m³
436 (Bourrouilh and Talandier, 1985), but has been now measured by photogrammetry at 369 m³
437 (Fig. 6). Photographs taken shortly after the 1983 cyclone when Bourrouilh and Talandier
438 estimated its volume show that the block had a shape identical to its current shape. According
439 to the coral blocks density values measured in the Tuamotu archipelago (density = 2.3 g.cm⁻³,
440 Etienne et al, 2014) or in the Phillipines (2.4 g.cm⁻³, May et al, 2015), the weight of this
441 block can be estimated between 849 and 886 tons. As block n°28 (172 m³), block n°27 was
442 set up by the cyclone of 1906.

443 In fact, the sampling bias can lead to date coral which died several years before the HEMI.
444 Therefore, the datings obtained may be older than the HEMI itself. Alternatively, it is not
445 possible for the HEMI to be older than the date indicated by the age of the dated coral. Thus,
446 as the sample is made from coral formed in 1894 AD, we are certain that the HEMI that
447 caused this block to emerge was later than 1894 but prior to the 1981 aerial image on which
448 the block is already visible. Moreover, the only known HEMI on the northwest coast of
449 Rangiroa is the cyclone of February 8, 1906. Such a volume is unusual for a cyclonic origin.
450 It can be related to the size of the swell that was considered "exceptional" by the
451 contemporaries of this cyclone (Marcade, 1915; Giovanelli, 1940) and where wave height
452 (Hs) was estimated between 15.5 and 18.5 m at Anaa early afternoon of February 8
453 (Canavesio, 2014).

454 On the northeast coast of Rangiroa the three blocks examined (144 to 162 m³) could not be
455 related to any known HEMI. In any case, they are much older (1554 to 2300 years BP). At
456 Tikehau, the dates for the blocks n°22 (96 m³) and n°23 (58 m³) also refer to unknown ancient
457 HEMI (2278 BP and 504 BP respectively). Because of this ancient water emersion, it is likely
458 that they have been moved several times since their emergence (and in particular in 1822 and
459 1906).

460 Anaa is the site of the most spectacular boulders field (Fig. 9). On this atoll, most of the
461 samples collected are made from coral that was alive in the eighteenth or nineteenth century
462 (Fig. 7). The sample taken from the largest block of 314 m³ (722 to 753 tons) was dated to
463 1831 AD +/-12 years. The margin of error makes it possible to attribute it to the cyclone of
464 1822, but it was probably set up by the cyclone of 1906. In any case, it is certain that it was
465 raised up by a HEMI of cyclonic origin since no other type of HEMI has been recorded in this
466 relatively recent period. Given its position relative to the reef edge (77 m), this attests to
467 exceptional flow velocities (Fig. 10). In addition, the cyclone of 1906 could be identified as
468 the HEMI responsible for the establishment of at least one block (n°8) of 239 m³ (550 to 574
469 tons).

470 This data confirms that cyclones in coral environments can produce blocks whose volume can
471 exceed 250 m³. This dislocation occurs only for cyclones being able to generate swells above

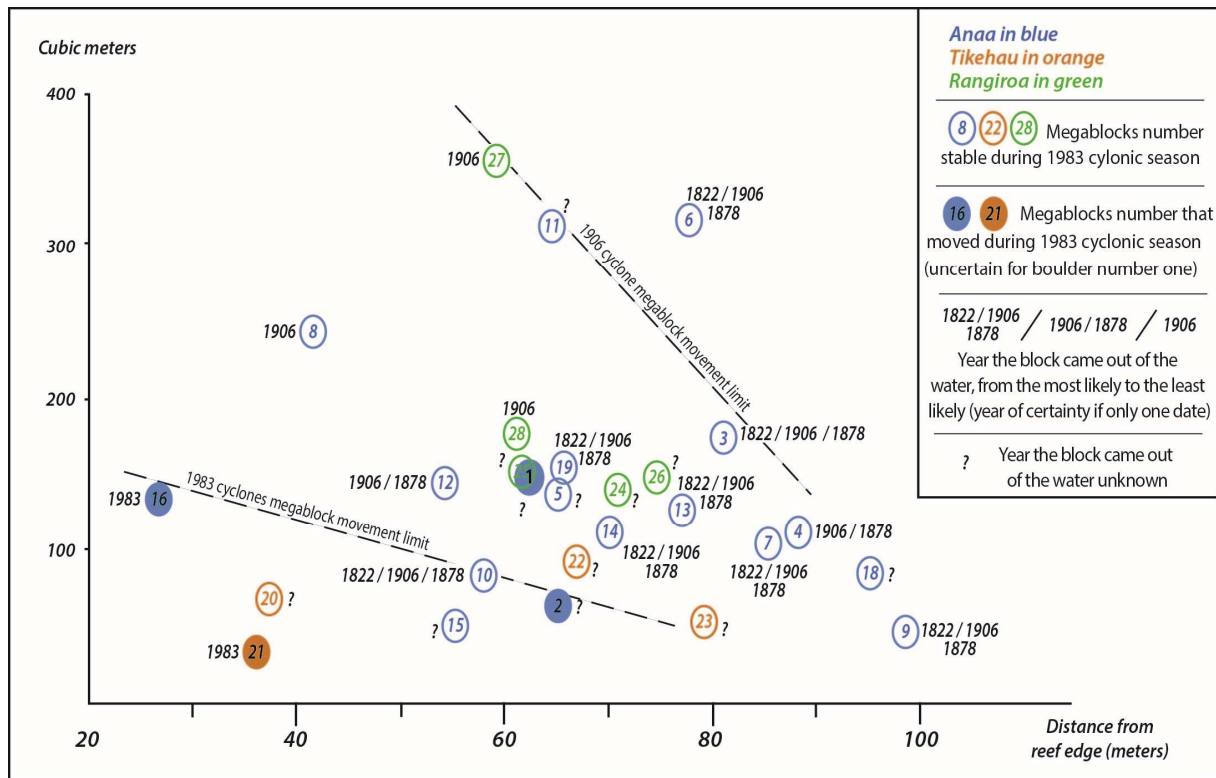
472 12 m (> 15 m likely). This data also shows that such a powerful HEMI is of very low
473 frequency (a few events per millennium) in French Polynesia. Since 1906, the archipelago has
474 not had to suffer that kind of cyclone (Fig. 1).



475
476
477
478

Fig. 9: With at least 13 blocks of more than 100 m³ spread over less than 2 km of coastline, the northwestern end of Anaa atoll stands out from other sites studied in French Polynesia

479 where boulders are more scattered. The majority of these coral boulders were put in place by
 480 the cyclones of 1822 and 1906. This is the case of coral boulder n ° 6 (314 m³) on which a
 481 sample was taken and U/Th dated at 1831 AD (+/- 12 years).
 482



483
 484
 485 Fig. 10: Volume of the blocks according to their distance from the reef edge at Anaa,
 486 Rangiroa and Tikehau. This graph shows that the blocks put in place and the blocks moved by
 487 the cyclone set of the year 1983 are of a significantly smaller size than those which were
 488 moved by the cyclone of 1906. This indicates that the flow velocities could have been, by far,
 489 much higher in 1906 on the investigated sites.
 490

491 5. Discussion

493 The main hypothesis of this study was that cyclonic HEMIs are the main drivers of atoll islet
 494 reshaping. By studying the medium term geomorphological dynamics of the western Tuamotu
 495 archipelago, we have been able to clearly distinguish the geomorphological structures
 496 produced by periods of calm weather from those resulting from exceptional cyclonic surges.
 497 The alternation between intense cyclonic events and multi-decade periods of calm weather is
 498 a feature we have been looking to produce this analysis. Such a situation is rare in other atoll
 499 archipelagos. By focusing on coastlines exposed to the north, our work gives an incomplete
 500 picture of the geomorphological dynamics at work on coastlines with other exposures and
 501 which are likely to be affected by more frequent medium-energy swells of (less intense
 502 cyclonic swells and more intense seasonal distant swells).
 503 It became clear that the establishment of sedimentary ridges (on both sides of the islets) is the
 504 result of sediment transport and accumulation during medium-intensity episodes which can
 505 occur several times per decade. Interviews with residents of Anaa, Rangiroa, Makemo,
 506 Hikueru and Marokau, conducted as part of other published studies, revealed that these coral-
 507 rubble and sandy ridges could provide a sense of security to the inhabitants regarding the risk

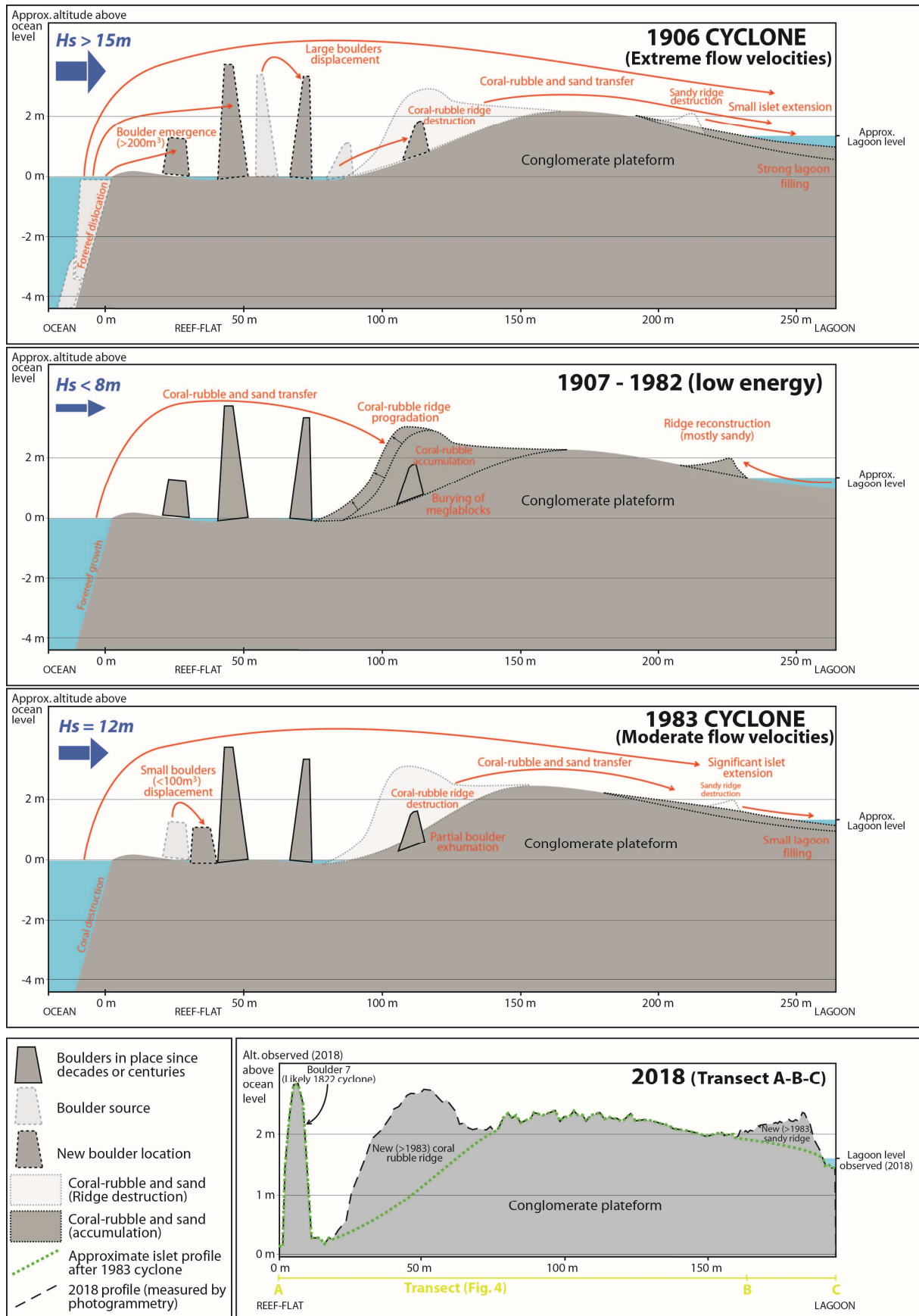
508 of submersions. In Makemon the cyclone shelters was deliberately located on the outer
509 sedimentary ridges to benefit from a maximum construction elevation (Canavesio, 2015).
510 However, we have shown that these ridges are not long-lasting geomorphological structures.
511 Cyclonic swells of more than 8 meters submerge and carry away these sedimentary
512 accumulations (Fig. 11). They significantly contribute to the builds up of the central part of
513 the islands and the sedimentary filling of the lagoons.

514 Our work also has aimed to reconstruct the main features of the morphoclimatic history of the
515 last two centuries and has showed that intense HEMIs have occurred five or six times during
516 the last two centuries (1822-2022 period) in the western part of the Tuamotu archipelago. It
517 occurred during the cyclones of 1822, 1878, 1905, 1906 and 1983 (with two distinct episodes
518 for each island in 1983). The cyclone census shows that the western Tuamotu has been much
519 more impacted by cyclones than the eastern part of the archipelago (1 or 2 cyclones
520 depending on the islands in 1903 and 1983). In the central part of the archipelago, some atolls
521 have not even experienced any catastrophic cyclones (known cyclones have passed more than
522 150 km from these islands) during the last two centuries. As a result, it is possible that coral
523 rubble mounds, whose construction would have begun before 1822, still exist in these atolls.

524 We cannot formally affirm that these frequencies are representative of the cyclonic activity
525 over the last millennium. Nevertheless, our work, which also focused on the establishment of
526 the Anaa, Rangiroa and Tikehau coral megablocks, allows us to make a first hypothesis. The
527 dating carried out on the largest blocks of these atolls indicates that the cyclones of 1822 and
528 1906 would have produced very rare meteorological conditions in this archipelago since the
529 sea level is close to the current level that is about 5000 - 6000 years BP in French Polynesia
530 (Pirazzoli, 1988; Montaggioni et al., 2023). Indeed, the megablocks are very durable, but, the
531 vast majority of the dated blocks indicates a recent installation (19th century) in this part of the
532 archipelago. Further east, the 1903 cyclone (Canavesio et al., 2018) would be at the origin of
533 all the megablocks of Hikueru and Marokau which supporting the hypothesis of an increase in
534 the ability of cyclones to generate extreme marine conditions during this period. Only a more
535 extensive study of the archipelago's megablocks could validate the hypothesis of an
536 intensification (cyclonic swell energy) of cyclones in the 19th and early 20th centuries.

537 The capacity of weather phenomena to move very large blocks has often been discussed.
538 According to Nott (2004), cyclones and storms would not be able to put in place blocks of
539 more than 100 tons. In 2013, the super typhoon Haiyan in the Phillipines moved a block with
540 an estimated volume of 75 to 121 m³ and a weight of 181 to 292 tons (May et al., 2015).
541 According to some authors (Parks Camp and Montgomery, 2001) in the past oceanic heat
542 waves (with a rise of the ocean surface temperature to more than 36°C) could have allowed
543 the activation of very intense cyclones. This cyclones more intense than those we currently
544 know, could have produce the displacement of even largest coral megablocks. This study
545 shows that tropical cyclones can produce coral boulders as heavy as those identified in a non-
546 tropical context (Cox et al., 2018). In a published study (Canavesio, 2014), we explained why
547 cyclones such as that of 1906, even of low atmospheric intensity, could generate extreme
548 flooding (Hs between 15.5 and 18.5m) when their displacement speed was high. At that time,
549 we could not establish the link between this cyclone and the movement of megablocks. What
550 is certain from the present study, is that the Anaa and northwest Rangiroa megablocks are of
551 cyclonic origin as suggested as a possibility by some authors (e.g., Bourrouilh and Talandier,
552 1985; Etienne et al., 2014;). The hypothesis of a local tsunami caused by a submarine
553 landslide which has been persistently invoked (Bourrouilh and Talandier, 1985; Hyvernaud,
554 2009) since ethnological sources revealed the possible existence of such an event in the
555 sixteenth century (Ottino, 1965), can thus be invalidated (at least for these dated megablocks).
556 At the same time these results, which demonstrate the ability of tropical cyclones to move
557 coral megablocks of several hundred cubic meters (and more than 500 tons), involve

558 reassessing the origin of the very large blocks found worldwide and whose placement had
559 been attributed (e.g.; Frohlich et al., 2009) to non-meteorological origins because of their
560 extreme size.⁶
561



562
 563
 564
 565

Fig. 11: Conceptual model of reef/islet morphodynamics

566 **6. Conclusion**

567 Identification of atoll islets reshaping in the last two centuries helps to highlight the following
568 new statements.

- 569 1. On the north sector, during usual times devoid of tropical cyclones, changes in lagoon
570 shoreline location are very limited. The main reshaping action is the slow accretion of
571 unconsolidated ridges on both sides of the islets. Periods of ridges building can extend
572 over several decades.
- 573 2. Tropical cyclones of common intensity are the main driver of islet reshaping. Their 8
574 to 12 meters waves level the ridges, pushing their elements landward. They produce
575 ground level elevation in the central part of largest islets (>500 m width). Islets of
576 smaller width can experience an important enlargement by the spilling of coral rubble
577 and sand in the lagoon.
- 578 3. Upper fore-reef dislocation and major megablocks displacement are linked of extreme
579 HEMIs. Evidences were found of megablocks up to 369 m³ emplaced by 1906 tropical
580 cyclone. Coral U/Th dating and archive analyse prove that western part of Tuamotu
581 archipelago has experience two of these extreme submersions in less than one century
582 (1822 and 1906).

583 Since these elements were observed in the climatic context of the 19th and 20th centuries, it
584 would be interesting to study how the gradual rise in sea level will modify sedimentary
585 movements in the coming decades. We also consider that an exhaustive study of the largest
586 megablocks of the Tuamotu archipelago would make it possible to better understand the
587 evolution of the climate of this part of the Pacific over the last 5000 years.

588
589
590 **Data availability**

591
592 UAV pictures used for the purpose of photogrammetric volumes calculation at Rangiroa
593 North-West investigation zone (including the famous Rangiroa megablock whose volume has
594 been refined at 369 m³) are publicly available through the Mendeley repository at : Rangiroa
595 (French polynesia) megablocks UAV imagery (2019) - Mendeley Data

596
597
598 **Declaration of competing interest**

599 The authors declare that they have no known competing financial interests or personal
600 relationships that could have appeared to influence the work reported in this paper.

601
602 **Acknowledgements**

603
604 We thank people and institutions that helped finance and improve this manuscript. We thank
605 the Polynesian urban planning department that gave us access to aerial photographs. Field
606 work at Rangiroa and Anaa has benefited from the help of both Hervé Corbière (Ecrans du
607 Monde, Merignac, France) and Benjamin Picard (Oceania Films, Papeete, French Polynesia)
608 in the frame of two video documentary. We also thank Serge Planes (CRIOBE, CNRS-EPHE,
609 French Polynesia) and Bruno Saura (EASTCO, University of French Polynesia) for providing

610 financial support to investigate field work at Tikehau and to finance UT/h dating of coral
611 samples. Finally, we also thank anonymous reviewer for their comments.

612
613

614 **References**

615

616 Andrefouët, S., Ardhuin, F., Queffeuilou, P., Le Gendre, R., 2012. Island shadow effects and
617 the wave climate of the western Tuamotu Archipelago (French Polynesia) inferred from
618 altimetry and numerical model data. *Mar. Pollut. Bull.* 65, 415–424.
619 <https://doi.org/10.1016/j.marpolbul.2012.05.042>

620

621 Bourrouilh, F.G., Talandier, J., 1985. Sédimentation et fracturation de haute énergie en milieu
622 récifal : tsunamis, ouragans et cyclones et leurs effets sur la sédimentologie et la
623 géomorphologie d'un atoll : motu et hoa, à Rangiroa, Tuamotu, Pacifique SE. *Mar Geol*, 67,
624 263-333. [https://doi.org/10.1016/0025-3227\(85\)90095-7](https://doi.org/10.1016/0025-3227(85)90095-7)

625

626 Canavesio, R., 2014. Estimer les houles cycloniques à partir d'observations météorologiques
627 limitées : exemple de la submersion d'Anaa en 1906 aux Tuamotu (Polynésie Française).
628 *Vertigo* 14. <https://doi.org/10.4000/vertigo.15375>.

629

630 Canavesio, R., 2017. Variabilité des risques de submersion aux Tuamotu. In: Bambridge, T.,
631 Latouche, J.P. (Eds.), *Les atolls du Pacifique face au changement climatique*. Karthala, Paris,
632 pp. 21–49

633

634 Canavesio, R., 2019. Distant swells and their impacts on atolls and tropical coastlines. The
635 example of submersions produced by lagoon water filing and flushing currents in French
636 Polynesia during 1996 and 2011 mega swells. *Glob Planet Change*. 177, 116-126.
637 <https://doi.org/10.1016/j.gloplacha.2019.03.018>

638

639 Canavesio, R., Pons-Branchu, E., Chancerelle, Y., 2018. Limitations to U/Th dating of
640 reef-platform carbonate boulders produced by high-energy marine inundations in
641 the Tuamotu Archipelago (French Polynesia). *Coral Reefs*. 37, 1139–1155.
642 <https://doi.org/10.1007/s00338-018-1732-8>

643

644 Cheng, H., Lawrence Edwards, R., Shen, C.C., Polyak, V. J., Asmerom, Y., Woodhead, J. D.,
645 Hellstrom, J., Wang, Y., Kong, X., Spötl, C., Wang, X., Calvin Alexander, E., 2013.
646 Improvements in ²³⁰Th dating, ²³⁰Th and ²³⁴U half-life values, and U–Th isotopic
647 measurements by multi-collector inductively coupled plasma mass spectrometry. *Earth Planet.*
648 *Sci. Lett.*, 371-372, 82–91. <https://doi.org/10.1016/j.epsl.2013.04.006>

649

650 Cox, R., Jahn, K.L., Watkins, O.G., Cox, P., 2018. Extraordinary boulder transport by storm
651 waves (west of Ireland, winter 2013-2014), and criteria for analysing coastal boulder deposits.
652 *Earth-Sciences Reviews*, 177, 623-636. <https://doi.org/10.1016/j.earscirev.2017.12.014>

653

654 Damlamian, H., Kruger, J., 2013. Modèle bidimensionnel couplé de Rangiroa-Cyclone
655 tropical OramaNisha (1983). CPS (secrétariat de la Communauté du Pacifique), 44p.

656

657 Dupon, J.F., 1984. Where the exception confirms the rule: The cyclones of 1982-1983 in
658 French Polynesia. *Disasters*. 8, 34-47. <https://doi.org/10.1111/j.1467-7717.1984.tb00851.x>

659

660 Duvat, V., Magnan, A., Canavesio, R., 2017. La reconstruction de chaînes d'impacts au
661 service de l'évaluation de la résilience des territoires et de la réduction des risques météo-
662 marins : le cas des atolls des Tuamotu, Polynésie française. *La Houille Blanche*, 2, 13-21.
663 <https://doi.org/10.1051/lhb/2018016>
664
665 Duvat, V.K.E., 2019. A global assessment of atoll island planform changes over the past
666 decades. *Wiley Interdiscip. Rev. Clim. Chang.* 10, 1-16. <https://doi.org/10.1002/wcc.557>
667
668
669 Ellis, W., 1831. *Polynesian Researches: During a residence of nearly eight year in the Society*
670 *and Sandwich Islands. Sec ed enlarged and improved.* Fisher, Son & Jackson. 407p.
671
672 Engel, M., May, S.M., 2012. Bonaire's boulder fields revisited: evidence for Holocene
673 tsunami impact on the Leeward Antilles. *Quat Sci Rev.* 54, 126–141.
674 <https://doi.org/10.1016/j.quascirev.2011.12.011>
675
676 Etienne, S., Couchoud, I., Jeanson, M., Lau, A., Paris, R., Terry, J., 2014. Les risques naturels
677 extrêmes sur les littoraux de la Polynésie française : archives géologiques - modélisation -
678 réduction des risques. RINALPOF research technical report. UPF- EPHE, 98p.
679
680 Etienne, S., Buckley, M., Paris, R., Nandasena, A.K., Clark, K., Strotz, L., Chagué-Goff, C.,
681 Goff, J., Richmond, B., 2011. The use of boulders for characterising past tsunamis: Lessons
682 from the 2004 Indian Ocean and 2009 South Pacific tsunamis. *Earth-Science Reviews.* 107,
683 76-90. <https://doi.org/10.1016/j.earscirev.2010.12.006>
684
685 Gienko, G.A., Terry, J.P., 2014. Three-dimensional modeling of coastal boulders using multi-
686 view image measurements. *Earth Surf. Process. Landf.* 39, 853–864.
687 <https://doi.org/10.1002/esp.3485>
688
689 Giovanelli, J.L., 1940. Les cyclones en Océanie française. *Bull. Soc. Etud. Océaniques.* 250-
690 267.
691
692 Goff, J., McFadgen, B.G., Chagué-Goff, C., 2004. Sedimentary differences between the 2002
693 Easter storm and the 15th-century Okoropunga tsunami, southeastern North Island, New
694 Zealand. *Mar Geol.* 204, 235-250. [https://doi.org/10.1016/S0025-3227\(03\)00352-9](https://doi.org/10.1016/S0025-3227(03)00352-9)
695
696 Goto, K., Okada, K., Imamura, F., 2009. Characteristics and hydrodynamics of boulders
697 transported by storm waves at Kudaka Island, Japan. *Mar Geol.* 262, 14–24.
698 <https://doi.org/10.1016/j.margeo.2009.03.001>
699
700 Goto, K., Miyagi Kawamata, H., Imamura, F., 2010. Discrimination of boulders deposited by
701 tsunamis and storm waves at Ishigaki Island, Japan. *Mar Geol.* 269, 34–54.
702 <https://doi.org/10.1016/j.margeo.2009.12.004>
703
704 Harmelin-Vivien, M.L., 1994. The effects of storms and cyclones on coral reefs: a review. *J.*
705 *Coast. Rec. Spec. Issue 12, Coastal Hazards.* 12, 211-231.
706
707 Hosking, P. L., 1991. Geomorphology of reef islands and atoll motu in Tuvalu. *S. Pac, j. Nat.*
708 *Sci.* 11, 167-189.
709

710 Hyvernaud, O., 2009. Dislocations des barrières récifales occasionnées par un cyclone de
711 forte énergie. 11th Pacific Science Inter-Congress, Tahiti.
712

713 Jaffey, A.H., Flynn, K.F., Glendenin, L.E., Bentley, W.C., Essling, A.M., 1971. Precision
714 measurements of half-lives and specific activities of ²³⁵U and ²³⁸U. *Phys. Rev. C*, 4(5),
715 1889–1906.
716

717 Kench P.S., 2014. Developments in coral reef and reef island geomorphology.
718 *Geomorphology*. 222, 1-2. <https://doi.org/10.1016/j.geomorph.2014.05.018>.
719

720 Larrue S., Chiron T., 2010. Les îles de Polynésie française face à l'aléa cyclonique. *Vertigo*.
721 10, 3, URL : <http://vertigo.revues.org/10558>
722

723 Lau, A.Y., Terry, J.P., Ziegler, A.D., Switzer, A.D., Lee, Y., Etienne, S., 2016. Understanding
724 the history of extreme wave events in the Tuamotu Archipelago of French Polynesia from
725 large carbonate boulders on Makemo Atoll, with implications for future threats in the central
726 South Pacific. *Mar Geol*, 174-190. <https://doi.org/10.1016/j.margeo.2016.04.018>
727

728 Lecacheux, S., Bulteau, T., Pedreros, R., Delvallee, E., Paris, F., 2013. Évaluation
729 probabiliste des houles et des surcotes cycloniques en Polynésie française. BRGM ARAI3
730 report, 124p.
731

732 Marcade, C., 1915. Régime des vents et marche des cyclones dans les parages de l'archipel
733 des Tuamotu. Imprimerie Nationale, Paris, 27p.
734

735 May, S.M., Engel, M., Brill, D., Cuadra, C., Lagmay, A.M.F., Santiago, J., Suarez, J.K.,
736 Reyes, M., Bruckner, H., 2015. Block and boulder transport in Eastern Samar (Philippines)
737 during Supertyphoon Haiyan. *Earth Surf. Dynam.* 3, 543-558. <https://doi.org/10.5194/esurf-3-543-2015>
738
739

740 *Messenger de Tahiti*, 1854, Archipel des Paumotu – L'île d'Anaa, *Messenger de Tahiti*, 2 juillet
741 1854.
742

743 Moerenhout, J.A., 1837. *Voyages aux îles du Grand Océan*, Adrien Maisoneuve ed. (new ed.),
744 Paris, 318p.
745

746 Montaggioni, L.F., Baltassat, J.M., Le Cozannet, G., Innocent, Ch., Martin-Garin, B., Salvat,
747 B., 2022. Reef-rim structure and building history, Rangiroa, an uplifted Atoll, French
748 Polynesia: The role of morphotectonics and extreme marine hazard events. *Mar Geol*. 445,
749 106748. <https://doi.org/10.1016/j.margeo.2022.106748>
750

751 Montaggioni, L.F., Salvat, B., Pons-Branchu, E., Dapoigny, A., Martin-Garin, B., Poli, G.,
752 Zanini, J.M., Wan, R., 2023. Mid-late holocene accretional history of low-lying, coral-reef
753 rim islets, South-Marutea Atoll, Tuamotu, central South Pacific: The key role of marine
754 hazard events, *Nat. Hazards Research*. <https://doi.org/10.1016/j.nhres.2023.02.004>
755

756 Nott, J., 2004. The tsunami hypothesis—Comparisons of the field evidence against the effects
757 on the western Australian coast, of some of the most powerful storms on Earth. *Mar Geol*.
758 208, 1-12. <https://doi.org/10.1016/j.margeo.2004.04.023>
759

760 Ottino, P., 1965. Ethno histoire de Rangiroa. Centre O.R.S.T.O.M., Papeete.
761
762 Parks Camp, J., Montgomery, M.T., 2001. Hurricane maximum intensity: Past and present.
763 *Mon Weather Rev.* 129, 1704-1717. [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0493(2001)129<1704:HMIPAP>2.0.CO;2)
764 [0493\(2001\)129<1704:HMIPAP>2.0.CO;2](https://doi.org/10.1175/1520-0493(2001)129<1704:HMIPAP>2.0.CO;2)
765
766 Pirazzoli, P.A., Montaggioni, L.F., Salvat, B., Faure, G., 1988. Late holocene sea level
767 indicators from twelve atolls in the central and eastern Tuamotu (Pacific Ocean). *Coral Reefs.*
768 7, 57–68. <https://doi.org/10.1007/BF00301642>
769
770 Pons-Branchu, E., Douville, E., Roy-Barman, M., Dumont, E., Branchu, E., Thil, F., Frank,
771 N., Bordier, L., Borst, W., 2014. A geochemical perspective on Parisian urban history based
772 on U-Th dating, laminae counting and yttrium and REE concentrations of recent carbonates in
773 underground aqueducts. *Quat Geochronol.* 24, 44–53.
774 <https://doi.org/10.1016/j.quageo.2014.08.001>
775
776 Ricard, M., 1985. Rangiroa Atoll, Tuamotu Archipelago. *Proc Fifth Int. Coral Reef Congr.*
777 *Tahiti 1*, 161-209.
778
779 Shaw, T.A., Baldwin, M., Barnes, E.A., Caballero, R., Garfinkel, C.I., Hwang, Y.T., Li, C.,
780 O’Gorman, P.A., Rivière, G., Simpson, I.R., Voigt, A., 2016. Storm track processes and the
781 opposing influences of climate change. *Nature Geosci.* 9, 656–664.
782 <https://doi.org/10.1038/ngeo2783>
783
784 Sladen, A., Hebert, H., Schindele, F., Reymond, D., 2007. Evaluation of far-field tsunami
785 hazard in French Polynesia based on historical data and numerical simulations. *Nat. Hazards*
786 *Earth Syst. Sci.* 7, 195-206. <https://doi.org/10.5194/nhess-7-195-2007>
787
788 Stoddart, D.R., Walsh, R.P.D., 1992. Environmental variability and environmental extremes
789 as factors in the island ecosystem. *Atoll Res Bull*, 356, 1–71.
790
791 Terry, J.P., Lau, A.A.Y., Etienne, S., 2013. Reef-platform coral boulders. Evidence for High-
792 Energy Marine Inundation Events on tropical Coastlines. Springer, 103p.
793 <https://doi.org/10.1007/978-981-4451-33-8>
794
795 Terry, J.P., Goff, J., 2014. Megaclasts: proposed Revised Nomenclature At the Coarse End of
796 the Udden-Wentworth Grain-Size Scale for sedimentary particles. *J Sediment Res.* 84, 192–
797 197. <https://doi.org/10.2110/jsr.2014.19>
798
799 Terry, J.P., Etienne, S., 2014. Potential for timing high-energy marine inundation events in the
800 recent geological pas through age-dating of reef boulders in Fiji. *Geosci. lett.* 1, 14.
801 <https://doi.org/10.1186/s40562-014-0014-8>
802
803 Terry, J.P., Dunne, K., Jankaew, K., 2016. Prehistorical frequency of high-energy marine
804 inundation events driven by typhoons in the bay of Bangkok (Thailand), interpreted from
805 coastal carbonate boulders. *Earth Surf. Process Landforms.* 41, 553–562.
806 <https://doi.org/10.1002/esp.3873>
807
808 Woodroffe, C.D., Biribo, N., 2011. Atolls. In: Hopley, D. (Ed.), *Encyclopedia of Modern*
809 *Coral Reefs. Encyclopedia of Earth Sciences Series.* Springer, Dordrecht, pp. 51–71.