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Understanding the history of extreme wave events in the Tuamotu Archipelago of French Polynesia from large carbonate boulders on Makemo Atoll, with implications for future threats in the central South Pacific

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ABSTRACT

Numerous large carbonate boulders up to 164 tonnes in mass were investigated on the reef flat and beaches of Makemo Atoll in the Tuamotu Archipelago of French Polynesia to reveal the past occurrence and to anticipate the future potential threat of extreme wave events, possibly generated by tropical cyclones and tsunamis. The modern reef edge and emerged mid-Holocene coastal landforms were identified as sources of boulders mobilized during extreme wave events in the past. The minimum flow velocities produced by extreme wave events were estimated to exceed 5.4–15.7 m/s at the reef edge on different parts of the atoll. Comparison of uranium–thorium ages of boulder coral fabric with written historical records indicates that two large boulders (77 and 68 tonnes) were possibly emplaced on the reef flat by a powerful cyclone in February 1878. Although most boulder dates are older than the earliest historical cyclone and tsunami records in French Polynesia, their ages concur with the following: (a) periods of "storminess" (i.e. increased cyclone activity compared to today) in the central South Pacific over the last millennium; and (b) periods of high sea-surface temperature (SST) at the Great Barrier Reef, possibly associated with higher-than-normal SSTs Pacific-wide that facilitated the generation of cyclones affecting the central South Pacific Ocean. None of the boulders on Makemo were dated younger than CE1900, implying that the last century has not experienced extreme waves of similar magnitude in the past. Nevertheless, the findings suggest that waves of comparable magnitudes to those that have transported large boulders on Makemo may recur in the Tuamotus and threaten island coasts across the central South Pacific in the future.

1. Introduction

The Tuamotu Archipelago (Tuamotus) consists of 77 atolls and one emerged limestone island, spread over 1500 km in a WNW-ESE chain across the central South Pacific Ocean. Extreme wave hazard assessment on these inhabited islands is hindered by the short and potentially incomplete historical record of tropical cyclones and tsunamis in the region, as well as the infrequent occurrence of such events in modern times. Proxy information is therefore useful for assessing the current-day threat. However, fine-grained sedimentary evidence, such as tsunami- or cyclone-deposited sand sheets, is not readily preserved in beach stratigraphies on low-lying coral atolls because of continual reworking by waves (Paris et al., 2010). Narrow atoll rims are also not ideal locations for the preservation of storm ridges of reef-derived gravel. Consequently, larger deposits, in particular tall-standing carbonate boulders that originate from the reef framework, are important features for investigating the age of, and energy associated with, extreme wave events in the archipelago. Such research has proven effective on the Great Barrier Reef of Australia (Nott, 1997; Yu et al., 2012; Liu et al., 2014), the Ryukyu Islands of Japan (Suzuki et al., 2008; Goto et al., 2010; Araoka et al., 2013), Tongatapu Island in Tonga (Frohlich et al., 2009); Sumatra in Indonesia (Paris et al., 2010); Taveuni Island in Fiji (Etienne and Terry, 2012); Bonaire in the Caribbean (Engel and May, 2012) and Lanyu Island in Taiwan (Nakamura et al., 2014).

The overall aim of this research is to improve current understanding on the potential threats of extreme marine wave hazards, namely tsunamis and tropical cyclones, for the atolls of the central South Pacific region. This is achieved by examining the extreme wave event history for the Tuamotus of French Polynesia. The objectives are threefold. First, the physical characteristics of the atolls in the Tuamotus and their relationship with Holocene sea-level change in the central South Pacific are

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examined (Section 2). Second, a comprehensive record of historical tsunamis and tropical cyclones is compiled for the Tuamotu Archipelago (Section 3). Third, field investigation of numerous large carbonate boulders on the reef flat of Makemo Atoll in the archipelago is conducted to interpret how and when boulders were transported (Sections 4 and 5). Finally, these findings are compared with the historical records of tsunamis and cyclones in attempt to assess the threat associated with extreme wave events in the greater Tuamotus.

2. Study area

2.1. The Tuamotu Archipelago

The Tuamotu Archipelago (Fig. 1) is one of the five island archipelagos of French Polynesia; the others are the Society, Austral, Marquesas and Gambier archipelagos. Situated far from any tectonic boundary, the atolls in the Tuamotus were built on top of volcanic basements that formed from hot spot activity at least 37.5 million years ago (Clague and Jarrard, 1973; Pirazzoli et al., 1988a). The submarine volcanic edifices supporting the archipelago rise over 4000 m from the ocean bottom at an angle exceeding 45°. Submarine slopes become more gradual at a depth of 1000 m (Vitousek, 1963; Jordahl et al., 2004). At the sea surface, low-lying islands form on top of atoll reefs. They are composed of coral rubble deposited by waves on the old coral platforms. The elevation of these coral islands rarely exceeds 10 m above sea level (Dupon, 1986; Etienne, 2012).

Annual weather in the Tuamotu Archipelago varies little. Humidity is high (~80%) most of the time; the summer season has a slightly higher temperature from November to April (25–30 °C) than the other six-month period (24–28 °C) (Sachet, 1983). The Tuamotu coasts are microtidal, with tides ranging from 0.2 to 0.7 m. Most waves are 1–3 m high and break at periods of 6–9 s (Intes and Caillart, 1994). The yearly average wave height measured in the western Tuamotus is 1.6 m (Andréfouët et al., 2012), although prevailing north-east trade winds can reach 30 knots and generate swells of 3–5 m in amplitude. As a result, islands of coral shingle have formed on the north-eastern atoll rims over time (D'Hauteserre, 1978; Pirazzoli and Montaggioni, 1988).

2.2. Holocene sea-level change and tectonics in the Tuamotu Archipelago: influence on coastal geomorphology

Relative sea-level change during the last glacial maximum (LGM) (23,000–17,000 BP) in the Tuamotu Archipelago was measured from the coral reef record at Mururoa Atoll at approximately 135–143 m below present sea level (p.s.l.) (Camoin et al., 2001). Following the post-LGM marine transgression, the sea level was estimated at 17–23 m below p.s.l. at 9000 BP, then rose sharply to 2–3 m below p.s.l. at about 8000 BP (Camoin et al., 2001). Sea level in the Tuamotus reached a Holocene highstand of 0.8 $\pm$ 0.2 m above p.s.l. from about 4500 BP to after 2000 BP, but has since gradually dropped to present sea level (Pirazzoli and Montaggioni, 1988; Pirazzoli et al., 1988a). Alternatively, recent research has suggested the sea level highstand in the Tuamotus reached about 1 m above p.s.l. and remained stable until CE800, before dropping steadily until CE1900, then subsequently rose to present sea level during the last century (Dickinson, 2003).

Meanwhile, local tectonic activity has induced vertical movement of atolls. In the tectonically stable part of the archipelago towards Vahitahi and Mururoa at the eastern end of the atoll chain, thermal subsidence occurs (Pirazzoli et al., 1987a). The rate of subsidence of Mururoa is estimated at 7–8 mm/1000 years, as determined by the K-Ar dating of the volcanic basement (Trichet et al., 1984; Camoin et al., 2001). In contrast, tectonic uplift is evident at the southern boundary on Makatea and Anaa (raised coral atolls), owing to lithospheric flexure associated with the hotspot where Mehetia is currently located and which created Tahiti during the Pleistocene (Montaggioni et al., 1985; Pirazzoli et al., 1988b; Pirazzoli and Montaggioni, 1988; Montaggioni and Camoin, 1997; Dickinson, 2001) (refer to Fig. 1).

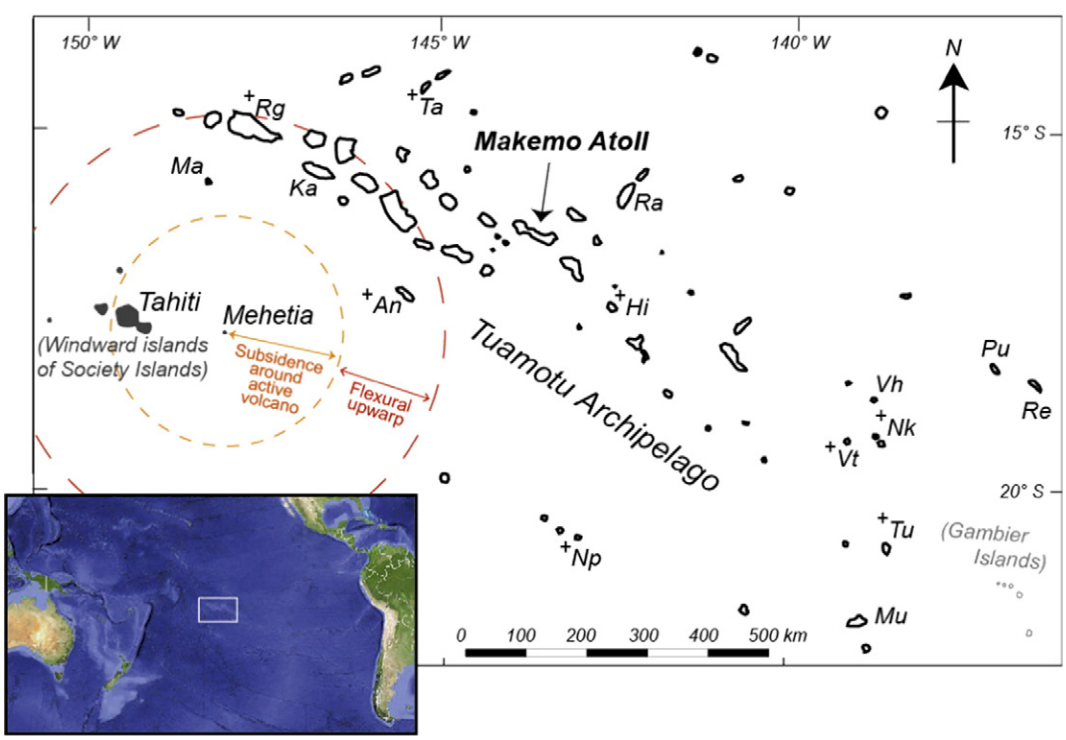

Fig. 1. Location map of Makemo Atoll in the Tuamotu Archipelago of French Polynesia. The hotspot that created Tahiti in the Pleistocene is currently located at Mehetia. This active volcano is causing subsidence around Mehetia, and the emergence of atolls including Anaa and Makatea due to flexural upwarp (red circle) outside the cone of subsidence (orange circle). Inferred extent of tectonic vertical movements is adapted from Dickinson (2001). Locations of other atolls mentioned in the text are also labelled. A "+" indicates that large boulder deposits have been reported by others (see Section 3.3). +An = Anaa; +Hi = Hikueru; Ka = Kaukura; Ma = Makatea; Mu = Mururoa; +Nk = Nukutavake; +Np = Nukutepipi; Pu = Pukarua; Ra = Raroia; Re = Reao; +Rg = Rangiroa; +Ta = Takapoto; +Tu = Tureia; Vh = Vahitahi; +Vt = Vairaatea. (Inset from Google Map).