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Abstract

The lagoons of seven French Polynesia and Cook Islands pearl farming atolls (Raroia, Takume, Mopelia, Takapoto, Ahe, Takaroa and Manihiki) were surveyed using multibeam and mono-beam sounders. From the detailed bathymetry, morphometric variables (average and maximum depth, frequency-area of depth, lagoon area and volume) are computed and compared. Remarkable geomorphological structures highlighted by bathymetric variations include deep reticulated structures and pinnacles. The seven atolls appear very different in

abundance, size and density of these entities. Considering them as markers of the geological, sedimentological and eustatic processes that shape atoll lagoons, they are discussed in the context of the general theory of atoll lagoon formations involving karstic dissolution during Pleistocene or earlier low sea-level stands. In terms of pearl farming management, accurate bathymetric maps help pearl oyster wild stock assessment, development of circulation and biogeochemical models, better lagoon zoning and strategy to remove pearl farming derelict gears.

Key-words: Tuamotu; karst; reticulated reef; pinnacle; Holocene; multi-beam bathymetry

Introduction

Well after Lyell (1832), Darwin (1842) or Daly (1910) first discussed their origins, the study of Pacific Ocean atolls has provided a wealth of original scientific information on ecology, geomorphology, sedimentology and geology of coral reefs and lagoons (Wiens 1962, Woodroffe and Biribo 2011). Starting in the 1950s, Pacific Ocean atolls were studied with modern methods in particular in a hydrogeology, sedimentology and physical oceanography context (e.g., Buddemeir and Oberdorfer 1997, Yamano et al. 2002). These researches were partly motivated by the nuclear tests conducted in the Pacific Ocean by various nations, but not only, and Newell (1952) and subsequent volumes for instance present naturalist expeditions in Raroia Atoll (Tuamotu Archipelago, French Polynesia). Biodiversity and resource assessment became a major focus in the 1980-1990s (e.g., Intes et al. 1995 for Tikehau Atoll), soon followed by the effects of sea level rise on reef islands (e;g., Yamano et al. 2007, Duvat et al. 2017).

In the Central Pacific Ocean, recent intensive scientific work on atolls have in particular looked at several aspects related to black pearl farming (Andréfouët et al. 2012, Johnston et al. 2019). These include a strong environmental component, culminating in 3D biophysical modelling of lagoons to study spat collecting potential and other processes important for management of this activity (Thomas et al. 2016). Few atolls however have benefited from a 3D numerical hydrodynamic model thus far. Earlier work was reviewed in Andréfouët et al. (2006) and since then models have been implemented in Tuamotu Archipelago: for Ahe Atoll (Dumas et al. 2012), Takaroa and Raroia atolls (Le Gendre et al. this issue), and are in progress in Cook Islands for Manihiki Atoll. The slow progress and the limited number of investigated atolls are partly due to the lack of bathymetry data, which constitutes an essential component of accurate biophysical models. In the context of pearl farming, knowledge of bathymetry for entire atoll lagoons is thus critical to achieve hydrodynamic numerical models. Furthermore, complete and accurate bathymetry is also useful for a variety of management applications, including marine resource stock assessment (Andréfouët et al. 2016), inventories of marine debris and micro-plastic generated by pearl farming (Andréfouët et al. 2014, Friot 2018), and water quality assessment (Tartinville et al. 1997, Andréfouët et al. 2001).

Until the late 1980s, atoll lagoon bathymetry was mapped only with traditional hydrographic survey methods by the French Hydrographic and Oceanographic Service (SHOM). In French Polynesia, these costly and time-consuming surveys focused first on navigation pathways between passes and villages, and rarely investigated entire lagoons. SHOM has a digital archive of hydrographic data available for research investigation. All remote atolls indeed have limited data, or no data at all if they have no passes To increase the coverage, several initiatives have used multispectral satellite imagery to estimate depth. In French Polynesia, SHOM pioneered in the late 1980s the release of 'spacemaps' that combined traditional hydrographic data with satellite-derived bathymetric data (Fourgassié 1990). SHOM clearly indicates in its products that satellite-derived depth was just an indication and not exact data safe for navigation. Furthermore, depth information was limited to 20 meter at most, which precluded a representation of entire lagoons. When looking at such spacemaps, wide lagoon areas remain without any information, except for the shallow areas which included lagoonal patch reef and pinnacles. The most recent satellite-derived bathymetric products have been released by Purkis et al. (2019) using very high resolution multispectral images. However, the inherent limitations of optical remote sensing also prevented mapping areas deeper than typically 25m with blue-green spectral band-algorithms, and sometimes less, depending on water clarity, solar angles and viewing geometry. Oceanographic cruises have also collected multi-beam data on selected areas of several atolls, but mostly in deep passages and forereefs, sometimes opportunistically. For instance, the French research vessel R/V Alis which is equipped with a SIMRAD EM1002 multi-beam sounder, has collected data in French Polynesia atolls for years for its own navigation safety when close to the reef and when transiting in and out of the Tuamotu lagoons, but no survey was ever planned specifically for entire atoll lagoons. Moreover, since 30 years, the number of shallow ropes and lines used, and often discarded and forgotten, for pearl farming installations prevents large ships from cruising freely even in deep lagoons, which also prevents fast bathymetry surveys (Andréfouët et al. 2014).

Recently, the number of French Polynesia atoll lagoons mapped entirely has increased thanks to dedicated surveys that were all initiated for pearl farming studies, first using a mono-beam acoustic sensor in 2008-2009 (Ahe and Takaroa atolls In Tuamotu Archipelago), and since 2017 using a portable multi-beam sensor. Raroia, Takume and Takapoto atolls in Tuamotu Archipelago and Mopelia Atoll in Society Archipelago have thus been mapped between 2017 and 2019, and complement, in a pearl farming context, the first multi-beam product available since 2001 for Manihiki Atoll in Cook Islands. All these sites are current pearl farming atolls, or atolls with a historical important stock of wild *Pinctada margaritifera*, which is the oyster species used for black pearl production. Complete lagoon bathymetry is thus now available for a collection of seven pearl farming atolls. This collection allows for the first time a precise estimate of a number of morphometric features (e.g., volume) and provides detailed views of each lagoon geomorphology and new potential for pearl farming related investigations. Other atoll lagoons, have also been covered, partly (Rangiroa) or entirely (Arutua, Kauehi, Penrhyn), but data were not yet available for this study.

Our objectives are to present the bathymetry of these seven pearl farming atolls and to report key morphometric and geomorphological features. The differences in geomorphological structures found between atolls prompted us to discuss the origin of some of these features (in particular honeycomb-like basins and pinnacles) through a literature review in the context of atoll lagoons. Unfortunately, the lack of drilling and dating specifically from these seven atolls prevent us for inferring the exact mechanisms that could have produced these structures. However, priorities can be identified for future quantitative works.

Material and methods

Geological context of the study sites

The French Polynesia and Cook Islands chains (Fig. 1) are composed of discrete volcanic edifices with ages that reflect the motion of the lithosphere with respect to the hotspot reference. The seafloor of French Polynesia was formed between 25 and 115 Ma by seafloor spreading from the east along the ancient Pacific-Farallon Ridge. Most oceanic island chains, including those of French Polynesia and Cook islands, were formed by mid-plate volcanism, away from oceanic spreading centers. However, French Polynesia also has a large oceanic plateau above which the Tuamotu atolls are now found (Ito et al. 1997). Oceanic plateaus are shallower large structures that are born from hotspots near or at oceanic spreading centers or rifted continental margins. The Tuamotu Plateau, 1500 km long by 800 km wide and <2000m depth, was possibly born from two hotspots (Ito et al. 1997) and ranges in age from about 30 Ma in the southeast to 65 Ma in the northwest. An alternative explanation is that lava flows from the East-Pacific spreading centre generated the Tuamotu Plateau and the atoll chains resulted from the later perforation of the plateau by hot spots (Patriat et al. 2002). The Manihiki Plateau, on which Manihiki Atoll is found on its southern side, has a complex origin. Most recent scenarios suggest that the massive initial giant Ontong Java-Manihiki-Hikurangi Plateau initiated 125 Ma ago at the Pacific-Farallon-Phoenix plates triple junction and broke off around ~115 Ma. The Manihiki Plateau drifting westward subsequently experienced different episodes of volcanism from 100 to 65 Ma (Pietsch and Uenzelmann-Neben 2015).

French Polynesia presents six main islands and seamounts chains. Four of them include atolls and are of interest here (Fig. 1). Ages of seamounts, islands and plateaus for this area were compiled by Clouard and Bonneville (2005) and references therein, and their numbers are used hereafter. First, the chain of the Tuamotu Archipelago can be described as a series of atolls superimposed on the Tuamotu Plateau. The oldest northernmost Tuamotu atolls formed as late as 47-55 Ma. A second chain of linear volcanic ridges and seamounts, the Puka-Puka chain lies on a seafloor 15-35 Ma old and extends east of the Tuamotu along a 2600-km-long, 50 to 75-km-wide corridor between Pukapuka atoll and the East Pacific Rise. No atoll from this latter chain is however investigated here. Then, the Society chain in the west extends over 500 km from the Mehetia island which lies just above the Tahiti/Society Hotspot south-east of Tahiti Island, till further west Scilly, Bellinghausen and Mopelia atolls. The seafloor age of the Society chain ranges from 65 Ma in the south to 80 Ma 750 km away in the north. For reference, Tahiti Island ranges in age from 0.4 to1.3 Ma.. The fourth main chain is the Duke of Gloucester-Moruroa-Gambier-Pitcairn chain built on an oceanic crust more than 30 Ma old south of the Tuamotu Plateau. Dates indicate that along that chain, Pitcairn Island, Mangareva

Island and Moruroa Atoll are on average 0.70 Ma, 5.79 Ma and 10.42 Ma old respectively. To our knowledge, the age of Manihiki Atoll is not available.

Island chains and Tuamotu plateau mostly trend N115°, which is the direction of motion for the Pacific plate, but there are exceptions. Indeed, the underlying oceanic crust displays ENE-WSW transform faults, magnetic lineations and volcanic ridges on which few atolls are located with an oblique direction compared to the general ESE-WNW direction displayed by the main chains supporting large atolls (Ito et al., 1995, Jordahl et al., 2004, Montaggioni et al. 2019a).

Study sites

The French Polynesia and Cook Islands study area includes a total of 85 atolls with lagoons according to Golderg (2016). The locations of the seven studied atolls are presented in Figure 1. The five Tuamotu atolls are not on the ESE-WNW trending Tuamotu ridge but are located on the border of the ridge and are elongated along a NE-SW direction, oblique and almost perpendicular to the ridge. As such, they are not typical of the rest of the Tuamotu.

Several of the studied atolls have been the subject of geomorphological monographs and studies, including Manihiki (Bullivant and McCann 1974), Takapoto (Chevalier et al. 1979, Salvat and Richard 1985, Zanini and Salvat 2000, Montaggioni et al. 2019a,b), Raroia (Newell 1952, 1954) and Mopelia (Guilcher et al. 1969). Several of these studies presented lagoon bathymetric profiles and soundings, but none had full lagoon coverage.

Bathymetry data and processing

In French Polynesia, Ahe and Takaroa bathymetry data were collected using a mono-beam Kongsberg EA 400SP sounder in 2008 and 2009 along 50m-spaced navigation tracks. Multi-beam data for Raroia, Takume, Mopelia and Takapoto were collected with a Norbitt IWBMS sounder, in 2018 and 2019. Data were collected to insure 50% overlap between parallel swaths (hence providing double coverage throughout) and full lagoon coverage, except for the shallowest areas. Coverage around pinnacles was tighter. Data collection time ranged between 10 days (Mopelia) to 5 months (Raroia). For Manihiki in Cook Islands, 120 multibeam transects were collected in September 2001, spaced of 100 meters, but several swaths were not overlapping, and no systematic coverage were made around pinnacles. The acquisition was performed with a SeaBat 8101 multibeam echosounder.

Sounding data points were quality checked and validated (filtering out aberrant values and performing tide-correction using data from pressure sensors deployed during the survey) by Geopolynésie and SOPAC and delivered *in fine* to IRD for this study. Point data were processed differently according to their sources, and keeping in mind the future utilization for 3D hydrodynamic model. In particular, multibeam point data were resampled and interpolated to achieve a 10m resolution grid (Manihiki, Mopelia, Raroia, Takapoto, Takume) while single-beam data were processed to achieve a 60m resolution grid (Ahe and Takaroa). After tide correction, the shallowest sampled areas were in the 0.1-0.3 m range, thus very shallow and capturing the upper limit of lagoon slope at the edge of the rim, except for Manihiki (2.7 m) and Mopelia (1.5 m) where the expedition surveys had to be conducted in shorter periods of time and avoided the time-consuming shallow zones at the edge of the lagoon. Deep areas on the oceanic side of passes of Ahe, Takaroa, Raroia and Mopelia were filtered out. During interpolation, top of pinnacles and *motu* shoreline were forced at 0m depth by contours defined using cloud-free, high quality, very high resolution pan-sharpened satellite images resampled at 2m resolution (IKONOS and Quickbird) and provided by French Polynesia and Cook Island governments. Optimal rendering of pinnacles was variable depending on data sets and local depth configuration, and inverse distance weighting interpolation parameters were selected after trials and errors to achieve a realistic rendering of pinnacles and shoreline for each individual atoll.

All data sets were made available in two geodetic projections (latitude longitude WGS84, and UTM WGS84 with the adequate zone). Processing were performed using the ®ENVI 4.7 and ® ESRI ArcMap 10.7.1 software.

The lagoon bathymetric maps used to compute morphometric parameters are presented on Figures 2 and 3. Note that due to the different lagoon sizes and depth ranges, different colour and geographic scales are used.

Lagoon morphometrics and geomorphologic features

The volume and surface area of lagoons were computed from bathymetry data. The edges of the lagoons were defined by the limit of multi-beam acquisition (see above). In other words, the very shallow reef flats and *hoa* along the atoll rim are not included in the lagoon surface area and volume.

The maximum depth of the lagoon was taken from the initial point data provided by Geopolynésie and SOPAC, and not after the resampling and interpolation.

Histograms of bathymetry range distribution were computed using a 10m bin.

Bathymetry maps (Figs 2, 3) allow to identify the outlines of reticulated structures, marked by their basins and walls. The number of reticulated basins, their locations, sizes, and depth are thus characterized.

Pinnacles (or *karena* in Polynesian) were counted from the contours defined on the satellite imagery (see above) but we considered separately the structures if they originated from a depth superior or inferior than 20 meters. This is an arbitrary threshold but it aims to separate structures that had rose vertically from a deep lagoon floor and possibly over an antecedent surface *versus* the largest coral bommies that could have recently grown from shallower areas without any antecedent relief. We thus defined here as pinnacles the structures that have their base deeper than 20 meters, while reaching the surface or sub-surface. This definition can be in contrast with previous description and definition used in the region (Battistini et al. 1975, Montaggioni et al. 2019a).

A density of pinnacles is computed by dividing the number of pinnacles by the lagoon area > 20m depth.

Finally, the ratio of surface of rim/ surface of lagoon was computed. The rim area included the horizontal projection of the forereef slope till about 30m deep as estimated by the Millennium Coral Reef Mapping Project using Landsat 7 images (Andréfouët et al. 2006, Andréfouët et al; 2008). The rim also included the *motu*, reef flat and passes which came directly from the bathymetry product. The lagoon area also included the surface areas of the pinnacles.

Results

Morphometry

The Table 1 summarizes the main computed morphometric variables. Maximum depths range between 41 to 76 meters. The deepest lagoons are not the largest. Average depth range between 20.4 (Takume) and 40.6 (Ahe) meters. Five atolls have their average depth in the 20-

30m range. Average depth is not congruent with lagoon sizes. Differences in lagoon sizes, volumes, and pinnacle/lagoon ratio reach more than one order of magnitude, while the number of pinnacles varies from 11 to 1434. The ratio rim/lagoon varies between 0.19 (Raroia) and 0.85 (Takume).

Figure 4 presents the histograms of depth distribution for each of the 7 atolls. A quasi Gaussian distribution is observed for 3 atolls (Takaroa, Raroia and Takapoto), while the distributions are skewed towards the highest depths for Ahe and Takume, and towards the lowest depths for Manihiki. Mopelia displays a fairly even histogram, with a lowest proportion of 10-20m areas which represent the inner lagoon slope. Takume has an asymmetrical histogram with a dominance in the 20-30m depth range, in agreement with its fairly flat lagoon floor (Fig. 3). The type of histogram shape is therefore not directly related to the size of the atoll.

Raroia's and Takapoto's lagoons are characterized by a smooth overall basin shape, in agreement with the Gaussian distribution of their depth histograms (Fig. 4), and similar to the saucer-morphology often assumed for atolls. They are however asymmetrical with the deepest part found on the western flank of the lagoons (Fig. 2, 3), and thus with a more gently slope on the east side.

Raroia is also characterized by its high number of pinnacles (1434, and with a total of 1618 if counting structures with their base shallower than 20 meters). However, Manihiki has the highest density of pinnacles in the lagoon area > 20 m depth (5.42.km^{-2}, Table 1).

Two atolls, Ahe and Manihiki, are characterized by their numerous and well-marked deep reticulated structures (Figs. 2, 3). Less marked and less numerous basins are present in Mopelia and Takaroa, but Raroia, Takapoto and Takume do not show any reticulations throughout their lagoons (Figs 2, 3). Ahe has deep basins separated by high walls in the central part of the lagoon. The depth of the basins is fairly uniform at 60-75 meters. Manihiki also has numerous basins, but in contrast to Ahe, they are located on three terraces, in the 60-80m (central part of the lagoon), ~50m, and 20-25m range (Figure 5). Raroia and Takume have small circular holes much deeper than their surroundings. These holes, called *koko* in French Polynesia, can be similar to sinkholes (Table 1). For six lagoons, the maximum depth was reached either at the bottom of a reticulated basin (Ahe, Manihiki, Takaroa, Mopelia) or at one of the detected *koko* (Raroia, Takume).

Vertical sections following the longest directions are provided for the seven lagoons to highlight the depth variation due to pinnacles, reticulations and terraces (Figs. 5 and 6). For Raroia, a mid-atoll section (Fig. 6b) is also provided to highlight the differences of lagoonal slopes in the E-W direction.

Discussion

The seven pearl farming atolls investigated here displayed different lagoon morphometry and morphology evidenced by the high quality bathymetric data. The diversity seen on these seven atolls (Table 1) does not suggest any particular single characteristics that would explain why they are suitable for pearl farming. However, in terms of pearl farming management, the newly available data will contribute to a better characterization of pearl oyster wild stocks (for sampling strategy and for stock estimates, Andréfouët et al. 2016), to the development of new 3D circulation and biogeochemical models useful to study spat collecting in present and future conditions (Dumas et al. 2012, Le Gendre et al. this issue), and to establish better lagoon zonation for concessions and optimized plans for the removal of pearl farming derelict gear. In the future, other Tuamotu atoll lagoons should be surveyed in 2021 and afterwards.

Indirectly, despite bathymetry data collection was not intended for that purpose, the present study also contributes to a better knowledge of lagoon geomorphologies and the processes behind them. Two features of the studied lagoons stand out: reticulated basins and pinnacles. These structures are discussed here in the general context of atoll lagoon formation theories, which are considered to be dissolution-driven during Pleistocene or earlier low sea stands, with karstification explaining the current lagoon relief (Purdy and Winterer 2001, Purdy and Gischler, 2005).

From a geology standpoint, atoll lagoons have been less studied than atoll forereefs and rims. The genesis of atoll coral reef formations in relation to sea level variations, antecedent Pleistocene relief and subsidence rates has been studied from cores and from surface observations. For the Holocene period and for the Tuamotu atolls (Montaggioni et al. 1985, Pirazzoli and Montaggioni 1986, Pirazzoli et al. 1988), the position of emerged conglomerate limestones on atoll rims was used to infer sea-level variations during the Holocene. These early work concluded that the Late Holocene experienced from 6 to 1 kyr BP, sea-levels >1m compared to present. Recently, Hallmann et al. (2018) did not confirm these previous conclusions from the study of micro-atolls in 12 French Polynesia islands and atolls. Instead, they highlight a sea-level highstand of less than a metre between 3.9 and 3.6 kyr BP only. In the northwest Tuamotu, recently, Montaggioni et al. (2019a, b) revisited the development of the reef islands and the forereef terraces of Takapoto atoll in the shallow 0-40m depth range, one of the seven Tuamotu atolls lying on a NE-SW direction in the north side of the Tuamotu Plateau. Drillings in Moruroa lagoon and rim have shed lights on the sequences of Late Pleistocene and Holocene coral reef growth since 300,000 years ago (Perrin 1990, Buigues et al. 1992, Camoin et al. 2001, Montaggioni et al. 2015). Comparison with cores in Moorea/Tahiti high islands barrier reef (Bard et al. 1996), and more recently in Tahiti and in Bora-Bora barrier and fringing reefs (Abbey et al. 2011, Camoin et al. 2012, Blanchon et al. 2014, Gischler et al. 2016) shows significant variations between islands. A 300m-long inclined core from Moruroa indicates Quaternary reef developments at four periods of relative sea-level highstands (Holocene, 125 ka, 212 ka and 332 ka) and three periods of relative lowstands (17–23 ka, 60 ka and 270 ka). However, except for Moruroa, in the south-east Tuamotu-Gambier, and Mataiva, in west Tuamotu, very few lagoon coring data exist for our region of interest.

For Cook Islands, Gray et al. (1992) and Gray and Hein (2005) have studied the lagoons of Rakahanga and Pukapuka atolls and Aitutaki Island using lagoon cores that reached the Pleistocene layers. Manihiki was not studied, but Rakahanga is close to Manihiki. In this atoll, two cores extracted from the lagoon floor and close to the edge of the lagoon showed that Holocene lagoonal reefs were established 8.0 ky B.P. on 130-200 ky old reef platforms that are presently 18-20 m below the floor of the present lagoon (Gray and Hein 2005). They also concluded that a higher (0.5 m) middle Holocene relative sea level occurred ca. 4610 years BP.

Reticulated basins and antecedent karst surfaces

Manihiki and Ahe lagoons in particular are characterized among our study sites by honeycomb structures in their deeper parts (Fig. 5), with basins separated by walls, suggesting karstification. Karstification is operating during emerged stages of carbonate platforms and karstic features such as caves and dolines are extensively known in uplifted coral islands (Mylroioe and Carew, 1995). Indeed, karstification is a fast process operating in a few thousand years as soon as a carbonate platform is submitted to rainfall. Karstification is linked to infiltration instability which produces a large range of wavelengths in dissolution features

(Ortoleva et al., 1987). Formation of a karstic network only needs dissolution of a connected void system, which requires a slight amount of dissolution of the initial carbonate material.

Reticulated and hexagonal structures drew from a long time attention of scientists. Darwin (1859) discussed formation of honeycomb structures in bee's nests. It was further demonstrated that a regular hexagonal mesh minimizes the total length of walls (Hales, 2001). This property probably explains why the honeycomb structure is often encountered in natural systems. Here, large deep honeycomb-shaped reticulated basins are visible in Manihiki, Mopelia, Ahe, and Takaroa, although Mopelia and Takaroa displayed only few basins less marked than in Manihiki or Ahe. Basins are located in the central and deeper area of each lagoon. None is visible on the bathymetry data in Takapoto and further east in Raroia and Takume. In western Tuamotu, Mataiva Atoll, a small (lagoon area is 12 km^2) uplifted atoll also displays similar basins but in shallow position. This atoll has been studied in the past considering the possible exploitation of phosphates (Delesalle et al. 1985a, b), including sub-surface coring. Mataiva lagoon is partitioned in approximately 70 basins, ranging from 100 m to over 2 km width, with an average depth of 8 m. The edges of the basins reach 0-1m depth at low tide and accommodate coral growth. Delesalle et al. (1985a,b) reported that the lagoon lies above a Mio-Pliocene antecedent surface buried under 10 to 15m of Holocene sediments. No Pleistocene layers were found in Mataiva, possibly due to its ~10m uplift as a result of the bumping of the underlying seafloor generated by the overloading of the nearby Tahiti-Moorea-Mehetia volcanic complex. This uplift and emergence would have prevented sediment production from the atoll rim. Several episodes of karstification and creation of basins by dissolution occurred, during the Pliocene periods of emergence, and during the Pleistocene.

With Makatea which is an uplifted, completely emerged, atoll from which phosphates deposits were exploited (Montaggioni et al. 1985), Mataiva was once considered as the only atoll of this region with a lagoon presenting such reticulated patterns (Delesalle et al. 1985a,b). We show here that Mataiva is not an exception, although the atolls investigated here present deeper depth basins, especially Ahe and Manihiki (Fig. 5). Lack of seismic data does not allow to assess if honeycomb-like, reticulated, structures exist also in Takapoto, Raroia and Takume, possibly below a layer of Holocene sediments. The complete filling of antecedent forms by sediments exported from the rim areas would not be surprising for Takume, considering its small lagoon relative to the rim size (ratio=0.85, Table 1) which is the highest among the seven atolls. This ratio allows to estimate the potential of carbonate sediments supply from the rim to fill the lagoonal space. However, lagoon filling by sediments to the point of hiding basins would be more difficult for Takapoto and especially for the large Raroia atoll. This process has been measured in Maldives for the small lagoons of *faro*, which are circular small patch reefs within main atoll lagoons (Perry et al. 2013). Small lagoon *faro* (<0.5 km^2) filled up by ca. 3000 years B.P, to the point of allowing reef island build-up, but *faro* > 0.5 km^2 are presently only partially filled, and still very deep for the largest ones (>1.25 km^2). In the Central Pacific , and at the scale of atoll lagoons, the clearly visible large basins on Manihiki, Mopelia and Mataiva - all fairly small atolls with large rim to lagoon ratio- indicate that lagoon filling by sediment in the last 6000 years of high sea level stands did not occur to the point of filling basins. Similar conclusion can be drawn for Rakahanga, next to Manihiki (Gray and Hein 2005).

Peculiar structures that confirm the karstic nature of lagoon antecedent surfaces are *koko*, sinkholes features similar to the 'blue holes' described on several reefs of the Pompei group of the Great Barrier Reef (Hopley 2006) or Maldives atoll rims (Purdy and Bertram 1991). They are also found in Raroia and Takume atolls. These features are circular small vertical holes that mark the maximum depth detected in these lagoons. In Raroia, one single 70m-diameter hole marks the deepest point of the lagoon at 68m deep. In Takume they are more numerous, and the deepest one reaches 58m. In the eastern Tuamotu, a *koko* is visible on satellite imagery as a peculiar dark patch in the shallow Vahitahi Atoll (Fig. 7). In March 2015, we could visit this 25m-diameter hole. Depth in the center of the hole was 28m, while the nearby lagoon floor was 5m deep. The deepest part of the lagoon elsewhere reached 20m. In the Tuamotu Archipelago, several atolls (e.g., Tepoto Sud, Tureia) are known for their *koko,* reported by the inhabitants. Never described in the Tuamotu literature to our knowledge, these *koko* appear as dark, deep, vertical holes in the lagoon floor or as shallow entrances to horizontal tunnels in the lagoon slope. It is said these *koko* provide direct communication with the ocean, due to strong current, cool water and presence of fauna typically associated with outer oceanic conditions and passes. Indeed, in Vahitahi, at the hole's edge, we observed fifteen large *Lutjanus bohar* confirming the presence of unusual lagoon fish fauna in these *koko*, since this species was not seen at any of the other 50 stations surveyed in Vahitahi atoll (SA, unpublished data) or in another East Tuamotu atoll lagoon, Fangatau (Mou-Tham et al. 2018). However, one dive conducted on the fringe of Raroia's hole did not suggest any particular fauna or current. The environment of these holes warrants further investigations, including the mooring of precise temperature sensors like it was done recently in various atoll lagoons (Van Wynsberge et al. 2017, this issue) to characterize water movement.

Reticulated networks such as those met in atolls can be considered as degraded forms of hexagonal networks and regularly spaced pinnacles may be considered as the summit of a hexagonal network (see discussion on atoll pinnacles below). Self-organization is very effective in producing remarkable patterns in natural systems and there is a large literature on this topics following the original work of Nicolis and Prigogine (1977). Blakeway and Hamblin (2015) explore the potential of self-organization in coral systems to form reticulated structures and prove that branching *Acropora* are able to collapse and join isolated coral patches. Using a cellular automaton model, they reproduced reticulated coral features with species distribution in agreement with their observations from the Maze of the Easter Abrolhos Reef in Wetsern Austraia. However, universality of this formation mechanism needs to be proven in a context where several different mechanisms of self-organization may operate simultaneously, while still resulting in similar patterns (Schlager and Purkis 2015). Thermal convection for instance was widely used in self-organization theory. It can lead to reticulated structures by interaction of different orientation convection rolls. Decrease of water viscosity with temperature squeezes the upwelling flow and induces a local supply of mineralized water. Also, polygonal structures of hectometric to kilometric size have been found independently of any tectonic event on clastic sediments. They are interpreted as compaction phenomena in clay layers (Lopez et al., 2018). These clay layers could be located in the sediment filling of the lagoon in case of continental sediment supply. Compaction of clay layers below the atoll could also lead to polygonal structures. This hypothesis and the consequence on the overlying atoll have never been considered, to our knowledge.

Schlager and Purkis (2015) and Blakeway and Hamblin (2015) show that in many cases the reticulated reef develops on a flat abrasion surface, which contradict the hypothesis of a karstic origin. These authors discussed shallow reticulated structures resulting from coral constructions that are similar to structures found in other Tuamotu atolls, but which are not the wide deep basins we described here on multi-beam data. Indeed, shallow reticulations are also commonly found on the east side of the lagoons of east Tuamotu atolls. Napuka and Tatakoto atolls for instance have reticulated reefs with basins at decametric scale and few meters depth (Fig. 7) which probably did not request antecedent karstic basement for their development. The east Tuamotu reticulated structures seem consistent with the formation processes described by these authors, except that in the case of these east Tuamotu atolls giant clam accumulation and not only corals also contributed to the ridge and wall constructions (Gilbert et al. 2006).

In Ishigaki Island, in the Ryukyu Archipelago of south Japan, high spatial resolution (1 m) multibeam data were used to classify the type of karst formations that were found on a coral reef and fluvial environment during periods of Quaternary sea-level lowstands (Kan et al. 2015). This included: doline, uvalas, mega-doline, cockpit karst, polygonal karst and fluviokarst. The main criteria for the classification of these structures are their three dimensional sizes and their depth. Drawing a parallel between Ishigaki Island and the atolls would be interesting, as there is a continuum of basin sizes found in Ahe (max=2.486 km^2, min=0.032 km^2, average= 0.551 km^2) and in Manihiki (max=1.850 km^2, min=0.002 km^2, average= 0.144 km^2) (Fig. 8) at different depth (Fig. 5). It is thus likely that also a range of karstic features could be described, between the largest karst basins and the small *koko* already described above. Except for the fluviokarst, it seems that most of the deep karst features described in Ishigaki could be found on atoll lagoons. There are however different scopes and data types between Kan et al. (2015) and our paper. First, considering we wanted to include as many atolls as possible in our compilation, we did not use the highest possible spatial resolution, and focus on a comparable range of resolution available for a consistent assessment (10-60m). Second, Kan et al. (2015) were able to collect field data, by SCUBA, and performed analysis of geological material, including cores. We still lack these types of materials. Unlike Ishigaki Island which is relatively easy to access with good local logistics, it still requires challenging expeditions to work on Tuamotu and Cook Islands atolls if significant logistics are involved (scuba, drilling, etc.). For instance, none of the studied atolls have any commercial (or professional, in pearl farms) scuba-diving facilities. However, similar to Kan et al. (2015), we plan for follow-up typological studies for Ahe and Manihiki, but also for Raroia and Takapoto this time using the highest possible resolution (1 to 5 m). These latter atolls are the largest of our study sites. They lack the prominent, obvious, basins detectable with 10m data, and therefore we aim to investigate if features mapped with higher resolution data could bring additional clues and enrich the type of karst and constructional features seen in 10 m spatial resolution data.

Coral pinnacles

Another remarkable pattern is the abundance of coral pinnacles found in Raroia Atoll. With 1618 pinnacles and large bommies, this is a unique atoll for the central Pacific Ocean, but also elsewhere, as no other atoll worldwide comes close in pinnacles number. There is however no obvious reason that can explain the high number of pinnacles in Raroia. Coral pinnacles in atoll lagoons have remained poorly studied. Guilcher (1991) reviewed the different hypotheses proposed for their origins in the context of atoll formations. Since then, to our knowledge, no new data sets have emerged by coring or seismic surveying in Cook Islands or Tuamotu atolls. We discuss various pinnacle formation hypotheses below.

Considering the depth of 60 m in Raroia and a 10 m of Holocene sediments above the initial surface, the bottom of the emerged lagoon present around 17000 years ago at the end of the Pleistocene started to be inundated around 12000 years ago according to the sea level curves (Montaggioni 2005). Assuming that coral growth could keep up with sea level rise, and assuming a plausible maximum accretion of $6mm.y^{-1}$ on top of the pinnacles typically dominated by *Porites* and crustose coralline algae (Montaggioni 2005, Montaggioni et al. 2015), this would mean that pinnacles could have grown from a flat area and reach their current high. If antecedent positive relief is present, and in shallower areas, the time or level of growth required would be accordingly less. A pinnacle drilled in Tikehau Atoll (Rougerie et al. 1997) revealed a 2m veneer of coral growth on top of a Miocene framework, without in this case any Pleistocene layer (Guilcher 1991). This may not be always the case elsewhere, as, similarly to Mataiva discussed above, Tikehau has been slightly uplifted which may have prevented coral growth and sediment production during Pleistocene high sea-level stands. Although, as shown in Tikehau, there is likely an antecedent basement, it appears that antecedent surfaces are not mandatory to explain the pinnacles range of relief. However, such vertical development occurring in isolation in specific locations warrants further discussion. Rougerie and Wauthy (1986) took as evidence of their endo-upwelling theory the presence of these isolated coral pinnacles. Their growth would have been favored by a suitable pathway of nutrients from the atoll basement to the location of the pinnacles on lagoon floors, and several experiments and drillings have tried to confirm this. Observations, from Moruroa or Tikehau atolls, seem to confirm the theory according to the level of nutrients found in the boreholes, similar to level found for deep oceanic waters (Guilcher 1991). The idea could be generalized to the growth of reticulated cells. However, as demonstrated by Leclerc et al. (1999), thermal convection inside the atoll structure is a significant transport mechanism in term of nutrient delivery, but only at geological time-scale and in fact can only provide a minor nutrient supply for coral reef ecosystems, and their continuous growth.

In Raroia, despite the absence of large reticulated basins, the *koko* seems to confirm the presence of karstic antecedent relief. Therefore Raroia pinnacles could be the only clearly visible feature of a past karstification event, with only them and the cryptic *koko* as indicators of karstification, but without the reticulated structures found in Ahe or Manihiki. As discussed above, sediment filling of all the putative basins could explain the absence of basins but this seems unlikely considering that in smaller reticulated lagoons, like Ahe, basins are still visible despite its higher rim/lagoon ratio (Table 1).

Pinnacles are generally thought to be the expression of Holocene coral growth on top of Pleistocene, or much earlier, relief. The likely relation with karst formations, providing the antecedent platform, is also well acknowledged in different part of the world (Guilcher 1991). Cockpit karst and polygonal karst - which were firstly defined in Jamaica and South China, respectively- consist of networks of closed depression separated by residual hills (Ford and Williams, 2007). Tower karst and polygonal karst are thought to consist of relics of carbonate layers, when everything else has been dissolved. Formation of such karst requires an annual rainfall higher than 1500 mm (Sweeting, 1972) and a time lapse estimated to a several Ma by Fleurant et al. (2008). This timing is consistent with the order of magnitude of denudation rates ranging from 35 to 130 m/Ma found by Purdy and Winterer (2001) from observations and dissolution kinetic considerations. Tower karst consists of isolated limestone towers rising from alluvian plains (Huang et al., 2013). It is suspected that polygonal and cockpit karsts may evolve toward tower karst with increasing dissolution. Either polygonal tower karst or cockpit karst is able to produce isolated pinnacles (or reticulated structure) after submersion. Many atolls however have no or only a small number of pinnacles that seem to be randomly distributed. Furthermore, in Ahe, the numerous pinnacles (n=141, Table 1) are not necessarily related to the network of karst-inherited reticulated basins (Fig. 3).

Eventually, the differences in pinnacles numbers and densities from one atoll to another cannot be explained, and the high number of pinnacles in Raroia lagoon is puzzling. Without new coring and datations, the number of Raroia pinnacles and their distribution will remain unexplained.

Fitting a general theory of atoll lagoon formation

Purdy and Winterer (2001) made the case of a relationship between the maximum lagoon depth (maxDepth hereafter) and paleo-rainfall (approximated by modern rainfall data, in $mm.y^{-1}$) occurring through the Miocene to pre-Holocene. These periods include several low-sea level stands and emergence times, with sea level typically 120 meters below the present one.

The maxDepth *vs* rainfall relationship was established for atolls worldwide. Despite several outliers, data from several well studied atolls confirmed with topographic evidences the role of dissolution during low sea-level stands to form the modern morphology of atoll lagoons. The topographic evidences for dissolution came from the absence of a thick, or significant, lagoonal Pleistocene sediment deposit that should have been produced during the -125ky sea-level high stands in several atolls for which drilling data are available (Purdy and Winterer 2001). The narrow deposits can be explained only by dissolution during periods of emergence in the glacial periods. Lagoon relief is therefore in part due to Pleistocene glacial ages, and possibly before since Miocene relief have been reached in Enewetak in Marshall Islands (Grow et al. 1986) or in Tikehau Atoll as discussed above. Tuamotu atolls providing such evidences include Moruroa atoll (Guille et al. 1995). Unfortunately coring and sediment thickness are unavailable for the seven atolls chartered here.

Rainfall *vs* maxDepth provided a stronger relationship when the area of the atolls was considered, with a highly significant Rainfall x Log_{10}(Area) *vs* maxDepth ($r=0.57$; $p<0.00$, $n=255$). Purdy and Winterer (2001) noted that, before integrating the Log_{10}(Area) factor, Tuamotu-Gambier alone did not make a particularly good case for their theory with a non-significant, $r=-0.05$ ($n=32$) statistical relationship between MaxDepth and Rainfall, possibly given the lack of rainfall gradient in this region. With the Log_{10}(Area) factor, r increased to 0.53. From the results of the present study, all other factors being kept the same as in Purdy and Winterer (2001), the correction in maximum depth for the atolls studied here decreases the correlation to $r=0.43$. The largest correction would be for Ahe (previously 54m *vs* 71m here), followed by Raroia (with 50m *vs* 68 m in its *koko*). Nevertheless, considering there are more evidences of dissolution on the western atolls with the presence of large reticulated basins, the Purdy and Winterer (2001) theory is reinforced if we take into account also the position of the South Pacific Convergence Zone (SPCZ) rainfall belt, which fringes the western French Polynesia and overlaps Cook Islands in normal periods, and could more easily affect the western atolls than the central one when it shifts slightly eastward, in particular during El Niño periods (Hopuare et al. 2015).

Perspectives for atoll lagoon research

It is expected that additional multi-beam surveys will be achieved in a short term future because they have an immediate interest for pearl farming management. In addition to these multi-beam surveys, we recommend to acquire seismic data, cores of pinnacles, and cores of deep reticulated structures. These data would all inform on the internal structures and formation processes of the remarkable structures discussed here and evidenced by bathymetric data. Fluid sampling inside pinnacles to detect nutrients transport would be useful, since thus far, only data from a short core are available for a Tikehau pinnacle. However, the investigation of the internal structure of lagoons requires significant logistics in remote atolls, and funds.

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Table 1: Morphometric variables for each studied atoll.

Atoll	Surface area (km^2)	Volume (km^3)	Maximum Depth (m)	Average depth (m)	Ration Rim/Lagoon	Number of Pinnacles	Number of Reticulated basins	Ratio Pinnacles-Lagoon area >20m
Raroia	367.95	11.86	68	32.2	0.19	1434	1 *koko*	4.65
Ahe	144.63	5.82	71	40.6	0.26	141	65	1.16
Takaroa	85.96	2.22	48	25.8	0.41	246	2	4.07
Takapoto	78.64	1.95	43	24.8	0.33	194	0	3.59
Manihiki	45.07	1.33	76	29.6	0.48	142	98	5.42
Takume	40.98	0.83	58	20.4	0.85	56	8 *koko*	2.08
Mopelia	28.92	0.75	41	26.0	0.77	11	5	0.50

Figure 1: Central Pacific Ocean seafloor features and positions of the studied atolls as well as atolls mentioned in the text (underlined). 1. Manihiki, 2. Mopelia, 3. Ahe, 4. Takapoto, 5. Takaroa, 6. Raroia, 7. Takume, 8. Moruroa, 9. Mataiva, 10. Vahitahi, 11. Tatakoto, 12. Scilly, 13. Bellinghausen, 14. Napuka. 15, Pukapuka (Tuamotu), 16. Rakahanga, 17. Pukapuka (Cook Islands). Islands are not shown.The Tuamotu Plateau is the foundation of the Tuamotu island chain mentioned in the text.

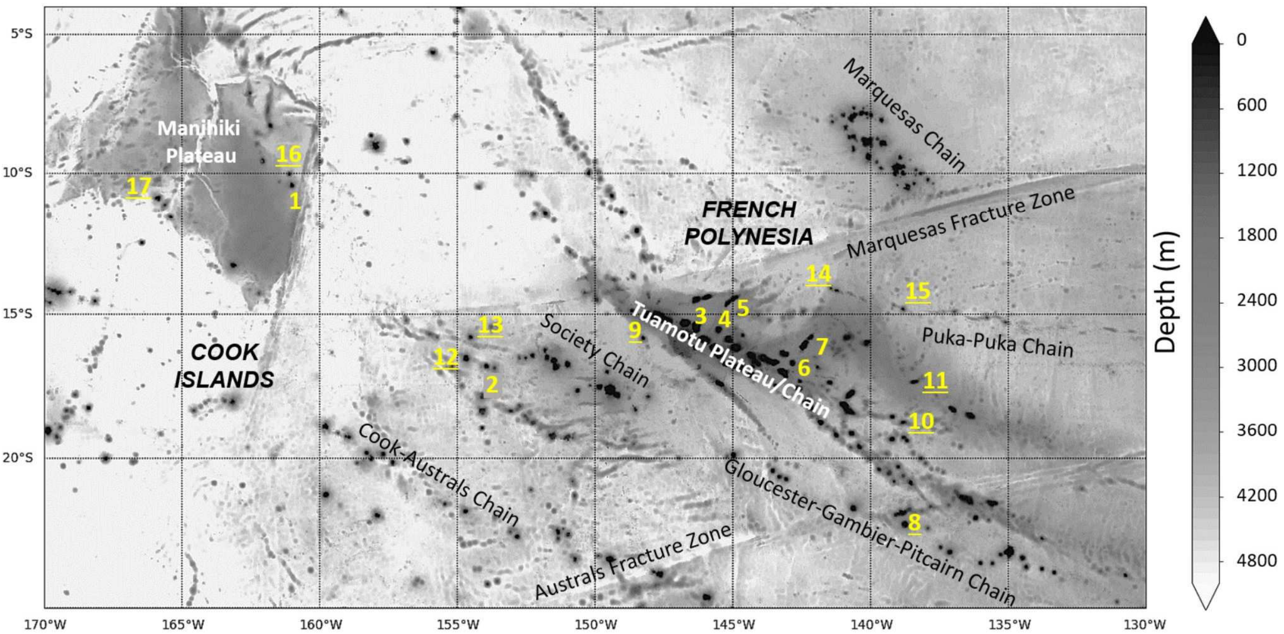

Figure 2: Bathymetric maps for Raroia, Ahe and Takaroa atolls.

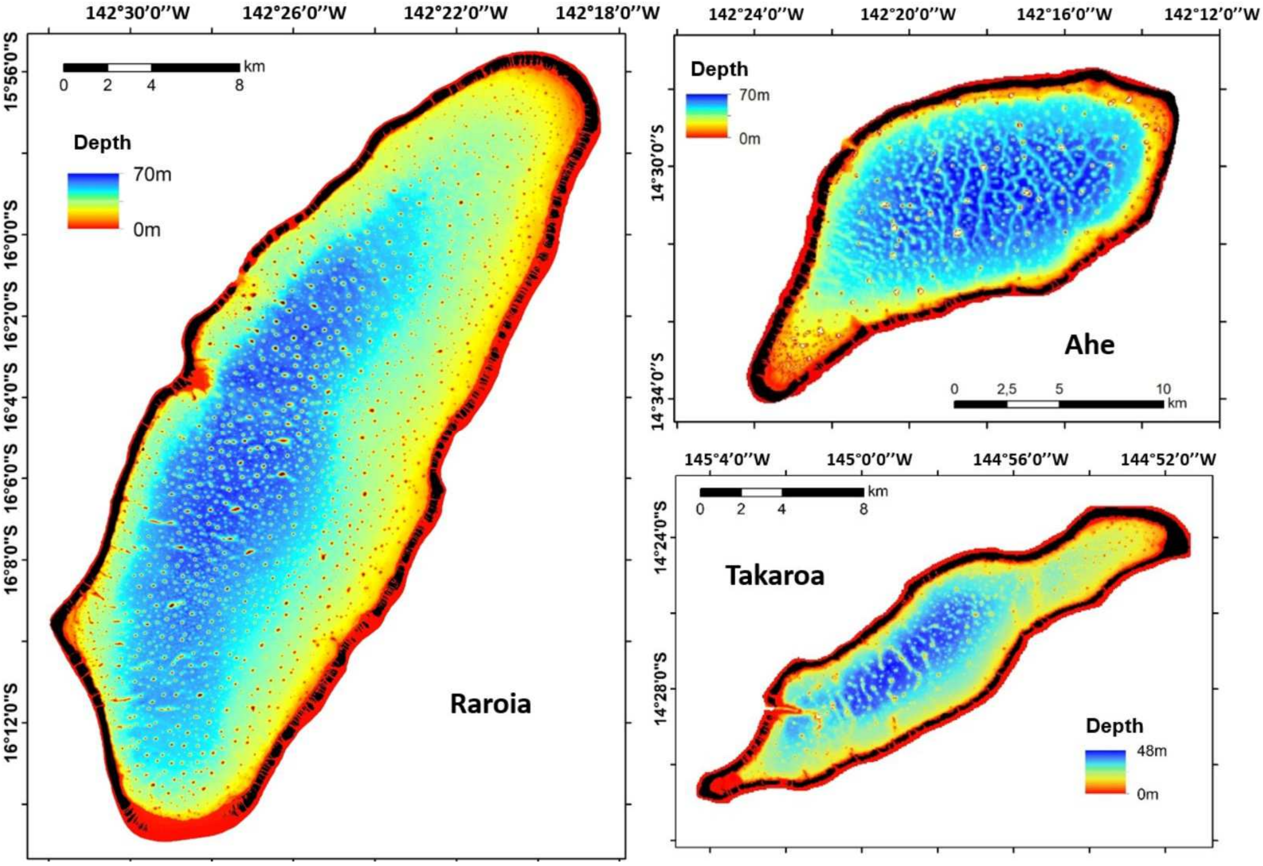

Figure 3: Bathymetric maps for Takapoto, Takume, Mopelia and Manihiki atolls.

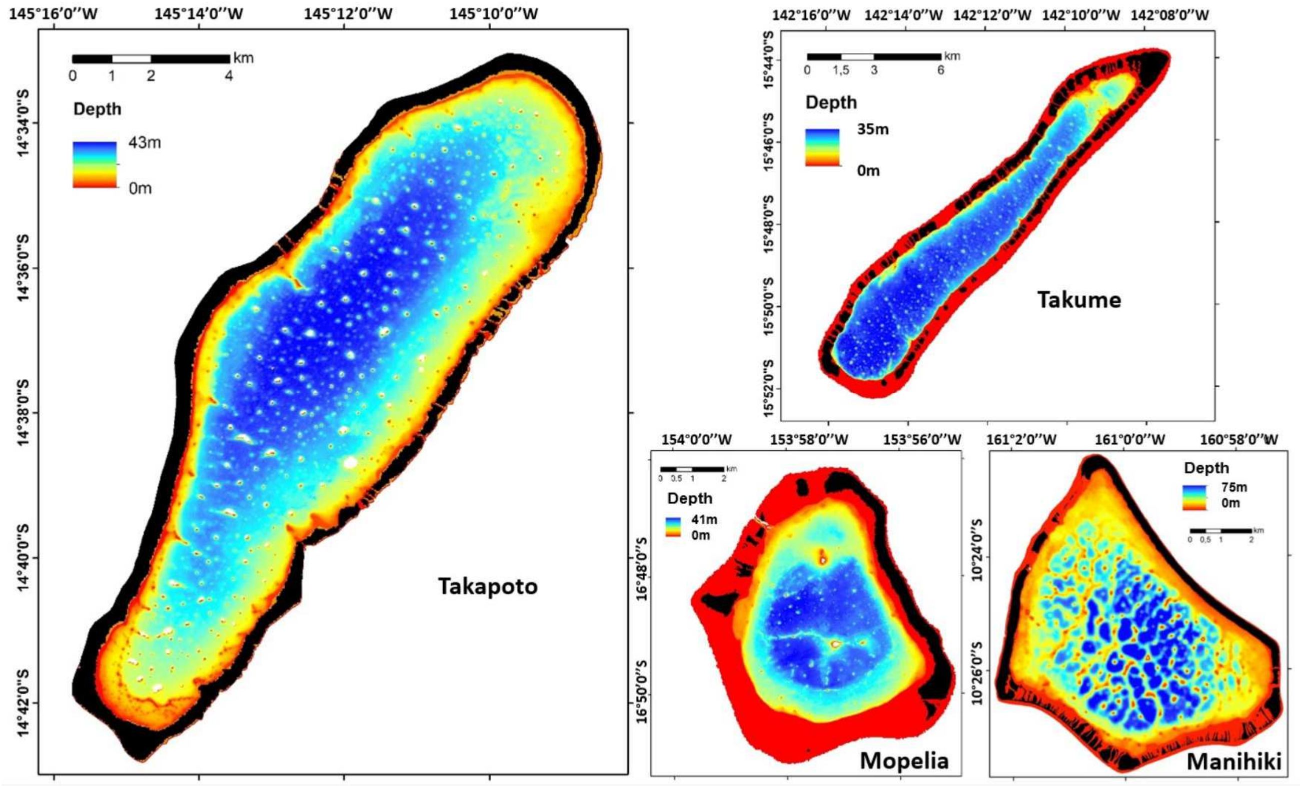

Figure 4: Histogram of depth distribution (in 10-meter bin) for the seven studies atolls.

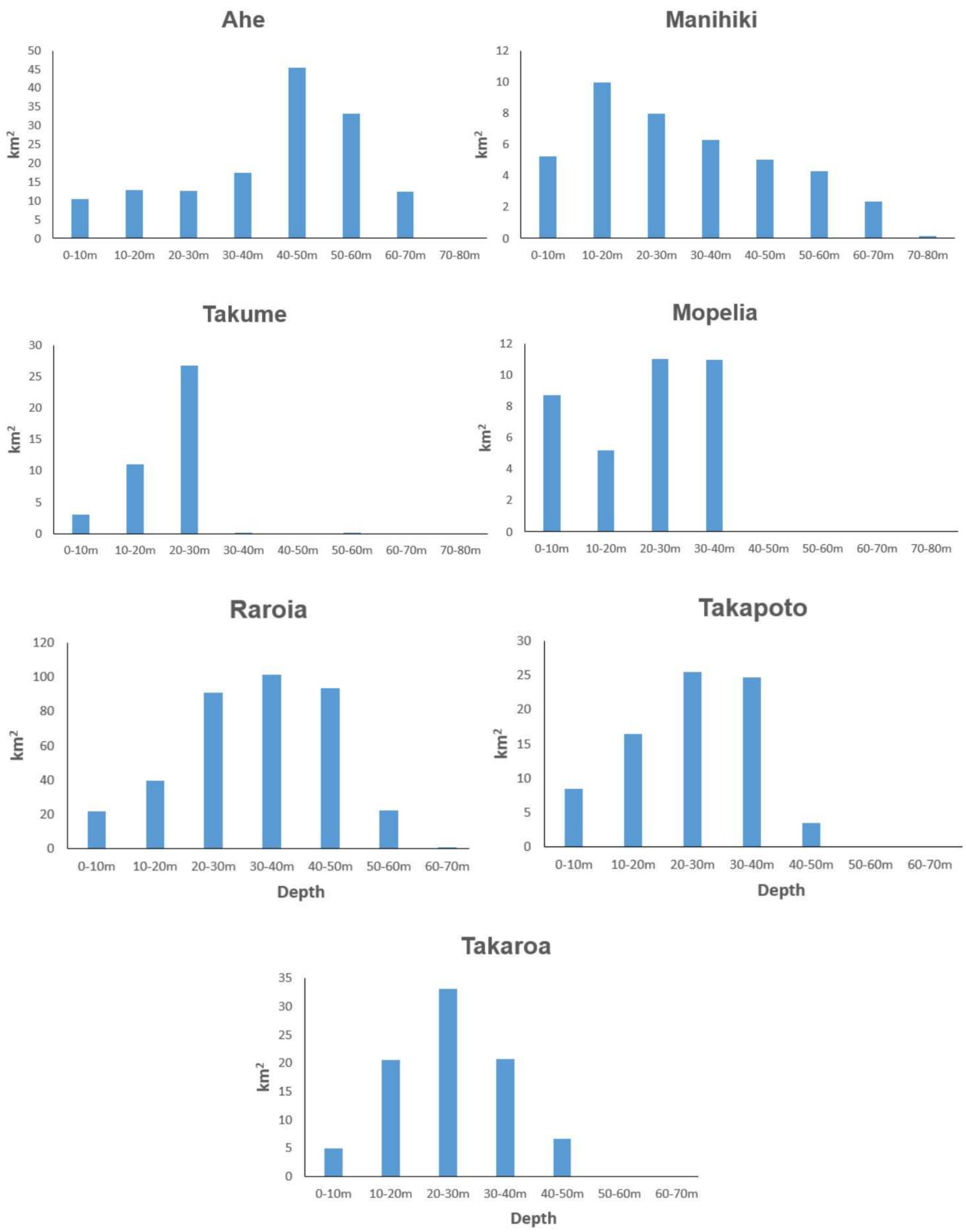

Figure 5: Sections across Manihiki and Ahe atolls (along the yellow lines overlaid on the atoll maps), showing vertical pinnacles and distribution of karstic basins and their walls. For Manihiki, basins are distributed following three terraces at different depth ranges (yellow-orange colors). In Ahe, basins are found at only one depth level (red box), similar to the Manihiki first level (yellow). However, the depth of the summit of the walls between basins (in green) are 10 meter shallower in Manihiki compared to Ahe.

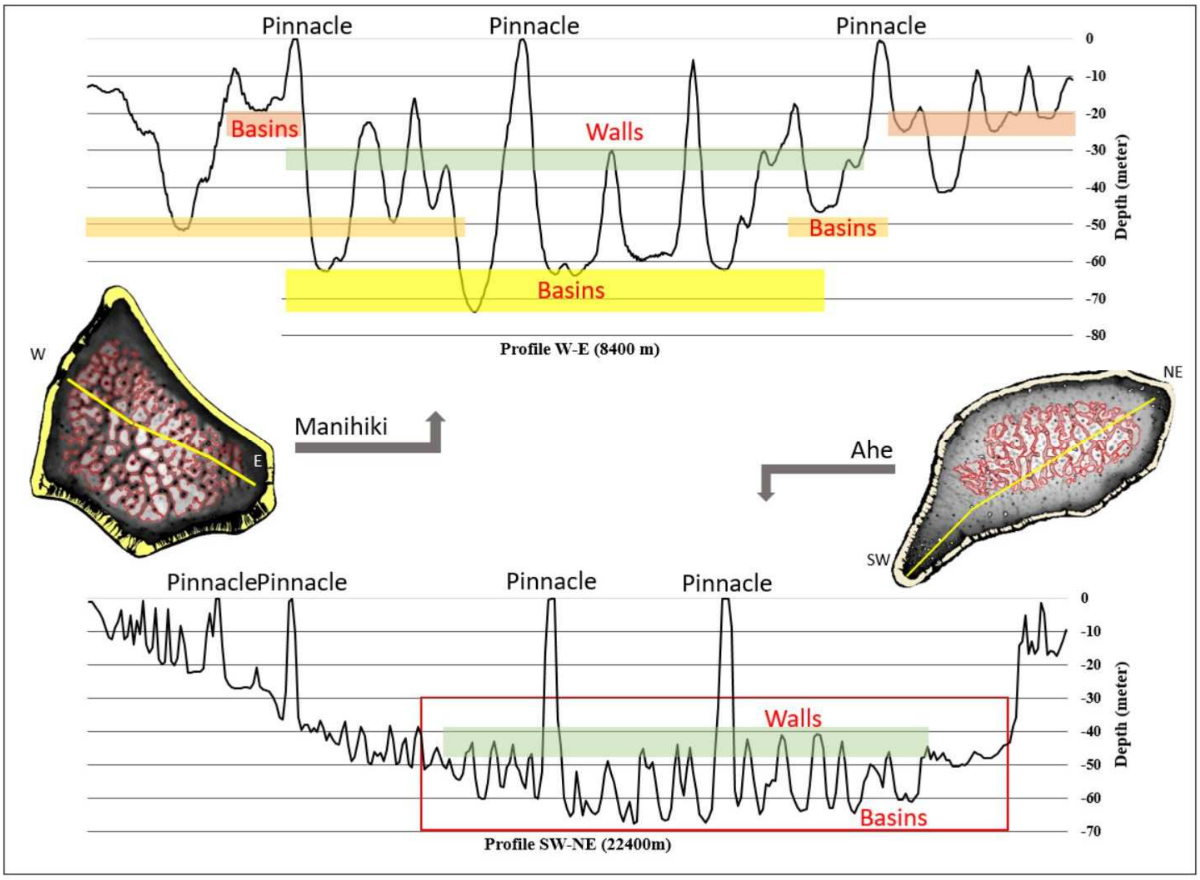

Figure 6: Sections across atolls (yellow lines overlaid on the atoll maps). A and B: Raroia, C: Takaroa, D: Takume, E: Mopelia, F: Takapoto.

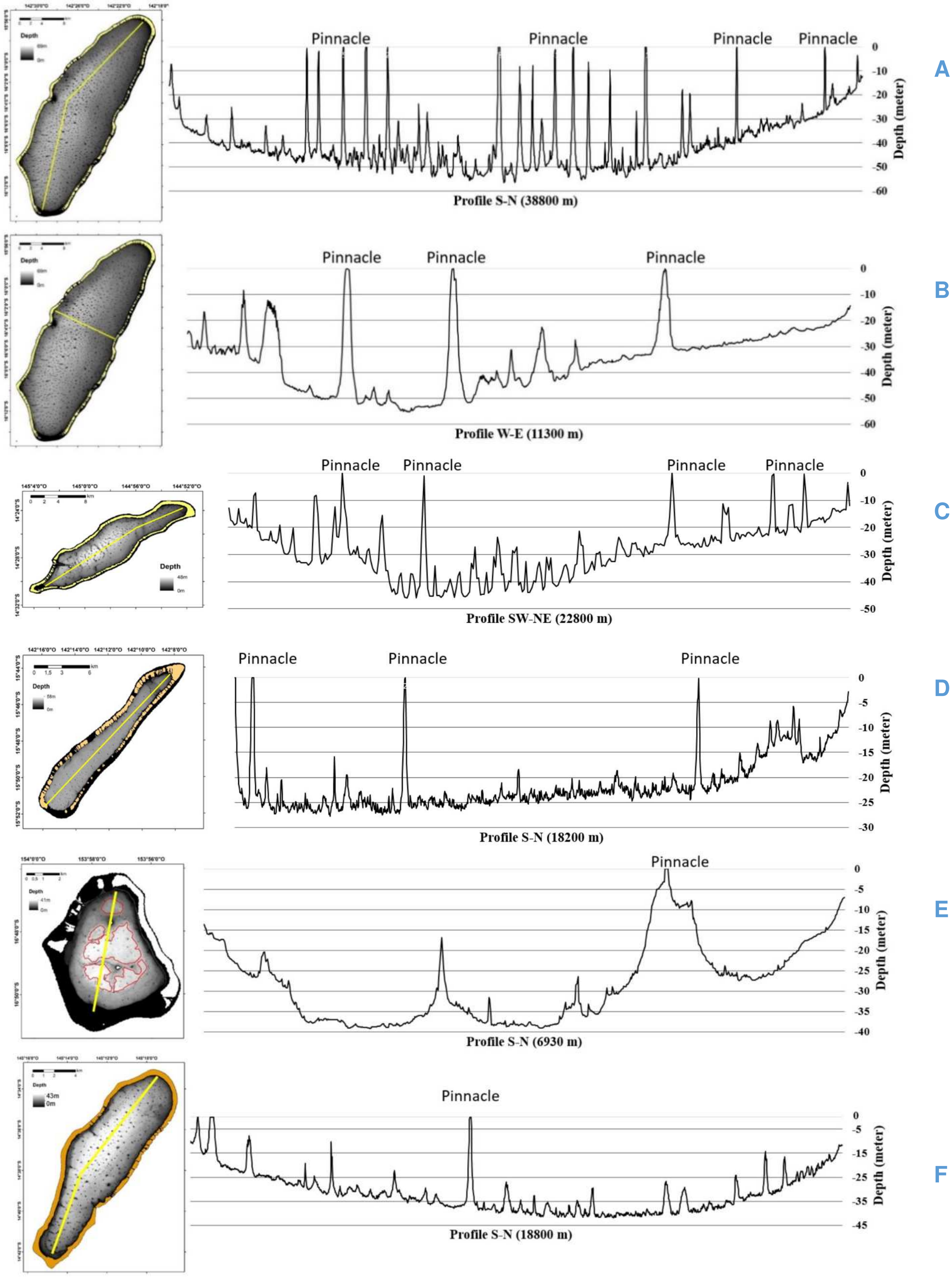

Figure 7: Geomorphological units found in East Tuamotu atolls and discussed in the text: A and B: *koko* in Vahitahi Atoll. C and D: reticulated shallow reefs in Tatakoto Atoll.

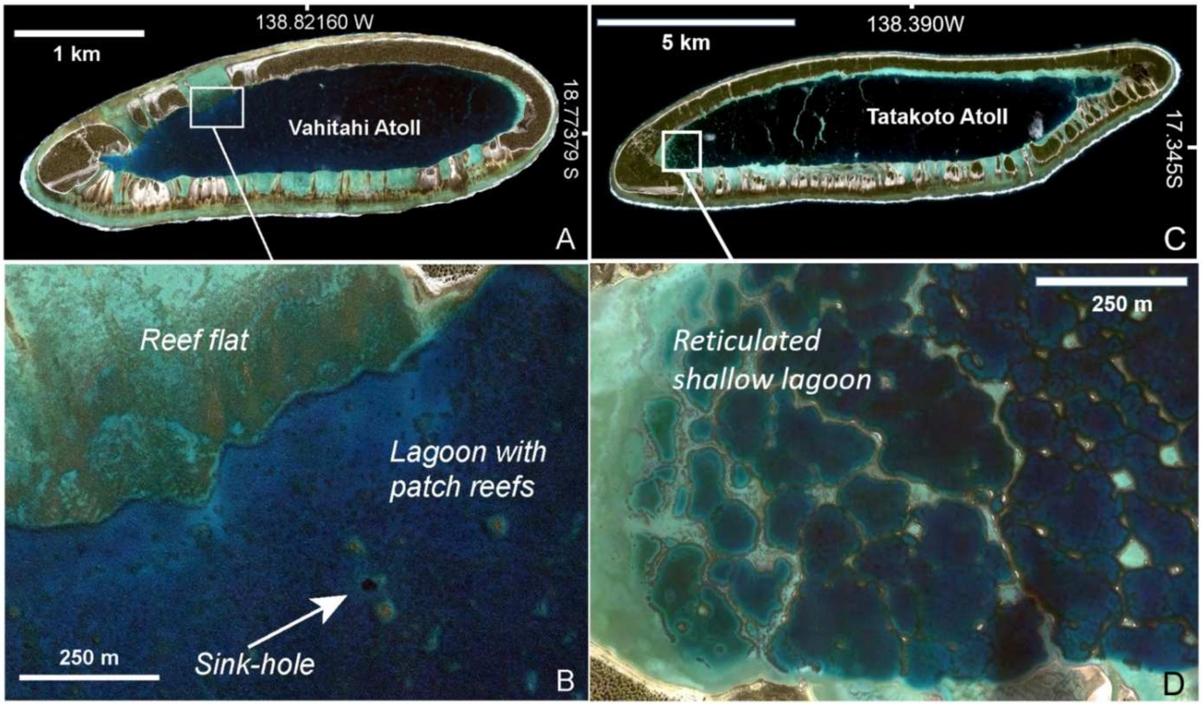

Figure 8: Size (in km^2) for each of the deep basin found in Ahe and Manihiki.