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Reef response to sea-level and environmental changes in the Central South Pacific over the past 6,000 years

Hallmann, N.^{a*}, Camoin, G.^a, Eisenhauer, A.^b, Samankassou, E.^c, Vella, C.^a, Botella, A.^d,
Milne, G.A.^d, Pothin, V.^a, Dussouillez, P.^a, Fleury, J.^a, Fietzke, J.^b, Goepfert, T.^c

^a Aix-Marseille Université, CNRS, IRD, INRAE, Coll France, CEREGE, Europôle
Méditerranéen de l'Arbois, BP80, 13545 Aix-en-Provence cedex 4, France

^b GEOMAR Helmholtz-Zentrum für Ozeanforschung Kiel, Wischhofstraße 1-3, 24148 Kiel,
Germany

^c University of Geneva, Department of Earth Sciences, Rue des Maraîchers 13, CH-1205
Geneva, Switzerland

^d University of Ottawa, Department of Earth and Environmental Sciences, Ottawa, Ontario
K1N 6N5, Canada

^e Arizona State University, School of Earth & Space Exploration, 550 E Tyler Mall, Tempe,
AZ 85287-1404, USA

* Corresponding author: hallmann@cerege.fr

Abstract

Geological records of coastal system evolution during past higher and/or rising sea levels provide an important baseline for developing projections regarding the response of modern coastal systems to future sea-level rise. The mid-late Holocene corresponds to the most recent window into natural variability prior to the Anthropocene and involves slow-rate and low-amplitude sea-level changes that were mostly governed by a limited glacio-eustatic contribution, most likely sourced from Antarctica, and ‘glacial isostatic adjustment’ processes.

This paper documents in unprecedented detail the response of coral reefs and coastal systems to changing accommodation space in relation to mid-late Holocene sea-level changes in French Polynesia.

The sea-level curve that underpins this study has a global significance and documents a single short-lived sea-level highstand between 4.10 and 3.40 kyr BP. The amplitude of the highstand is less than one metre, within the range of the predicted sea level at the end of the current century. The reported relative sea-level changes are characterized by slow rates ranging from a few tens of millimetres per year to up to 2.5 mm/yr and by significant sea-level stability (stillstands) lasting more than a century and up to 250 years, defining a step-like pattern. Sea-level variability probably driven by climatic oscillations on interannual to millennial time scales is evidenced during the entire time window.

The detailed reconstruction of reef development over the last 6,000 years brings valuable information regarding coral reef dynamics and coastal processes during periods of higher sea level and wave energy regimes. The persistence of stable and optimal depositional environments over the last 6,000 years is demonstrated by the constant overall composition and diversity of reef communities and the almost continuous development of coral microatolls. The facies distribution as well as the lateral extension and shift of facies belts have been governed by variations in accommodation space, which are controlled by relative

53 sea-level changes and antecedent topography. The widespread development of mid-late
54 Holocene reef deposits in coastal areas suggests that they have played a prominent role in
55 global processes related to the formation and shaping of modern islands.

56

57 **Keywords**

58 *Porites* microatolls; mid-late Holocene sea level; U-series dating; French Polynesia; low-lying
59 islands; storm deposits

1. Introduction

One of the most societally relevant objectives of research in the Earth Sciences is to better understand past environmental changes to enable future projections with improved accuracy. Increasing atmospheric $p\text{CO}_2$ is expected to be the main driving force for future climatic changes, of which sea-level rise and changes in the hydrological cycle are among the most pressing issues for coastal societies. Over the past few decades, most of the measured global mean sea-level rise (i.e., 3.5 mm/yr since the early 1990s; Church et al., 2013) has been ascribed to the melting of polar ice caps and the thermal expansion of the ocean in response to global warming. Global mean sea level is expected to rise between 0.5 and 1.5 m by the year 2100 as a consequence of warming from greenhouse gas forcing (Alley et al., 2007; Church et al., 2013; IPCC, 2018). Such a rise in sea level would have severe impacts on coastal ecosystems, water supplies and densely populated coastal areas in the Low-Elevation Coastal Zone (McGranahan et al., 2007; Kekeh et al., 2020), especially on low-lying islands, which stand less than 3 m above mean sea level. However, projections of sea-level rise remain highly uncertain, primarily due to our poor understanding of the sensitivity of ice sheets to sustained warming (IPCC, 2018) and, accordingly, the future evolution of coastal systems cannot be accurately predicted.

The future response of shorelines to rising sea level can be evaluated based on high-resolution studies of geological analogues involving past periods of higher and/or rising sea level characterized by slow-rate, low-amplitude and high-frequency relative sea-level (RSL) changes (see Camoin and Webster, 2015 and references therein). Investigating Holocene analogues to evaluate future sea-level scenarios is a common approach (e.g., Woodroffe and Murray-Wallace, 2012; Helfensdorfer et al., 2019). The mid-late Holocene represents the most recent period characterized by a higher than present sea level. Responses of coral reefs and coastal systems to RSL changes, including changes in sedimentation patterns and island development, during this time window are of global significance. However, so far, these

processes have been scarcely documented in the mid-late Holocene (Hopley, 1982; Hopley et al., 2007; Harris et al., 2015), and nowhere near at the temporal and spatial resolutions that are needed to better predict the future evolution of coastal systems, especially coral reefs. Furthermore, the impact of mid-late Holocene RSL changes and other environmental factors on reef architecture and composition remains poorly resolved (Camoin and Webster, 2015). These are key aspects of this study.

Mid-late Holocene RSL changes were mostly governed by a limited glacio-eustatic contribution and ‘glacial isostatic adjustment’ (GIA) processes (e.g., Camoin and Webster, 2015 and references therein). At ‘far-field’ sites, the ‘equatorial ocean syphoning’ (Mitrovica and Peltier, 1991; Mitrovica and Milne, 2002) and hydro-isostasy are generally the key processes that result in and control the timing and amplitude of sea-level highstands of a few decimetres to about a metre, similar in amplitude to the sea-level rise that is expected before the end of the current century (Alley et al., 2007; Church et al., 2013; IPCC, 2018). GIA processes display significant spatial variability (Milne and Mitrovica, 2008; Lambeck et al., 2010) that induces regional disparities in mid-late Holocene RSL changes (Milne et al., 2009; Camoin and Webster, 2015) and hence in reef development histories.

Given the spatial variability in Holocene RSL, detailed regional studies are, in general, necessary to constrain accurately the timing and amplitude of the mid-late Holocene RSL changes and to evaluate their impact on coral reef growth and the evolution of coastal systems during this time window.

Among sea-level indicators that are used to reconstruct mid-late Holocene RSL changes, coral microatolls represent unique archives of the mean low water springs (MLWS) level in open water settings. Their accurate dating by multiple techniques (e.g., ^{14}C , U-series; see Camoin and Webster, 2015) allows them to be used to track the evolution of MLWS through time, as well as regional sea-level trends and climatic oscillations on interannual to millennial time scales (Hallmann et al., 2018). Their vertical growth is constrained by exposure at lowest tides

(Smithers and Woodroffe, 2000; Hopley et al., 2007; Meltzner and Woodroffe, 2015), which is reflected by their overall flat dead upper surface (Fig. 1a-c; ‘microatoll plane’) and their lateral growth. In addition, the upper surface of coral microatolls reflects subtle sea-level changes. A rise in sea level is indicated by a higher outer margin compared to the central depression, as well as overgrowths along the outer margin and/or on top of the former coral colony that may record a time elapse between two periods of coral growth (Fig. 1d). On the contrary, a sea-level fall is typified by the occurrence of a lower margin compared to the central part (Fig. 1e-g). A more complex microtopography of the upper surface of coral microatolls may include a succession of ridges and overgrowths (Fig. 1h), up to 20 cm high, that reflect sea-level variations on decadal to sub-decadal time scales.

The Central South Pacific, especially French Polynesia, is an ideal region for palaeo-sea-level studies targeted at understanding environmental drivers of sea-level change. This is due to its location in the ‘far-field’ as well as the latitudinal distribution of its islands and their tectonic stability and/or well constrained subsidence rates during deglacial and postglacial periods (Camoin et al., 2012; Deschamps et al., 2012). This paper documents, in unprecedented detail and at high resolution, the responses of coral reefs and coastal systems to mid-late Holocene RSL changes in this region by focusing on microatoll fields and reef flat areas that are at or near sea level. It provides the opportunity to better assess how these systems might respond to low-amplitude (~1 m) sea-level changes that are expected before the end of the current century (Alley et al., 2007; Church et al., 2013; IPCC, 2018).

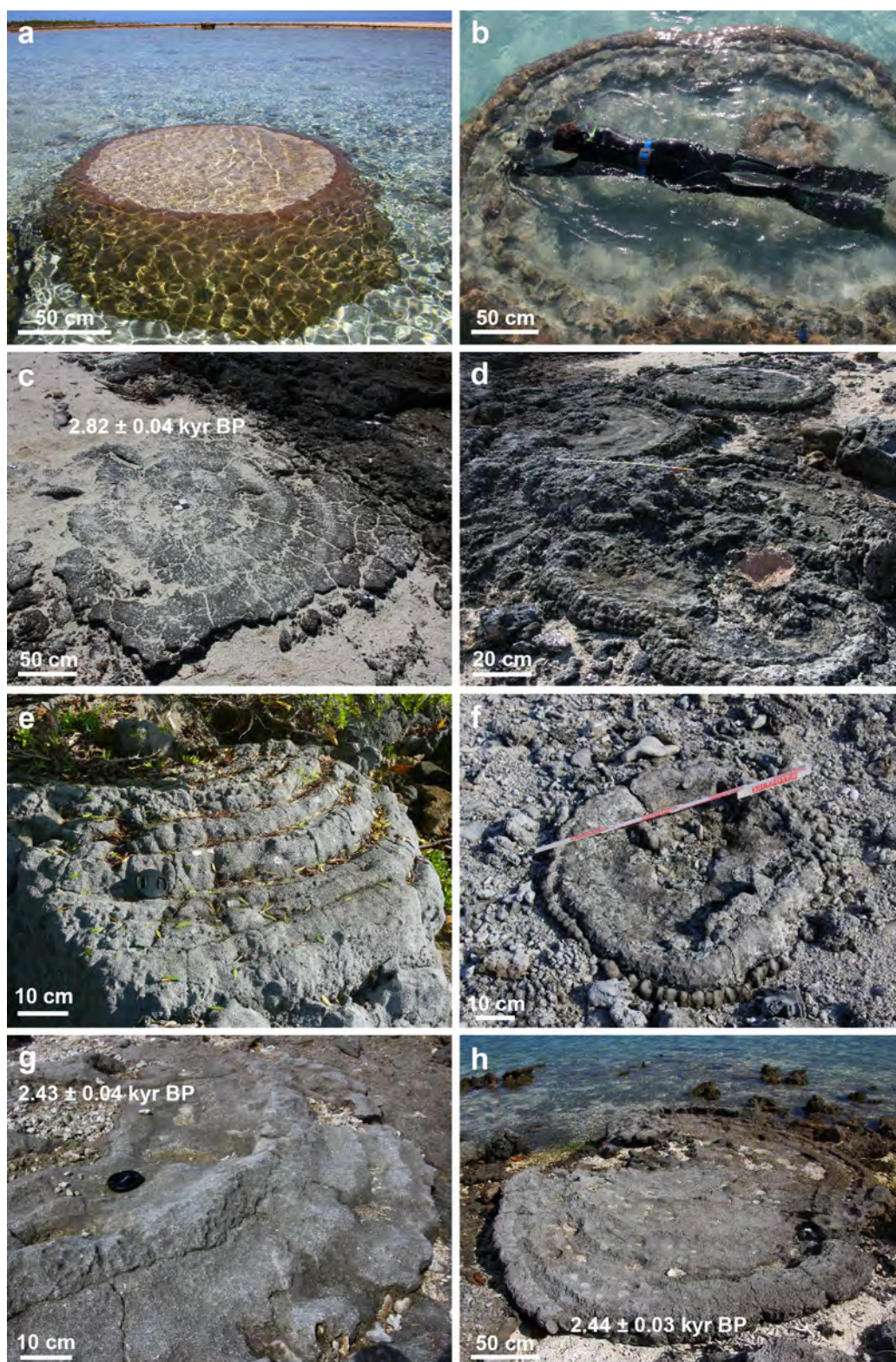


Fig. 1. *Porites* microatolls. (a) and (b) Modern microatolls (Makemo, Fakarava). (c) Microatoll with a flat surface indicating a stable sea level (SL) for about 150 years (Bora Bora). (d) Field of microatolls with a higher margin reflecting a SL rise during their growth (Maupiti). (e) Microatoll with a lower margin indicating a SL fall during its growth

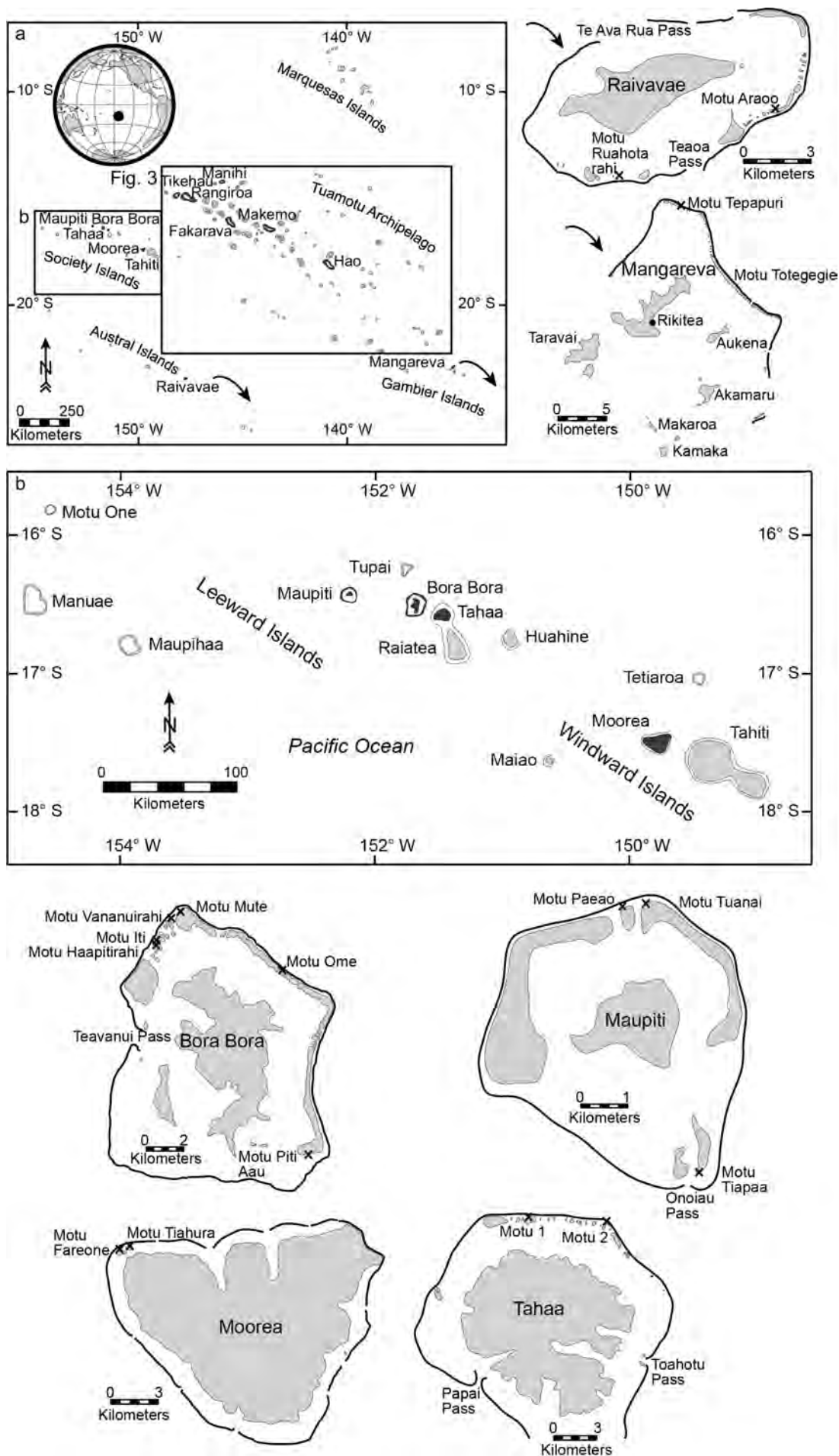
(Fakarava). (f) Microatoll exhibiting late overgrowth along its margin (Bora Bora). (g) Microatoll with a lower margin indicating a SL fall during its growth and ridges on its surface typifying low-amplitude, high-frequency SL changes (Bora Bora). (h) Microatoll displaying ridges on its upper surface reflecting low-amplitude, high-frequency SL changes (Bora Bora).

2. Setting

2.1. Regional and climatic settings

French Polynesia covers a vast oceanic region located in the Central South Pacific. It includes 83 atolls or low-lying islands and 35 high volcanic islands that form five archipelagos dispersed along a general NW-SE axis: Society, Tuamotu, Austral, Marquesas and Gambier (Fig. 2). French Polynesian reef systems are comprised of oceanic reefs developed on atolls, banks and high islands.

The twelve islands that were investigated during this study cover a wide range of latitudes and longitudes (S14°20' to S23°54', W152°18' to W134°50'). They are distributed in the Society Archipelago (Moorea, Bora Bora, Maupiti and Tahaa), in the Tuamotu Archipelago (Makemo, Manihi, Tikehau, Rangiroa, Fakarava and Hao), in the Austral Islands (Raivavae) and Gambier Islands (Figs. 2, 3). The location of our study sites on these islands are indicated in Figure 2. In addition, three other high islands, Raiatea and Tahiti (Society Archipelago) and Tubuai (Austral Islands) were explored, but no sampling was carried out.



162 Fig. 2. Map of French Polynesia. (a) Islands have been studied in four archipelagos: Society,
163 Tuamotu (see details in Fig. 3), Austral and Gambier Islands. The two black arrows direct to
164 detailed maps of Raivavae and Mangareva. (b) Map of the Society Islands with studied
165 islands in black and detailed maps of the four studied islands in this archipelago below.
166 Motus in grey, barrier reef as black lines and study sites are indicated by crosses.
167

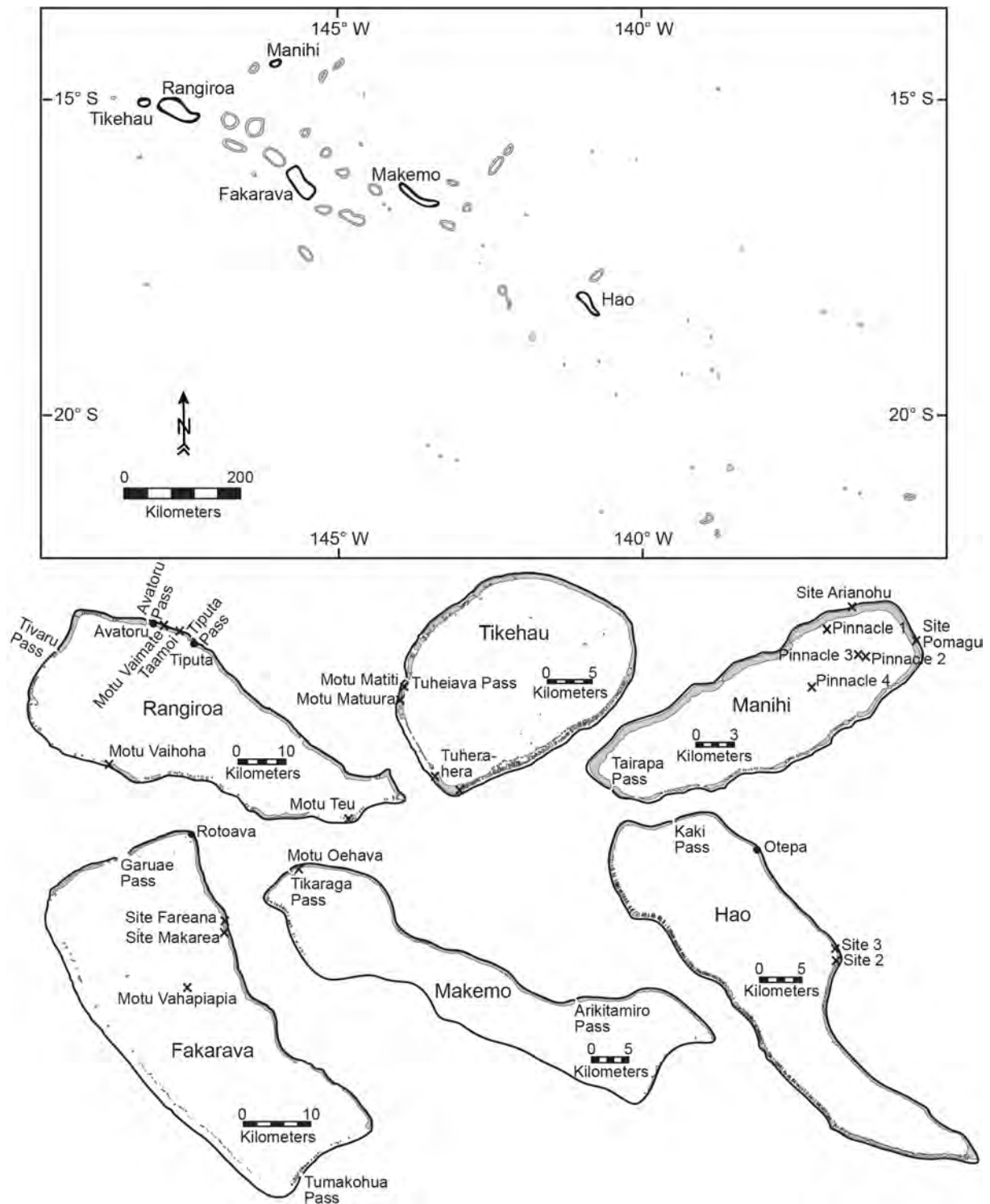


Fig. 3. Map of the Tuamotu Archipelago and detailed maps of the studied atolls in this archipelago.

The climate in French Polynesia is tropical and humid and includes two distinct seasons: a warm and rainy season from November to April and a cool and relatively dry season from

May to October (see details in Gabri   and Salvat, 1985; Galzin and Pointier, 1985; Harmelin-Vivien, 1985).

French Polynesia is in the trade-wind zone. The dominant winds generally blow from the N and NE, except from May to October when they blow from the SE. There are long periods of calm from April to June. Tropical cyclones may come both from the NE and the NW from November to April and are generally rare, from one to three per century in the Marquesas, the northern Tuamotus and the Austral Islands to four to eight per century in a region extending from the Tuamotus to the Gambier Islands, through the Society Islands. However, some years, such as in 1982-1983, have been characterized by an exceptional high number of cyclones, eight in total (Gabri   and Salvat, 1985).

The tidal amplitude is low on French Polynesian islands and ranges from 0.15 m on the Society Islands up to 0.5 m on the Gambier Islands (Hallmann et al., 2018).

Based on sparsely distributed tide gauge records and shorter gridded sea level fields based on satellite altimetry data and outputs of two numerical ocean models, it has been demonstrated that in French Polynesia, the climate-related sea level rose at an average rate of 2.4 mm/yr significantly faster (40%) than the mean global mean rate (of about 1.7 mm/yr) over the 1950-2010 time span (Meyssignac et al., 2012).

2.2. Geological setting

French Polynesian islands are distributed along five linear, subparallel chains that were created by volcanic processes driven by stationary hot spots from the Paleocene to the present: Mehetia (Society), McDonald Seamount (Cook-Austral), Fatu-Hiva (Marquesas) and Pitcairn (Gambier-Tuamotu; see e.g., Duncan and McDougall, 1974, 1976). Tectonic movements affecting Polynesian islands are related to the volcanic evolution of the region. The Society islands experienced a slow and regular subsidence during the Late Pleistocene and the Holocene, especially due to the cooling and the concomitant sinking of aging

lithosphere (Blais et al., 2000; Guillou et al., 2005; Yamamoto et al., 2007; Neall and Trewick, 2008). Subsidence rates of 0.25 mm/yr have been estimated for Tahiti based on drill core data (Bard et al., 1996; Camoin et al., 2012; Deschamps et al., 2012), while a rate of 0.15 ± 0.15 mm has been deduced from five independent geophysical measurements (Fadil et al., 2011). Subsidence rates for Bora Bora have been estimated to 0.05 to 0.14 mm/yr, based on drill core data (Gischler et al., 2016), while subsidence rates of less than 0.05 mm/yr can be assumed for Maupiti, which is located 45 km west of Bora Bora and thus further away from the Mehetia active hot spot. Subsidence rates for the Tuamotus are assumed to be of 0.01 mm/yr, based on the cooling of Miocene volcanoes (Jarrard and Clague, 1977; Parsons and Sclater, 1977; Detrick and Crough, 1978; Schlanger et al., 1984; Duncan and Clague, 1985). Some northern Tuamotu islands, e.g., Anaa (Pirazzoli et al., 1988) and Makatea (Montaggioni and Camoin, 1997) have been uplifted as the result of the loading of the Tahiti and Moorea volcanic systems (Lambeck, 1981). The coeval uplift rates for Rangiroa and Tikehau, which are located approximately 80 km north of Makatea, have been less than 0.05 mm/yr, but led to the exposure of *feos* (= fossil reef deposits) of up to 2 m and 6 m high for Rangiroa and Tikehau, respectively. Fakarava, Manihi, Makemo and Hao, which are located between 400 km and 850 km away from Tahiti were too far to be affected by the loading of the Tahiti and Moorea volcanic systems. Subsidence rates of the southern Tuamotus, including the Gambier Islands, are assumed to be of 0.03 mm/yr, based on the cooling of late Miocene and Pliocene volcanoes related to the Pitcairn hot spot (Brousse et al., 1972; Guillou et al., 1994). The 2000 km long Cook-Austral volcanic chain is aligned in a NW-SE direction and reveals a complex geological history with islands originating from different hot spots and subsidence rates of the Austral Islands are assumed to be of 0.03 mm/yr (e.g., Duncan and McDougall, 1976; McNutt et al., 1997; Clouard and Bonneville, 2001; Bonneville et al., 2002, 2006).

3. Material and Methods

226 The present study is based on field studies, high-precision GPS positioning and surveying, as
227 well as a chronological study of all components of mid-late Holocene coral reef systems.

228 All collected samples of coral colonies and associated sediments were cut with a rock saw and
229 subsequently studied with regard to sedimentology, including the reconstruction of
230 depositional environments, petrography and carbonate diagenesis. Thin sections were
231 qualitatively studied under a polarization microscope. Corals were identified at the lowest
232 taxonomic level possible using the standard publications of Wallace (1999), Veron (2000) and
233 Humblet et al. (2015). Snorkel trips around the study sites were undertaken to collect
234 qualitative data regarding bottom characteristics and modern reef assemblages to be compared
235 to their mid-late Holocene counterparts.

236 Radiometric U-series ages have been obtained from *in situ* coral microatolls and *in situ* coral
237 colonies that are associated to microatolls or occurring in reef flat units, and have been used to
238 reconstruct RSL changes. In addition, reworked coral colonies that form the bulk of
239 conglomerate units and reef boulders have been dated to further unravel the mid-late
240 Holocene development of reef systems. Overall, 305 pristine coral samples, showing an
241 average aragonite content of 97.6% (see details in Hallmann et al., 2018), were dated by U-
242 series measurements performed at the GEOMAR (Kiel, Germany) using a Thermo Fisher
243 Neptune multi-ion-counting inductively coupled plasma mass spectrometer (MC-ICP-MS).

244 The chemical preparation, dating procedures and the age calculation are described in Fietzke
245 et al. (2005) and Hallmann et al. (2018). Seventy-eight samples from 72 microatolls
246 represented the database on which the mid-late Holocene sea-level curve has been initially
247 reconstructed (Hallmann et al., 2018). Thirteen samples from six additional microatolls, 84
248 samples of *in situ* corals in reef flat units, 48 coral samples from conglomerates have been
249 dated for the current study, in addition to 20 samples from reef boulders (Supplementary
250 Tables 1 and 2).

251 The methods used for acquiring and processing GPS data are described in Hallmann et al.
252 (2018). Mid-late Holocene RSL changes have been reconstructed using two methods
253 (Hallmann et al., 2018): 1) The definition of a biological elevation reference for each study
254 site allowed to compare directly the elevations of fossil and modern microatolls to deduce
255 relative sea-level changes, and 2) the GPS measurements of dated microatolls referenced to
256 the RGPF (geodetic datum in French Polynesia) associated with the NGPF (vertical datum),
257 which is a semi-dynamic system that is especially based on sites equipped with DORIS
258 (Doppler Orbitography by Radiopositioning Integrated by Satellite) stations. In this study,
259 dated reef flat units have been referenced to RGPF and NGPF to be directly compared to the
260 distribution of microatolls. The elevations of dated coral colonies, including microatolls,
261 have been corrected for subsidence. Rates of sea-level changes have been calculated based
262 on the age and elevation differences between two successive coral microatolls with reference
263 to the elevation of modern microatolls. These rates therefore reflect changes in MLWS level
264 throughout the mid-late Holocene. Uncertainties related to measurements of microatoll
265 elevation are of ± 2 cm and uncertainties concerning their ages are of 1% or less of the
266 measured ages. In addition to GPS positioning of samples, high-resolution maps and
267 transects were generated using ArcGIS 10.1 (Fig. 4) and structure-from-motion
268 photogrammetry was used to produce high-resolution 3D topographic maps (Fig. 5).

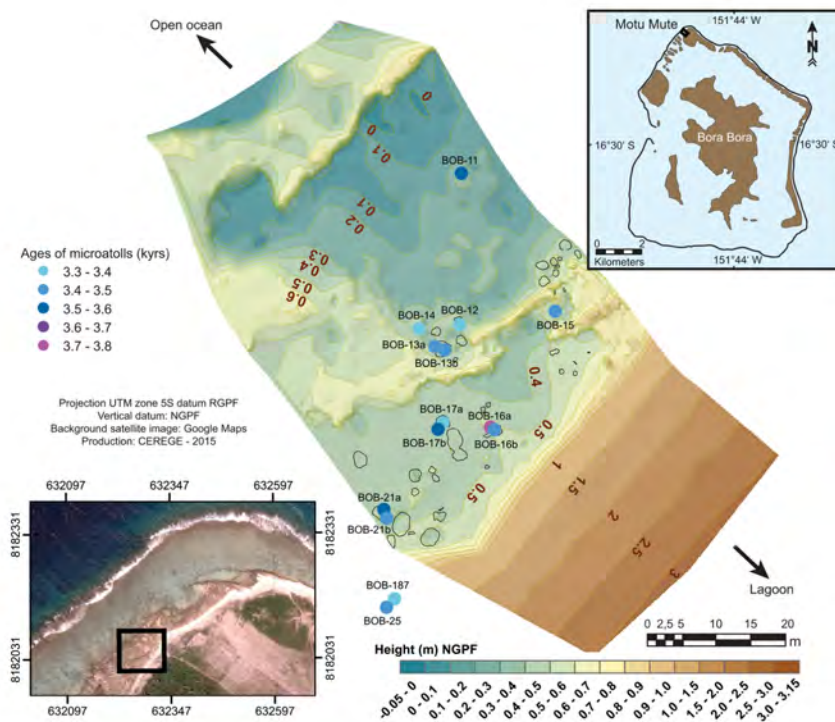


Fig. 4. High-resolution map of the Bora Bora study site on Motu Mute. Map of Bora Bora shows the location of Motu Mute and the black box on Motu Mute indicates the mapped area. The more detailed inset map shows the location of the mapped area (black box) close to the airstrip on Motu Mute. Circles on the high-resolution map indicate position and ages of *Porites* microatoll samples. Fields of microatolls are located on the Holocene reef flat and are partly covered by conglomerates. Elevations are based on NGPF measurements (geodetic datum in French Polynesia).

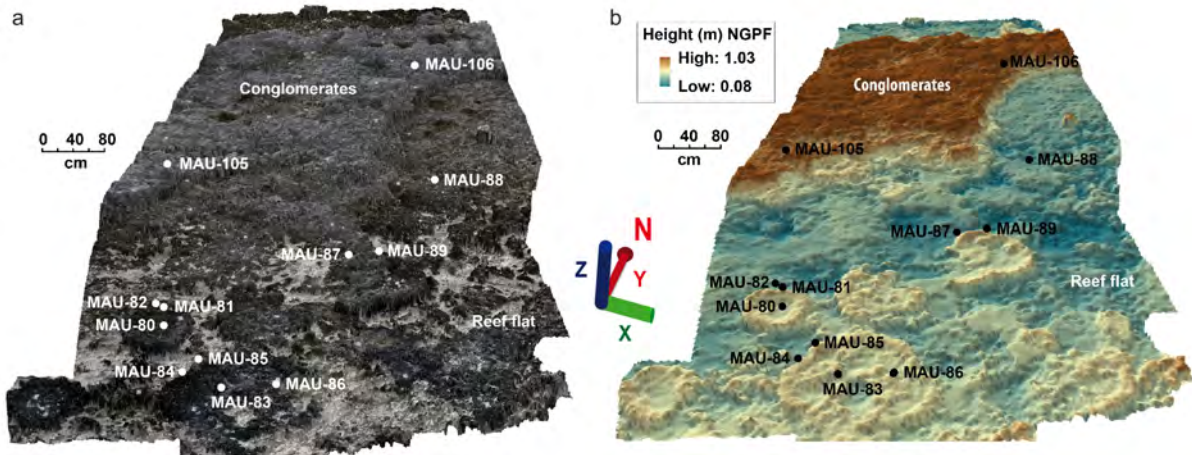


Fig. 5. Photogrammetry of a study site on Maupiti (Motu Tuanai). 3D reconstruction with (a) photographic texture and (b) coloured texture indicating heights. *Porites* microatolls overlay Holocene reef flat units and are partly covered by conglomerates. Circles indicate the sample positions. The scale changes due to the perspective view. Agisoft Photoscan Professional version 1.2 was used to produce the 3D model. Elevations are based on NGPF measurements (geodetic datum in French Polynesia).

4. Results

4.1. Mid-late Holocene reef sequence

In the following text, current elevations and depths measured in the field refer to present mean sea level. For microatolls, reference to modern MLWS is indicated when appropriate.

In the studied islands, the mid-late Holocene reef sequence generally forms the transition between modern beach deposits and reef environments, including lagoonal and reef flat areas (Fig. 6), from about 4 m deep to 2 m high. This reef sequence occurs at various elevations on the ocean sides of *motus* (Gabri  and Salvat, 1985; Pirazzoli et al., 1985, 1988; Pirazzoli and Montaggioni, 1988; Rashid et al., 2014; Hallmann et al., 2018), which are small vegetated islets and sand cays that are located on barrier reef systems. A large number of narrow,

shallow waterways called *hoas* are located on the reef rim between elongated *motus* and connect permanently or temporarily the lagoon with the ocean (Fig. 6).



Fig. 6. Morphological units of a Bora Bora study site (Motu Mute). Hol mic: Holocene microatolls, Mod mic: modern microatolls, Hol rf: Holocene reef flat, Im rf: inner modern reef flat, Om rf: outer modern reef flat, Cgm: conglomerates, Br: beachrock, Rc: reef crest.

The mid-late Holocene sequence encompasses the last 6,000 years (Fig. 7). It forms distinctive elevated terraces that are comprised of coral microatoll terraces (Fig. 1d), which generally rest on, or are connected laterally to, Holocene reef flat units. Coral microatoll terraces and reef flat units are unevenly covered by thick accumulations of conglomerates composed of reworked coral colonies (e.g., Matuura/Tikehau, northern part of Rangiroa, Makemo), and interpreted as storm deposits (Figs. 4-6). The palaeobiological composition and facies distribution of mid-late Holocene reef units are similar to their modern counterparts.

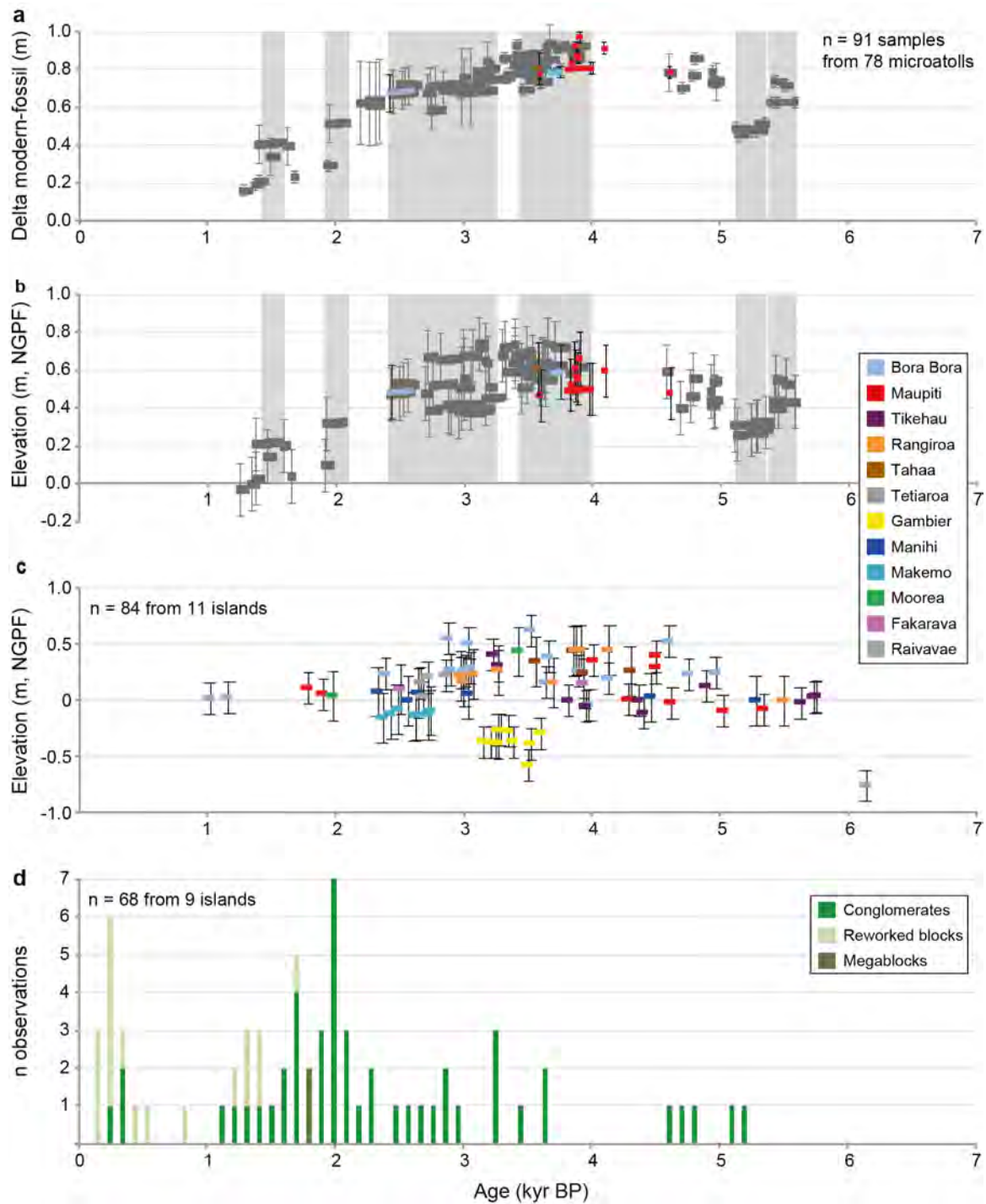


Fig. 7. Mid-late Holocene RSL changes and reef development. (a) Age vs elevation plot of dated microatolls. Calculated elevations are based on the height difference between living microatolls and their fossil counterparts ('Delta modern-fossil'). The grey shaded areas indicate specific time windows characterized by century-scale stillstands during which large microatolls with a diameter of ≥ 2.5 m developed. Data concerning Tetiaroa were obtained

during a parallel study (A.E., unpublished). (b) Age vs elevation plot of dated microatolls. Elevations are based on NGPF measurements (geodetic datum in French Polynesia). (c) Age vs elevation plot of dated *in situ* reef flat facies. Elevations are based on NGPF measurements (geodetic datum in French Polynesia). (d) Age distribution of conglomerates and reef boulders. For (a) and (b), the grey data points are from Hallmann et al. (2018) and the data points in other colours are from this study. Error values for ages and elevations are 2-sigma (Hallmann et al., 2018) in (a), (b) and (c). Elevations have been corrected for subsidence (see Supplementary Table 1).

4.1.1. Microatolls and microatoll fields

At our study sites, modern coral microatolls are mostly made by *Porites* (Fig. 1a, b) and, to a lesser extent, merulinids. They are especially abundant on Bora Bora, Maupiti, Tahaa, Tikehau, Manihi and Makemo, and scarce on Tahiti, Fakarava, Rangiroa and Raivavae. On the Society Islands, microatoll fields exclusively occur in the northern part of the islands. Modern coral microatolls were not observed on Raiatea, Moorea, Hao, Tubuai and the Gambier Islands. The diameters of modern coral microatolls range from 0.2 to 1 m (0.5 m on average) and therefore represent a time span of 10 to 50 years based on the average growth rate (12 mm/yr) of modern *Porites* colonies in the study area (Farley et al., work in progress). The largest reported modern *Porites* microatoll displays a diameter of 3 m and is located on Fakarava. The top of modern living microatolls, called the ‘biological level’, occurs at 0.18 m deep in reef flat environments, at 0.23 m in lagoonal areas and at 0.26 m in *hoas* (Hallmann et al., 2018), thus reflecting short-term changes in water level induced by winds and/or swells or local hydrodynamic conditions (Pirazzoli and Montaggioni, 1984; Rougerie, 1995). No moating effect is reported on the studied islands, thus implying that the palaeo-water depth significance of Holocene coral microatolls is well constrained to 0.18 to 0.26 m, depending on

the environment. Continuous growth of coral microatolls therefore indicates a sea-level stability during their lifetime, involving variations in sea level smaller than 20 cm.

Holocene *Porites* microatolls were reported on seven of the 15 studied islands where they display a specific distribution related to prevailing environmental conditions. They occur from 0.03 m deep to 0.65 m high and give ages ranging from 4.96 ± 0.07 to 1.38 ± 0.03 kyr BP on the Society Islands and from 5.59 ± 0.05 to 1.26 ± 0.02 kyr BP on the Tuamotus (Supplementary Table 1), thus encompassing most of the mid-late Holocene time span. Only reworked coral microatolls were observed on Fakarava and Manihi. Like their modern counterparts, Holocene microatolls have not been reported on the Austral and Gambier Islands. The surface covered by Holocene microatoll fields generally represents 1 to 6% of the studied areas; fields of Holocene microatolls were not reported in the northern part of Rangiroa and on Makemo.

Individual Holocene coral microatolls display a wide range of diameters, from 0.2 to 6.2 m, and typify sea-level stillstands on decadal to centennial time scales when sea-level variations were smaller than 20 cm over the corals' lifetime. Most microatolls (~75%, $n = 149$) average 0.6 to 1.7 m in diameter and therefore represent a time span of 25 to 70 years. Significantly larger microatolls, displaying diameters ranging from 2.5 to 6.2 m, occur on Bora Bora, Maupiti and Tikehau, indicating longer sea-level stillstands (i.e., up to 250 years) during six specific time windows between 5.59 ± 0.05 and 1.38 ± 0.03 kyr BP, i.e. during most of the mid-late Holocene sea-level history (Fig. 7a, b).

Coral microatolls usually form compact fields, especially on Tikehau, Bora Bora and Maupiti. In contrast, when the assemblages are looser, the spaces between the coral microatolls are filled by *in situ* and reworked coral colonies, including branching *Acropora* and *Pocillopora* exhibiting a lateral growth pattern, massive merulinids and *Porites*, lamellar and pseudocolumnar *Porites* and solitary *Fungia*; bivalves (mainly *Tridacna*) are common.

4.1.2. Reef flat units

Holocene reef flat units generally occur seawards of coral microatoll fields (Figs. 5, 6) and commonly exhibit a gentle seaward slope. They mainly occur close to modern mean sea level, from 0.4 m high to 0.2 m deep, where they form the substrate of the modern shoreline and display a typical brownish colour (Fig. 8a). They have been observed on ten studied islands where they encompass different time windows covering most of the mid-late Holocene, from 5.76 ± 0.17 to 3.41 ± 0.07 kyr BP on the Society Islands and from 5.75 ± 0.03 to 2.31 ± 0.02 kyr BP on the Tuamotus (Figs. 7, 9; Supplementary Table 1). The oldest dated *in situ* coral sample has an age of 6.13 ± 0.07 kyr BP and corresponds to a flat coral colony included in reef flat units occurring at 1 m deep on Raivavae (Ruahota Rahi). Reef flat units cover surfaces that currently represent 9 to 46% of the studied areas, with an average of 25%; however, their maximum extension during the mid-late Holocene is estimated to have been four to seven times larger, in relation to the higher sea-level stand.

Their composition is similar to that of their modern counterparts and consist of *in situ* and reworked coral colonies of robust branching *Acropora* and *Pocillopora* (Fig. 8b-e), massive *Porites* and foliaceous merulinids, while *Millepora* and solitary *Fungia* are clearly subordinate. Branching coral colonies generally display a lateral growth pattern, which indicates that their growth was influenced or even limited by sea surface and/or tidal currents. Dense assemblages of flattened branching or foliaceous coral colonies locally end up with the formation of a compact pavement. The outer margins of patches of branching colonies are commonly overgrown by lamellar *Porites* colonies and then coated by thick coralline algal crusts. Flat *Porites* colonies averaging 0.7 m and up to 6.5 m in diameter (e.g., on Maupiti) and, to a lesser extent, meandroid corals with an elongated to circular shape (Fig. 8f) are common components of Holocene reef flat units. These colonies have developed under the influence of the tidal regime and may correspond to an early microatoll development stage (see Hopley et al., 2007), generally at a few tens of centimetres to 1 m below the sea surface,

398 and up to 1.5 m deep in areas typified by a greater tidal range (e.g., Gambier Islands). They
399 can be therefore considered as lower limit indicators and their dating therefore helps to further
400 constrain sea-level changes and reef responses to those changes. The common elongated
401 morphology of these coral colonies, the occurrence of ridges that are perpendicular to the
402 shore and the presence of thick crusts of *Porolithon* gr. *onkodes* (Fig. 8g, h) reflect their
403 growth in an environment dominated by high-energy conditions (Camoin et al., 2012).
404 Subcolumnar *Porites* colonies may occur between large flat *Porites* colonies.
405 The upper surface of reef flat units displays abundant algal crusts and mollusks (mostly
406 *Tridacna*); it is commonly irregular and exhibits bioerosion features as well as cavities and
407 conduits that are partly filled by pieces of microatolls reworked from the overlying unit,
408 indicating that they correspond to post-depositional erosional processes.

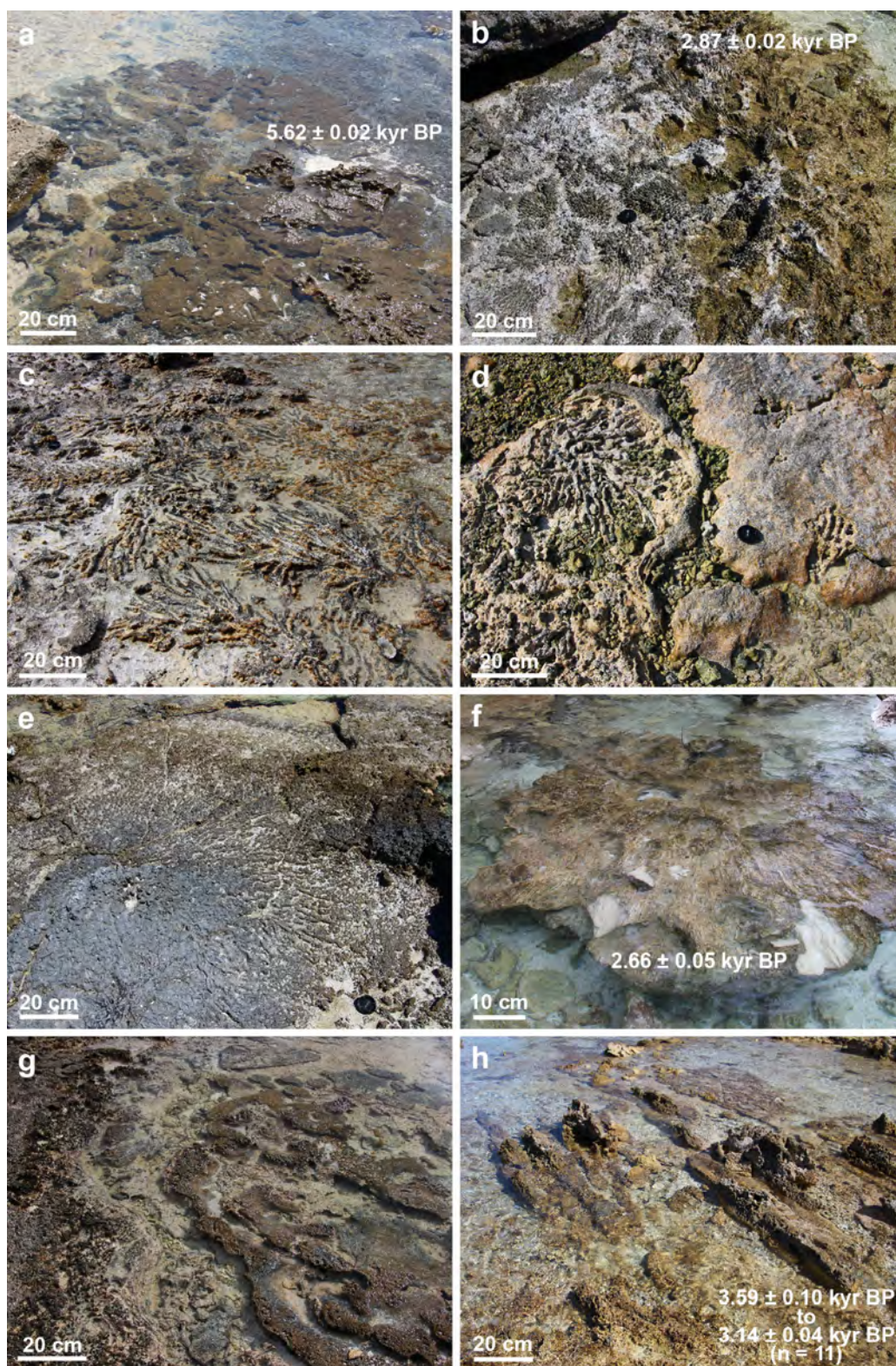
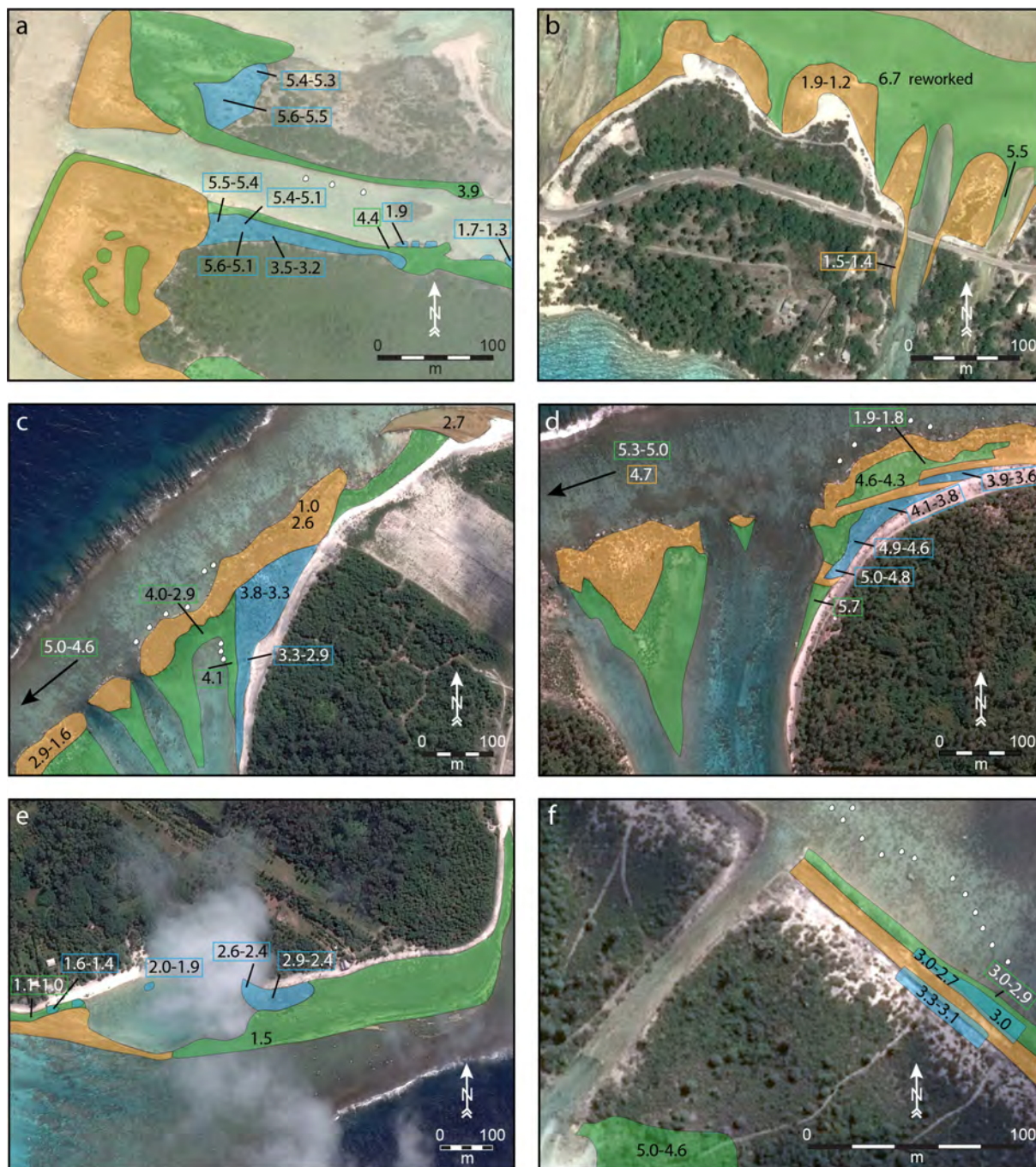


Fig. 8. Holocene reef flat units. (a) Reef flat with massive colonies (Tikehau). (b) and (c) Reef flat with branching *Acropora* (Bora Bora and Maupiti). (d) Reef flat with branching and massive corals thickly encrusted by coralline algae (Maupiti and Bora Bora). (e) Reef flat with large branching colonies displaying a lateral growth pattern (Tikehau). (f) Flat,

414 meandroid coral colony (Raivavae). (g) Reef flat with branching and massive corals
 415 encrusted by coralline algae (Maupiti and Bora Bora). (h) Reef flat with elongated *Porites*
 416 colonies (Gambier Islands).



417
 418 Fig. 9. Ages and distribution of morphological units. (a) Motu Matuura, Tikehau. (b)
 419 Taamoi, Rangiroa. (c) Motu Mute, Bora Bora. (d) Motu Tuanai, Maupiti. (e) Motu Piti Aau,
 420 Bora Bora. (f) Motu Ome, Bora Bora. Blue: Holocene microatolls, green: Holocene reef flat,
 421 orange: conglomerates. The white circles indicate the position of major living microatolls.

The exact position of some samples cannot be shown on this map section and is indicated by a black arrow. Their position is shifted by a few hundreds of metres in arrow direction.

4.1.3. Conglomerates and reworked reef blocks

On all studied islands, Holocene coral microatoll terraces and reef flat units are unevenly covered by accumulations of poorly-sorted conglomerates of variable thickness up to 1.5 m thick (Figs. 4-6; Fig. 10a-d) and covering 4 to 26% of studied areas, with an average of 15%.

These conglomerate units are usually comprised of successive beds displaying sedimentary slopes dipping seawards; they thicken in the direction of the open ocean and pinch out in the direction of the lagoon. They form significant reliefs along the modern coastline, generally parallel to it, and may form scattered islets in the lagoon. They often plaster the morphology of underlying units, especially microatoll fields (Fig. 10c), and/or pinch out against antecedent topography formed by *feos* on Tikehau and Rangiroa. Their upper surface commonly forms an overall flat, near-horizontal platform suggesting the occurrence of subsequent abrasion processes (Fig. 10b).

Conglomerates are mostly composed of reworked, disoriented, sometimes eroded and cemented coral colonies and boulders, associated to fragments of corals, mollusks (mostly *Tridacna*, oysters and gastropods) and echinoids; thick coralline algal crusts around coral colonies as well as algal bushes are locally abundant, especially at the top of conglomerate pavements. Coral colonies are usually up to 40-50 cm in size and include especially robust branching *Acropora* and *Pocillopora*, tabular *Acropora*, lamellar and massive *Porites* and merulinids, as well as fewer lamellar and meandroid corals and solitary *Fungia*. Larger scattered dome-shaped colonies of *Porites* (Fig. 10b) and merulinids of up to 1.5 m occur at the top of conglomerate platforms on all studied islands. Rapid grain size variations occur in the matrix of conglomerates and irregular alternations of big fragments, gravels and coarse

sand deposits are observed locally; the matrix is commonly composed of *Halimeda*-rich gravels and sands.

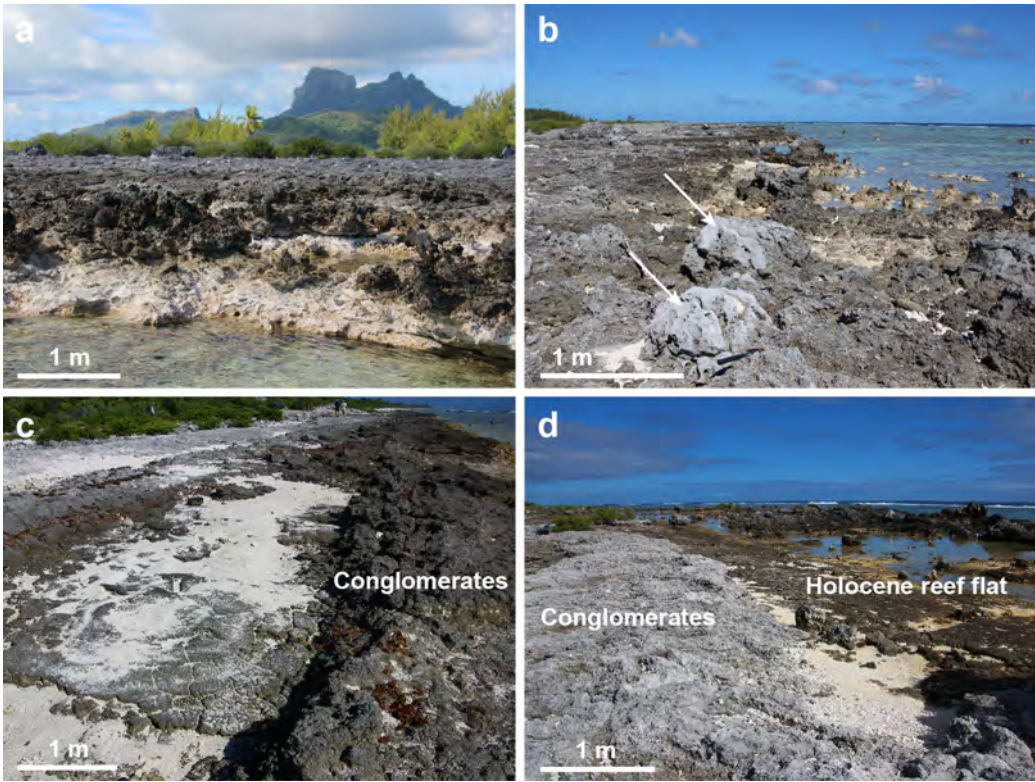


Fig. 10. Conglomerates. (a) Conglomerate platform with an elevation of about 1 m above mean sea level (Bora Bora). (b) Conglomerate platform with reworked, dome-shaped *Porites* colonies (arrows; Bora Bora). (c) Large flat microatoll surrounded by conglomerates (Bora Bora). (d) Holocene reef flat partly covered by conglomerates (Maupiti).

Sampling of conglomerate units were conducted both at their surface and along vertical sections to avoid sampling bias as much as possible; it is therefore considered as representative of the composition of these units. These units are interpreted to correspond to storm deposits and corals dated from within these units cover a wide range of ages from 5.18 ± 0.04 to 0.06 ± 0.01 kyr BP ($n = 48$; Supplementary Table 1). Their occurrence peaks in four distinctive time periods of variable importance: 5.2-4.6, 3.6-3.2, 2.9-1.0 and 0.2-0.1 kyr BP (Fig. 7d); however, their maximum occurrence is reported between 2.2 and 1.5 kyr BP. Sustained storm activity during these periods is in good agreement with data obtained on

Tahaa, where two prominent intervals of increased storm-derived coarse-grained deposition were reported: 5.0-3.8 kyr BP and 2.9-0.5 kyr BP (Toomey et al., 2013). On most islands, conglomerate units are usually overlain by recent beachrock deposits rich in coral fragments and *Tridacna* shells.

On all studied islands, loose reef boulders of several metres in size rest on various parts of the modern reef system, especially on the reef flat and in lagoonal areas. They are interpreted as having been plucked from the adjacent reef and transported by storm waves. Ages obtained from storm boulders range from 1.74 ± 0.01 to 0.04 ± 0.02 kyr BP, with a maximum occurrence between 1.7 and 1.1 kyr BP, and 0.4 and 0.04 kyr BP; they are especially abundant on Fakarava (Fareana) where the largest blocks have been dated at 1.7 kyr BP.

4.2. The evolution of the mid-late Holocene reef complex through time

Mid-late Holocene RSL changes encompassing the last 6,000 years on a century time scale are reconstructed based on high-precision GPS positioning and U/Th dating of 78 *in situ* coral microatolls from five islands (Hallmann et al., 2018) and 13 samples from six additional microatolls in the frame of the current study (Figs. 7, 11). The elevations of Holocene microatolls have been directly compared to those of their living counterparts growing in the same depositional environment to track relative changes of the MLWS level throughout the mid-late Holocene (Fig. 7a). It has been assumed that the relationship between microatolls and the tidal cycle has remained the same over the last 6,000 years (Hallmann et al., 2018). Moreover, GPS measurements of microatoll elevations have been referenced to local tidal parameters defined by the NGPF (Fig. 7b). In addition, the dating of 132 coral samples from mid-late Holocene reef flat units and conglomerates and their vertical and lateral relationships with microatoll fields help to further constrain relative sea-level changes and to reconstruct successive stages of reef development (Fig. 7c, d). The curve based on dated reef flat units follows the reconstructed sea-level curve based on microatolls, but lies generally 0.3 to 0.4 m

below it on average, thus reflecting the water depth of their depositional environment (Fig. 7b).

The reconstructed sea-level curve documents a short-lived, ~700-year, sea-level highstand of less than a metre between 4.10 and 3.40 kyr BP, following an overall sea-level rise from 6.0 to 4.10 kyr BP and preceding a fall in sea level between 3.40 and 1.26 kyr BP (Figs. 7, 11).

As a consequence of these low-amplitude sea-level variations, successive generations of coral microatolls and associated reef deposits are usually mixed and the reconstruction of reef development relies both on accurate U-series dating and relevant GPS positioning, and on the relationships between different reef facies in successive time windows. Three islands document significant time windows of the sea-level history:

- Tikehau, where a sea-level fall is recorded between 5.59 and 5.12 kyr BP and during the 3.51-3.19 and 1.96-1.26 kyr BP time windows;
- Maupiti, where a sea-level rise is documented between 4.99 and 4.61 kyr BP and the sea-level highstand between 4.10 and 3.60 kyr BP;
- Bora Bora, where the sea-level highstand is recorded between 3.81 and 3.40 kyr BP, followed by a fall in sea level between 3.40 and 1.38 kyr BP.

The other islands have provided information on shorter time windows, which complemented the data from the three main islands, providing eventually the accurate reconstruction of the mid-late Holocene sea-level history. The high-resolution reconstruction of sea-level changes provides the necessary frame to analyze their impact on reef geometry, composition and evolution over the last 6,000 years, as well as the respective role played by variations in accommodation space, antecedent topography and environmental changes.

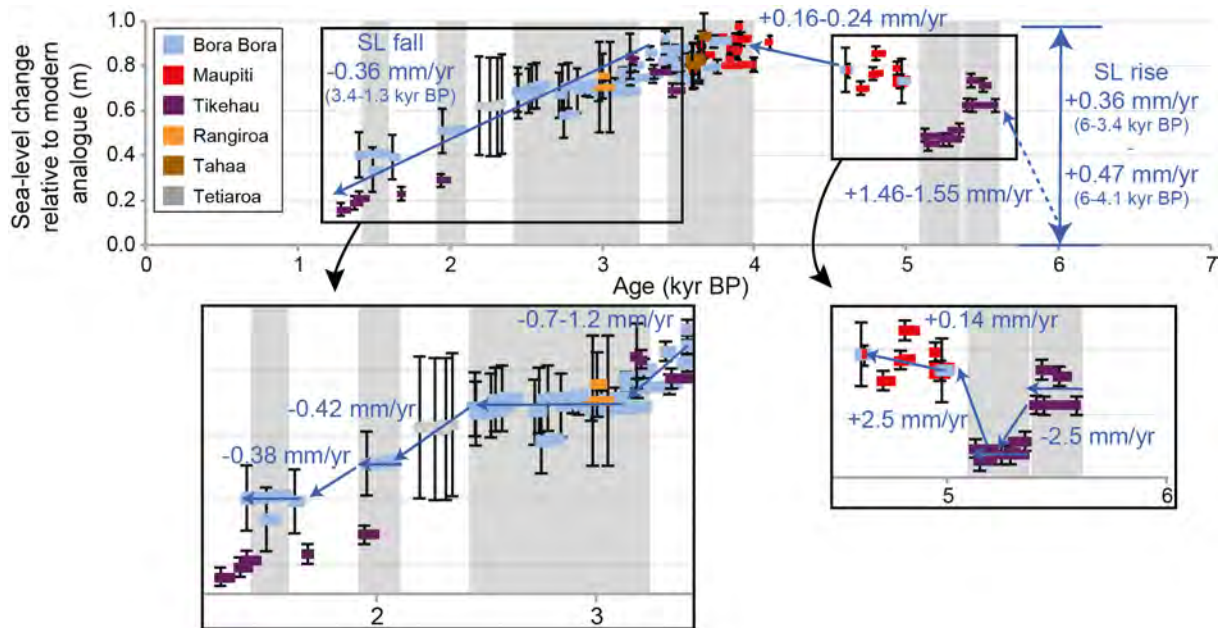


Fig. 11. Rates of mid-late Holocene sea-level change. These rates have been calculated based on the age and elevation differences between two successive coral microatoll samples with reference to the elevation of modern microatolls. Error values for ages and elevations are 2-sigma (see Hallmann et al., 2018). The grey shaded areas indicate specific time windows characterized by century-scale stillstands during which large microatolls with a diameter of ≥ 2.5 m developed. Microatoll elevations have been corrected for subsidence (see Supplementary Table 1).

4.2.1. Sea-level rise (6.0 - 4.10 kyr BP; Figs. 7, 11)

The rate of sea-level rise from 6.0 kyr BP to the start of the highstand at 4.1 kyr BP averages 0.36 to 0.47 mm/yr. Microatoll fields on Tikehau (Matuura) occur at two distinctive present elevations: 0.4-0.5 and 0.3 m. They form terraces that are gently dipping towards the modern *hoa* and the lower terrace pinches out against the morphology of the upper terrace. They yield ages ranging from 5.59 ± 0.05 to 5.41 ± 0.08 and 5.37 ± 0.05 to 5.12 ± 0.04 kyr BP, respectively, thus indicating MLWS levels of 0.6-0.7 m and 0.5 m above the present position during these time intervals, respectively. These two successive generations of microatolls therefore document a sea-level rise averaging 1.46 to 1.55 mm/yr between 6.0 and 5.6 kyr BP,

529 followed by a slight sea-level drop of 0.2-0.3 m in amplitude. The relevant microatoll fields
 530 are primarily comprised of microatolls larger than 1.6 m in diameter, thus indicating that they
 531 developed during sea-level still stands longer than 70 years. These large microatolls have
 532 been systematically sampled both at their center and on their outer rim. The largest
 533 microatolls, up to 5 m in diameter, belong to the oldest generation. The rate of the sea-level
 534 fall that is evidenced between the development of the two microatoll fields is of 2.5 mm/yr
 535 (Fig. 11). Coeval reworked microatolls, 0.3 to 0.6 m in diameter, with ages ranging from 5.69
 536 ± 0.06 to 5.48 ± 0.09 kyr BP have been observed elsewhere (Matiti, Tikehau). The microatoll
 537 fields are associated laterally to reef flat units that occur a few tens of centimetres lower. The
 538 vertical succession involving reef flat units overlain by the second generation of microatolls is
 539 related to a sea-level drop between 5.43 ± 0.04 and 5.37 ± 0.05 kyr BP. Reef flat units are
 540 mostly comprised of *in situ* coral colonies, including large flat *Porites* and merulinids up to a
 541 few metres in diameter, branching *Acropora* and *Pocillopora* with a distinctive lateral growth
 542 pattern, and lamellar *Porites* that occur at the edge of large flat *Porites* and around coral
 543 patches (Fig. 8a); reworked massive merulinids are clearly subordinate.
 544 Very slow rates of sea-level rise (0.16-0.24 mm/yr) characterize the end of the 4.6-4.1 kyr BP
 545 period when microatoll fields display extensive development. These fields are comprised of
 546 coalescing patches of several microatolls ranging from 0.5 to 0.8 m in diameter that are coated
 547 by lamellar coral colonies and thick crusts of coralline algae. The depressions between
 548 microatolls display a variety of coral colonies including subcolumnar and lamellar *Porites*,
 549 branching *Pocillopora* and *Acropora* often characterized by lateral growth pattern, and
 550 flattened merulinids; the occurrence of abundant and thick crusts of coralline algae indicates
 551 the prevalence of high-energy conditions. These microatoll fields crop out at present
 552 elevations of 0.4-0.6 m on Maupiti (Tuanai) and Bora Bora (Ome), indicating that the MLWS
 553 level was located at 0.7 to 0.8 m above its present level between 5.0 and 4.6 kyr BP. On
 554 Maupiti (Tuanai), these microatolls overlie reef flat units dated at 5.7 kyr BP (Fig. 9). A sea-

level rise of 0.2 to 0.3 m at a rate of 2.5 mm/yr is therefore evidenced between 5.12 and 4.99 kyr BP (Fig. 11). Reworked microatolls, including large ones of up to 2.6 m in diameter, are reported on Tikehau (Matiti) and yield ages ranging from 5.69 ± 0.06 to 4.75 ± 0.07 kyr BP. The microatoll fields that characterize a sea-level rise between 5.6 and 4.6 kyr BP usually grade laterally to reef flat units that form very flat areas dipping gently seawards at lower elevations than microatoll fields. On Tikehau (Tuherahera), *in situ* flat colonies of *Porites* that are larger than 1 m in diameter, are observed at present mean sea level and yield ages ranging from 5.75 ± 0.03 to 5.62 ± 0.02 kyr BP. Reef flat units include large flat and subcolumnar colonies of *Porites* associated with foliaceous colonies of merulinids characterized by a lateral growth pattern and, to a lesser extent, branching colonies of *Pocillopora* and *Acropora*. High-energy conditions are typified by the occurrence of thick coralline algal crusts, which delineate the various patches composing the fossil reef flat. Cavities, conduits and channels are common in these units and suggest mechanical abrasion and/or dissolution processes. Similar and coeval reef flat units are observed on Bora Bora (Mute, Ome, Iti and Haapitirahi), Rangiroa (Taamoi) and Manihi (Arianohu); reef flat units dominated by robust branching *Pocillopora* and thick coralline algal crusts occur at a current elevation of 0.1-0.2 m on Maupiti (Tuanai) and are dated at 5.76 ± 0.17 and 5.74 ± 0.10 kyr BP. On Tikehau (Matiti), storm deposits comprised of conglomerate units are dated between 5.18 and 5.12 kyr BP and between 4.79 and 4.61 kyr BP, and were therefore deposited during a rise in sea level.

4.2.2. Sea-level highstand (4.10 - 3.40 kyr BP; Figs. 7, 11)

A sea-level highstand involving a MLWS level of up to 0.97 m above its present position is inferred between 4.10 and 3.40 kyr BP; the highest elevation has been recorded on Maupiti and corresponds to an age of 3.91 ± 0.03 kyr BP. Our sea-level curve differs markedly from previous reconstructions, which include either a higher amplitude, estimated at a minimum of +1.5 m (Rashid et al., 2014), and/or a much longer sea-level highstand in the 5.0-1.5 kyr BP

581 (Pirazzoli and Montaggioni, 1988) and 5.4-2.0 kyr BP (Rashid et al., 2014) time windows.
 582 More generally, most of our microatoll data plot below these former sea-level reconstructions.
 583 We assume that these discrepancies may result from inaccurate measurements of elevations
 584 and/or from the dating of coral colonies reworked in storm deposits that commonly overlie the
 585 microatoll fields.

586 The precise start of the sea-level highstand could not be determined, as no microatoll has been
 587 recorded in the 4.6-4.1 kyr BP time interval; thus, the rates of sea-level rise must be
 588 considered as minimum values. The lack of microatoll development may result from
 589 temporary and/or local changes in environmental conditions, or to a sampling bias despite the
 590 thorough exploration of the studied islands. A rapid and short-lived sea-level fall after 4.6 kyr
 591 BP, as suggested by other records (Lewis et al., 2008, 2013), cannot be discarded. However,
 592 the reef flat units covering the 5 to 4 kyr BP time window do not display any change in their
 593 depth distribution, thus arguing against such an interpretation. Large flat colonies of *Porites*
 594 and merulinids are observed in reef flat units on Maupiti (Tuanai, Tiapaa) and Rangiroa (Teu)
 595 at present elevations of 0.15 to 0.25 m and 0.45 m, respectively, i.e. ~1 m above their modern
 596 counterparts. They give ages ranging from 4.48 ± 0.03 to 4.0 ± 0.05 kyr BP on Maupiti and
 597 from 4.13 ± 0.03 to 3.87 ± 0.02 on Rangiroa. On Tahaa and Tikehau (Tuherahera, Matiti),
 598 corals forming reef flat units occur at present sea level and give ages ranging from 4.29 ± 0.04
 599 to 3.55 ± 0.05 and from 4.36 ± 0.01 to 3.80 ± 0.02 kyr BP, respectively.

600 The sea-level highstand is typified by the widespread development of microatoll fields (Figs.
 601 1d, 4, 5) that are especially well exposed on Maupiti, Tahaa and Bora Bora (Mute) where they
 602 yield ages ranging from 4.10 ± 0.04 to 3.40 ± 0.05 kyr BP. The diameter of the microatolls
 603 ranges generally from 0.4 to 1.2 m in diameter, but some individuals are much larger,
 604 especially in the 4.0-3.8 kyr BP time window. The largest coral microatoll exhibits a diameter
 605 of 2.75 m, equivalent to about 115 years of continuous coral growth; this has been confirmed
 606 by direct dating of the central part and the edge of the microatoll colony, which yield ages of

607 3.95 \pm 0.04 and 3.84 \pm 0.03 kyr BP, respectively. The upper surface of the microatolls is
608 generally flat, but the elevated outer margin of some individuals indicates a slight sea-level
609 rise during their late development, as found on Maupiti (Tuanai) during the 4.1-3.8 kyr BP
610 time window (Fig. 12a-c). This demonstrates that minor sea-level variations have occurred
611 during the sea-level highstand. In the same area, the start of sea-level fall at 3.6 kyr BP is
612 documented by the development of the outer margin of microatolls at a lower elevation than
613 their central part. Branching *Acropora* and *Pocillopora* and pseudocolumnar *Porites* colonies
614 occur between microatolls (Fig. 12d). Microatoll fields overlay reef flat units that were
615 deposited during the former sea-level rise and which form the basement of the current
616 shoreline; on Maupiti (Tuanai), these reef flat units are dated between 4.62 \pm 0.05 and 4.29 \pm
617 0.05 kyr BP. Reef flat units usually occur 0.3 to 0.4 m below coeval microatoll fields, and are
618 slightly inclined seawards. They exhibit a typical brownish colour, a rather compact structure
619 and a very flat topography. On Bora Bora (Mute), reef flat units occur at modern mean sea
620 level and give ages ranging from 4.1 and 2.9 kyr BP (Fig. 9c). Reef flat units are mostly
621 comprised of a dense pavement of large flat colonies of *Porites*, ranging from 1 to 6.5 m in
622 diameter, with a slightly irregular upper surface displaying abundant bioerosion. The largest
623 flat colonies of *Porites* are observed at an elevation of 0.2 m on Bora Bora (Mute) and yield
624 ages ranging from 3.8 to 3.6 kyr BP. Branching colonies of *Acropora* and *Pocillopora* are
625 commonly associated and display a conspicuous lateral growth pattern, indicating that their
626 vertical development was constrained by the water surface and/or tidal currents.

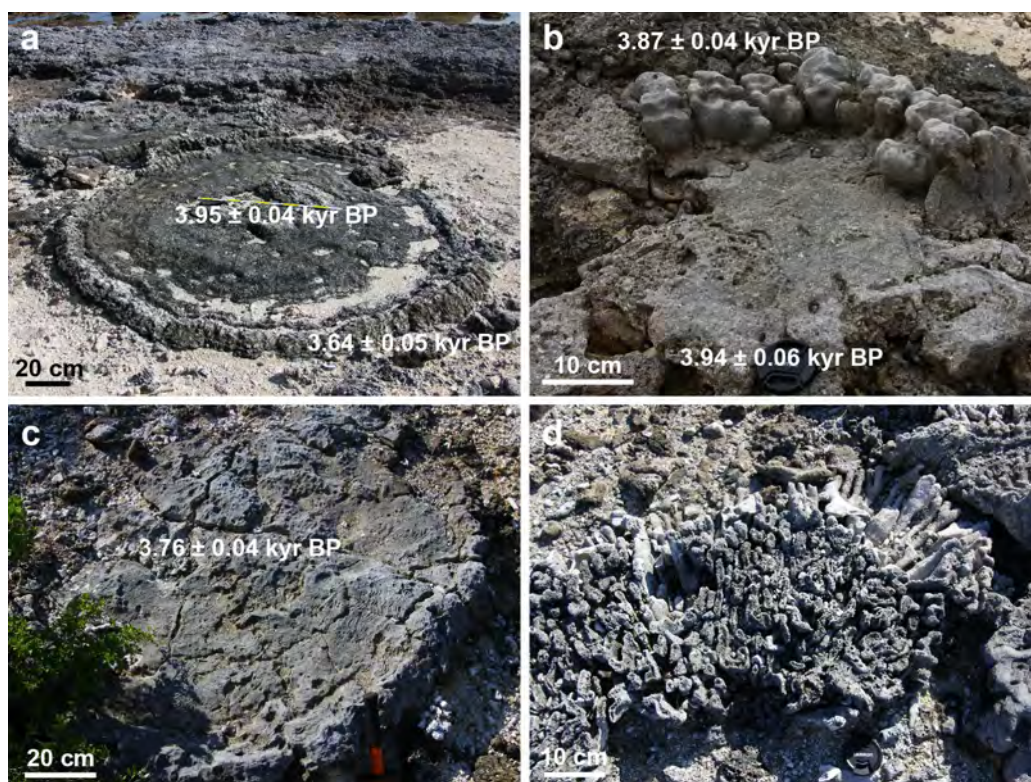


Fig. 12. Mid-late Holocene sea-level highstand. (a) *Porites* microatoll with a higher margin indicating a sea-level rise during its growth, and ridges on the surface related to low-amplitude, high-frequency sea-level changes over ca. 140 years (Maupiti). (b) *Porites* microatoll exhibiting overgrowth on its margin reflecting a sea-level rise of about 6 cm (Maupiti). (c) *Porites* microatoll with visible annual growth lines on its surface (Bora Bora). (d) *In situ Pocillopora* branching colony growing between *Porites* microatolls (Bora Bora).

4.2.3. Sea-level fall (3.40 – 1.26 kyr BP; Figs. 7, 11)

The distribution and the dating of microatoll fields from Bora Bora, Tikehau and Rangiroa, document a fall in MLWS level from 0.93 m at 3.40 kyr BP to about 0.16 m at 1.26 kyr BP above its present position, at an average rate of 0.36 mm/yr (Fig. 11). This rate is consistent with data reported from nearby archipelagos like the Cook Islands (Goodwin and Harvey, 2008) and is typical for mid-ocean regions of the South Tropical Pacific during mid-late Holocene (Mitrovica and Milne, 2002). The youngest *in situ* coral microatoll is reported on Tikehau (Matuura) and yields an age of 1.26 ± 0.02 kyr BP; younger reworked microatolls

dated 1.15 ± 0.02 and 1.16 ± 0.02 kyr BP have been recorded on Fakarava (Vahapiapia). Our results are therefore in clear contradiction with the occurrence of a short-lived sea-level peak of 1 m in amplitude between 2.0 and 1.5 kyr BP (Pirazzoli and Montaggioni, 1988).

The occurrence of large microatolls of more than 2.5 m in diameter in three specific time windows, 3.2-2.4, 2.1-1.9 and 1.6-1.4 kyr BP, characterizes relative sea-level stillstands longer than 100 years (Fig. 11). This indicates that sea level did not fall at a continuous rate, but was characterized by significant variability, involving extended periods of relative sea-level stability.

The 3.4-3.1 kyr BP time span is characterized by rates of sea-level fall ranging from 0.7 to 1.2 mm/yr (Fig. 11). It is documented by microatoll fields that occur at present elevations of 0.4 to 0.7 m on Bora Bora (Mute) and Tikehau (Matuura), respectively, thus characterizing a MLWS level at about 0.5 to 0.8 m above its present position and slightly lower than during the former sea-level highstand. On Bora Bora, the microatoll fields rest on previous reef flat units, indicating a lowering of the sea level. In contrast, on Tikehau (Matuura), they overlay microatoll fields developed during the 5.6-5.1 kyr BP time span and reef flat units dated at 4.89 ± 0.05 kyr BP. This indicates that there was no coral growth at that site for at least 1,500 years (i.e. between 4.89 and 3.4 kyr BP), especially during the whole duration of the sea-level highstand. This may be due to unfavorable high-energy conditions during this period, as this area is located in the most exposed side of the atoll. Microatoll fields on Bora Bora are comprised of closely packed colonies generally ranging in diameters from 0.2 to 2 m in diameter, the larger ones yielding ages of 3.4 kyr BP. Some colonies display an irregular topography typified by concentric ridges and indicating low amplitude sea-level variations at the start of the sea-level fall. The occurrence of a peripheral ridge at a lower elevation than the core of the colony indicates a sea-level fall during the development of the microatoll, as found on Bora Bora (Mute) for a microatoll dated at 3.40 ± 0.05 kyr BP.

668 The 3.1-2.7 kyr BP time span is typified by a very stable sea-level position allowing the
 669 widespread development of compact microatoll fields at elevations of 0.7 m above present
 670 MLWS on two islands: Bora Bora (Mute, Ome) and Rangiroa (Teu, Vaihoha) where they
 671 cover former reef flat units. *Porites* microatolls display diameters larger than 0.7 m,
 672 commonly larger than 2 m and up to 5 m, thus typifying stillstands lasting for up to 200 years
 673 long. In contrast, merulinid microatolls generally display diameters less than a metre. The
 674 development of thick coralline algal crusts at the edge of coral microatolls indicates the
 675 prevalence of high-energy conditions.

676 The 2.70-1.26 kyr BP time window is especially well documented in the southern part of Bora
 677 Bora (Piti Aau) where microatoll fields are distributed at elevations ranging from about 0.7 to
 678 0.4 m above present MLWS level, with ages of 2.76-2.43 and 1.93-1.38 kyr BP. This
 679 descending succession of microatolls (Fig. 1g, h) typifies a fall in sea level at rates ranging
 680 from 0.38 to 0.42 mm/yr (Fig. 11). A similar succession close to modern sea level is observed
 681 on Tikehau (Matuura) and corresponds to the 1.92-1.26 kyr BP time window, thus
 682 documenting the last part of the sea-level fall with a MLWS level falling from 0.29 to 0.16 m
 683 above its present position. Their development on reef flat units dated at 4.39 ± 0.06 kyr BP
 684 that occurs at modern sea level indicates a hiatus coinciding with the sea-level highstand at
 685 that particular site; this hiatus could be related to local unfavorable high-energy conditions
 686 during this period. Most microatolls characterizing the 2.70-1.26 kyr BP time window
 687 coalesce laterally to form compact fields and display large diameters, commonly larger than
 688 2.5 m, thus recording extended sea-level stillstands. The overall upper surface of microatolls
 689 is flat, but also exhibit a microtopography that reflects high-frequency and low-amplitude
 690 (less than 20 cm) sea-level variations during this time window.

691 All generations of microatolls developed during the sea-level fall are associated laterally to
 692 reef flat units that are slightly inclined seawards and occur at lower elevations than microatoll
 693 fields. Reef flat units that were deposited during this fall in sea level also occur on islands

where microatoll fields do not crop out, such as Mangareva (Tepapuri), Manihi (Pomagu), Hao, Makemo (Oehava), Tahaa, Moorea (Fareone, Tiahura) and Fakarava (Fareana, Vahapiapia). They are primarily composed of *in situ* colonies of massive and flat *Porites* and merulinids, branching *Acropora*, and to a lesser extent *Pocillopora*, that are characterized by a lateral growth pattern, and lamellar *Porites* that develop at the margins of clusters of coral colonies and around large flat coral colonies. The upper surface of coral colonies is generally irregular and exhibits abundant bioerosion features. Reworked coral colonies are locally abundant. On Raivavae (Araoo), flat colonies of meandroid corals and merulinids, 0.3 to 1 m in diameter (Fig. 8f), overlay a karstified reef flat bearing *Acropora* colonies to form a compact field at present elevations of 0.10 to 0.15 m; they yield ages ranging from 2.86 ± 0.03 to 2.65 ± 0.05 kyr BP.

Most of the conglomerate units corresponding to storm deposits, which represent a major component of the mid-late Holocene sequence (Figs. 9, 10), were deposited during the duration of the sea-level fall. However, they are especially conspicuous during the 2.2-1.5 kyr BP time span, indicating sustained storm activity during this period. These storm deposits usually cover microatoll fields and reef flat units. However, on Bora Bora (Piti Aau), they are interlayered between generations of microatolls, thus indicating that their deposition was locally coeval to the development of microatolls.

5. Discussion

5.1. Reef and coastal responses to sea-level and associated environmental changes over the last 6,000 years

The impact of future sea-level rise on coastal ecosystems is amongst the most pressing scientific and societal issues posed by warming from greenhouse gas forcing. This problem is especially acute for low-lying islands, which will face dramatic issues in the context of future sea-level rise (IPCC, 2018). There is therefore a clear need to investigate coastal and coral

reef responses to low-amplitude, high-frequency sea-level changes that are expected to dominate over the coming decades. However, so far, these processes have been scarcely documented in the mid-late Holocene (Hopley, 1982; Hopley et al., 2007; Harris et al., 2015), and nowhere near at the temporal and spatial resolutions that are needed to better predict the future evolution of coastal systems, especially coral reefs. Furthermore, the impact of mid-late Holocene sea-level change and other environmental factors on reef architecture and composition remains poorly resolved (Camoin and Webster, 2015).

The mid-late Holocene reef sequence presented in this study provides the opportunity to document at high-resolution the response of coral reefs and coastal systems to sea-level changes over the last 6,000 years, a period that is typified by slow-rate, low-amplitude and high-frequency sea-level changes. The high-resolution reconstruction of reef geometry, composition and evolution during this time window summarizes the adjustments that reef systems have had to make to changes in accommodation space driven by variations in relative sea level (sea-level rise, stillstand and fall). It therefore helps in the understanding of reef dynamic processes that are of global importance. In addition, it has potentially important implications for predicting how modern reefs might respond to a sea-level rise of similar amplitude, 0.5 to 1.5 m, before the end of the current century (Alley et al., 2007; Church et al., 2013; IPCC, 2018). In this study, a special emphasis has been given to understand how reef areas that are at or near sea level, e.g., microatoll fields and reef flat units, have responded in terms of reef development, architecture and composition to changes in accommodation space, which is controlled by changes in relative sea level and antecedent topography.

In French Polynesia, drill core data have demonstrated that coral reefs have accreted continuously over the last 16,000 years, mostly through aggradational processes, at growth rates averaging 10 mm/yr (Camoin et al., 2012). Growth rates then decreased sharply throughout the Holocene to about 0.4 mm/yr during the stabilisation of the sea level at its

present position at 6 kyr BP (Cabioch et al., 1999; Camoin et al., 1999, 2001; Hallmann et al., 2018) as a consequence of decreasing accommodation space. On Bora Bora, the Holocene fringing reefs started to develop at 8.7 kyr BP, retrograded over a Pleistocene fringing reef until ca. 6 kyr BP, and then prograded towards the lagoon after sea-level had reached its present level (Gischler et al., 2016, 2019).

After the stabilisation of sea level at its present position, the new development of reef systems was initiated by the creation of accommodation space due to a glacio-eustatic sea-level rise, most likely sourced from Antarctica, and controlled by the antecedent topography of the islands. The reversal from rise to fall records the time at which the eustatic signal reduced and GIA (syphoning) became dominant, thus controlling regional histories of reef development. The reconstructed sea-level curve is almost continuous over the last 6,000 years (Hallmann et al., 2018). It unravels mid-late Holocene RSL changes in unprecedented detail and has therefore a global significance. Regional differences between the mid-late Holocene sea-level curve defined in French Polynesia and sea-level data obtained in neighbouring islands and continental margins can be resolved through the use of geophysical models to decipher GIA processes (Botella, 2015; Hallmann et al., 2018).

The course of RSL is characterized by the occurrence of a single short-lived sea-level highstand of less than one metre between 4.10 and 3.40 kyr BP, which enhanced reef development, followed by a sea-level fall leading to the partial emergence of the mid-late Holocene reef system (Figs 7, 11). Overall, sea-level changes are characterized by slow rates and low amplitudes. All periods of the sea-level history are characterized by significant sea-level stability (stillstands) lasting more than a century and up to 250 years, as demonstrated by the occurrence of large microatolls ranging from 2.5 to 6.2 m in diameter in specific time windows. This defines a stepped pattern for the sea-level rise and fall, involving periods of sea-level stability and periods of slow sea-level variations at rates ranging from a few tens of millimetres per year to up to 2.5 mm/yr (Fig. 11). This last value is similar to the average rise

772 in sea level that has been recorded over the 1950-2010 time span in French Polynesia
 773 (Meyssignac et al., 2012).

774 The complex microtopography of some large microatolls exhibiting ridges and different
 775 generations of overgrowths with heights of up to 20 cm reflects high-frequency, low-
 776 amplitude decadal to sub-decadal sea-level variations superimposed on longer term sea-level
 777 changes. This sea-level variability may have been driven by climatic oscillations such as
 778 ENSO (El Niño-Southern Oscillation) and PDO (Pacific Decadal Oscillation), which induce
 779 sea-level highs and lows of such an amplitude compared to normal conditions in the western
 780 Tropical Pacific (Becker et al., 2012; Church et al., 2013). However, some of this variability
 781 could be due to the 18.6-year tidal cycle (Meltzner et al., 2017).

782 Continuous reef development was maintained throughout the last 6,000 years with no break in
 783 reef growth being identified during this time window, with the exception of the site of
 784 Matuura on Tikehau due to local environmental conditions during the mid-late Holocene
 785 highstand. The only period during for which no microatoll development was recorded
 786 concerns the 4.6-4.1 kyr BP time window and may reflect a sampling bias in the studied
 787 islands. This contrasts with some other Pacific regions, including the southern Great Barrier
 788 Reef (One Tree Reef) where the lack of coral microatolls younger than 2 kyr BP and the turn-
 789 off of reef flat carbonate production were interpreted as resulting from a 1.0-1.3 m fall in sea
 790 level (Harris et al., 2015).

791 Mid-late Holocene coral assemblages and their modern counterparts display similar overall
 792 composition and diversity, in agreement with the analysis of coral communities during the
 793 same time window on the Great Barrier Reef (Roche et al., 2011). Since corals are sensitive to
 794 subtle ecological changes affecting their environment (e.g., Camoin and Webster, 2015), this
 795 suggests that most of the environmental parameters, such as light conditions, turbidity, water
 796 energy and nutrient levels, did not significantly change over the last 6,000 years, with the
 797 exception of the hydrodynamic regime. Moreover, the persistence of stable depositional

798 environments and facies distribution is demonstrated by the almost continuous development
799 of microatolls, which typify optimal environmental conditions for their growth during this
800 time window. Furthermore, the recurrent sea-level stillstands that punctuated the mid-late
801 Holocene sea-level history may have played a significant role in the widespread development
802 of dense reef frameworks.

803 The facies distribution and the lateral extension of the facies belts were governed by
804 variations in accommodation space, which are mostly controlled by relative sea-level changes
805 and the antecedent topography. A lateral shift of facies belts typifies sea-level changes during
806 the relevant period, involving a transgressive pattern ('retrogradation') during sea-level rise
807 and an oceanward shift during the subsequent sea-level fall. In contrast, there was no change
808 in accommodation space during the sea-level highstand period (4.1 to 3.4 kyr BP) and
809 recurrent periods of sea-level stillstands, which lasted more than a century and up to 250
810 years. During the mid-late Holocene, microatoll fields have migrated accordingly a few tens
811 of metres and up to 200 m, depending on the palaeotopography of the islands. The surface
812 that they cover did not change significantly over the last 6,000 years and represents 1 to 6% of
813 the reef system in the studied areas. However, the development of microatoll fields was not
814 uniform as it was subordinate to specific environmental conditions in localized areas.

815 In contrast to microatoll fields, reef flat units were much more developed during the mid-late
816 Holocene compared to modern environments, with a maximum extension that was estimated
817 to be four to seven times larger compared to their modern counterparts. This extensive
818 development occurred in prevalent high-energy and very shallow-water conditions. The
819 lateral extension of reef flat units during the mid-late Holocene sea-level rise and sea-level
820 highstand has been clearly subordinate to the antecedent topography and their lateral shift
821 usually ranges from 200 to 500 m. Their development has therefore played a prominent role
822 in reef dynamics as they usually form the substrate of microatoll fields during the sea-level
823 highstand, which occurred between 4.1 and 3.4 kyr BP, but also in the subsequent

824 development of modern islands by providing a substrate for subsequent sediment
825 accumulation.

826 The situation described in French Polynesia contrasts with the southern and northern Great
827 Barrier Reef, where a 2.3-kyr hiatus in lateral reef accretion has been documented from 3.9 to
828 1.5 kyr BP, as a consequence of a relative fall in sea level of ~0.5 m from its maximum
829 highstand at approximately 4.0-3.5 kyr BP (Lewis et al., 2013; Dechnik et al., 2017).

830 However, a fall in sea level and subsequent reef turn off at ~3.6 kyr BP is apparently not
831 supported by microatoll data from One Tree Reef (Harris et al., 2015). On the inner Great
832 Barrier Reef, a new phase of reef flat development occurred at approximately 2 kyr BP
833 following a 3.2-kyr hiatus in reef growth (Perry and Smithers, 2011). Greater hydro-isostatic
834 adjustment and subsidence along the Australian continental margin may have provided greater
835 vertical accommodation for mid-outer reefs of the central Great Barrier Reef where no hiatus
836 in reef flat development was reported (Dechnik et al., 2017).

837 On the Keppel Islands, Leonard et al. (2016, 2018) identified a hiatus in reef flat growth
838 between 4.6 and 2.8 kyr BP, with a possible earlier fall in relative sea level at ~5.5-5.3 kyr
839 BP. However, the timing and course of the relative sea-level fall after the mid-Holocene
840 highstand on the Great Barrier Reef has been interpreted in different ways, through a
841 smoothly falling sea level to present (Chappell, 1983), an abrupt sea-level fall after ~2 kyr BP
842 (Sloss et al., 2007) or 1.2 kyr BP (Lewis et al., 2015), or an oscillating sea level involving
843 metre-scale fluctuations (Lewis et al., 2008; Leonard et al., 2016, 2018).

844 Conglomerate accumulations and pavements comprise the third component of the mid-late
845 Holocene reef sequence in French Polynesia, where they represent a prominent morphological
846 feature, which is up to 1.5 m-thick and covers surfaces ranging from 4 to 26% (average: 15%)
847 of the studied areas. This suggests that these units may have played a prominent role in the
848 recent development of the islands, especially as they accumulated mostly during the late
849 Holocene sea-level fall, which is considered as an important trigger for the emergence of reef

850 islands in the Central Pacific (Dickinson, 2004, 2009; Kench et al., 2014 and references
851 therein). These conglomerates cover unevenly the coral microatoll terraces and the reef flat
852 units and have been interpreted as storm deposits. Their more extensive development during
853 the Holocene compared to modern environments is primarily related to higher sea-level stands
854 and not necessarily to more intense or more frequent storms during this period (Etienne and
855 Terry, 2012). However, the timing of the maximum occurrence of storm deposits that we have
856 reported between 2.2 and 1.5 kyr BP coincides with a peak in accumulation of storm deposits
857 observed between 3.25 and 1.5 kyr BP on the Society Islands and the entire Central South
858 Pacific (Toomey et al., 2013), as well as other Pacific islands such as the Marshall Islands
859 (Kench et al., 2014). The majority of loose reef boulders of several metres that were
860 transported by storm waves onto the reef flat also belong mostly to this time window as their
861 maximum abundance has been reported between 1.7 and 1.1 kyr BP.

862 Mid-late Holocene reef deposits, especially reef flat units as well as conglomerate pavements
863 and accumulations, display an extensive development in the relevant coastal areas and extend
864 partly below modern islets. This suggests that they have played a prominent role in the
865 formation and shaping of modern islands. Based on their distribution, it seems likely that the
866 accumulations of conglomerates, and to a lesser extent of reef flat units, have formed
867 foundations for island initiation through the creation of prominent topographic features that
868 governed or influenced further deposition of sediments. Higher Holocene sea-level stands
869 have been essential in promoting the stranding of extensive spreads of conglomerates on
870 former reef units, which probably correspond to the last vertical accretion stage of the
871 Holocene reef before the sea level reached its present position at 6 kyr BP. Moreover, these
872 thick conglomerate units, including large reworked coral colonies, could correspond to such
873 foundations and were mostly accumulated between 2.2 and 1.5 kyr BP, i.e. during the most
874 recent sea-level fall when sea level was only about 0.2 to 0.4 m higher than modern sea level
875 (Fig. 7). However, this would need to be ascertained in drill cores carried out through modern

islets. If confirmed, cyclone activity and high-energy wave events could have initiated, and further controlled, the early development of these islands. The combined role of higher than present sea levels and associated high-energy to storm wave events has been regarded as pivotal in the initiation of other islands, such as Funafuti atoll (Tuvalu; Kench et al., 2018) and the southern Maldives (East et al., 2018). Moreover, it has been demonstrated that Takapoto atoll was gradually formed through the stacking of successive shingle ridges over the last millennium, suggesting that modern islet forms were acquired about 500 to 300 years ago (Montaggioni et al., 2018). This model therefore infers that islands have accreted recently when conglomeratic foundations were emergent and sea level was at its present position.

5.2 Importance for future sea-level rise

Geological records of coastal system evolution during past higher and/or rising sea levels provide an important baseline for developing projections regarding the response of modern coastal systems to future sea-level rise. The potential analogues that are currently used are from the Holocene and the Last Interglacial (Woodroffe and Murray-Wallace, 2012; Camoin and Webster, 2015), but neither of these periods appears as a direct analogue for the future.

The development, architecture and composition of reef systems are governed by changes in accommodation space, which are mostly controlled by RSL changes and the antecedent topography. Both the amplitude and rates of RSL changes are of prime importance to help forecasting the response of coral reefs and coastal systems to future sea-level change.

A key aspect of this study is to document a high-resolution record of coral reef and coastal system responses to mid-late Holocene RSL changes, which is of global significance. The course of mid-late Holocene RSL changes is typified by a succession of episodes of slow sea-level variations separated from each other by extended periods of sea-level stillstands on decadal to centennial time scales (Hallmann et al., 2018). As such, it differs from the predicted sea-level curve for the next decades, which is expected to rise continuously and

902 probably to accelerate sharply in the second part of the current century (IPCC, 2018).

903 However, the mid-late Holocene provides the opportunity to document the response of coral
904 reefs and coastal systems to an increased accommodation space following a sea-level rise of
905 about 1 m in amplitude. The inferred amplitude of RSL changes (~1 m) displays therefore
906 some similarities with ongoing and future sea-level rise (Alley et al., 2007; Church et al.,
907 2013; IPCC, 2018).

908 Rates of mid-late Holocene RSL changes range from a few tens of millimetres per year to 2.5
909 mm/yr and are therefore lower than the predicted rates of sea-level rise by the end of the
910 century, which should range between 5.5 and 10 mm/yr depending on the various scenarios of
911 global warming (IPCC, 2018). In contrast, rates of Holocene sea-level rise before stabilisation
912 of sea level at its present position range from 6 to 10 mm/yr (see review in Camoin and
913 Webster, 2015) are closer to the predicted rates of sea-level rise by the year 2100. However,
914 the more limited accommodation space during most of the Holocene transgression compared
915 to the current situation suggests that this period cannot be seen as a strict analogue of
916 conditions that might prevail for reef development in the future.

917 All studies concerning the timing and processes of island formation during periods of higher
918 sea level, such as the mid-late Holocene, help to better predict the island evolution in the
919 context of global warming and related sea-level rise. However, any prediction must be
920 considered with care due to the different time scales involved, a millennial time scale for
921 island formation vs a decadal/centennial time scale for their future evolution. One could
922 consider in a first analysis that the future evolution of the coastal zones in tropical islands
923 could mimic the mid-late Holocene situation with a more extensive development of reef
924 systems, especially reef flat units, and widespread accumulations of reworked material related
925 to increased cyclone activity and high-energy wave events. The combined effects of these
926 processes could therefore induce another phase of island building in future higher sea-level
927 conditions. However, the growth capacity of coral reefs has decreased sharply over the last

decades, mostly due to detrimental factors like sea surface temperature increase, ocean acidification and environmental pollution, and is significantly lower than during the Holocene when ecological conditions were seemingly optimal. A period of enhanced reef development is therefore questionable. The pivotal role of high-energy wave events in a future phase of island formation has been considered (East et al., 2018), but this will be dependent both on the morphology and internal structure of the relevant islands and on the magnitude and frequency of future extreme climate events. A uniform response of tropical islands to future sea-level and climate changes will not occur. A better understanding of this response will require detailed studies regarding reef development as well as island formation and evolution in context of higher and rising sea levels.

6. Conclusions

This paper documents in unprecedented detail the impact of RSL changes on reef and coastal development during the mid-late Holocene, a period characterized by slow-rate, low-amplitude and high-frequency sea-level changes. It provides the opportunity to document the response of coral reefs and coastal systems to changing accommodation space in relation to low-amplitude (~1 m) RSL changes. This might help to better assess how these systems might respond to the sea-level rise that is expected by the year 2100.

1 - The high-resolution reconstruction of reef geometry, composition and evolution during the mid-late Holocene sheds new light on coral reef responses to low-amplitude, high-frequency RSL changes, at rates ranging from a few tens of millimetres per year up to 2.5 mm/yr. It summarizes the adjustments that reef systems have to make to longer-term changes in accommodation space driven by variations in relative sea level (sea-level rise, stillstand and fall) and therefore helps in the understanding of reef dynamic processes that are of global importance.

After the stabilisation of sea level at its present position, the new development of reef systems was initiated by the creation of accommodation space due to a glacio-eustatic sea-level rise from 6.0 to 4.10 kyr BP, most likely sourced from Antarctica, and controlled by the antecedent topography of the islands. A single short-lived sea-level highstand of less than one metre between 4.10 and 3.40 kyr BP is documented. The reversal from rise to fall records the time at which the eustatic signal reduces and GIA (syphoning) becomes dominant, between 4.1 and 3.4 kyr BP. Minor sea-level variability probably driven by climatic oscillations has been evidenced during the entire time window, including during the sea-level fall between 3.4 and 1.26 kyr BP.

Regionally, continuous reef development was maintained throughout the last 6,000 years and typified by the widespread development of microatoll fields and reef flat units. The persistence of reef assemblages displaying similar overall composition and diversity during the whole period and the continuous development of coral microatolls suggest optimal environmental conditions. The facies distribution as well as the lateral extension and shift of facies belts have been governed by variations in accommodation space, which are controlled by changes in relative sea-level and antecedent topography. The recurrent sea-level stillstands, lasting more than a century and up to 250 years, that punctuated the mid-late Holocene sea-level history have played a significant role in the development of dense reef frameworks.

2 - The detailed reconstruction of reef development over the last 6,000 years brings valuable information regarding the timing and processes of island formation during periods of higher sea level. It therefore helps predicting how low-lying islands might respond to rising sea levels over the coming decades.

The widespread development of mid-late Holocene reef deposits in coastal areas, especially reef flat units and storm conglomerate deposits, suggests that they have played a prominent role in the formation and shaping of modern islands and islets, through the creation of significant topographic features that formed the foundations for island initiation and

governed/influenced further deposition of sediments. Further investigations are needed to better unravel the formation of modern islands.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request. Measurements of elevations and absolute ages of mid-late Holocene features are available in the data repository PANGAEA: <https://doi.pangaea.de/10.1594/PANGAEA.883846> (Hallmann et al., 2018) and XY (this study).

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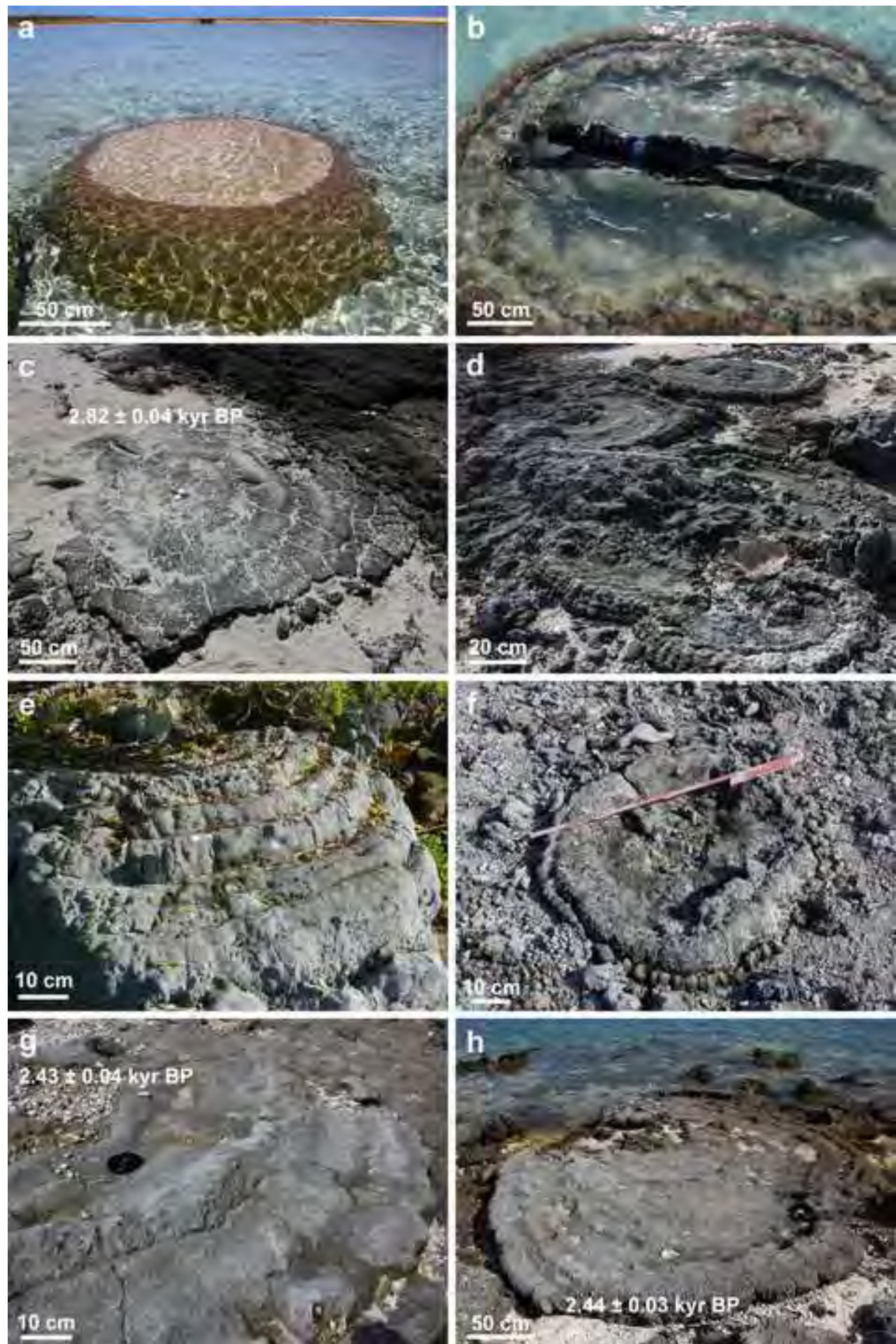


Figure 2

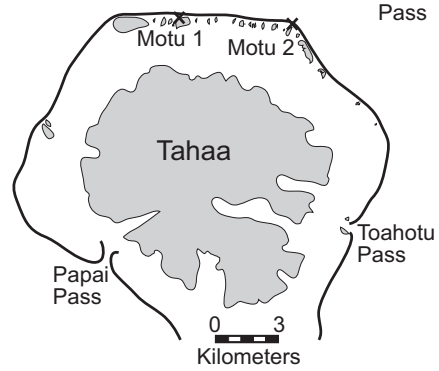
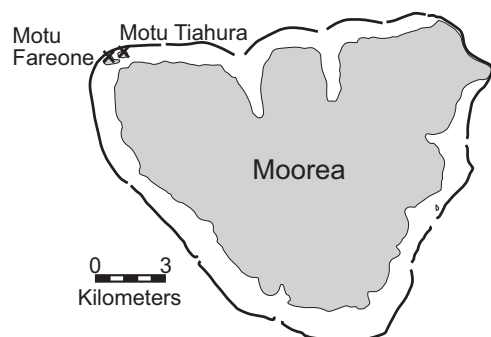
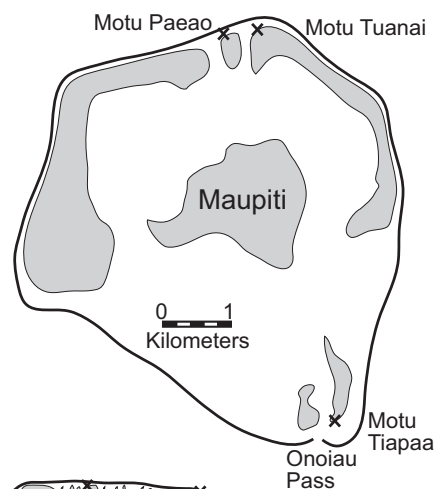
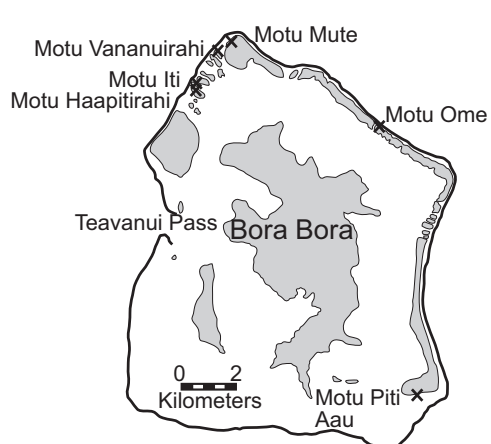
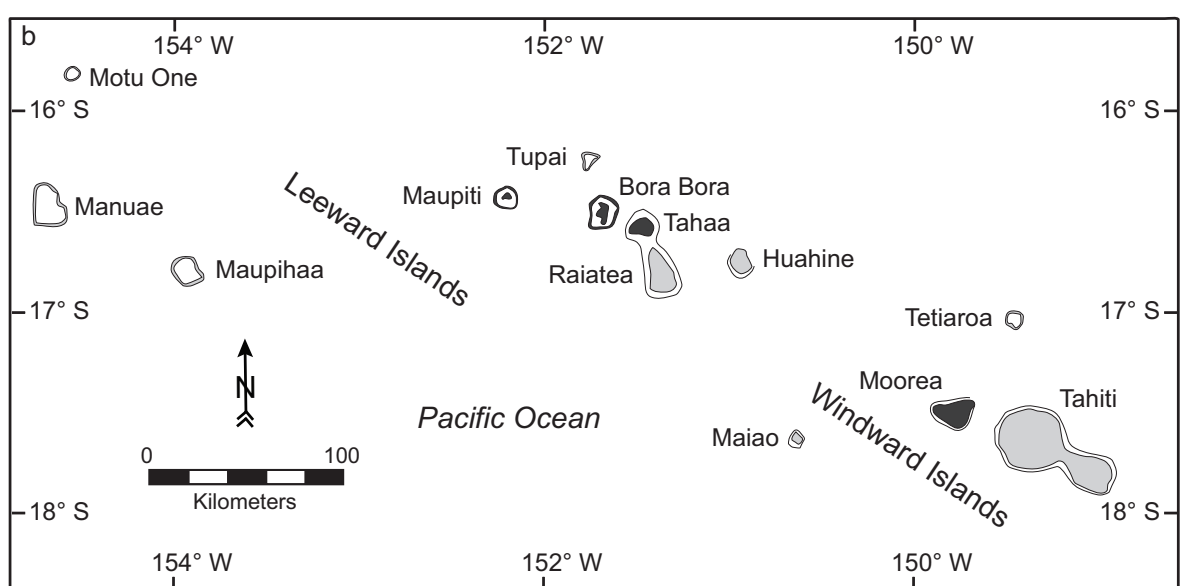
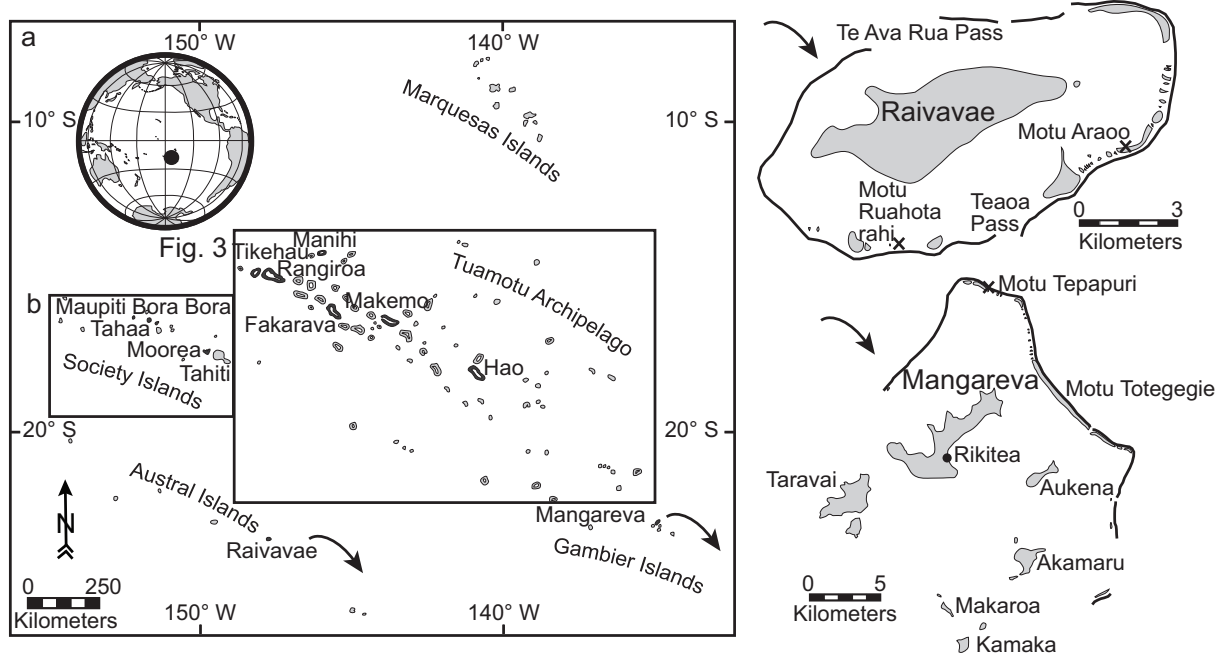


Figure 3

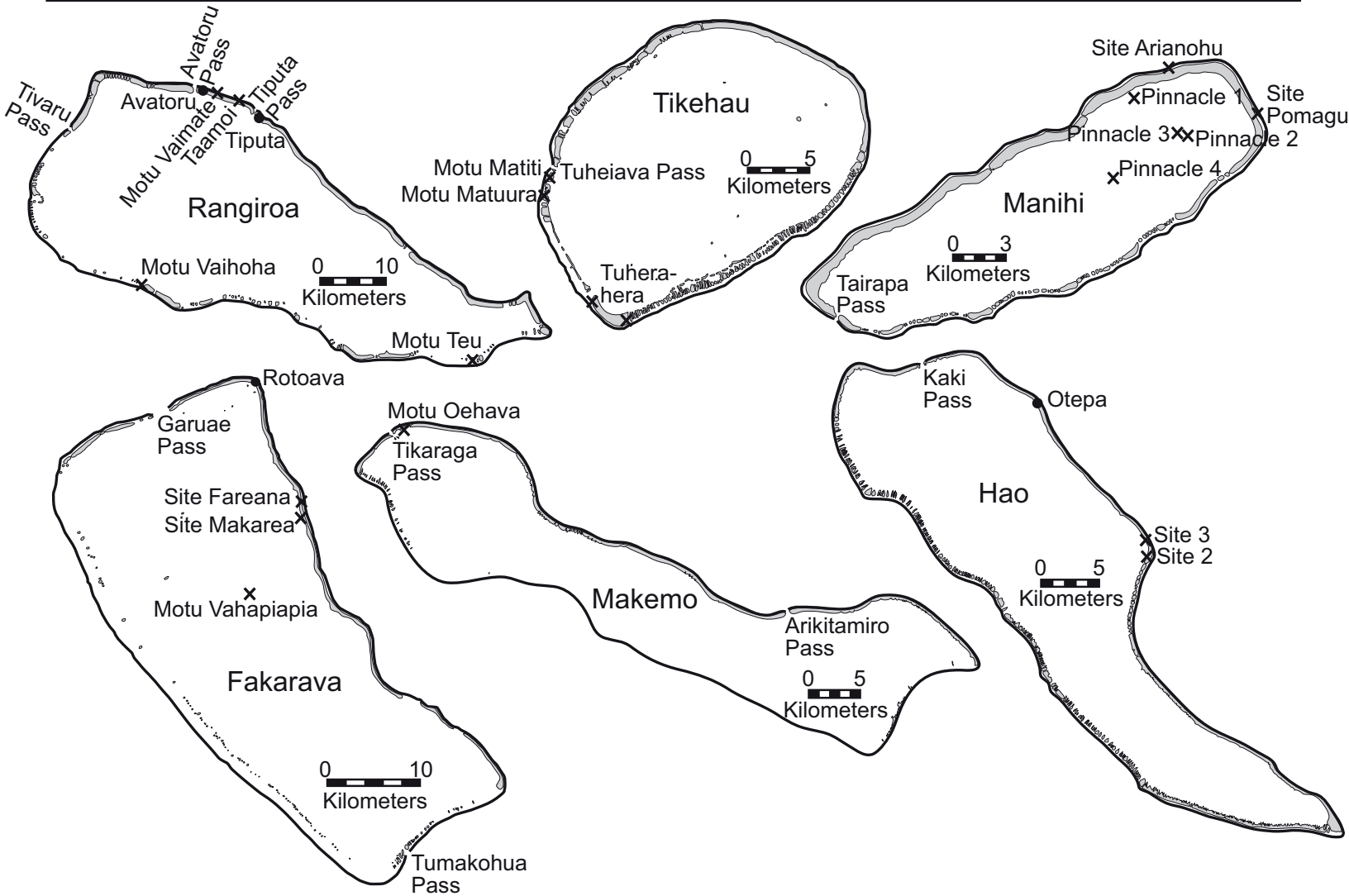
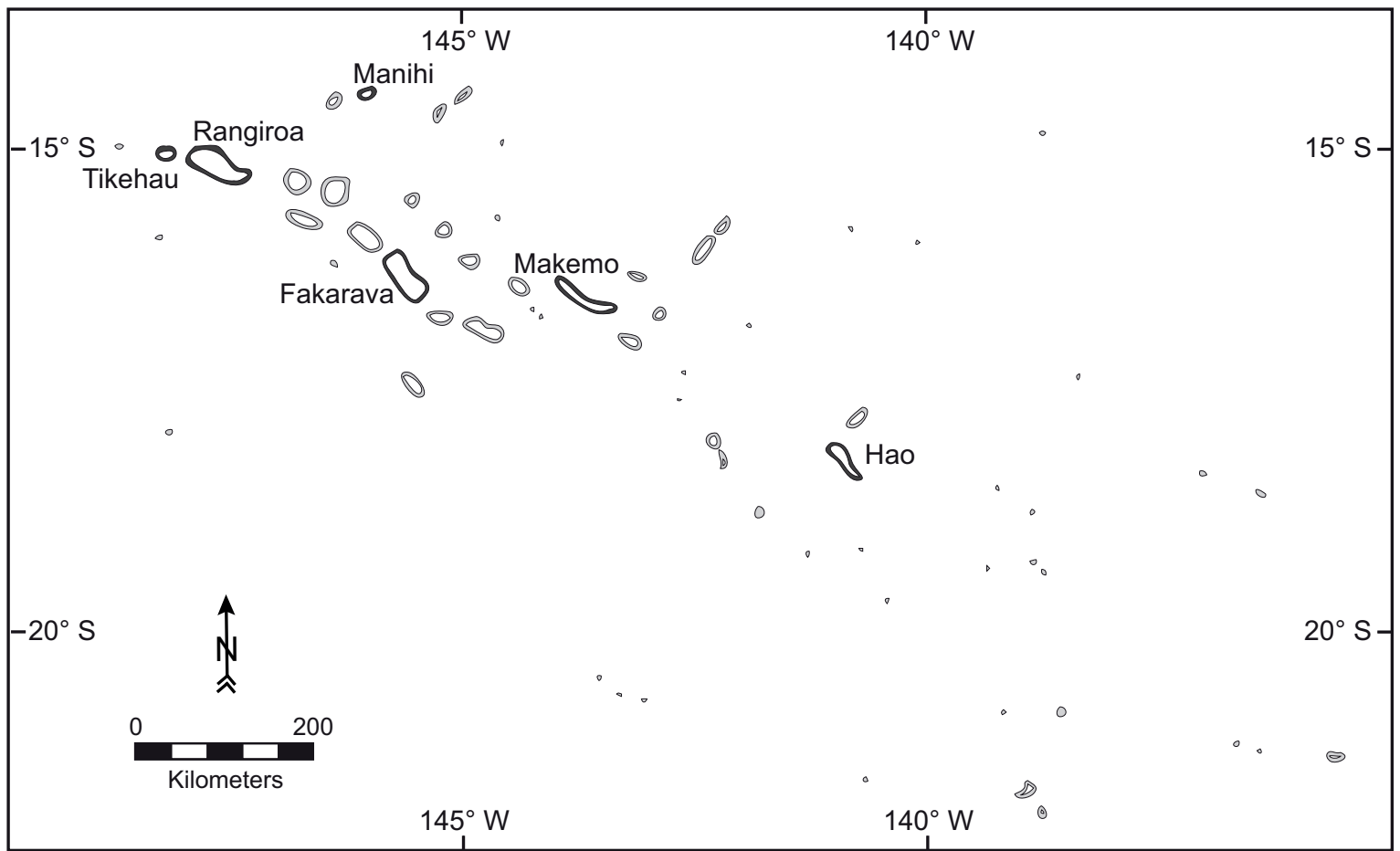


Figure 4

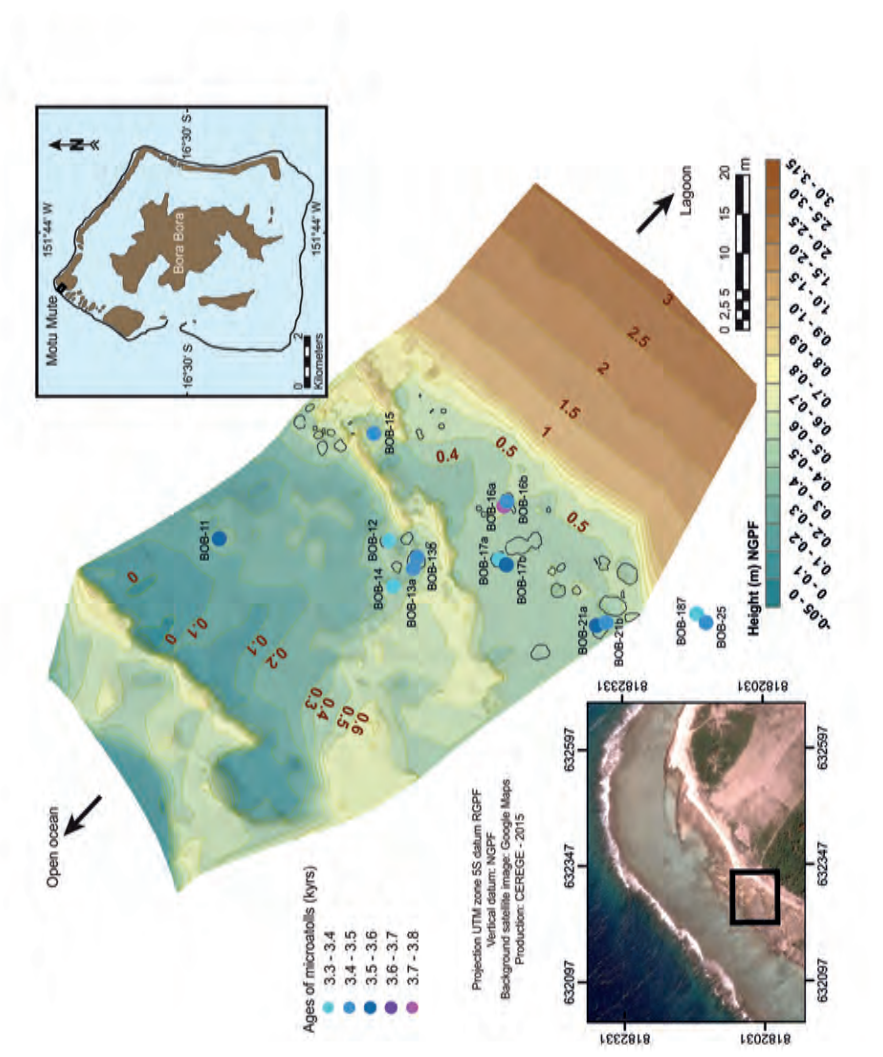


Figure 5

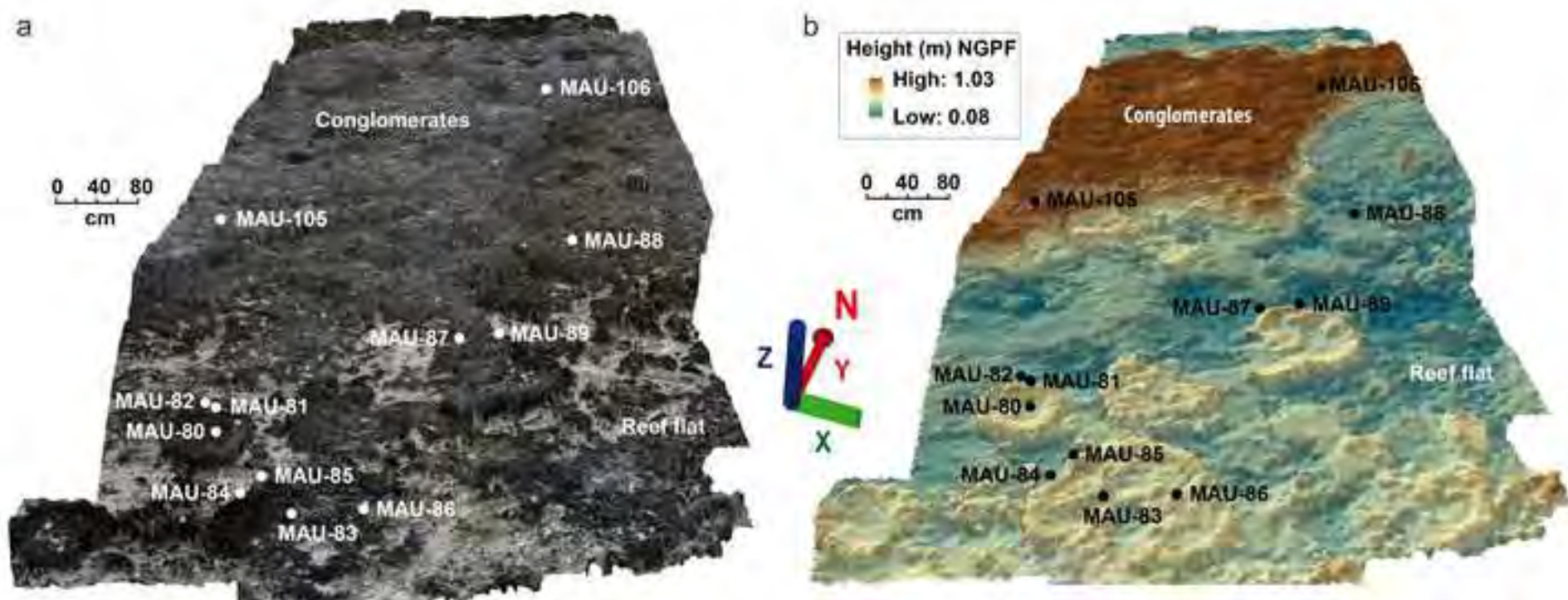
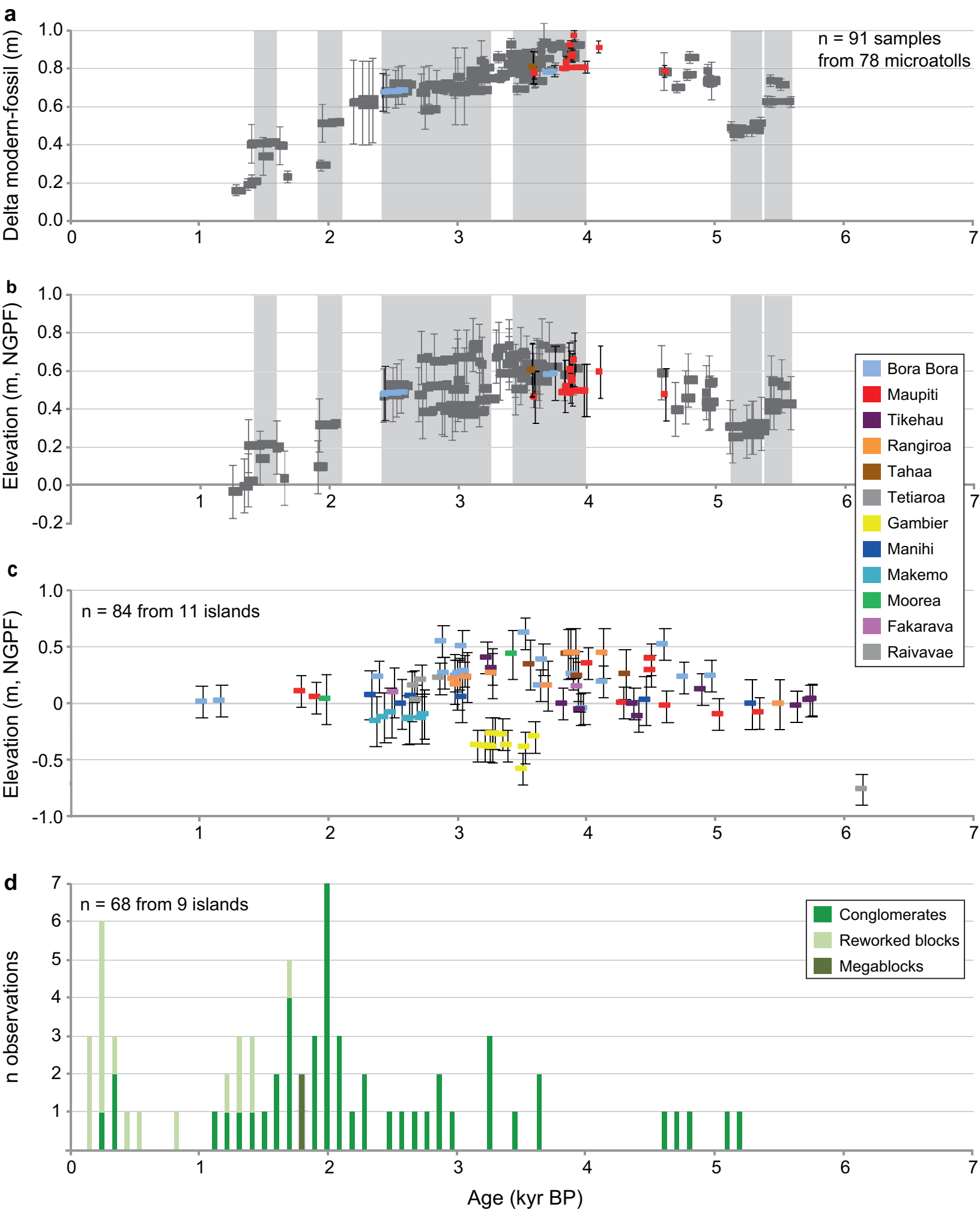
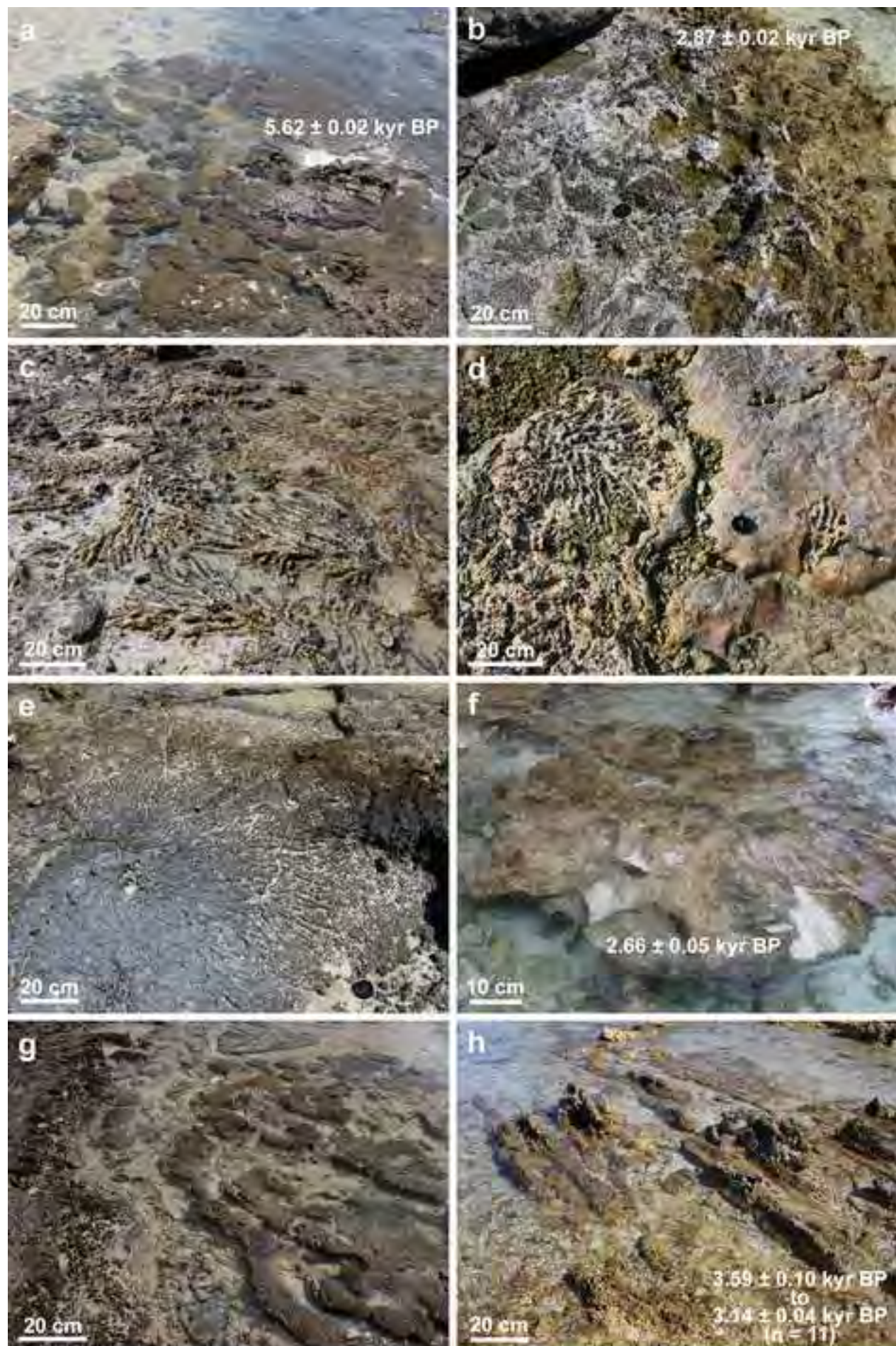


Figure 6



Figure 7





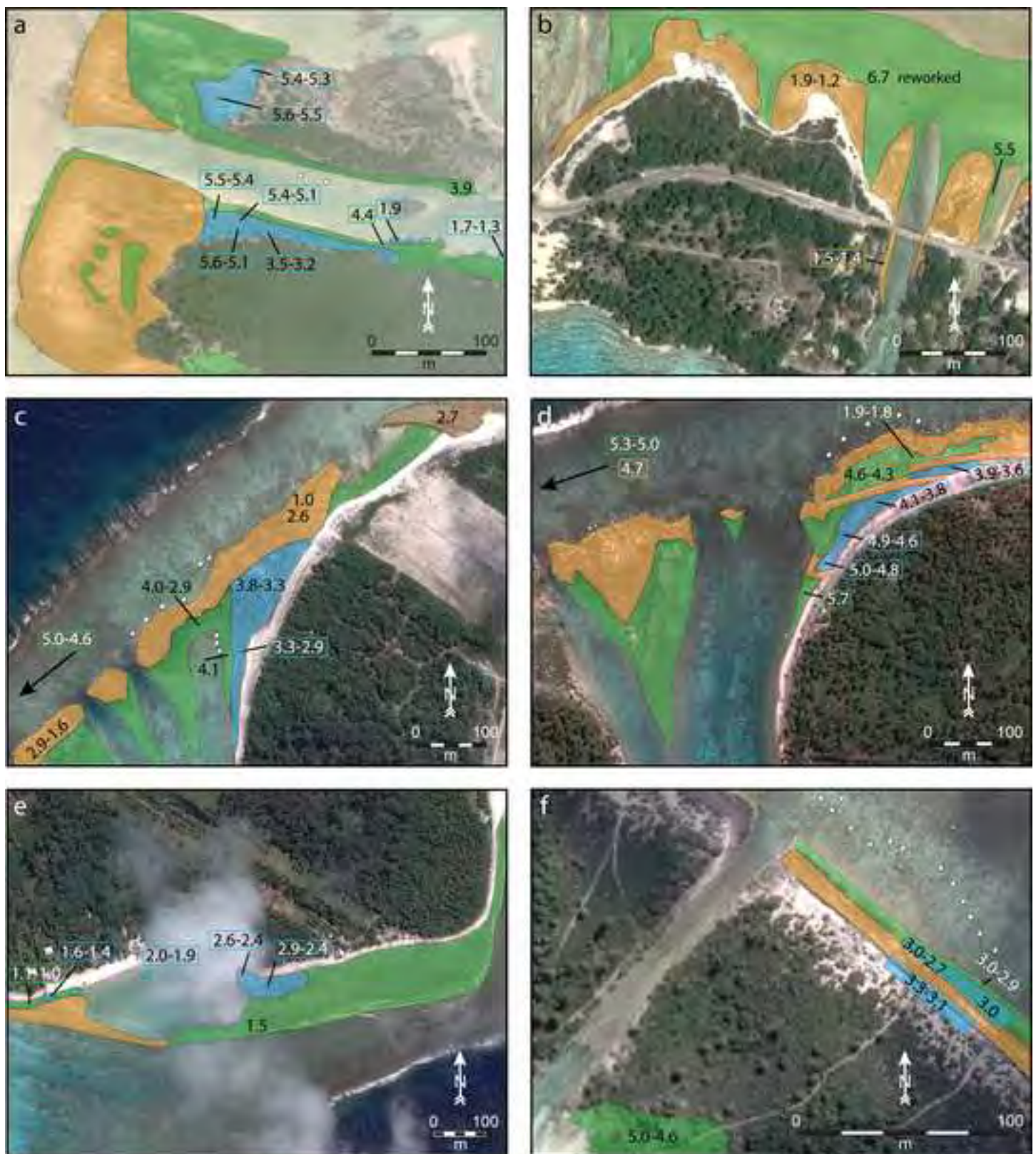


Figure 10



Figure 11

