

Limitations to U/Th dating of reef-platform carbonate boulders produced by high-energy marine inundations in the Tuamotu Archipelago (French Polynesia)

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Abstract On intertropical coastlines, coral boulders located on the reef platform are often used to characterize high-energy marine inundations of the past. Precise U/Th coral dating provides opportunities to assess the timing and recurrence of these events. However, this method of dating is subject to several limitations, as revealed by studying live coral cover at five islands in French Polynesia, since the early 1990s. We show that live coral assemblages experience very different changes within the islands of the same archipelago. Moreover, our observations show that the passage of a cyclone causes almost complete disappearance of the most recent coral in the coral boulder formation zone. This analysis shows that the probability of taking coral samples that were alive on the day of the high-energy marine inundation is extremely low. We have clarified the limitations of this method based on the dating of coral assumed to be alive on the day of the well-

documented high-energy marine inundation of 1903 AD. The dating of 24 samples taken from 22 boulders from 3 islands of the Tuamotu Archipelago shows that important parts of the coral were dead when displaced by the marine inundations, thereby overestimating the timing of the disturbance event. As such, U/Th coral dating has limited application for establishing the precise timing for high-energy marine inundations with a return period of less than a century, but may be useful for exploring infrequent and extreme events such as the cyclone that ravaged the Tuamotu atolls in 1903. Indeed, we observed that this cyclone is the one that produced the world's largest reef-platform coral boulders (more than 100 m³). We also provide evidence of an earlier event in the center of the Tuamotu Archipelago, during the middle of the first century AD.

Keywords Coral cover · Storm surge · Tropical cyclone · Boulders · Dating · South Pacific

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Introduction

High-energy marine inundation boulder research

Over the last fifteen years, dating of high-energy marine inundations (HEMIs) has seen renewed interest. This field of research became particularly popular after the major tsunamis affecting Indonesia (2004) and Japan (2011) and following the growing media coverage of storm surges on the US coastline (cyclones Katrina in 2005 and Sandy in 2012).

HEMIs can be analyzed with a variety of increasingly reliable methods (e.g., remote sensing) as well as recurrent observations (e.g., May et al. 2015). Nevertheless, in order to know more about the recurrence and importance of

HEMIs, it is necessary to extend the observation period. The analysis of centuries-old events requires the use of other methods. In many areas, written records are limited to a relatively recent period (after the sixteenth century) and are often incomplete and heterogeneous. Oral tradition can sometimes provide interesting information, but the completeness and accuracy of such evidence are difficult to validate.

The analysis of sediments displaced by HEMIs provides an opportunity to further establish the timing and causes of specific HEMIs. Indeed, major submersions produce and displace sediments on the coastline. In the most intense HEMIs, blocks of several cubic meters can be torn off the reef barrier. They are then moved by wave-generated run-up, sometimes over several hundred meters. The movement of blocks of more than 75 m³ has been observed in the Philippines during a cyclonic swell (May et al. 2015). These blocks have stability over time which makes them particularly interesting for the analysis of ancient HEMIs (Terry and Etienne 2014). In tropical regions where these blocks often consist of coral substrate, they can be dated, providing insights into the recurrence of extreme events. Current research on HEMIs is organized around three main themes: (1) Goto et al. (2009) and Etienne et al. (2014) attempt to determine the intensity of HEMIs (velocity of currents, height of water) from size, shape and position of the blocks, (2) Goto et al. (2010), Engel and May (2012) and Terry et al. (2013) focus on identifying the cause of the HEMIs (cyclone or tsunami), (3) Terry and Etienne (2014), Lau et al. (2016), Terry et al., (2016) explored the recurrence of extreme events based on dating of HEMIs. The purpose of this study is to assess the application and limitations of using U/Th (uranium/thorium) dating of coral samples, as applied to HEMIs.

Reef-platform carbonate boulder dating and HEMI returning period

In intertropical zones where blocks are identified as reef-platform carbonate boulders (RPCBs), geomorphologists use a range of different methods to date HEMIs. These methods are based on the dating of coral present on the youngest face of the blocks. U/Th dating is particularly suited for these studies, with the possibility of precise coral age determination from a few years to 500,000 yrs. It consists of dating the coral that is believed to be alive at the time the block was formed. Indeed, once out of the water the coral dies, and its death thus records the date of the HEMI with great precision.

Given high levels of precision, it would be theoretically possible to distinguish two different HEMIs, separated by about a decade that occurred hundreds of years ago. Accordingly, some research suggests the existence of

HEMIs separated from a few years to a few decades in regions that are rarely impacted by cyclones (e.g., Lau et al. 2016). However, we believe that these analyses may be spurious due to sampling limitations and unknown deviation of dated age. Potential sources of error that could lead to erroneous dating include: (1) the specific nature of dated elements, (2) the position of blocks (upright or inverted), (3) the original coral recovery rate (percentage of seabed consisting of living coral) and (4) the alteration of RPCBs caused by the HEMI and those produced after settlement.

Sampling limitations

When sampling for dating, several problems arise, especially given the typically very small sample sizes due to the relatively high cost of dating. Indeed, RPCBs aged from several tens of years to several millennia are often strongly altered making it difficult to distinguish the nature of the samples taken (Fig. 1).

A first difficulty arises from the exact nature of the dated element. Some coral has a rapid growth (several centimeters per year) and could theoretically record the date of HEMIs with great precision. These branching corals are often very fragile, and it is very unlikely that they can have resisted the HEMI and the displacement of the block. The coral still available on the surface of the RPCBs is thus essentially made of massive coral with slow growth. Some coral and living organisms grow so slowly that a sampling made a few centimeters away from another (on the same marine organism) can lead to time lags of several decades.

A second difficulty arises from the fact that RPCBs have often been overturned several times at the time of settlement, and many of them are therefore inverted. Identification of the top and bottom is essential since the age of the coral can vary by several centuries per meter (Terry and Etienne 2014). Fortunately, it is relatively easy to identify the position of large RPCBs in order to take the sample on the most recent face.

A third weakness is that the coral cover in the area of origin of RPCBs is never 100% alive at the time the HEMI occurs. Once the block is settled, it is impossible to assess whether a coral colony was still alive on HEMI day or if it had already been dead for decades or centuries. By taking samples on the recent face of the blocks in a random manner, there is therefore a high risk of dating the coral that had died several years before the HEMI occurred.

Finally, the RPCBs are made up of an assemblage of corals. They can thus easily break and their surface is subject to considerable erosion during HEMIs (slippage and/or rotation). This fragility poses a major problem for sampling, since the most recent surface coral may be grated down by tens of centimeters during its displacement

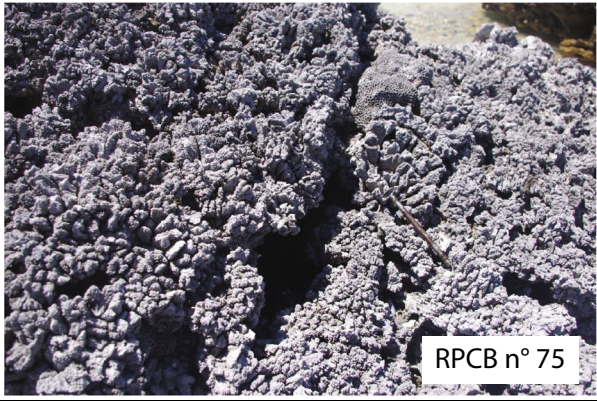

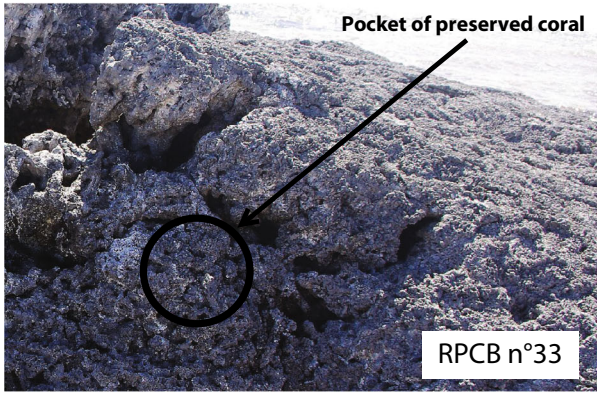

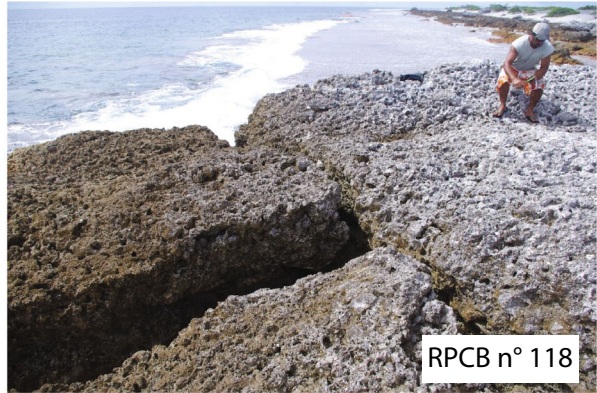



	Youngest face appearance	Main features	Sample examples
VERY GOOD		<ul style="list-style-type: none"> - Preserved coral dominant (unbroken coral colonies) - Extensive diversity of coral colonies available for sampling 	 <p>RPCB n° 75</p>
GOOD		<ul style="list-style-type: none"> - Deteriorated coral colonies dominant - Pockets of preserved coral colonies - Limited diversity of coral colonies available for sampling 	 <p>RPCB n° 33</p>
DEGRADED		<ul style="list-style-type: none"> - Coral colonies deteriorated in the totality of the face (top decapitated) - Unidentifiable coral colonies 	 <p>RPCB n° 118</p>
VERY DEGRADED		<ul style="list-style-type: none"> - Inverted boulders - Very limited choice for sampling - Post-HEMI contamination of samples probable 	 <p>RPCB n° 128</p>

Fig. 1 RPCB surface quality nomenclature for U/Th dating

(friction with the ground) or when the block is subjected to regular wave action after its positioning.

Given these pitfalls, samples taken from RPCBs rarely yield precise dates of HEMIs. We propose to specify the limits of this method by studying the live coral assemblages on reef and the alteration of superficial parts of RPCBs during HEMIs and after their displacement.

Materials and methods

We compared two methods to evaluate the capacity of coral samples to determine the date of RPCB formation. The first method consists in analyzing changes in live coral assemblages over several years in the block's formation zone. The second is to date 24 coral samples taken from the recent surface of 22 coral blocks from three atolls of the Tuamotu Archipelago (French Polynesia).

Living Coral Cover (LCC) changes in French Polynesia

Live coral assemblages

We used data from the Polynesia Mana network collected by the CNRS-CRIOBE laboratory in order to explore changes in LCC. The laboratory has been tracking coral assemblages since the late 1970s on the island of Moorea. Since the 1990s, surveys were conducted every 2 yrs and were extended to many other islands within French Polynesia. Surveys involve a combination of fixed (permanent) and random transects, but only data from fixed transects were used in this study. Fixed transects are 20 m and delineated with stakes. During surveys, a cable is positioned between stakes, and coral surveyed within a 1-m² quadrat fixed to the cable. Fixed transects are located on outer slope at depths of 5–20 m which is precisely the RPCB formation zone (Fig. 2). All quadrats along fixed transects are photographed during each survey. We analyzed these photographs and quantified live coral cover based on proportion of fixed points (81 per quadrat) that intersected live corals. The sampling sites are located on the North, the West or the North-West coasts of the islands.

Living Coral Cover sites characteristics

In February 2010, Cyclone Oli directly impacted western French Polynesia. The swell reached 4 m in Tikehau, 7 m on the north coast of Moorea and 12 m in Tubuai (Canavesio et al. 2014) where a major HEMI was observed (Etienne 2012). The Tikehau atoll (Tuamotu) was also hit simultaneously by two major swells at the end of January 1998 (Duvat et al. 2017) producing a destructive swell at

the studied site. The last two islands (Takapoto and Nengonengo) experienced no major swells over the period.

By studying temporal changes in live coral cover, we explored the capacity of extreme swells to alter coral reef habitats as well as the time required for recovery of coral assemblages after a cyclone. In this way, we can evaluate the reliability of the dating performed on samples taken on coral surfaces having undergone one or more major swells.

Verification: U/Th coral boulder dating in Tuamotu Archipelago

After studying the LCC in the RPCB formation zone, we analyzed the results of several datings made on blocks from three atolls in the Tuamotu Archipelago. To evaluate the reliability of the results obtained by the U/Th method, it is necessary to perform some analysis on blocks of which the date of installation could be known with certainty.

RPCBs source

The observations recorded in archives since the European presence and the collective memory of the inhabitants suggest that tsunamis were not causes of HEMIs in the Tuamotu Archipelago (Etienne 2012). Both numerical modeling and observations (Sladen et al. 2007) demonstrate that the atolls of this archipelago received small waves from far-field tsunamis. Cyclones are therefore the only known origin of blocks in this area.

Cyclones can produce gigantic swells but are much smaller than high-latitude storms due to a particularly narrow wind gradient (Holland 1980). Around the center of the cyclone, the radius in which the swell exceeds ten meters reaches 200 km (Lecacheux et al. 2013). Observations carried out on a global scale suggest that beyond this distance, the movement of blocks exceeding 10 m³ is very unlikely.

In order to determine whether or not a cyclone has been able to produce RPCBs, we believe that it is therefore necessary to know the precise trajectory and intensity of the cyclones. This is particularly important in an archipelago like the Tuamotu Archipelago, measuring about 2000 km from east to west. Indeed, numerical modeling (Lecacheux et al. 2013) and field observations (Marcade 1915; Dupon 1984) have shown that a cyclone over the western Tuamotu Archipelago could have almost no effect on the eastern part of the archipelago, and vice versa. Enormous differences can even occur on an island-wide scale depending on the orientation of the coast and the shadow effects of neighboring islands (Andrefouët et al. 2012).

To identify the HEMI that produced the blocks that we dated, it was necessary to determine the trajectory of the

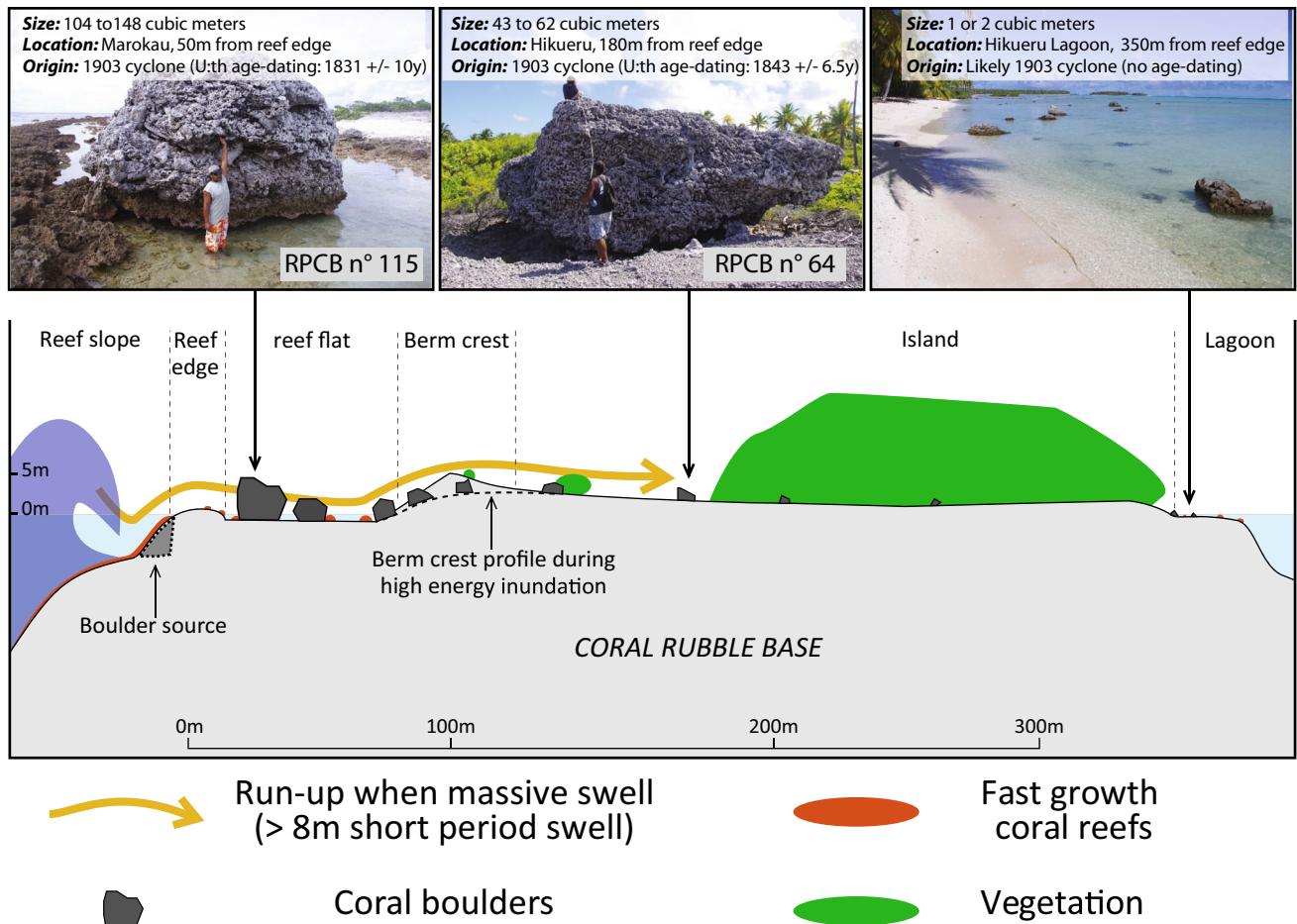


Fig. 2 Profile and zonation of a cyclonic boulder field in the Tuamotu Archipelago

cyclones in the Tuamotu Archipelago before satellite observation.

Historical cyclone records

It is possible to identify the trajectory of cyclones in French Polynesia for the last two centuries by consulting different archives and calling upon collective memory. We consulted the territorial archives in Tahiti and the French colonial archives to clarify the intensity and the trajectory of cyclones prior to the 1970s. Between the 1820s and the 1860s, increased relations with Europe and the USA (scientific missions, evangelism, early colonization and whaling) provided frequent observations over a large spatial scale. According to Buck and Hiroa (2013), 5 British scientific trips took place in the Tuamotu Archipelago between 1800 and 1837. In addition, 5 French scientific expeditions were financed between 1822 and 1840 (Blais 2005). Moreover, from 1863 onward, a population census became regular in the Tuamotu Archipelago, indicating close administrative control. Finally, the archives accumulated in the context of evangelization (since 1797),

scientific exploration (since 1800) and French colonization (from 1842) offer a thorough census of high-intensity climatic events since the beginning of the nineteenth century.

In the Tuamotu Archipelago (Fig. 3), the frequency of cyclones is extremely low, especially in the east. According to the NOAA hurricane world tracks database, only one cyclone has passed through the westernmost islands of Tuamotu Archipelago over the last 25 yrs. Since the beginning of satellite observation, no cyclone has passed through the center of the archipelago.

Archives corroborate observations made since the early 1970s concerning the frequency, the trajectory (North–South to the Tuamotu) and the intensity (that can reach “category 5” on the Saffir–Simpson scale (Simpson 1974)) of cyclones in the Tuamotu Archipelago. While 7 cyclones have directly affected at least part of the archipelago during the last century (1917–2017), we have been able to trace the approximate trajectory of an additional 5 cyclones during the previous century.

The first known cyclone in the Tuamotu Archipelago was in 1822 (Moerenhout 1837), which strongly affected the atoll of Anaa (Ellis 1831; Moerenhout 1837). In 1878,

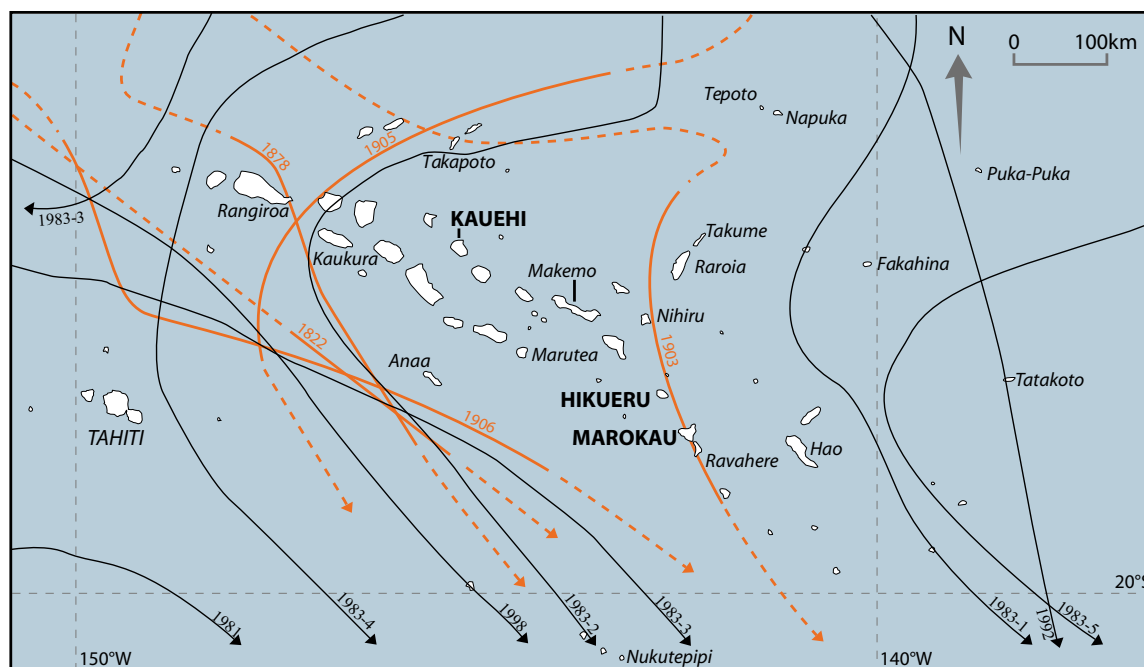


Fig. 3 Cyclones in the Tuamotu Archipelago since the beginning of the nineteenth century. Cyclones whose trajectories were identified by satellites are shown in black. Older cyclones are represented by red

lines. The red dotted lines indicate the trajectory when the uncertainty is greater than 100 km. Atolls from which the dated samples originate are written in bold

another major cyclone hit the westernmost atolls of the archipelago again (Marcade 1915). In 1903, an extremely intense cyclone crossed the center of the Tuamotu Archipelago, killing more than 500 inhabitants. In 1905 and then again in 1906, two cyclones again massively affected the western Tuamotu Archipelago. During the cyclone of February 1906, the swell was over 16 m at Anaa (Canavesio 2014).

Wave-deposit boulders in Tuamotu Archipelago: a review

The establishment or movement of blocks in different Tuamotu islands is well documented during the last two centuries. The earliest writings mention a cyclone in 1822 that displaced enormous coral boulders on Anaa (Morenhout 1837). In the numerous archives consulted, however, there were no RPCBs that were displaced by the cyclone in 1878, although this does not necessarily mean that none were produced. They might just not have been noted by observers. At the beginning of the twentieth

century, several studies and reports corroborate the establishment of blocks as in Raroia (Giovanelli 1940; Stoddart and Walsh 1992) and Marokau (Segalen 1903) during the cyclone in 1903, in Kaukura during the 1905 cyclone (Marcade 1905), or in Rangiroa during the 1906 cyclone. More recently, blocks have also been set upon or displaced on Takapoto (Sachet 1983), Nukutepipi (Salvat and Salvat 1992) and Anaa (Etienne et al. 2014) during the unusually intense cyclone season of 1983. RPCBs are rarely georeferenced and are sometimes added to preexisting block fields disturbed by recent cyclones. These uncertainties make it difficult to clearly determine the HEMI that caused each of the blocks to come out of the water.

Although written records do not extend back to the end of the eighteenth century, RPCBs suggest the occurrence of at least two prehistoric HEMIs. Indeed, ¹⁴C dating suggests the occurrence of an HEMI in the eastern Tuamotu Archipelago between 2007 BC and 768 AD (Pirazzoli et al. 1988) and another HEMI in the western part of the

archipelago in the seventeenth or eighteenth century (Hyvernaud 2009).

Sampling choice

Cyclone mapping (Fig. 3) shows that the center of the Tuamotu Archipelago was affected only once by a cyclone during the last two centuries (1903). According to the information derived from De Precaire (1903) and Palmer (1903) at two different points of the atoll, this cyclone hits Marokau with full force after the eye of the cyclone had traveled along the east coast of Hikueru (Fig. 4) in the afternoon of January 15th. Due to the absence of cyclones in central Tuamotu between the beginning of the nineteenth century and 1903, we consider that any large block (several tens of cubic meters) located on atolls in the central Tuamotu Archipelago, dating between the beginning of the nineteenth century and 1906, could be attributed only to the cyclone in 1903 or, for some coastlines exposed to western swells (western coasts of Hikueru and Marokau; RPCBs 74 and 75), to the cyclone in 1906.

Based on this observation, we inquired about the presence of coral boulders in these islands. Google Earth images show the presence of mesoboulders (according to Terry and Goff (2014) megaclast scale) in most of the atolls in the central Tuamotu Archipelago. Five atolls have particularly impressive boulder fields, each on the eastern and northeastern coasts (Nihiru, Marutea, Hikueru, Marokau and Ravahere). It was, however, not possible to gather samples in each of these islands.

We focused on Hikueru and Marokau because their history is particularly well known. Indeed, Hikueru was the economic center of the Tuamotu Archipelago in the nineteenth century because of mother-of-pearl fishing. Moreover, the cyclone in 1903 was extremely dangerous in these atolls (377 deaths in Hikueru and 96 deaths in Marokau). For Hikueru, we also have photographs (Fig. 4) of the

disaster as evidence of the extreme violence of the HEMI, while a text by Victor Segalen (1903) clearly evokes the appearance of RPCBs on the coasts of Marokau:

The next morning, across from Marokau, our second stage, it is once again the immutable horizontal setting. Unfortunately, too, the resemblance is accentuated as well in the saddest of details: graveyard sediment again left by the hurricane. Desolation is amplified by the disappearance of every living being (...). Enormous blocks have rolled over onto the coral; new dunes have appeared; the pass is blocked, the landscape renewed. (Segalen, to the victims, p76, author translation).

Based on this testimony, we were hopeful of dating RPCBs set up by the 1903 cyclone in the Marokau and Hikueru atolls. In March 2015, we conducted a mission to study the particularly large and voluminous blocks on the North and East coasts of these two atolls. Sixty-three blocks were measured on Hikueru. Samples were taken from 15 boulders, and six datings were made from these samples, two from the largest of these blocks (RPCB 33). On the Marokau atoll, we also measured 63 boulders and took samples on 13 of them. Nine datings were carried out, each time on different blocks.

Finally, in March 2016 we carried out a second mission in Kauehi where comparable RPCBs had been identified using Google Earth. In this atoll, the blocks are concentrated on the North coast, close to the airport. We measured 37 boulders and collected samples from 16 of them. Nine datings were carried out, and two of them came from the largest block (RPCB 160). By dating the Kauehi boulders whose date of establishment is unknown, but prior to the nineteenth century, we wanted to evaluate the RPCB alteration rhythm from when they were put into place and the consequences of alterations on the preciseness of the dating method.



Fig. 4 Damage caused by the 1903 cyclone to Hikueru and Raroia (source: French Polynesia Archives)

As boulder fields can be the result of several events throughout centuries, we selected samples from blocks that, because of their size and their distance from the reef (Fig. 5), seemed to have been set up by the same HEMI (the most intense). We measured an average value of boulder axes in the field. Because accurate measurements (Gienko and Terry 2014) of boulder volumes have demonstrated that volumes of boulders are only a fraction of those estimated using rectangular geometry, a correction factor of 0.7 was used to calculate the volume of the boulders.

We were able to clearly identify the direction of the blocks on which we took samples, and we always collected samples on the youngest face of the blocks devoid of incrusting material. We favored boulders positioned upright because it is easier to identify and to choose the samples. Among these upright RPCBs, we selected those that were most reliable according to the criteria of reliability presented in figure two. Each time, we tried to take samples from the corals that seemed to be the most recent.

Finally, apart from two samples (RPCBs 108 and 128) from inverted boulders that were judged to be unreliable, we found surfaces that were favorable to performing a sampling of good quality, or very good quality (see Fig. 1). In total, we then dated 24 samples from 22 different blocks (Table 1).

Coral dating

Uranium–thorium analyses were performed at the Laboratoire des Sciences du Climat et de l'Environnement in Gif-sur-Yvette (France). Small skeleton fragments were extracted and mechanically cleaned using a micro-saw. They were then ultrasonicated in mQ water. After adding the triple ^{229}Th ^{233}U – ^{236}U spike in a Teflon beaker, the clean samples were dissolved with diluted HCl. The U and Th fractions were separated using UTEVA resin (Eichrom Technologies), following the procedure described in Pons-Branchu et al. 2014. Approximately 200–600 mg of coral fragment was used for each U–Th analysis.

Fig. 5 Location, distribution and sampling areas on Hikueru, Marokau and Kauehi atolls

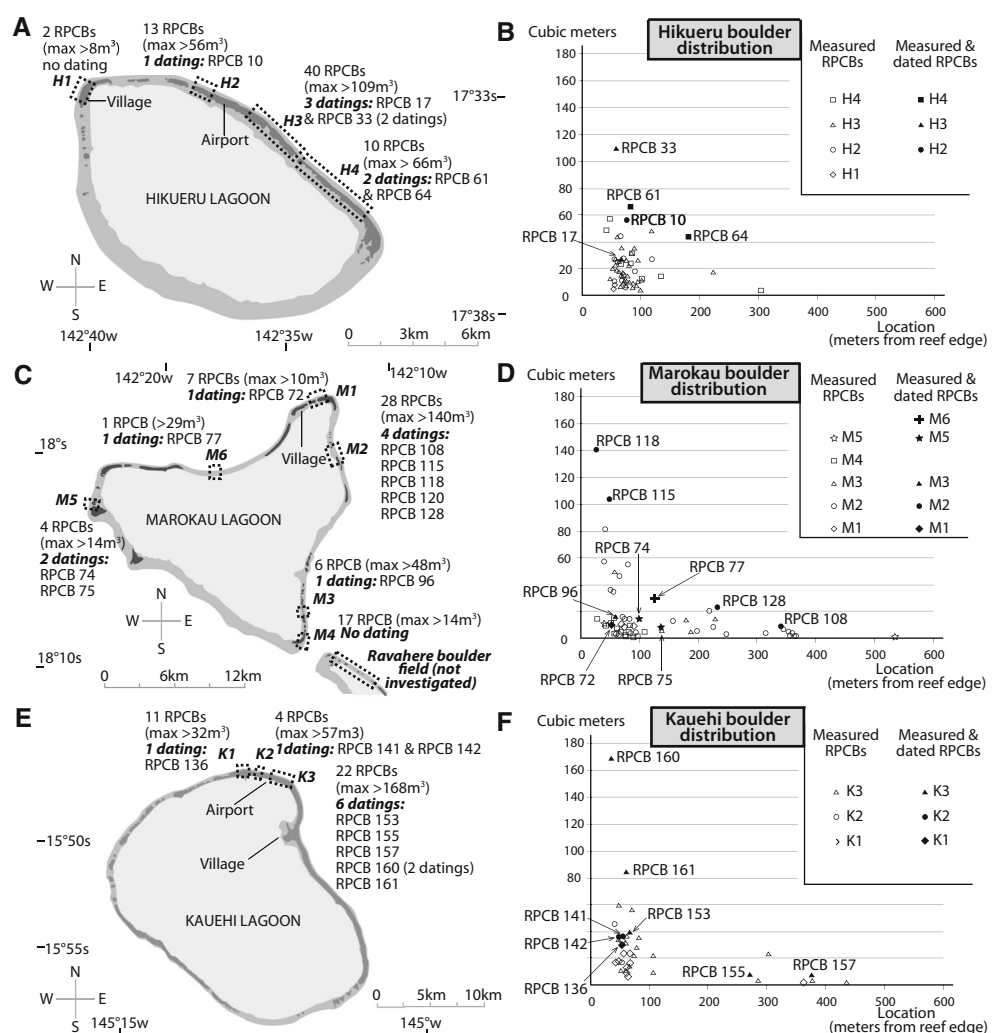


Table 1 Coral mortality age and features of RPCBs from Hikueru, Marokau and Kauehi

Sample RPCB number	$[^{238}\text{U}]^b$		$[^{232}\text{Th}]$		$\delta^{234}\text{U}_M^b$		$(^{230}\text{Th}/^{238}\text{U}^b)$		$(^{230}\text{Th}/^{232}\text{Th})$		$\delta^{234}\text{U}^{b0}$		Corrected ^a ages	
	ppm	±	ppb	±	(‰)	±	±	±	±	(‰)	±	Yrs	±	
10	2.883	0.003	0.021	0.00008	146.8	1.1	0.0018	0.0001	741	30	146.9	1.1	171	8
17	2.928	0.003	0.025	0.00008	144.8	0.6	0.0016	0.0001	593	23	144.8	0.6	155	7
33	2.955	0.003	0.010	0.00004	145.8	1.0	0.0015	0.0001	1330	48	145.8	1.0	141	6
33	2.956	0.003	0.012	0.00005	146.4	0.7	0.0016	0.0001	1274	53	146.5	0.7	156	7
61	2.940	0.007	0.060	0.00009	146.9	1.3	0.0025	0.0001	364	14	147.0	1.3	233	12
64	2.627	0.003	0.021	0.00005	147.0	1.4	0.0018	0.0001	683	25	147.1	1.4	174	6.5
72	3.116	0.003	0.021	0.00004	146.2	1.1	0.0019	0.0001	867	28	146.2	1.1	179	6.5
74	2.605	0.003	0.008	0.00002	146.8	1.0	0.0013	0.0000	1288	39	146.9	1.0	126	5
75	2.652	0.003	0.021	0.00006	147.6	0.7	0.0013	0.0001	493	25	147.6	0.7	121	7.5
77	3.046	0.004	0.015	0.00005	148.2	1.2	0.0016	0.0001	856	66	148.3	1.2	148	9.5
96	3.154	0.002	0.005	0.00006	147.5	0.8	0.0014	0.0001	2614	105	147.5	0.8	131	5.5
108	2.440	0.002	0.102	0.00012	146.3	1.2	0.0158	0.0001	1236	9	146.9	1.2	1508	17
115	2.865	0.006	0.028	0.00028	146.4	1.1	0.0019	0.0001	1996	30	146.5	1.1	185	10
118	2.365	0.002	0.047	0.00014	146.8	1.2	0.0040	0.0001	661	11	146.9	1.2	382	9
128	2.564	0.002	0.038	0.00008	145.8	0.9	0.0041	0.0001	843	20	145.9	0.9	390	12
136	3.149	0.025	0.011	0.0001	146.5	0.8	0.0215	0.0001	19417	78	147.3	0.8	2063	11
141	2.796	0.026	0.012	0.0001	148.3	1.9	0.0206	0.0002	14848	137	149.2	1.9	1976	23
142	2.849	0.025	0.028	0.0002	144.2	1.3	0.0220	0.0001	6742	42	145.1	1.3	2115	17
153	3.668	0.032	0.027	0.0002	143.7	1.5	0.0219	0.0002	9007	100	144.5	1.5	2105	28
155	3.373	0.030	0.021	0.0002	144.8	1.3	0.0205	0.0001	9932	43	145.6	1.3	1971	13
157	3.676	0.030	0.024	0.0002	144.2	1.3	0.0214	0.0001	10293	44	145.1	1.3	2065	13
160	3.039	0.025	0.020	0.0002	145.6	1.5	0.0218	0.0001	10183	28	146.4	1.5	2093	9
160	3.320	0.027	0.028	0.0002	145.1	1.1	0.0209	0.0001	7635	21	145.9	1.1	2010	8
161	2.704	0.022	0.019	0.0002	145.5	1.0	0.0211	0.0001	9414	52	146.3	1.0	2031	14

^aCorrected ages are expressed as age (in year) before measurement (2016–2017). Ages were corrected assuming an initial activity ratio of $^{230}\text{Th}/^{232}\text{Th} = 7 \pm 50\%$

^b $^{234}\text{U}/^{238}\text{U}$ ratios are expressed as: $\delta^{234}\text{U} = ((^{234}\text{U}/^{238}\text{U})_{\text{activity}} - 1) \times 1000$

The U and Th isotopic compositions were analyzed on the Neptune Plus Plasma multi-collector inductively coupled plasma mass spectrometer. In order to measure uranium and thorium isotopes during the same analysis, we mixed fractions of the uranium and thorium purified fractions in order to obtain a 229 signal between 2 and 10 mV, and 238 between 3 and 15 volts on Faraday cups. In a few cases, low 229 signals were analyzed of ion counter. For U and Th mass fractionation correction, we used an exponential mass fractionation law (to natural $^{238}\text{U}/^{235}\text{U}$ isotopic ratio) and standard/sample bracketing (using a mixture between our triple spike and Hu-1).

Results

Living Coral Cover (LCC) changes

Living Coral Cover changes (general remarks)

Submarine photographs taken since the early 1990s show that LCC varied greatly over time and space. These variations result from heterogeneous ecological (coral predators), climatic (water temperatures) and hydrodynamic (exposure to swells) conditions, even within the same archipelago.

On the outer slope of the Takapoto and Nengonengo atolls, LCC varied from 12.1% (Takapoto in 1998) to 32.22% (Takapoto in 2008). Of the five sites studied, the maximum LCC ranges from 43.58% in Moorea (2004) to 25.43% in Tubuai (2005). Reefs with major coral mortality

crises (strong swells, bleaching, etc.) have all had extremely low minimum values in some years (less than 1%).

These results are in line with what has been observed in Indo-Pacific archipelagos (Bruno and Selig 2007). Moreover, underwater photographs taken at the same place of the reef every 2 yrs show that in the RPCB formation area most of the coral cover is composed of corals that have been dead (gray color) for more than a decade.

Impacts of cyclone swell on coral cover

The photographs of the reef made before and after the passage of a cyclone (Fig. 6) on a strictly identical zone show that the cyclonic swell renders the underwater landscapes totally unrecognizable. Down to 40 m (Bourrouilh and Talandier 1985; Harmelin-Vivien 1994; Etienne 2012), the swell tears, breaks and moves the vast majority of corals. The most recent colonies on the surface of the reef were the most vulnerable to this destruction. After the cyclone, the underwater landscapes were so transformed that the photographs did not make it possible to precisely quantify the part of the surfaces (consisting of dead or living coral before the cyclone) that resisted the swell. In Moorea and Tubuai, less than 1% of the surface was made up of living coral after cyclone Oli (February 2010).

Figure 7a also shows that the time required to recover LCC above 25% varies greatly from site to site. While it took only 6–7 yrs for the Moorea and Tikehau reefs to exceed this threshold, the Tubuai reef is still composed of less than 2% of living coral 7 yrs after cyclone Oli.

U/Th dating results in Hikueru, Marokau and Kauehi

General remarks

The 24 dates obtained (Table 2) confirm and specify the limits of the HEMI dating method by the U/Th dating of selected samples on the most recent surface of RPCBs. The dates obtained are between 98 BC and 1895 AD. They show two groups of samples of roughly similar ages (Fig. 8).

The datings of the most recent group are dispersed over a period of 111 yrs (1784 AD to 1895 AD). This group is composed of the majority (12/15) of the samples taken from Hikueru and Marokau. This group consists mainly of all the samples from these islands, the reliability of which is judged good to very good. Eleven of the twelve samples that make up this group are after 1830. These eleven samples are therefore dated from a period in which the history of the two atolls is well known. Given the size and position of these blocks, we can say that these eleven blocks were put into place by the cyclone of 1903. The twelfth sample of this group (1784 AD) is too old to belong to the period in which the history of these islands is known in detail. However, we think that this RPCB has been very highly likely produced by the same cyclone. Finally, we note that the closest date to the event obtained is 8 yrs distant (before) from the date of the cyclone.

The oldest group (98 BC to 46 AD) consists of all nine samples from Kauehi. This boulder group of the same age (datings dispersed over 144 yrs) is very likely to have been produced by the same event. The precise date of this HEMI cannot be defined with certainty in the absence of historical sources. Having achieved a relatively high number of datings on blocks produced by this HEMI, we can

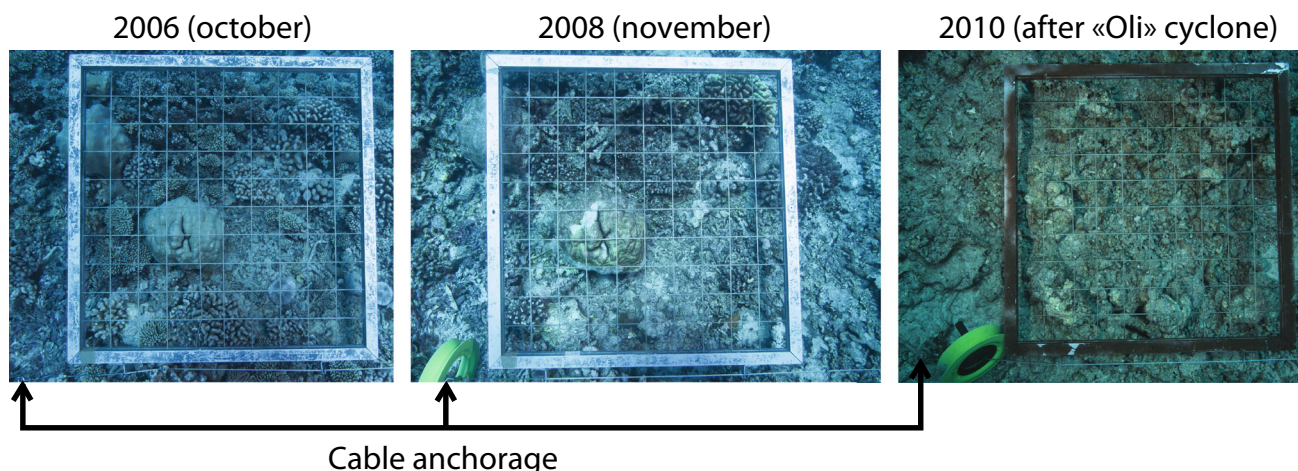
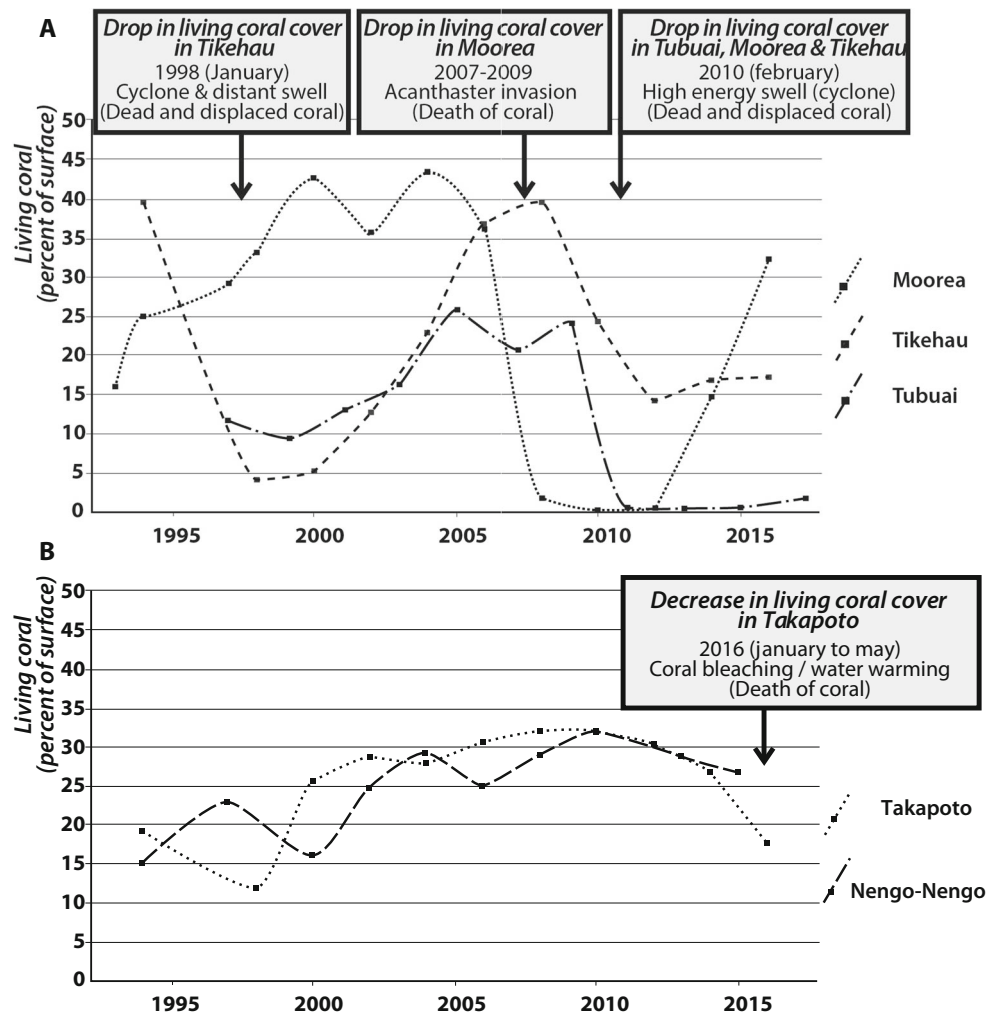


Fig. 6 Living coral cover photographs (same part of reef outer slope) before and after the *Acanthaster planci* invasion (2006/2008) and before and after a 7-m swell (2008/2010)

Fig. 7 Changes in the living coral cover on the outer slope (5–20 m depth) of French Polynesian islands since the beginning of the 1990s. The bottom graph (7B) represents this change in islands without high mortality episodes, whereas the top one (7A) shows this change in islands having experienced massive episodes of mortality



nevertheless propose (logically) that the most recent date we have obtained must be relatively close to the actual date of the event. We estimated the date of 54 AD for this event, based on the 8-yr lag observed between the cyclone of 1903 and the most recent date obtained for Hikueru and Marokau.

In addition, three samples from Marokau produced very different datings from those of these two groups. Two of these samples (RPCBs 108 and 128) were taken from inverted coral boulders and are therefore considered to be very unreliable. The third sample (RPCB 118) is judged to be of degraded reliability. We note, however, that other samples whose quality was also rated as degraded produced results that were only slightly less accurate than the high-quality samples. Furthermore, the date of the sample produced by RPCB 118 (1634 AD) is extremely close to the one of RPCB 128 (1627 AD). It is therefore likely that a HEMI occurred on the east coast of Marokau in the middle of the seventeenth century.

Dating results dispersion for a known HEMI

In Hikueru and Kauehi, we dated two samples on the top face of the same boulder (for a total of four datings), the reliability of which was judged to be good. These samples demonstrate the variability from this type of dating (Figs. 8, 9).

On RPCB 33, set up by the cyclone of 1903, the two dates obtained (1860 and 1876) are spaced by 16 yrs and they increase the age of the HEMI from 27 to 43 yrs. In Kauehi where the exact date of the HEMI is not known, the two datings performed on RPCB 160 are spaced 82 yrs apart (75 BC and 7 AD). If we consider that the HEMI occurred in 54 (AD), this means that these datings increase the age of the HEMI from 47 to 129 yrs. These dates confirm the inconsistencies that had been revealed by the study of coral surfaces by underwater photography. Indeed, the datings performed on samples from boulders youngest faces vary by > 100 yrs. In the case where the dating is only performed on the blocks offering the best reliability (good and very good quality), the examples from Hikueru

Table 2 U and Th content, activity ratios and U–Th ages

RPCB number	Sampling area and GPS location	Dimension (m) (a-, b-, c- axis)	Volume ^a (cubic meters)	Distance from reef edge (m)	Orientation	Apparent sampling quality ^b	U–Th corrected age (yr)	Age Bp (2018)
10	H2 17°32'42.26"S/ 142°36'56.61"W	6.1 × 4.7 × 2.8	56	76	Right way up	Very good	1845 AD ± 8	173
17	H3 17°33'02.94"S/ 142°36'09.76"W	6.5 × 3.6 × 1.7	28	68	Right way up	Very good	1861 AD ± 7	157
33	H3 17°33'54.62"S/ 142°35'01.34"W	9.8 × 5.7 × 2.8	109	59	Right way up	Good	1876 AD ± 6	142
33	H3 17°33'54.62"S/ 142°35'01.34"W	9.8 × 5.7 × 2.8	109	59	Right way up	Good	1860 AD ± 7	158
61	H4 17°35'11.14"S/ 142°33'32.12"W	9.4 × 6.3 × 1.6	66	83	Right way up	Degraded	1784 AD ± 12	234
64	H4 17°35'22.38"S/ 142°33'23.15"W	6.5 × 4.8 × 2.0	44	180	Right way up	Degraded	1843 AD ± 6.5	175
72	M1 17°57'26.05"S/ 142°1252.43"W	5.1 × 2.8 × 1.0	10	53	Right way up	Very good	1838 AD ± 6.5	180
74	M5 18°02'19.62"S/ 142°23'48.60"W	4.3 × 3.0 × 1.6	14	100	Right way up	Very good	1890 AD ± 5	128
75	M5 18°02'22.83"S/ 142°23'47.3244W	3.1 × 2.5 × 1.5	8	138	Right way up	Very good	1895 AD ± 7.5	123
77	M6 18°00'53.43"S/ 142°18'07.56"W	4.4 × 3.5 × 2.7	29	128	Right way up	Very good	1869 AD ± 9.5	149
96	M3 18°07'24.55"S/ 142°13'17.28"W	3.5 × 3.0 × 2.2	16	60	Right way up	Good	1886 AD ± 5.5	132
108	M2 18°00'23.97"S/ 142°11'40.71"W	3.4 × 2.5 × 1.5	9	342	Inverted	Very degraded	509 AD ± 17	1509
115	M2 18°00'17.68"S/ 142°11'32.89"W	6.3 × 4.2 × 5.6	104	50	Right way up	Good	1831 AD ± 10	187
118	M2 18°00'05.80"S/ 142°11'41.59"W	10.7 × 7.5 × 2.5	140	27	Right way up	Degraded	1634 AD ± 9	384
128	M2 17°59'59.31"S/ 142°11'52.81"W	5.8 × 2.4 × 2.4	23	234	Inverted	Very degraded	1627 AD ± 12	391
136	K1 15°46'31.92"S/ 145°08'36.27"W	7.2 × 4.9 × 1.2	30	54	Right way up	Good	45 BC ± 11	2063

Table 2 continued

RPCB number	Sampling area and GPS location	Dimension (m) (a-, b-, c- axis)	Volume ^a (cubic meters)	Distance from reef edge (m)	Orientation	Apparent sampling quality ^b	U–Th corrected age (yr)	Age Bp (2018)
141	K2 15°46′36.70″S/ 145°08′19.47″W	4.9 × 4.1 × 2.5	35	53	Right way up	Good	41 AD ± 23	1977
142	K2 15°46′36.63″S/ 145°08′19.00″W	6.8 × 3.2 × 2.3	35	51	Right way up	Degraded	98 BC ± 17	2116
153	K3 15°46′47.77″S/ 145°07′26.19″W	6.2 × 5.0 × 1.8	39	68	Right way up	Good	87 BC ± 28	2105
155	K3 15°47′03.92″S/ 145°06′55.72″W	4.1 × 2.7 × 1.0	8	271	Right way up	Good	46 AD ± 13	1972
157	K3 15°47′10.38″S/ 145°06′49.32″W	3.9 × 1.6 × 1.5	7	376	Right way up	Degraded	48 BC ± 13	2066
160	K3 15°47′02.13″S/ 145°06′41.31″W	12.0 × 5.9 × 3.4	169	34	Right way up	Good	75 BC ± 9	2093
160	K3 15°47′02.13″S/ 145°06′41.31″W	12.0 × 5.9 × 3.4	169	34	Right way up	Good	7 AD ± 8	2011
161	K3 15°47′02.84″S/ 145°06′41.41″W	8.2 × 6.6 × 2.2	83	61	Right way up	Good	13 BC ± 14	2031

^a(0.7 × a × b × c) Accurate measurements of boulder volumes 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

^bEvaluated according to the level of overall degradation of the most recent face of the boulders

and Marokau show that 50% of the dates obtained increase the age of the event by at least 40 yrs (Fig. 9a).

Discussion

Limits and potentials of HEMI dating

This study shows that the dating of HEMIs using U/Th dating of coral samples taken from RPCBs remains valid, but only under certain conditions. The reliability of HEMI dating essentially depends on the frequency of HEMI, but is also conditional upon the sampling method.

We have seen that despite very high precision of coral dating by the U/Th method, there are sampling constraints that significantly reduce the reliability of HEMI dating. Indeed, in the best of cases, random sampling on the surface of a block that would have been taken out of water intact would have less than one chance in two of being

carried out on a coral colony alive on the eve of the HEMI. Moreover, the results show that during the HEMI, and before the boulder settlement, coral cover is very strongly deteriorated. The probability of taking a sample of coral living on the eve of the HEMI on the blocks is therefore very low. As a result, dating random samples from the most recent face of the RPCBs can sometimes give results that are far removed from the date of the HEMI. In the case where several datings are performed, a dispersion of over several decades is to be expected in the results. Thus, coral dating gives a limit age (minimum age) of the HEMI, since the coral could have been dead for several decades.

Dating of HEMIs using U/Th methods remains relevant if it is deployed on coastlines where the establishment of coral boulders occurs less than once per century. This frequency is compatible with the majority of large HEMIs generated by tectonic phenomena (tsunamis). This method is also valid where cyclonic activity is extremely rare (French Polynesia, Hawaii, North-West Indian Ocean and

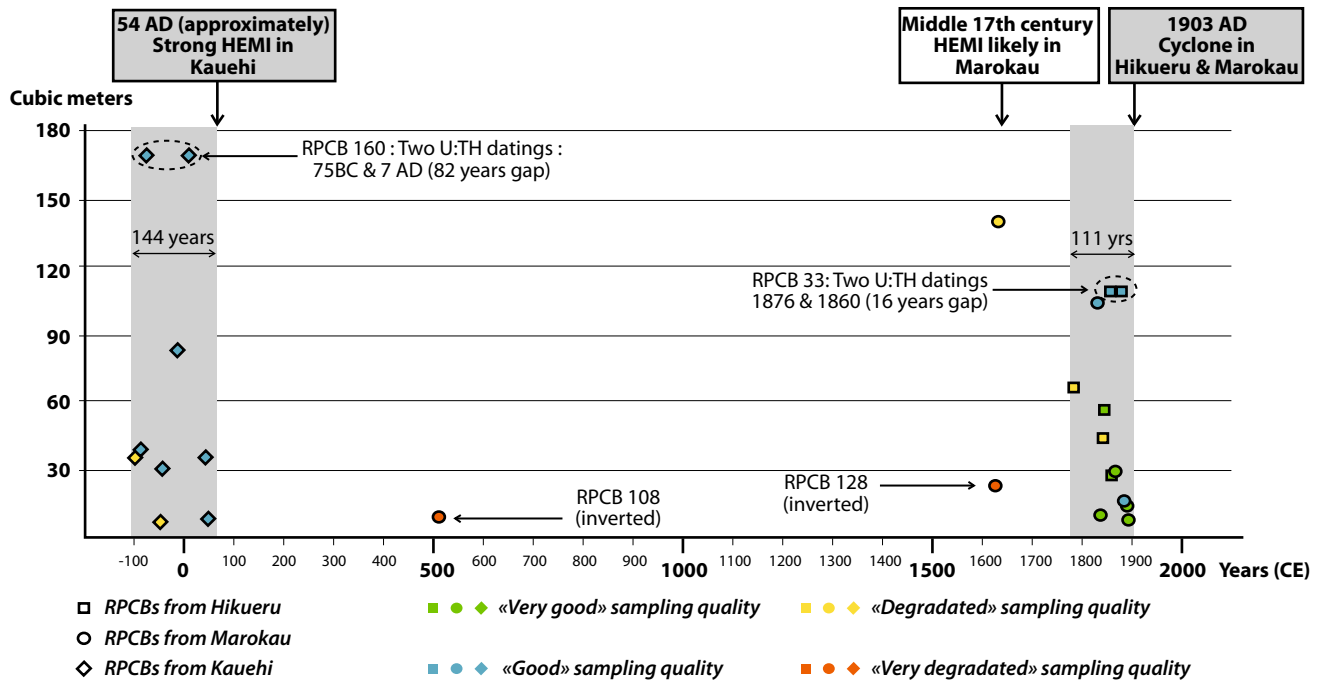


Fig. 8 Coral mortality ages of 24 samples from 22 coral boulders. Boulder groups (gray bands) of the same age are very likely to be produced by the same event

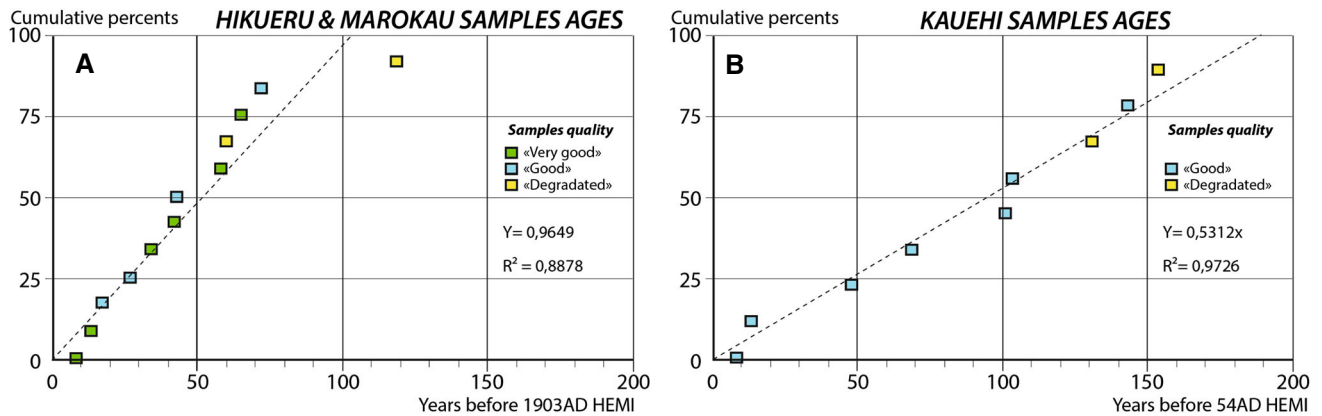


Fig. 9 Dates dispersion (U/Th dating) of coral boulders set up by the 1903 (AD) cyclone at Hikueru and Marokau (left graph) and by the HEMI of 54 (AD) at Kauehi (right graph)

Brazil coastlines). This method may still be useful for dating the most intense events by working only on larger blocks in areas where HEMIs are frequently producing coral boulders. On the other hand, due to these different constraints (limited coral recovery rate, uneven LCC, high alteration of the surface of RPCBs during HEMIs), it seems impossible to distinguish two HEMIs which would have occurred a few decades apart from the U/Th dating of corals.

By applying the dating method to sites that were affected by two different HEMIs that were supposed to be several centuries apart from each other, we also hoped to evaluate the method’s loss of reliability for the very old

events (more than a millennia) compare to events from the historic time (last two centuries). From the sampling phase a difference appeared. Indeed, we could not find a block with very good sampling reliability in Kauehi, while about 15% of the boulders measured on Marokau and Hikueru had this level of reliability. Moreover, the dispersion of the results between the dating performed on the blocks set up in 1903 (AD) and those put in place by the HEMI of 54 (AD) seems to show a significant loss of precision of the method for the very old HEMIs. Indeed, while the dating is dispersed over a period of 111 yrs for the blocks set up in 1903, the dates obtained from RPCBs produced by the 54 HEMI are dispersed over 144 yrs. This loss of reliability is

likely produced by the alteration of boulders' surfaces after their settlement when exposed to bad weather (waves in particular) or to human activities.

At the sampling level, we believe that sampling on inverted RPCBs exposes date age to larger deviation because of the fast alteration of coral in proximity of soil/waters, and because of the limited choice for sampling (unreachable surfaces). We also noticed that the small boulders near the ocean rarely show coral in good condition. These boulders are frequently subjected to the action of waves that alter the surface. Moreover, the dating of a large number of samples appears essential to be able to date, with relative precision, the HEMIs that would not have been referenced in the archives. When an isolated block is present, dating several samples on the same block can bring a substantial gain of precision. Given the price of U/Th dating, the required multiplication of samples remains one of the main limits of the method. In any case, these results have been obtained with the study of RPCBs devoid of encrusting material. Thus, we assume that single coral or fragments of boulders made of encrustations (as observed in the British Virgin Islands by Atwater et al. (2017)) such as vermetid worm tubes, barnacles or boring bivalves, may potentially provide different age date deviations.

HEMI frequency and intensity in the Tuamotu Archipelago

Despite this limited frequency, history has shown that cyclones can be extremely powerful and cause tragedies in French Polynesia. The study of RPCBs of Hikueru and Marokau showed the exceptional rarity and intensity of 1903 cyclone.

From the point of view of the intensity of the swell, the boulders observed provide very interesting information. Indeed, at least two blocks of more than 100 m³ have been set up by this cyclone. These values are world records because the largest known RPCBs (displaced by cyclones) are between 50 and 75 m³ (May et al. 2015). The 3D reconstruction of the boulders that we have dated and the improvement of the hydrodynamic models of wave breaking will probably make it possible in the future to precisely evaluate wave size allowing the placement of such exceptional blocks. With the available information (photographs of vegetation, size and position of RPCBs) and comparisons with recent events in the rest of the world (e.g., Goto et al. 2009), we can say that this cyclone was a category 4 to 5 on the Saffir–Simpson scale and that the swell generated was greater than 12 m.

In the last century, only cyclone Orama on Anaa (in 1983) has approached this intensity both in terms of wind speed and the volume of displaced blocks (Etienne et al.

2014). The cyclone of 1906 (Canavesio 2014) may also have reached or surpassed (from the point of view of the swell) the intensity of the 1903 cyclone. In any case, for the scale of an island, frequency of return of a HEMI as intense as the cyclone of 1903 is extremely low (several centuries).

The blocks located on the north coast of Kauehi are comparable to, or even greater than, those observed at Hikueru and Marokau and prove the existence of a major HEMI hitherto unknown in the center of the Tuamotu during the middle of the first century AD. In the absence of block dating in neighboring islands attesting to this event, we cannot specify its nature (cyclone, tsunami produced by submarine landslide, or other) or evaluate the extent of the area concerned (trajectory of the cyclone if cyclone).

We believe that the dating of blocks over 50 m³ on the Tuamotu Islands would clearly identify the most intense HEMIs of the last millennia. Such a study would therefore provide very interesting insights into the evolution of the climate in this part of the Pacific.

Climate change, reef growth and cyclonic swells

The responses of reefs to climate change play an important role in the more global reflection of intertropical coastline resilience (Duvat 2015). Indeed, reefs are ecologically and economically important. Reefs can, for example, provide protection to coastlines and coastal infrastructure in some situations (Harris et al. 2018).

This issue is particularly addressed by ecologists and biologists who analyze the response of organisms making up the constituent elements of reefs to the gradual change of physical–chemical parameters of water under the effects of climate change. This work seeks to identify whether changes in these parameters are capable of stopping or slowing down the growth of reef-building organisms.

Our analysis of LCC (confirmed by the dating results) shows that very short and infrequent weather events could also have a significant impact on the long-term growth/elevation of the reef. Indeed, cyclonic swells can destroy decades of reef construction in a few hours. A high frequency of tropical cyclones could therefore lead to a reduction in coral reef elevation, even when they retain favorable ecological conditions for coral growth. Consequently, the frequency, intensity and trajectory of tropical cyclones appear to be a major factor in understanding the intertropical coastline resilience to changing climatic and environmental conditions.

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