A Global Atlas of Atolls

Walter M. Goldberg
Emeritus Professor of Biological Sciences,
Florida International University, Miami, FL, USA

Eugene C. Rankey
Professor of Geology, University of Kansas, Lawrence KS, USA

First edition published 2024

ISBN: 978-1-032-26246-8 (hbk)
ISBN: 978-1-003-28733-9 (ebk)

Chapter 3
The Polynesian Pacific and the Atolls of the Tuamotu Archipelago

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DOI: 10.1201/9781003287339-3

The Open Access version of this chapter was funded by Walter M. Goldberg.

CRC Press
Taylor & Francis Group
Boca Raton London New York

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Taylor & Francis Group, an **informa** business

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Polynesia is composed of more than 1,000 islands spread over an area of more than 2 million km^2 forming a triangular area that extends from New Zealand to the south, to Easter Island to the east, and to Hawai'i to the north. Polynesian ancestors, the Lapita people, set out from Taiwan and settled Remote Oceania between 3,200 and 3,000 years ago, although there is evidence of Lapita settlements in the Bismarck Archipelago as early as 4,000 years ago. The Lapita ancestors became skilled seafarers who shared a common culture, language, art forms, houses, and a panoply of deities. Sites of early Polynesian migration to Tonga and Samoa left few footprints to indicate the pathways and timing of the early voyages from there to the rest of Polynesia. The conflicting dates from ethnography, linguistics, tool or building similarities, and even DNA analysis of the Pacific rat further confuse this history (see reviews by Kirch, 2000; 2010). However, based on Polynesian genomic analysis, a migration to the Society Islands from the Cook Islands and from there to the islands of the northwest Tuamotu group occurred about 1,100 years ago (Ioannidis et al., 2021). High islands were preferred for obvious reasons, but some atolls that may have been mere rest stops became permanently occupied if freshwater could be found. Occupation of many atolls, however, was temporally constrained by falling sea levels that occurred between 900 and 1,200 years before the present time. Before that, many low islands and atolls would have been under water (Pirazzoli and Montaggioni, 1986; Dickinson, 2009).

Polynesian atolls (excluding the New Zealand area) occupy a roughly triangular area, about 1.4 million km^2, of the south, central, and northern Pacific Ocean. The base includes of atoll-bearing Polynesia includes Tuvalu in the west, followed by the Cook and Society Islands in the center, and the Tuamotu Archipelago to the east. Tokelau, the Phoenix islands, and the Line islands occupy the center, and the Northwest Hawaiian Islands form the northern apex (Figure 3.1). We begin with the Tuamotu group.

The Tuamotu and associated archipelagoes

The Tuamotu Archipelago ('distant islands') represents the largest concentration of atolls in the world and extends for about 1,500 km (Figure 3.2). In addition to the Tuamotu group, the southeastern atolls are often included administratively as the Gambier Islands, and the two are often referred to collectively as the Tuamotu-Gambier Islands. Other atolls shown in Figure 3.2 that extend the area farther to the south and to the southeast are described below. Of the 73 atolls shown in this figure, only 26 atolls are formed with open lagoons, most of which are found in the northern third of the chain. Another 47 atolls develop closed or semi-closed lagoons, four of which include waters with markedly altered salinity or other chemical conditions as shown by color codes.

The northwestern Tuamotu Islands are formed on volcanoes that rise from the summit of a long submarine plateau (the Tuamotu Plateau) at a depth of 1,500–3,000 m, rather than from the surrounding waters at a depth of 4,000–4,500 m. This volcanic basement of the islands in the northwest is covered with 500–800 m thick carbonate because they have been subsiding for at least 50 million years. In addition to the main axis of the plateau, there are four smaller ridge systems at the northwest that have developed at right angles and are oriented northeast–southwest.

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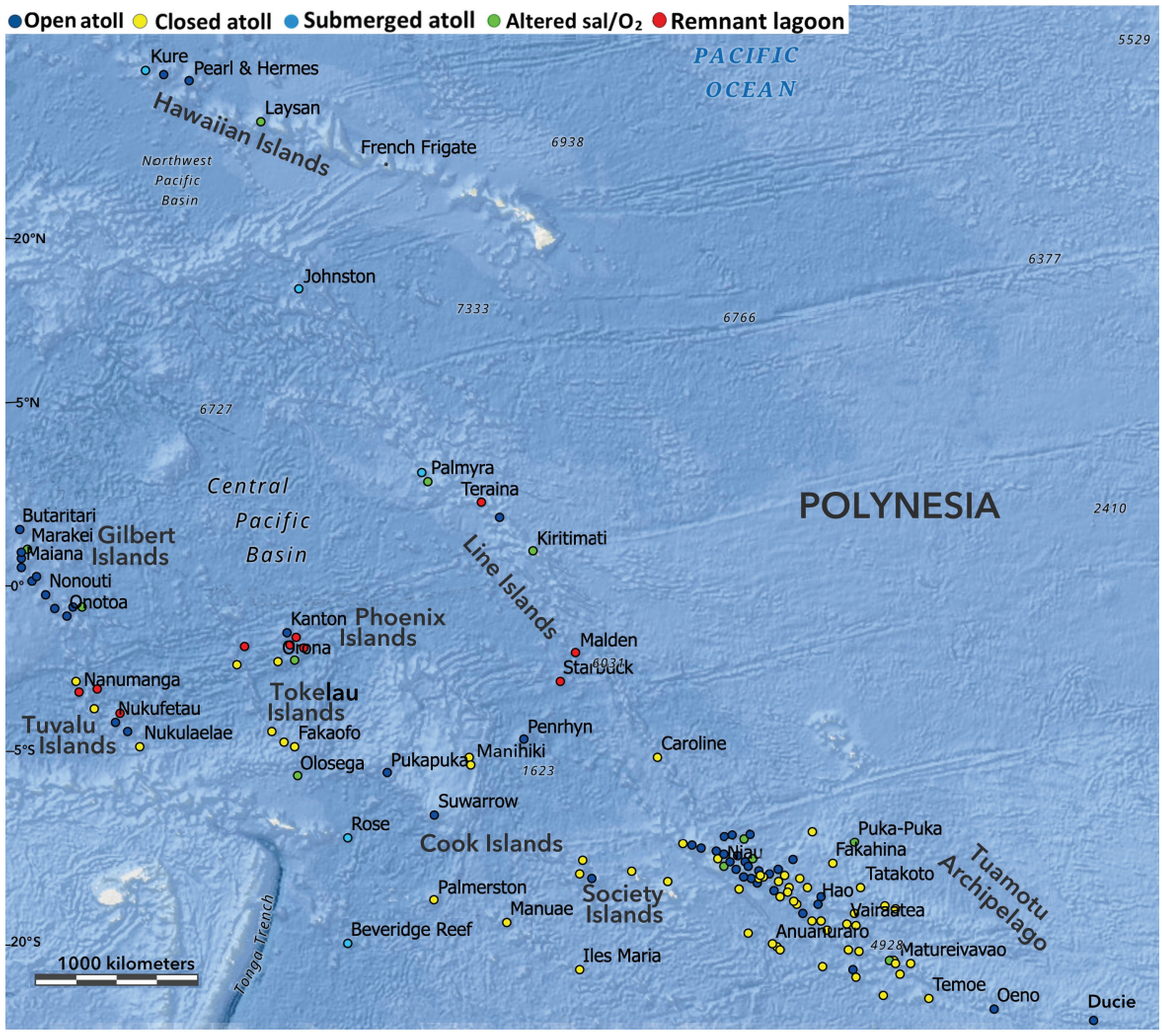

Figure 3.1 Atolls within Polynesia cover a vast region of the Pacific that range from the Tuamoto Archipelago to the southeast, the Gilbert Islands in the west, and the Northwest Hawaiian Islands. The atolls are color coded with respect to the condition of the rim and lagoon including rims that are open, closed, submerged, closed with alteration of the lagoon waters, or closed with remnant lagoons.

The seven atolls here were formed on erupting fissures generated from fracture zones. The northernmost ridge is occupied by Manihi and Ahe, the second contains Takaroa and Takapoto, the third supports Takume and Rarioa, and the southernmost is occupied by Amanu, all of which have the same orientation with respect to their rims and lagoons (Montaggioni et al., 2019). Second, a more northerly volcanic ridge system to the northeast includes Puka-Puka and Napuka atolls (Figure 3.2). Lastly, a third chain extends as a subparallel track south of the Tuamotu Plateau extending from the Duke of Gloucester Islands (four atolls from Herheretue to Nukutepipi) to the southeastern Tuamotu group, expanding the Tuamotu chain to the southeast including atolls from Tenararo to Temoe. These atolls originated as small volcanic islands that formed on top of a broad marine volcanic plateau. Two additional atolls (Ducie and Oeno) are part of the Pitcairn Islands (Figure 3.2 inset). These southeastern atolls are younger than those of the Tuamotu Islands, perhaps originating on volcanics only a few million years old, as described later. These age differences suggest that the atolls of the archipelago have had dissimilar origins and a complex history (Montaggioni and Camoin, 1997; Clouard and Bonneville, 2005; Bonneville, 2009).

Regional climate and oceanography

The Tuamotu Islands are bounded in the north at 14.66°S and at the south at 23.22°S, essentially at the Tropic of Capricorn (–23.50°). Despite the extensive areal coverage of 13,500 km^2, less than 5% is dry land. As of 2017, 16,881 people lived in the Tuamotu Archipelago (Institut de la statistique de la Polynésie française, 2017), including 2,709 who live on Rangiroa, the most populated and the largest of the atolls.

The dominant surface current is the trade wind-driven South Equatorial Current, which forms part of a counterclockwise gyre that washes through the

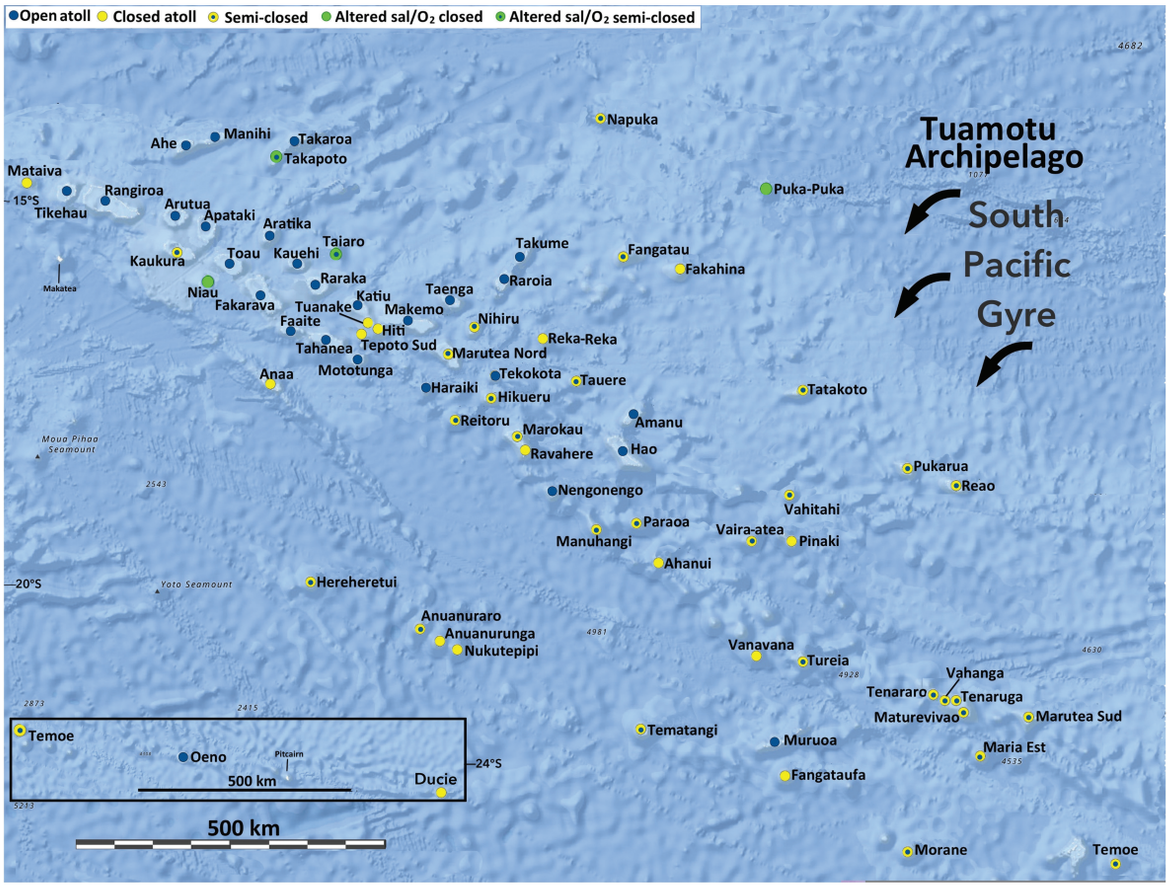

Figure 3.2 Atolls of the Tuamotu and associated archipelagoes. Atolls to the south include the Tuamotu, Gambier, and Duke of Gloucester Islands and are either closed or semi-closed. Oeno and Ducie atolls among the easternmost Pitcairn Islands are shown in the inset. The predominant current system is the counterclockwise flow of the South Equatorial Current.

archipelago (Rougerie et al., 1997a). Rainfall is typically between 130 and 190 cm/year with a mean of 178 cm per year for the islands. However, the rainfall distribution throughout the year is uneven, with about 65% during the wet season (November to March, the austral summer). For example, in January, an average rainfall of about 23 cm falls. However, during the austral winter (April to October), monthly rainfall levels drop by 66% so that in August, for example, only about 7.5 cm of rain falls on average. In addition, there can be considerable variability of rainfall from year to year (Intes and Caillart, 1994).

Few trees grow well in these environments, but coconut palms are widespread, in part because they occur naturally and more often because they have been planted. In French Polynesia and elsewhere in the tropical Pacific, coconut palm plantations exploded from the late 19th century on, where the unfortunate technique was to cut down all the native vegetation, allow it to dry, and then set it afire. Newly planted coconut trees were then spaced 100–250 per hectare. Not only were these plantations subject to the boom-and-bust cycle of the global copra trade but the trees are susceptible to cyclone damage and to the process of aging. Many that have been planted in French Polynesia are now too old to bear fruit (Bourdeix et al., 2009). Nonetheless, a close Google Earth view of almost any of the islands—even the motu—in the Tuamotu Archipelago will reveal how widespread these plantations are.

Shaped by the archipelago's position in the trade wind belt, surface winds range from northeasterly to southeasterly 250 days of the year or more (Intes and Caillart, 1994) (Figure 3.3). The austral summer winds are generally moderate, but during the austral winter, trade winds can generate waves between 1 and 3 m from the east and southeast in the Tuamotu Archipelago. Swells from distant storms and the Southern Ocean can reach the Tuamotu Islands, and their exposed atoll margins and shores (which can be either windward or leeward) may be more heavily pummeled by these waves than with those produced by local winds. Storms from the northern hemisphere in the austral summer or from the southern hemisphere during the austral winter can generate swells in excess of 4 m high. However, atolls located on the flanks of the Tuamotu chain may dissipate storm waves from different directions by blocking or reflecting them, thereby providing atolls on the opposite side with some protection due

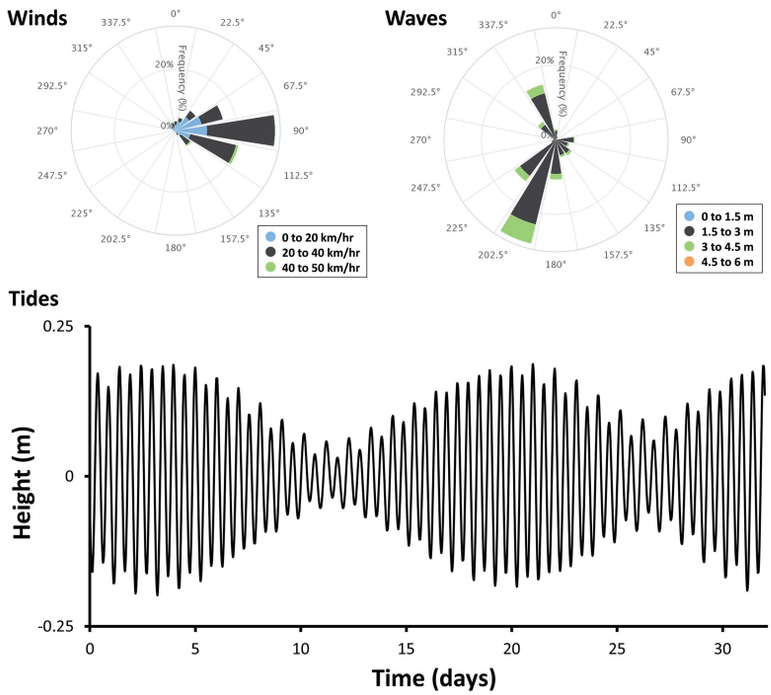

Figure 3.3 Trade winds range from northeasterly to southeasterly 250 days of the year or more. Swell from distant storms and the Southern Ocean can reach the Tuamotus, where exposed atoll margins and shores may be pummeled more by these than by local wind-generated waves. The tides are semidiurnal (two highs and lows per day) and generally less than 50 cm range, such as those from Rangiroa shown here.

to an atoll 'shadow effect' (Andréfouët et al., 2012). Thus, even nearby groups of northern and southern atolls may have a different wave climate. In addition, cyclonic storms that pass near the area can produce waves more than 10 m high basically from any direction (Intes and Caillart, 1994), although direct hits by cyclones are infrequent except during El Niño periods (Larrue and Chiron, 2010). Wave data from near Rangiroa (Figure 3.3) illustrate these patterns and include the most frequent larger waves from the southwest and northwest.

All these processes and events may have considerable influence on ocean water exchange with atoll lagoons. Lagoon water residence (turnover) time is complex and depends to a large extent on the degree of rim closure, depth, and wind and wave conditions. The structure of the rim—its passes, hoa, and reef flat—is key in determining this factor. More open lagoon rims allow swells or local storm waves and winds to exchange water with the lagoon most readily, but large atolls and those with closed and deep lagoons may require years to fully exchange lagoon water (Andréfouët et al., 2001; Pagés and Andréfouët, 2001). Likewise, residence time in a closed atoll may depend on storm and swell conditions that wash over the rim, and in the absence of such wave activity, the equilibrium between rainfall and evaporation as well as the permeability of the submerged rim structure may be the most important factors (Andréfouët et al., 2001).

Tides in the Tuamotu Islands are semidiurnal. At Rangiroa, the spring tidal range is 40 cm, but in the vicinity of Tikehau 13 km to the west, the amplitude of spring tides is only 15 cm, and at neap tide, the amplitude is almost zero (Intes and Caillart, 1994). Likewise, tidal amplitude is only 30 cm in Ahe lagoon in the northwest of the Tuamotu group. These small (microtidal) variations in amplitude are due to proximity to an amphidromic node near Maupiti (Society Islands to the west) where tides rotate at a focal point and the total tidal variation is typically 20 cm or less (e.g., Rankey, 2021). However, even these small tidal ranges are sufficient to create a jet through the single pass in the rim of Ahe Atoll, a dynamic that significantly alters oceanic-water exchange time in the lagoon (Dumas et al., 2012), as described later. By comparison, the tidal range at Mangareva and Temoe at the opposite end of the archipelago—the islands in the Tuamotu group farthest away from the amphidromic node—increases to about 70 cm (Pirazzoli, 1987).

The Tuamotu atolls

The Tuamotu Islands are divided into small administrative groups or larger groups related to their positions within the chain. Here, we describe the atolls in six groups from northwest to southeast. These include the Palliser Islands, the northern islands, two central island groups, the southeastern Tuamotu atolls, and the Pitcairn group.

The Palliser Islands

From the northwest, the first group is the Palliser Islands, named after the Comptroller of the British Navy by Captain James Cook who sighted some of them (noted by an asterisk in the next sentence) in 1774. There are ten atolls in this group, described in the following order: Mataiva, Tikehau, Rangiroa, Arutua*, Apataki*, Aratika, Kaukura*, Toau*, Niau, and Fakarava. Interestingly, of the ten Palliser Islands, only Kaukura and Toau were sighted by Cook (Quanchi and Robson, 2005).

The most northwesterly of the Tuamotu Islands is **Mataiva** (Figure 3.4), a small ovoid atoll about 10 km long and 5 km wide. The platform area is 49.9 km^2 and it is surrounded by an outer reef that is about 360 m wide to the southeast where it is best developed. The rim is asymmetrical and is narrower to the north (0.2–0.5 km) where the rim includes a continuous island; by contrast, it is wider (1.0–1.5 km) in the south, where the rim is punctuated by a cluster of several hoa and is exposed to southerly swell. A few patch reefs are associated with the hoa reef flats. Mataiva means 'nine eyes' in Tuamotuan, a reference to nine hoa on this part of the atoll.

A small channel penetrates the northwestern, leeward rim, and although it is sometimes referred to as a pass, it is only about 0.5 m deep (Sailing Directions, 2017). According to Salvat (2009), this pass is the product of both natural and anthropogenic processes. The entire island was uplifted by 3.5 m in the past few thousand years, like the others in the

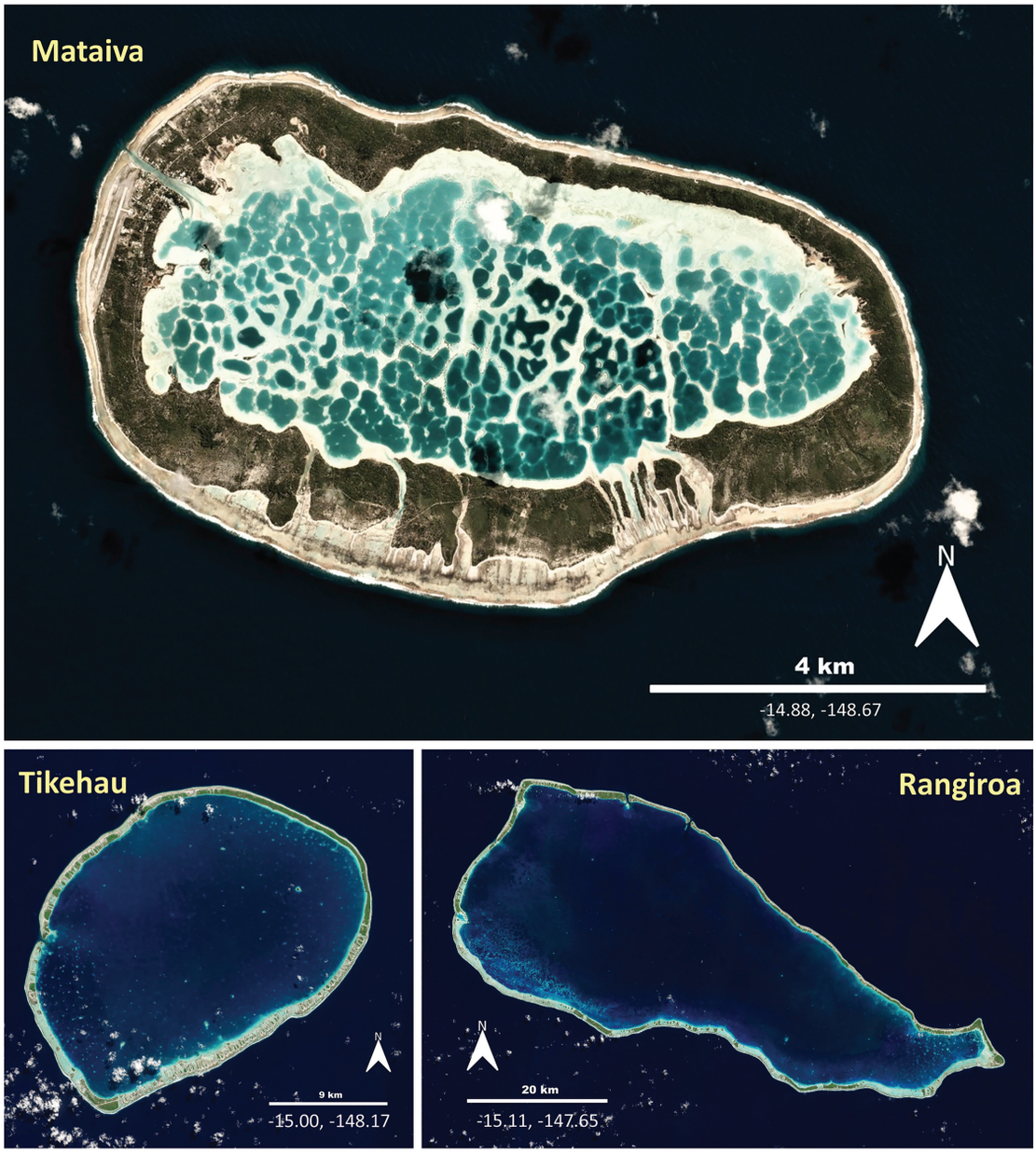

Figure 3.4 Remote-sensing images of the atolls of Mataiva, Tikehau, and Rangiroa. Images © 2021, Planet Labs PBC.

NW Tuamotu group, due to oceanic crust flexure and bulging associated with volcanic activity from nearby Tahiti. For comparison, Makatea, a raised atoll 135 km to the southeast of Mataiva (see Figure 1.14b), is closer to the highest part of the bulge and is uplifted 113 m (Montaggioni et al., 1987). This atoll is closed.

The lagoon is highly reticulated by an inner reef flat and covers an area of approximately 18.6 km^2 (eliminating as much of the inner reef flat as possible). It is partitioned into about 70 pools ranging from 100 m to more than 2 km in diameter and 4–8 m deep (Delesalle et al., 1985; Pagés and Andréfouët, 2001). The Allen Atlas suggests that pools in the center, inboard of the southern hoa, have developed patch reefs. This interpretation is consistent with Delesalle et al. (1985), who report normal salinity in the vicinity of the hoa, whereas in more distant pools, the salinity values can vary seasonally, and perhaps this explains why lagoon salinity has been reported as brackish (Rougerie et al., 1997a). Nonetheless, the lagoon is generally sandy, while those in the east are similar but include some coral/algae development. The water renewal time, the period that it takes for waves and tides to force oceanic water through the rim and completely flush the lagoon, is estimated to be 21 days (Pagés and Andréfouët, 2001).

Tikehau (Figure 3.4) is the native Polynesian word for 'paradise,' or 'a place of peace' (Young, 1899). The island of Tikehau also is known as Porutukai; this term is linguistically like other Polynesian phrases including Polutu (Samoan), Mbulotu (Fijian), and Bulotu (Tongan), which variably mean a place of departure to the underworld or the underworld itself. This atoll is 40 km east of Mataiva and is about 27 by 20 km. The platform area is 351 km^2 (Purdy, 2001). The platform has been uplifted 4 m, bringing previously underwater reefs well above sea level (Montaggioni et al., 1987; Dufour et al., 2001). The outer reefs are generally narrow and are less than 300 m wide. The rim is narrow, 0.6–1.2 km wide, and includes a long, single island in the northeast and a wider but shorter island with an airstrip in the southwest. A reef flat occupies the southwestern rim. There is a single pass about 90 m wide and 3.7–11 m deep at the west-facing reef rim (Sailing Directions, 2017). The rest of the rim (southeast, northeast, and northwest) is composed of numerous scattered low motu and hoa. A very narrow sand apron runs around the lagoon, which has an area of 394 km^2 and an average depth of 28 m; the maximum depth is 40 m and the estimated renewal time is 60 days (Pagés and Andréfouët, 2001; Purdy, 2001). There are numerous reef-rimmed pinnacles in the southwestern lagoon associated to the pass by proximity. Fewer pinnacles occur in the protected lee of the island at the northeast. Both areas with pinnacles are associated with the lagoonal slope. Additional pinnacles appear in the center lagoon that are too deep to code.

Rangiroa (Figure 3.4) is the largest atoll in the Tuamotu group and is one of the largest in the world. It is irregularly shaped, narrowing to the southeast, and is 81 km long and 33 km wide at its longest axes. Its platform covers 1,762 km^2 (Purdy, 2001), but its total land area is only about 170 km^2. Like other Palliser Islands, Rangiroa has been uplifted 3.5 m from its submerged condition 2,500–1,000 years before present (Andréfouët et al., 2008; Montaggioni et al., 2021). The rim is surrounded by a narrow outer reef band that is wider to the southeast where it is commonly2 60–325 m wide. The rim is 1.6 km wide at the southeastern corner of the atoll but is only about 0.5 km wide elsewhere. The windward rim is northwest–southeast and is composed of multiple hoa with motu that exhibit an ocean-facing elevated beach ridge composed of coarse coral shingle and rubble or blocks (Duvat et al., 2021). There are two passes on the northeast-facing margin. The more northwesterly of the two is Passe Avatoru, which is about 300 m wide and has a charted depth of 14 m, although the Allen Atlas suggests some shoaling by sand and coral at the lagoon entry. The east pass, Passe Tiputa, is about 200 m wide and 8.7 m deep (Sailing directions, 2017). The leeward, southern, and western rims with their numerous, small motu are exposed to swell, especially during the austral winter (Vollbrecht et al., 2021).

A narrow (100–300 m wide) sand apron surrounds the Rangiroa lagoon, which measures 1592 km^2 and has an average depth of 45 m with a maximum depth of 70 m; its renewal time is estimated to be 155 days (Pagés and Andréfouët, 2001; Purdy, 2001). The Atlas shows some minor patch reef and sand pinnacle development associated with the southwest and southeast lagoon slope but some areas are too deep to code. Reef-rimmed pinnacles occur scattered through the lagoon center.

Arutua Atoll (Figure 3.5) is about 34 km east of Rangiroa and is ovoid with a somewhat concave side to the northwest. The platform is about 27 by 30 km, covers 590 km^2, and it is surrounded by a narrow band of deep outer reef that is less well developed on the windward eastern and northeastern margins. The shallow outer reef is best developed on the west. There, small islands form on the rim, which is consistently less than 500 m wide. The northwestern rim is composed of numerous elongated or rounded motu and hoa, whereas the southwestern and southern rims are primarily a reef flat. Here, mixes of coral development and sandy inner reef flats constitute broad rims, commonly greater than

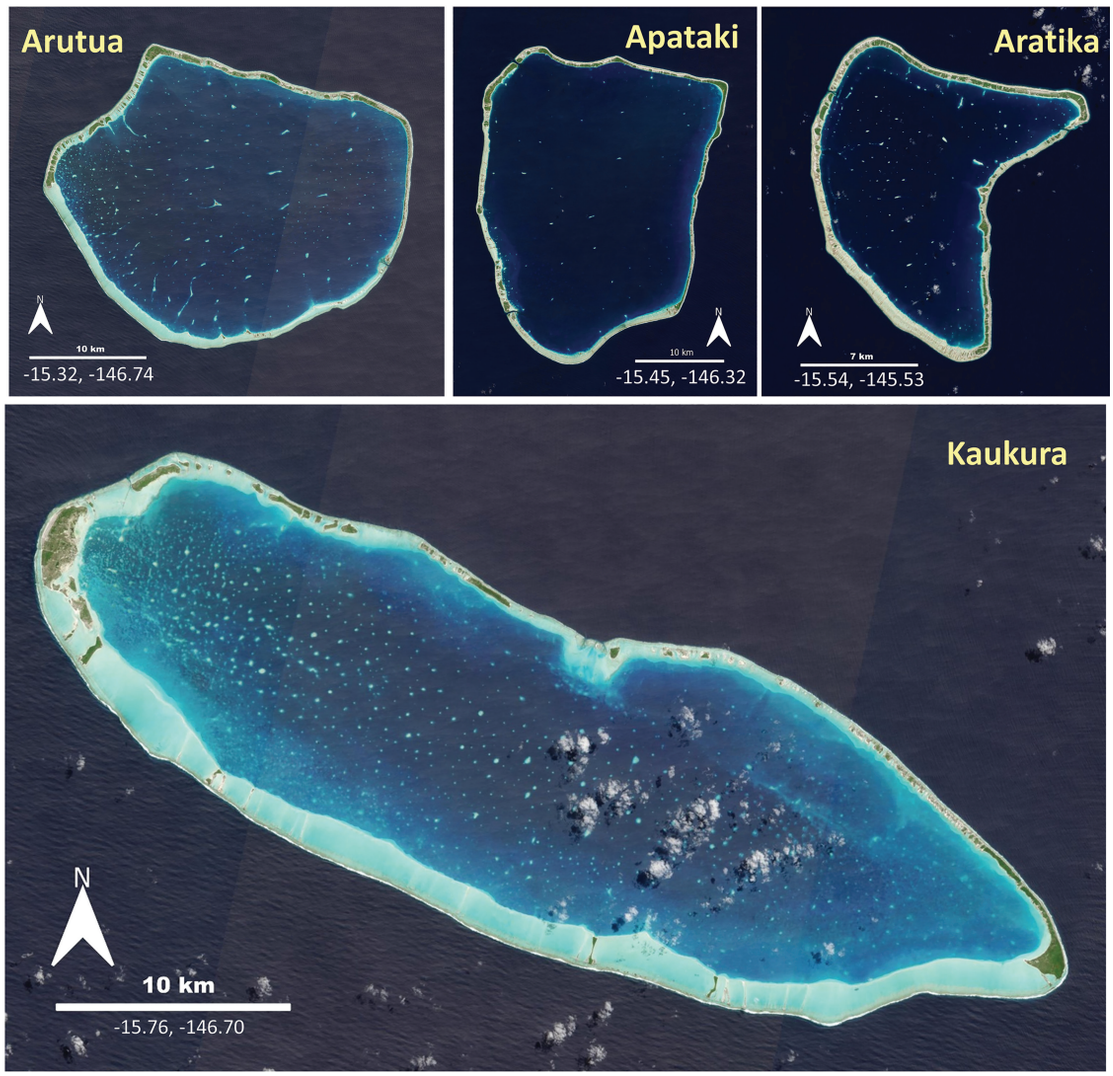

Figure 3.5 Remote-sensing images of the atolls of Arutua, Apataki, Aratika, and Kaukura. Note the broad reef and reef sand apron on the southwest-facing margin that faces into Southern Ocean swell. Images © 2021, Planet Labs PBC.

750 m wide. A single, small channel in the southeast is passable only by small vessels. The lagoon covers an area of 516 km^2 with an average depth of 35 m; its renewal time is estimated to be 60 days (Pagés and Andréfouët, 2001). A band of patch reefs occurs on the lagoon slope extending from the northeast to (and into) the channel on the southeast, as well as on the western lagoon slope. Sand and coral pinnacles are clustered in the deeper western lagoon and extend across it, and although they are numerous, they are not as densely packed in the center and the east compared with the west. Some are elongate, more than 1,000 m long, and appear to be aligned, perhaps by currents in the lagoon.

Apataki Atoll (Figure 3.5) is 17.5 km east of Arutua and has a distorted rectangular shape with rounded southeast and southwest sections. Its axes are about 25 km wide (east to west) and 35 km long (north to south). The platform covers 753 km^2 (Purdy, 2001) and its outer reefs are narrow but surround the atoll more or less uniformly. Rim islands are best developed to the north and the east. The southern and western rims are primarily a reef flat and sand apron; many areas are more than 500–750 m and include several motu. There are two passes on the western rim. Passe Tehere in the northwest is about 130 m wide and 5.8 m deep (Sailing Directions, 2017), whereas the one on the southeastern rim is narrower. Both passes are lined with coral development as extensions of the outer reef, but the southern pass appears to be blocked on the lagoon side. A very narrow and submerged shallow lagoon area surrounds the deep lagoon, which is 683 km^2 with an average depth of 33 m and a maximum depth of 50 m. The renewal time is estimated to be 101 days (Pagés and Andréfouët, 2001; Purdy, 2001). The lagoon slope narrowly surrounds the basin; all the pinnacles (~30) are covered with dense, healthy corals (Andréfouët, pers. com.) and are coded as reef by the latest version of the Allen Atlas.

Aratika Atoll (Figure 3.5) is approximately 68 km east of Apataki. It is rounded on the western side and indented on the east forming a triangular protuberance to the northeast. It is about 17 km across through the apex and 20 km at its widest. The platform area is 184 km^2 and it is enveloped by an outer reef that reaches more than 200 m to the northeast but is somewhat narrower elsewhere. Islands have formed on the rim from the northwest to the south, although there are sections of reef flat and a pass on the indented eastern side. Neither this pass nor a second pass on the northwestern rim are suitably wide or deep enough to allow the passage of larger vessels. The remainder of the rim on the west and southwest is composed of outer and inner reef flats that are consistently more than 500 m wide and are more expansive than other margins. The lagoon is surrounded by a narrow and submerged shallow area; the deep lagoon is 151 km^2 and up to 30 m deep (Purdy, 2001). Sand or sand and reef-rimmed pinnacles, some of which are distinctly elongated, are scattered throughout the lagoon.

A second, parallel chain of Palliser atolls lies to the south of those just described, and these have a different geomorphology, perhaps due in part to the protective effect of their brethren to the north (Andréfouët et al., 2012) and the lack of protection from southern swells. This chain is composed of atolls that tend to be elongated and oriented from northwest to southeast. The westernmost of them is **Kaukura** Atoll (Figure 3.5), located about 25 km south of Arutua. It is sausage shaped with a pointed end to the southeast, about 15 km wide at the middle and 48 km through the long axis. The 531-km^2 platform has been uplifted 3.5 m, like others in the NW Tuamotu Islands (Montaggioni et al., 1987). An outer reef is best developed, up to 400 m wide, on the southwest-facing margin, which corresponds to the waveward side of the atoll (Rankey and Garza-Pérez, 2012). Outer reefs are also prominent around the southeast corner of the atoll but continue along the waveward side. The northeast side of Kaukura represents the windward side and it develops a shallow and deep outer reef consisting of scattered, narrow ribbons. The northwest and southeast margins have the largest islands (Raitahiti at the northwest and Faro at the southeast) with several small and elongated ones between them. There are no passes, and the rim is closed.

The sand apron is markedly asymmetrical (Rankey and Garza-Pérez, 2012). The northeast-facing, windward section is relatively narrow, generally ranging from 200 to 800 m wide, whereas the waveward, southwestern side is more typically 1–1.9 km wide, far broader than atolls farther north that have been described previously. These sand aprons surround the lagoon, which covers an area of 421 km^2. The lagoon slope to the northwest is a sandy extension of the apron that grades into sandy pinnacles approximately 2.5 km from Raitahiti Island. Large populations of giant clams (genus *Tridacna*) are found in the lagoon and occur in sand as well as on hard substrata (e.g., Andréfouët et al., 2005). They will be described in more detail below. The lagoon basin is crowded with sand-topped, reef-rimmed pinnacles.

Toau Atoll (Figure 3.6) has a rectangular shape, about 36 × 20 km at the longer axes and is about 28 km east of Kaukura. The platform is 652 km^2 in extent (Charpy et al., 1997). As on Kaukura, the platform is surrounded by an outer reef that extends from the southeastern to the northwestern, waveward sides, where the rim is composed of a rock and rubble reef flat rather than the sandier Kaukura. The outer reefs occur all around the platform, but they are somewhat wider to the south and southeast where they may exceed 300 m. The shallow reefs become more strongly developed on the windward northeastern outer reef flats. The east-facing rim from the northwest to the southeast includes small islands that are more elongated toward the southeast. There are three passes, with two to the southeast, including Passe Otuni that is up to 8 m deep and is wide enough for large vessels. Nepo Pass on the northwest side is wide, but not deep enough for large vessels (Sailing Directions, 2017), as it has become partly filled with sand due to the development of an apron on the lagoon side. The lagoon covers 561 km^2 (Charpy et al., 1997) and the deeper lagoon and slope contain numerous pinnacles, several of which reach the surface as shallow reef or sand islands. The pinnacles are more concentrated to the northeastern part of the basin. The lagoon is up to 24 m deep (Purdy, 2001) and has numerous sand and coral pinnacles through the deeper center.

Niau (Figure 3.6) is a small, polygonal atoll about eight km in diameter, 30 km southwest of Toau. Its platform is 58.5 km^2, and because it is closer to the edge of the Tuamotu Plateau, it has been raised 7.5 m more than the other uplifted atolls described previously in the Tuamotu group. The outer reefs are widest along the southern and southeastern edge of the platform where they reach more than 400 m from the rim, less so to the northwest sectors. The lagoon is 32.6 km^2 in extent. Because of the elevated rim, the lagoon is closed, and as exchange with oceanic water is infrequent, it is brackish (25‰–32‰). The lagoon is also shallow with a mean depth of 2 m and a maximum depth of 6 m (Delrieu-Trottin et al., 2018). The dark green color of the lagoon is due to the presence of cyanobacterial mats, called kopara in Polynesian, that are several meters thick. The mats are rich in phosphorous, and after decomposition,

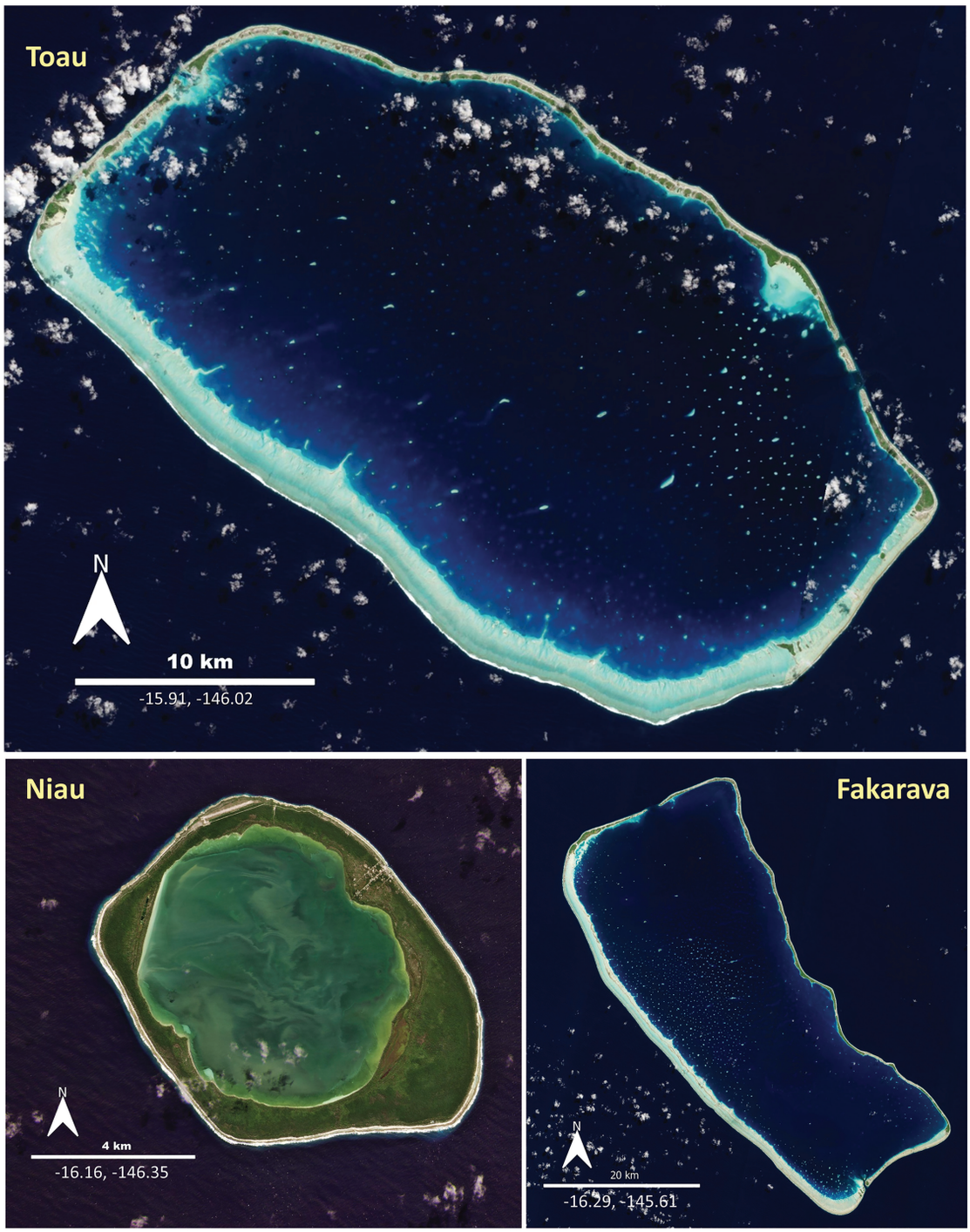

Figure 3.6 Remote-sensing images of the atolls of Toau, Niau, and Fakarava. Images © 2021, Planet Labs PBC.

they lead to deposits of the phosphate-rich mineral apatite (Rougerie et al., 1997b). There is also a population of milkfish in the lagoon which grow to a kilogram. These fish are common in brackish water and remnant lagoons across the Pacific, where they feed on cyanobacteria. They in turn are consumed by the local population, and since there are few food sources in such lagoons, they are also commonly the subject of aquaculture (Delrieu-Trotten et al., 2018).

Fakarava Atoll (Figure 3.6) is 51 km west of Niau where it forms a large and rectangular, 55 km long by 18 km wide, and has a northwest–southeast orientation. The platform is 1,246 km^2 in extent (Andréfouët et al., 2001) and has outer reef that is about 250–300 m wide to the south and southeast, and narrower to the north and northeast, similar to its neighbors. Narrow islands develop along the northern and eastern sides where the rim is about 0.5 km wide; the remainder of the west-facing rim is a reef flat, roughly 1.5 km wide and is composed of a combination of rubble, rock, and sand. A narrower reef flat occurs on the southeastern margin. There are two passes

through the rim; the northwestern pass is suitable for vessels drawing less than 2.7 m. The southern pass is 1.4 km wide and has been cleared to a depth of 10 m (Sailing Directions, 2017) and it is flanked by low motu and hoa. Surrounding the lagoon, a sand apron is about a kilometer wide from the northwest to the south on the waveward margin where it is mixed with considerable rubble. On the opposite island-bearing side facing the wind, the apron can be up to 300 m wide, but is more typically a third of that.

The lagoon covers an area of 1,112 km^2 with an average depth of 45 m; its renewal time is estimated to be 75 days (Pagés and Andréfouët, 2001). It has few shallow areas and there are numerous sand and sand/coral pinnacles that are clustered in the center west, but some in the northwest and southwest are represented as well. Some of these near the center break the surface and one forms a vegetated motu of about 2 ha.

The central Tuamotu Islands

The second group of the Tuamotu group lies in the center of the chain where atolls tend to be tightly clustered. Several were visited or sighted in 1820 by Russian Admiral Thaddeus Bellingshausen who assigned Russian names, usually those of admirals and generals, to each. It is true that the good captain was not the first to sight some of the Tuamotu Islands that he recorded in his logbook, but he did discover some that were new to Europeans including Mataiva, Fakarava, and Tikehau (Barratt, 1999), which are now credited to Captain Cook as members of the Palliser group. Perhaps the lack of acclaim for those discoveries motivated Admiral Bellingshausen's belief that the entire chain should be named 'the Russian Islands' (Debenham, 2016). However, the only eponym that has stood the test of time is that of the Raevsky (Raeffsky) Islands—and there remain three of them—that were named after a Russian general who fought against the French as they invaded Russia during the sixth Napoleonic War. Leaving aside the irony of that honorific, we include 16 atolls in this group, many of which either were visited or sighted by Bellingshausen in the center of the chain (these are marked with an asterisk; Barratt, 1999) or are adjacent to them and are included for the sake of geographic propinquity. In order of presentation, these are as follows: Kauehi, Taiaro, Raraka, Katiu*, Makemo*, Taenga*, Nihiru, and Marutea Nord that fall along the northern rim of the Tuamotu Plateau. The more southerly line of atolls in this group includes Faaite*, Anaa at the extreme southern side of the Tuamotu Plateau, Tahanea*, Mototunga*, and Haraiki. The Raevski trio, Tepoto Sud*, Tuanake*, and Hiti are small atolls sandwiched between Makemo in the north and Mototunga in the south (Figure 3.2). We arbitrarily drew the line for this second group at a natural break that occurs in the plateau southeast of Nihiru, Marutea Sud, and Haraiki.

Kauehi Atoll (Figure 3.7) is ovoid, oriented northwest to southeast, and lies about 34 km from Aratika. The platform is about 24 by 15 km, with an area of 343 km^2 (Charpy et al., 1997; Adjeroud et al., 2000). It is lined by a continuous outer reef that extends 175–190 m wide to the northeast and up to 285 m to the southeast. Islands are found on much of the rim; motu are common to the northwest and north, and these pass on the eastern, windward atoll flank into a single island about 24 km long and mostly about 300–500 m wide (except for a small protuberant area 1.2 km wide at the northeast where a village is located). A reef flat comprises part of the western rim, although this area also includes numerous motu. Narrow, elongated islands occupy much of the southwestern rim and they are interrupted in the southwest by single pass, Arikitamiro, that is about 300 m wide and 15 m deep (Adjeroud et al., 2000). A narrow sand apron, generally ~200 m wide, occurs along most of the lagoon except for along the western islands where there are ribbon-like reefs adjacent to the island shores on the lagoon side. Reefs also extend from the outer reef into the pass in the southwest. The lagoon area is 315 km^2 with an average depth of 35 m and a renewal time of 77 days (Pagés and Andréfouët, 2001). Numerous coral-rimmed pinnacles occur, especially along the eastern and southern sides. The deeper central lagoon contains fewer such pinnacles. Nonetheless, Adjeroud et al. (2000) found a diverse community that included 22 coral genera in the Kauehi lagoon.

Taiaro Atoll (Figure 3.7) is about 49 km northeast of Kauehi. The platform is ovoid, less than 6 km long and 4 km wide, and covers an area of 18.3 km^2. It has an outer reef that is continuous around the rim where it is mostly 150–175 m wide to the north and southeast (coded somewhat wider by the Atlas), and narrower west–northwest clockwise. Most of the rim is composed of an essentially continuous island, ranging in width from 150 m to about 600 m. Although there are apparent hoa, all but one has been blocked by storm debris and they are not functional; the one that may be open is likely functional only during storms. In addition, Taiaro was uplifted by about 1 m during the ninth century (Galzin et al., 1998). This atoll is closed. With rainfall totals of about 110 cm/year, the 12 km^2 lagoon has become hypersaline, with salinity of about 43 ‰, compared with 36.5 ‰ in the open ocean. Adjeroud et al. (2000) found only one coral genus represented here, but there is a surprisingly high diversity of

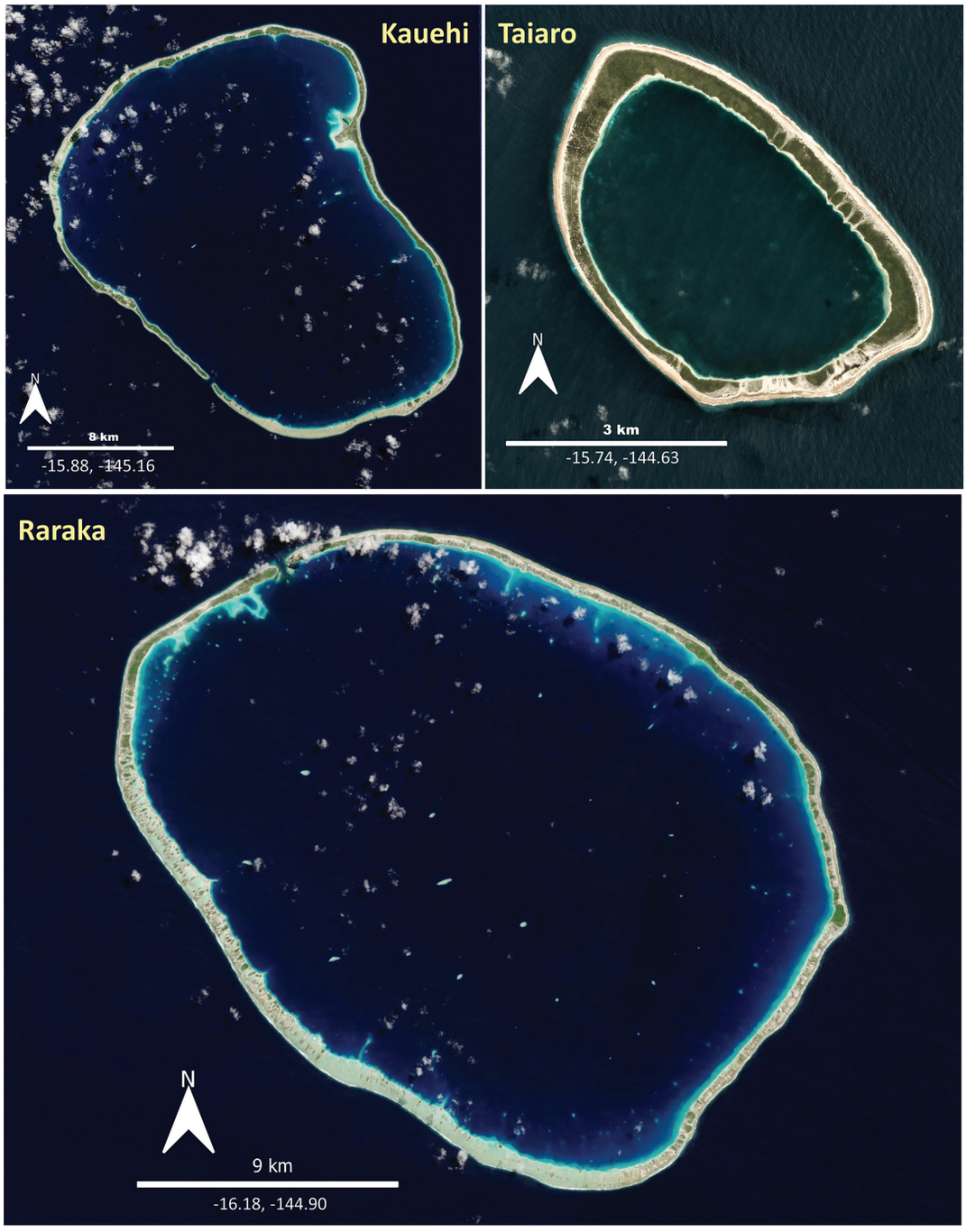

Figure 3.7 Remote-sensing images of the atolls of Kauehi, Taiaro, and Raraka. Images © 2021, Planet Labs PBC.

fishes in the lagoon. The mean lagoon depth is 15 m, the maximum depth is 27 m, and the renewal time is estimated to be 4.8 years (Galzin et al., 1998; Pagés and Andréfouët, 2001). This atoll is uninhabited and also privately owned (Salvat and Myer, 2009).

Raraka Atoll (Figure 3.7) is oval, 27 km long and 19 km wide, and lies about 18 km southeast of Kauehi. The platform covers 402 km^2 and it is marked by an outer reef that extends northwest–southeast where it is about 175–250 m wide and is narrower elsewhere. The outer reef is essentially absent on the windward, northern, and eastern sections of the platform. The rim is 300–400 m wide, and islands are best developed on the northwest and northern side, although islands are also present on part of the eastern side. The northeastern rim is composed of windward motu, whereas the remainder of the rim (west to southeast) is a reef flat that includes tapered or fusiform motu. A single pass between islands in the northwest is about 45 m wide but only 5 m deep (Sailing Directions, 2017). There is a reef at the lagoon end of this channel, and there are small reef areas associated with motu on the western and southwestern reef flat. A sand apron 200–450 m wide occurs around the lagoon except on the western side, where it is wider. Shallow sand also extends along several ridges that

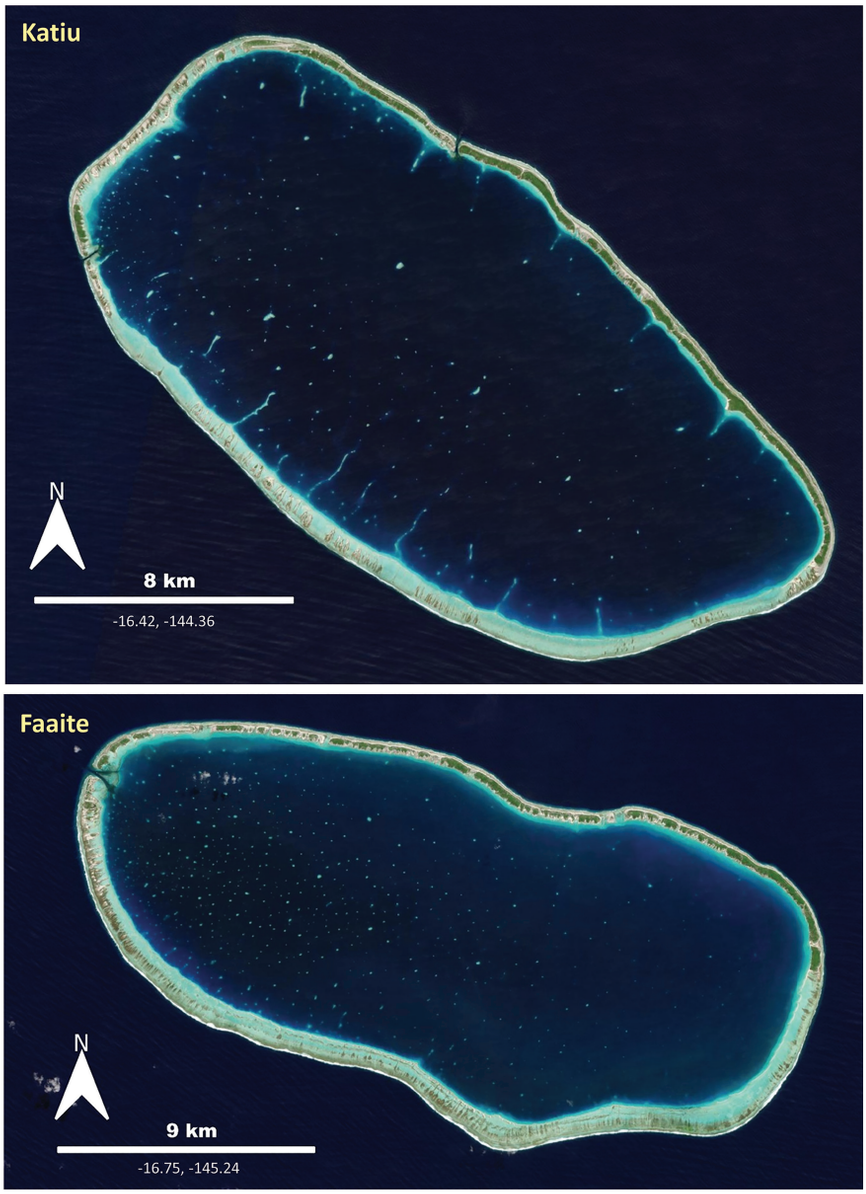

Figure 3.8 Remote-sensing images of the atolls of Katiu and Faaite. Images © 2021, Planet Labs PBC.

project from the apron area into the deep lagoon. The lagoon area is 355 km^2. There are pinnacles in the lagoon mostly northwest–southeast clockwise along with others that rise from the deep lagoon.

Katiu (Figure 3.8) is another ovoid atoll with a northwest–southeast elongation. It has a long axis of about 24 km and is less than 13 km wide. The platform covers 263 km^2 and bears a circumferential outer reef that is roughly 150–200 m wide with areas of lesser development to the southeast and west. Rim islands are developed most extensively between the northeastern side, where there is an airstrip, and the southeastern side. The rim here is from 350 to just over 600 m wide. The remainder of the rim is a south-facing reef flat that is 600–900 m wide with scattered motu, especially on the northwestern side where some reef growth is apparent on the southwest reef flats associated with motu.

There are two passes. The one facing the northeast between elongated islands (Pakata Pass) is about 30 m wide and at least 3.3 m deep; the other in the west is smaller. Both are usable only by small boats (Sailing Directions, 2017). In addition, both passes are associated with reef development. The lagoon area is 229 km^2 and is enveloped partly by a sand apron about 180–250 m wide on the east and southeast and 400–500 m wide at the northwest, west, and southwestern sides. The lagoon depth is up to 20 m deep (Purdy, 2001) and includes prominent narrow coral- and sand-covered ridges that protrude more than 1 km from the shallow lagoon slope, especially in the southwest. The lagoon slope includes reef-covered pinnacles that are especially concentrated toward the southwest; fewer pinnacles occur to the eastern and southern slopes but many occur in central lagoon.

Figure 3.9 Remote-sensing images of the atolls of the uplifted atoll of Anaa, as well as Tahanea, and Motutunga. Images © 2021, Planet Labs PBC.

Faaite Atoll (Figure 3.8) lies 56 km southwest of Raraka and 22 km southeast of Fakarava. Its platform is 271 km^2 in extent. An outer reef extends around the reef circumference and ranges from 150–200 m wide, although it is more consistently developed to the north. Reefs to the south are generally about 100 m wide. The rim is composed of an inner and outer reef flat that is mostly 700–1,100 m wide. Slender islands with motu and a few hoa occupy the windward northern and northeastern rim, which is mostly 300–400 m wide, and there is a single y-shaped channel at the northwest that is reportedly 50 m wide with a depth of at least 3.5 m (Sailing Directions, 2017). The Allen Atlas clearly shows reef growth through the channel as an extension of the outer reef. The lagoon extent is 224 km^2. Numerous reef-rimmed pinnacles occur throughout the lagoon and are more tightly clustered in its western half. Purdy (2001) records the depth maximum as 20 m.

Anaa Atoll (Figure 3.9) is about 65 km southwest of Faaite. It is roughly 28 km long, 7 km at its widest, and is elongated northwest–southeast, like many of the southern Tuamotu Islands. However, Anaa includes a hook-like bend to the northwest and is raised 6 m more than other atolls at the edge of the Tuamotu Plateau (Montaggioni et al., 1987; Pirazzoli et al., 1988a). This elevation is due to its passage over the tectonic flexural bulge associated with volcanic activity from nearby Tahiti, the same process that elevated Makatea to 113 m. Anaa lies along the same platform edge and is taking the same path that Makatea took (Figure 3.1). Indeed, Anaa in now in the same position that Makatea was three million years ago and will likely be uplifted to the same

extent several million years from now (Pirazzoli and Montaggioni 2018). The 178 km^2 platform includes outer reefs that are more or less uniform around the platform and range from about 150–250 m wide. The rim is closed and develops reef-rimmed islands on most of its extent. The remainder of the rim includes hoa that are not functional because of the uplift, although passageways through a reef flat at the northeast near Tukuhora Village allow for exchange of lagoon water and spawning aggregations of bonefish to pass in and out of the lagoon (Filous et al., 2020). The lagoon covers an area of 106 km^2, has an average depth of 4 m, and has an estimated renewal time of 9 days. About 15 km^2 of the northwest lagoon is partly partitioned by rock and rubble forming what is known locally as the 'Petit Lagoon' as opposed to the remainder, called the 'Grand Lagoon' (Filous et al., 2020). The lagoon shallows are dominated by sand that expands to cover much of Petit Lagoon and divides Grand Lagoon in half along a shallow ridge. Small reefs are associated with the reef flat in the northeast and on the inner face of some islands in the western lagoon. Much of the western lagoon bottom is shallow and covered with sand, and the mid- and southern lagoon shallows are surrounded by sand. The deepest lagoon areas occur to the southeast, where pockets up to 10 m deep are found (Purdy, 2001).

Although it lies on the flank of the archipelago, Anaa Atoll was once the home of the most powerful tribe in the Tuamotu Islands. At their peak, they reportedly had more canoes than all the other islands combined! The first European to discover Anaa was Pedro Fernándo de Quirós in 1606. It was the first inhabited island he encountered in the tropical Pacific, which he named La Conversion de San Pablo according to the date of arrival on the Catholic calendar. However, given the positioning equipment of the day and the absence of charts, chief pilot Gaspar Gonzalez de Leza believed this to be Hao Atoll farther south, whereas others initially thought this was Tahiti which lies farther west, but given the description of the island and the cruise track, it was very likely Anaa (Markham, 1904). James Cook was the next European to encounter Anaa in 1769. He described the atoll as 'a double range of low woody islands [motu] joined together by reefs to form one island in the form of an ellipsis or oval, with a lake in the middle of it. The small islands and reefs that circumscribe the lake have the appearance of a chain, and we therefore gave it the name of Chain Island' (Hawksworth, 1773). More recently, Tahiti's royal family—the Pomare Dynasty—claims Anaa as its birthplace. Current Anaa residents are known for their javelin throwing skills and their sustainable bonefish fishing program.

Tahanea Atoll (Figure 3.9) is 15 km east–southeast of Faaite and is shoe shaped. The platform covers 643 km^2 and displays an outer reef from the west to southeast (from heel to the toe) where the rim is a reef flat dotted with several hoa, some of which develop reef growth around them. The largest island occurs in the northwest and is about 2.6 km long by roughly 50 m wide. The remainder of the north-facing rim is a combination of slender islands, sand, and rocky bottom, which is 350–450 m wide. There are three passes separated by two islands in the northeast across distance of 4.5 km (the laces). The centermost pass is Teavatapu which is about 320 m wide and 11–13 m deep. The two on either side of it are impinged by coral growth and may be hazardous (Sailing Directions, 2017). The lagoon is 545 km^2 with an average depth of 45 m and a renewal time estimated to be 59 days (Andréfouët et al., 2001). The shallow lagoon reef sand apron extends to about a kilometer wide to the south and narrows to less than 200 m wide to the north. A few reef islets occur within the apron especially to the southeast along with patch reefs and ribbons along the shoe opening and at the heel counter (western lagoon). The deeper slope is associated with coral-rimmed pinnacles that are especially abundant in the west and southeast. Additional pinnacle development occurs in the deeper lagoon basin. As on Fakarava, some of these break the surface, and one forms a vegetated motu of about 2 ha.

Mototunga Atoll (Figure 3.9) is located about 20 km southeast of shoe-shaped Tahanea. It is ovotriangular with the wider side to the southwest. The platform is 13 km from there to mid-base and about 15 km at its widest. The platform area is 163 km^2, and it is surrounded by an outer reef that is generally about 250–275 m wide but narrows to about 150–175 m wide to the north. The rim along most of the east, the south, and the west sides is composed of an inner and outer reef flat. The reef flat is narrowest in the east, where it is about 500 km across, and widest in the south, where it is ~1.3 km across. The west side that is about 800 m wide has the most numerous reef flat motu and hoa, many of which are associated with reef growth. The northern and northeastern rims are composed of small islands, motu and hoa, with coral growth on their reef flats. The largest islands cover 65 ha (in the northeast) and 61 ha (in the northwest). There are two passes through the rim, both on the north-facing, and it appears to have substantial coral growth that extends to the edge of the lagoon. The lagoon area is 126 km^2 and is surrounded by a shallow, sandy edge less than 100 m wide to the east. Numerous reef-rimmed pinnacles are scattered across the lagoon. We are unaware of depth data for the lagoon.

There are three small, oval or ovoid atolls 25–40 km northeast of Mototunga and 15–33 km southeast of Katiu. These are the Raevsky Islands referred to above, all of which lie in the center of this group of atolls. They all are surrounded by a shallow outer reef that is least well developed on the eastern (windward) side. The closest one to Mototunga is **Tepoto Sud** (Figure 3.10) whose platform area is 7.5 km^2. An outer reef generally 150–200 m wide surrounds most of the platform, but it is somewhat more weakly developed to the north. Two islands with an area of 1.2 km^2 occupy the north and northeast half of the island that are unequally divided by the pass. The southern rim is a rock and rubble-strewn outer reef flat that is 1,000–1,100 m wide, interspersed with elongated motu and hoa. A narrow band of sandy inner reef flat occurs at the eastern edge of the lagoon.

The lagoon area is approximately 1.4 km^2 and has a wide sand apron around it that represents about 59% of the lagoon area. Isaac and Gischler (2015) calculated the apron as 29% of the platform size, although they used a different platform area than that reported here. The lagoon has an average depth of 5 m and is renewed in a matter of hours or days depending on swell conditions (Pagés and Andréfouët, 2001). Reef growth occurs in the pass. Adjeroud et al. (2000)

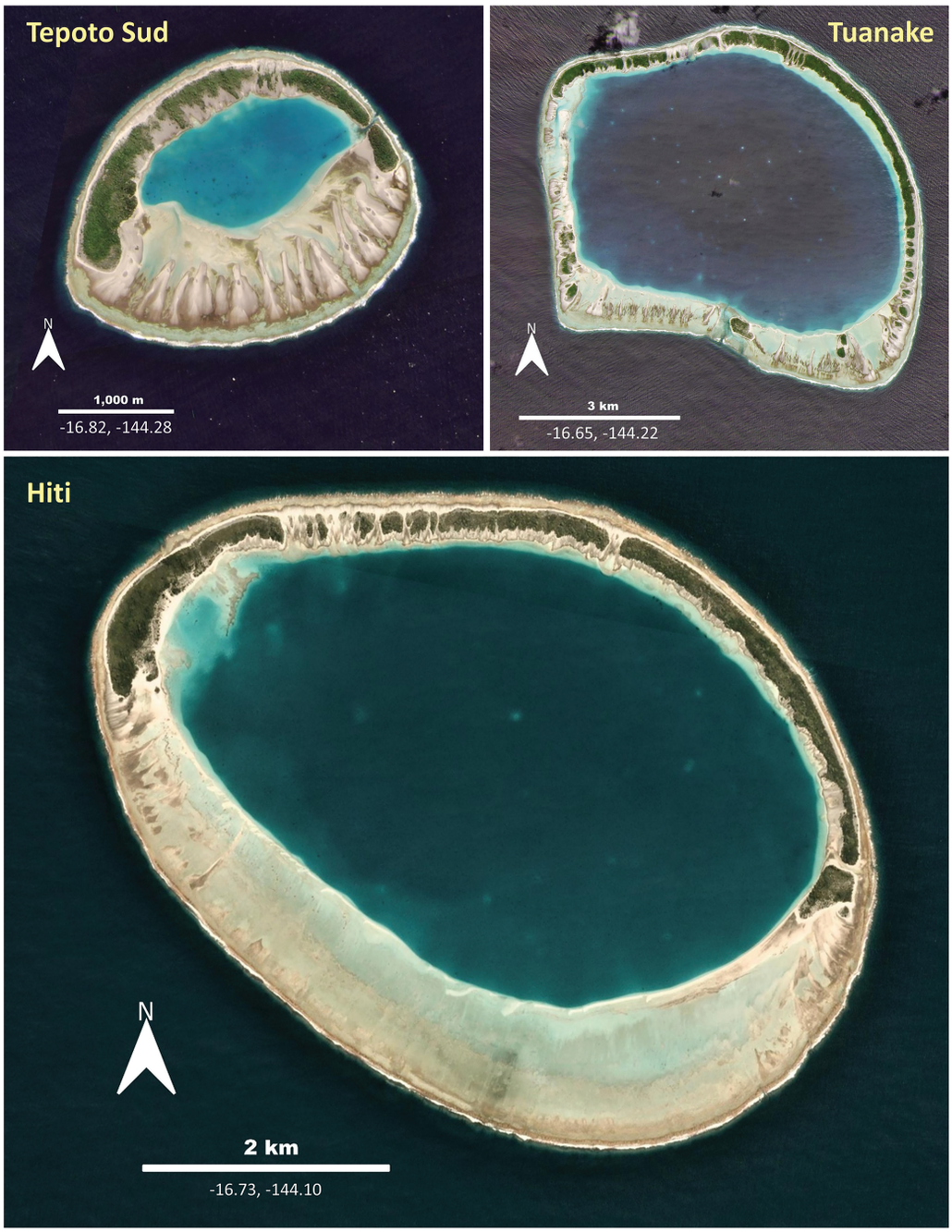

Figure 3.10 Remote-sensing images of the atolls of Tepotu Sud, Tuanake, and Hiti. Images © 2021, Planet Labs PBC.

found ten genera of coral in lagoon reefs. Nonetheless, Salvat (2009) considered this lagoon closed. We tentatively mark it here as partly open.

Tepotu Sud Atoll has been rumored to be the site of treasure, stolen from a church in Pisco, Peru, and buried there by four thieves in the 19th century. Although one recent explorer found some medallions from South America on the atoll, no mother lode of gold, silver, or jewels has been found.

Tuanake Atoll (Figure 3.10) is 16 km northeast of Tepoto Sud and forms a rounded D shape with the flat side facing south. The platform extent is 41.6 km^2 and it is 6 km wide at the flat side by about 7 km in diameter. The outer reef extends around most of the atoll and is about 250 m wide. A few small reef areas on the windward reef flats. Motu and one hoa occur to the north, and slender islands that extend from the northwest to more than halfway down the eastern rim. The remainder of the windward east (southeast rim) is composed of motu. The southern and western rims are composed of inner and outer reef flats, primarily with elongated motu and hoa. There are no passes, and the lagoon is closed, although there is a small, submerged area in the middle of the southern rim. The lagoon is 26 km^2 in area, has an average depth of 25 m, and a renewal time of 17 days (Pagés and Andréfouët, 2001). A narrow, submerged apron in the shallow lagoon is up to 200 m wide in the northeast, but less than 100 m wide elsewhere. Isaac and Gischler (2015) found that the apron comprises about 5% of the platform area using a smaller platform area than that reported here. The deep lagoon slope and lagoon develop multiple reef-rimmed pinnacles.

Hiti Atoll (Figure 3.10) is seven km southeast of Tuanake and is an oval that is 6.8 km along the main axis and about 5 km wide. The platform area is 29.27 km^2. The outer reef is generally about 200 m wide, narrowing to about 150 m to the north and northwest. The distribution of islands from northwest to southeast is also like Tuanake. Islands 2 km long in the northwest corner are followed to the east by windward motu and another island 1.6 km long at the north-most bend. Another island 3.3 km long is followed by a smaller 0.5 km long island on the east.

The lagoon is 15 km^2 with an average depth of 10 m and a renewal time of 3 days (Adjeroud et al., 2000; Pagés and Andréfouët, 2001). The southeast- to the west-facing rim includes inner and outer reef flats up to 1,200 m wide, making the rim quite asymmetrical. Large parts of it are covered with sand. There are no passes, and the lagoon is closed. The shallow lagoon from west to southeast is bordered by a narrow, submerged apron that widens at the northwest, where some reef develops. Isaac and Gischler (2015) calculated an apron area of about 14% of the platform using a smaller total area than that used here. The lagoon develops plateaus in the northeast. Several reef-rimmed pinnacles occur on the slope as well as three near the lagoon center. Adjeroud et al. (2000) found 11 genera of corals in the lagoon, which is consistent with a rapid renewal rate comparable to the lagoon at Tepoto Sud.

Makemo Atoll (Figure 3.11) is elongate, 62–68 km long and of variable width but it is generally keyhole shaped. It lies parallel to the northern edge of the Tuamotu Plateau, in contrast to the smaller atolls just described (Figure 3.1). Because of this position and orientation, it is open to extreme storm waves, especially on the northern rim, where numerous boulders have been dislocated and deposited on the reef flat. Some of these measure 130 m^3 and weigh more than 300 metric tons (Lau et al., 2014). In addition, distal swell from the southwest occasionally floods the lagoon, raising water levels up to 2.75 m, flooding villages, and contaminating groundwater (Canavesio, 2019).

The platform area is 716 km^2 (Purdy, 2001) which includes the surrounding outer reefs that are generally 175–250 m wide. The windward, northeastern rim is 400–500 m wide and supports elongated islands that are interspersed with motu. In addition, there are two passes. The one in the northwest, Passe Tupuhiria, is 90 m wide and 7 m deep, and it may be blocked by reef growth. The other pass, 50 km to the east on the north rim, is Passe Arikitamiro, which is 160 m wide and 14–27 m deep (Sailing Directions, 2017), but it is divided into three channels by coral growth. The Allen Atlas shows that it is flanked on both sides by coral that extends from the outer reef, wraps around the opening, and then extends 13 km along the shallow lagoon toward the west and another 5 km toward the east. Although some motu occur toward the northwest, the south-facing, waveward margin from the southwest to the southeast is a 1-km-wide reef flat with few motu, and most of the rim is reef or sand. In contrast, on much of the north-facing margin, the apron is narrow, mostly 200–300 m wide especially where islands occur. The lagoon area is 603 km^2 with an average depth of 18 m, a depth maximum of 60 m, and an estimated renewal time of 15 days (Purdy, 2001; Pagés and Andréfouët, 2001). The passes are flanked by reefs. The deep slope and lagoon present numerous reef-rimmed pinnacles that are widely distributed throughout the lagoon system.

Ovotriangular **Taenga** Atoll (Figure 3.11) is located about 35 km northeast of Makemo. The platform is close to 11 km from south-facing apex to mid-base, and about 27 km at its widest, parallel to

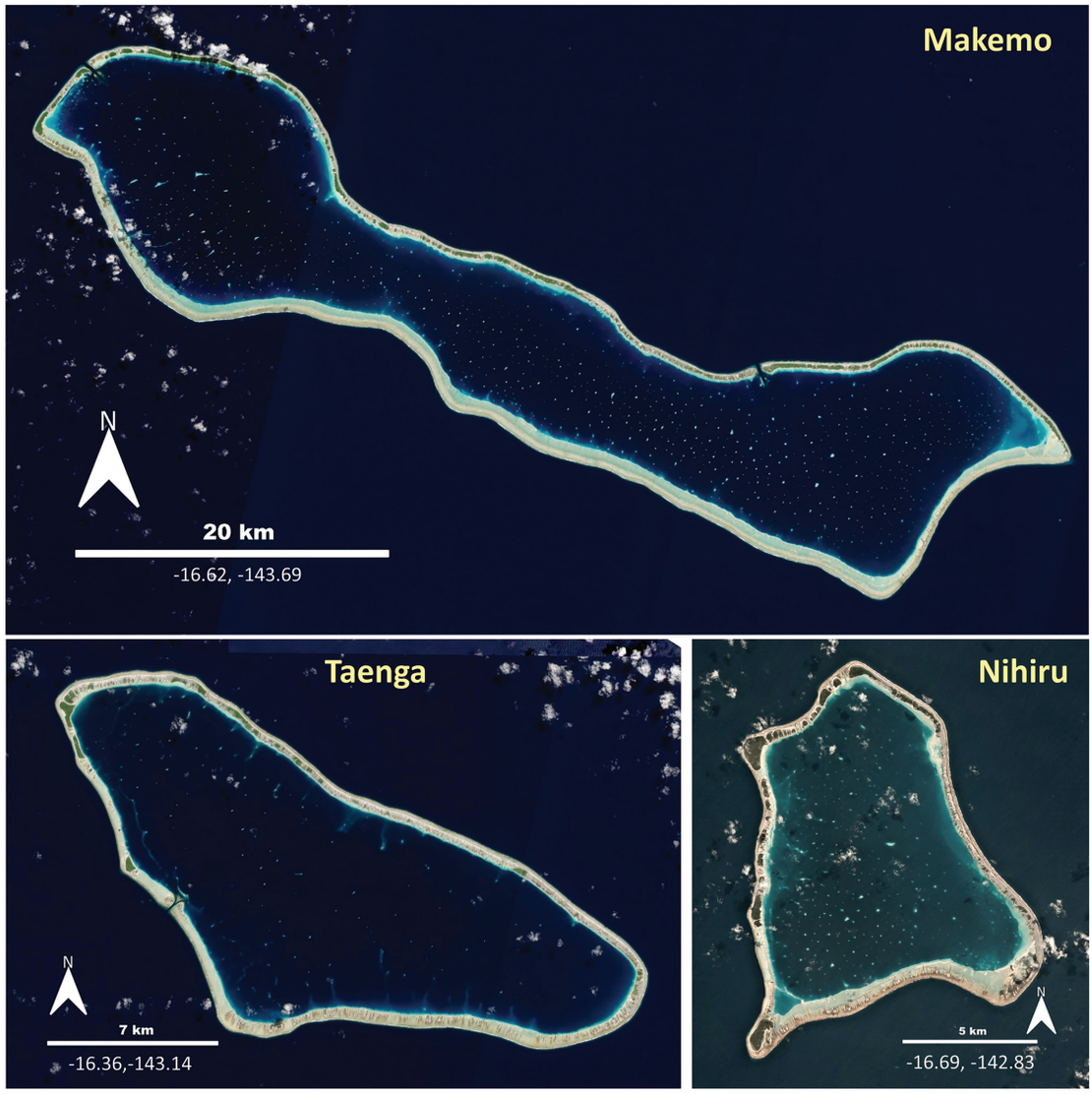

Figure 3.11 Remote-sensing images of the atolls of Makemo, Taenga, and Nihiru. Images © 2021, Planet Labs PBC.

the base and covers an area of 173 km^2 (Purdy, 2001). Outer reefs surround the platform and are widest to the southwest where they extend up to about 250 m from the rim. A spur and groove system surrounds the entire atoll. The western rim is primarily a reef flat, 350–550 m wide, that is bisected by a 30-m-wide pass. Although the channel may be at least 1.5 m deep (Sailing Directions, 2017), it may be occluded at the lagoon end by coral growth and rock, as well as a sand bank. The remainder of the rim, which is about 400 m wide, is composed of windward motu between the northwest and the southeast, although there are two small islands in the northwest totaling 56 ha and small reefs on their lagoon side. The lagoon is 172 km^2; the deepest portions are 14 m (Purdy, 2001), but this depth likely is an underestimate. A sand apron is up to 200 m wide, but commonly is less than 70 m wide, as it extends on the south-facing rim between the northwest and the southwest. More than ten narrow ridges extend into the lagoon perpendicular to the southern rim, and another 4–6 penetrate from the northeast. Most of the ridges that are shallow enough likely are enveloped by reef growth. Reef-rimmed pinnacles and ridges also are found in the deep lagoon.

Nihiru Atoll (Figure 3.11) is polygonal, extending about 14 km wide along both main axes. Located about 30 km southeast of Taenga, the platform covers 100 km^2 (Adjeroud et al., 2000; Dufour et al., 2001), and it is surrounded by an outer reef system that is commonly 250–280 m wide but expands to the southeast to more than 325 m and narrows in part of the southern platform to about 125 m. A spur and groove system is found along the south and the east rim. The rim is composed of elongated or rounded reef-rimmed islands and motu, especially on the windward northeastern and northwestern sides. The eastern rim appears to be discontinuous with sediment partly covering a rocky substrate. The waveward, southeastern to

the southwestern sides include inner and outer reef flats, most of which are dotted with motu and hoa, as well as a 59-ha island in the southwest corner. An artificial channel has been constructed through the rim just north of this island. Small, shallow reefs develop seaward of the eastern rim. There are several hoa at the northwest, but there are no passes, and the rim is closed.

The 80 km^2 lagoon has an average depth of 20 m and an estimated renewal time of 17 days (Pagés and Andréfouët, 2001). Numerous pinnacles are found throughout most of the lagoon basin, especially in the southern half. Adjeroud et al. (2000) found 18 coral genera associated with the inner reef flats and pinnacles of this atoll. Pearl oysters were at one time greatly diminished by overexploitation but have recovered in more recent years (Andréfouët pers. com.).

Marutea Nord (Figure 3.12) forms a rounded triangle-like atoll, 43 km long and 19 km wide at the northeast-facing 'apex.' It is located on the northern line of these atolls about 25 km southeast of Makemo and 32 km southwest of Nihiru. The platform is 534 km^2 in area and is surrounded by outer reefs that are about 250–300 m wide to the south and west, the

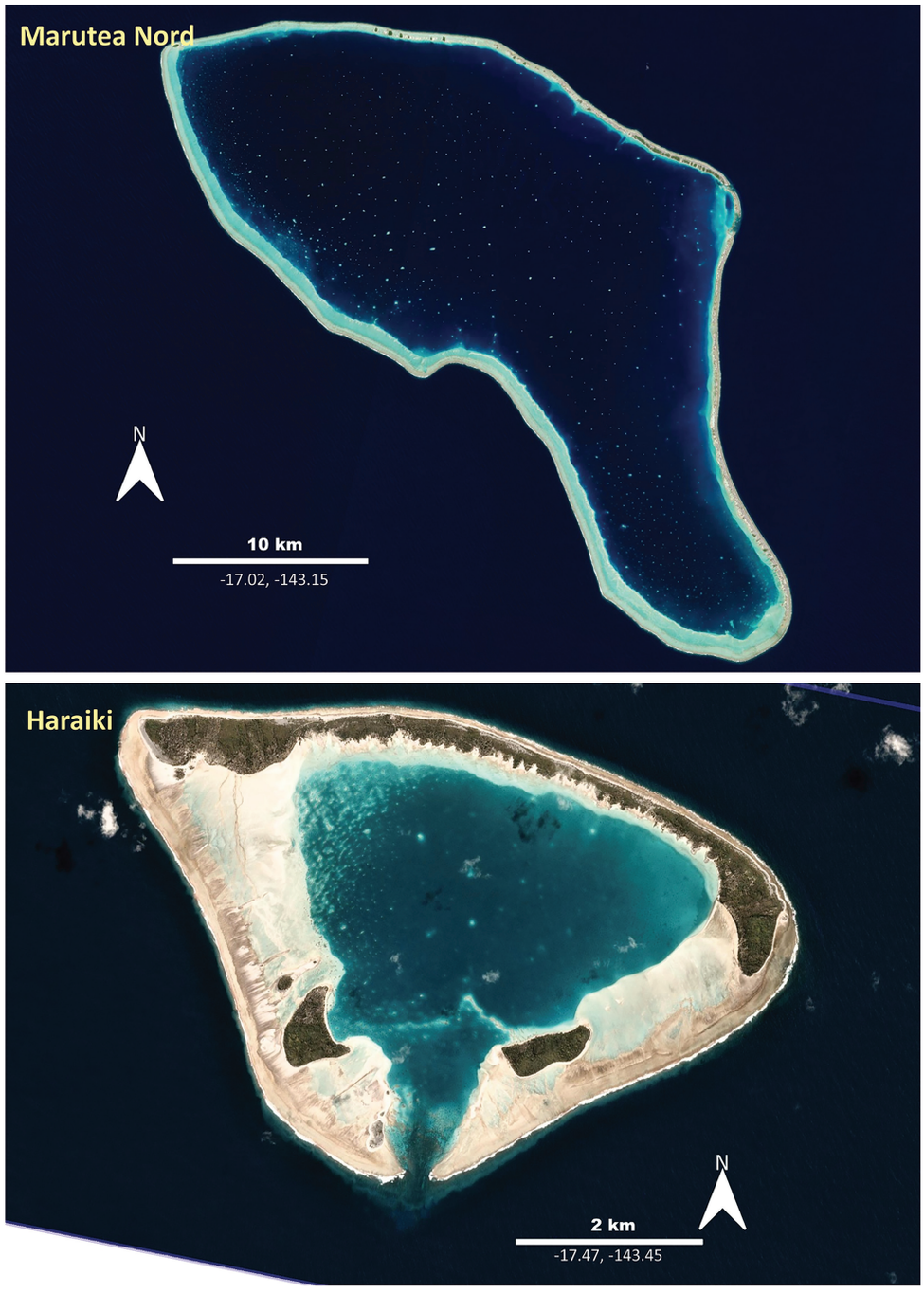

Figure 3.12 Remote-sensing images of the atolls of Marutea Nord and Haraiki. Images © 2021, Planet Labs PBC.

waveward side, and narrow to about 150–200 m wide elsewhere. The rim develops few islands, but there is a 5.5-km-long line of them at the north side of the eastern apex; there are also a few motu in the north, and there is a line of gray sand and rubble ridges with a few motu at the southeast corner of the atoll. Reefs develop on the flats immediately north and south of the eastern facing apex but are less pronounced on the lagoon side of the islands to the north. The rest of the rim along the waveward south and west is a reef sand apron 750–1,100 m wide. According to Sailing Directions (2017), these reef flats are completely submerged. The lagoon covers 450 km^2, and although there is a small (likely artificial) channel at the apex, there are no passes; numerous reef-rimmed pinnacles occur in the lagoon, especially to the northwest and south where they are clustered. We do not have information on the depth of this lagoon. Because of those features and the high diversity of bivalves (Salvat, 2009), this lagoon is regarded as semi-closed.

Haraiki (Figure 3.12) is a triangular atoll 44 km southwest of Marutea Nord and 95 km southeast of Mototunga. It is the last of the southern line of group 2 atolls. The rim is 4.9 km through the apex and 7.6 km at its widest. The platform area is 26 km^2 and is surrounded by an outer reef that is generally 200–350 m wide but extends to more than 500 to the south where a prominent pass is found (see below). The rim on the north consists of a single island 7.9 km long and 690 m at its widest. Reef growth occurs on the island's perimeter. A large pass about 285 m wide occurs at the south-facing apex. We are not aware of its depth, but there is expansive reef growth at the entrance that may form a barrier to the entrance of the lagoon. Flanking the pass are two islands, each about a kilometer from the pass. The one to the northeast is 28 ha; the other to the northwest is 32 ha. Reef growth flanks the channel opening. The rim is open. The lagoon area is 10 km^2, the average depth is 14 m, and the approximate renewal time is 3 days (Pagés and Andréfouët, 2001). A sand apron up to 100 m wide occurs to the northwest and narrows east–west clockwise with a 525 m gap to the southeast that coincides with a ridge. The lagoon slope develops pinnacles to the west and several reef pinnacles occur in the deep lagoon as well. Adjeroud et al. (2000) found a diverse suite of 15 coral genera in this lagoon.

The south-central Tuamotu Islands

This group of 18 atolls takes a southeasterly course across about 700 km of the Tuamotu Archipelago. We begin with **Rekareka** (Figure 3.13), whose nearest neighbor is Nuhiru, about 90 km to the northwest. This small ovoid atoll is elongated on a northwest–southeast axis. It is 5.6 by 2.3 km, and its platform covers an area of 7.3 km^2. Outer reefs surround the platform, although a prominent shelf with deep reef and ridges in the southeast is the widest and extends more than 500 m from the rim. A large, vegetated island up to 140 m wide to the east and 650 m to the west dominates the rim. The windward, eastern portion of the island is a gray sandy ridge with a narrow strip of vegetation that is 80–100 m wide. Much of this appears to be a coconut plantation. A 76-ha island on the south-facing margin is flanked on either side by hoa that may only be functional during storms. The rim is closed. The lagoon is 0.7 km^2, about a meter deep, and because only 1.7% of the rim allows water exchange (Torréton et al., 2002), the lagoon is poorly flushed and has an estimated renewal time of about 81 days (Adjeroud et al., 2000; Pagés and Andréfouët, 2001). Correspondingly, elevated water temperatures and depressed oxygen levels provide a challenging environment (Salvat, 2009).

Tekokota (Figure 3.13) is a small, egg-shaped atoll about 4.5 km long by 2.5 km wide located about 85 km southwest of Rekareka. It is elongated on a northwest–southeast axis and is located about 48 km southeast of Marutea Nord. The platform area is 9.9 km^2. Its outer reef is especially well developed to the south where it is about 350 m wide. Outer reefs elsewhere around the rim range from 170–295 m wide. The eastern rim includes a single vegetated island that is about 1 km long, 270 m wide at the center, tapering at both ends. The island is flanked by gray sand and rubble ridges that become especially prominent on the southern half of the eastern rim. The southwest-facing rim is about 250 m wide and is composed of a reef flat with several elongated motu. The rim at the southeast is submerged due to tilting of the platform but it has formed a spur and groove system that is open to the lagoon. The breadth of this opening is about 700 m, but it is shallow, only about a meter deep (Torréton et al., 2002).

Although the lagoon appears to have an area of 5.1 km^2 (Dufour et al., 2001; Torréton et al., 2002), there are relatively large rocky areas of inner and outer reef flats that encroach its boundaries. If these are considered, the lagoon area is closer to 4.0 km^2. The average depth is about 3 m, and because nearly 60% of the rim is available for exchange with ocean water, it has an estimated renewal time of about 7 hours (Pagés and Andréfouët, 2001). This atoll is open. Some reef extends into the lagoon through the open rim at the southeast, but otherwise the lagoon bottom is sand and small patch reefs.

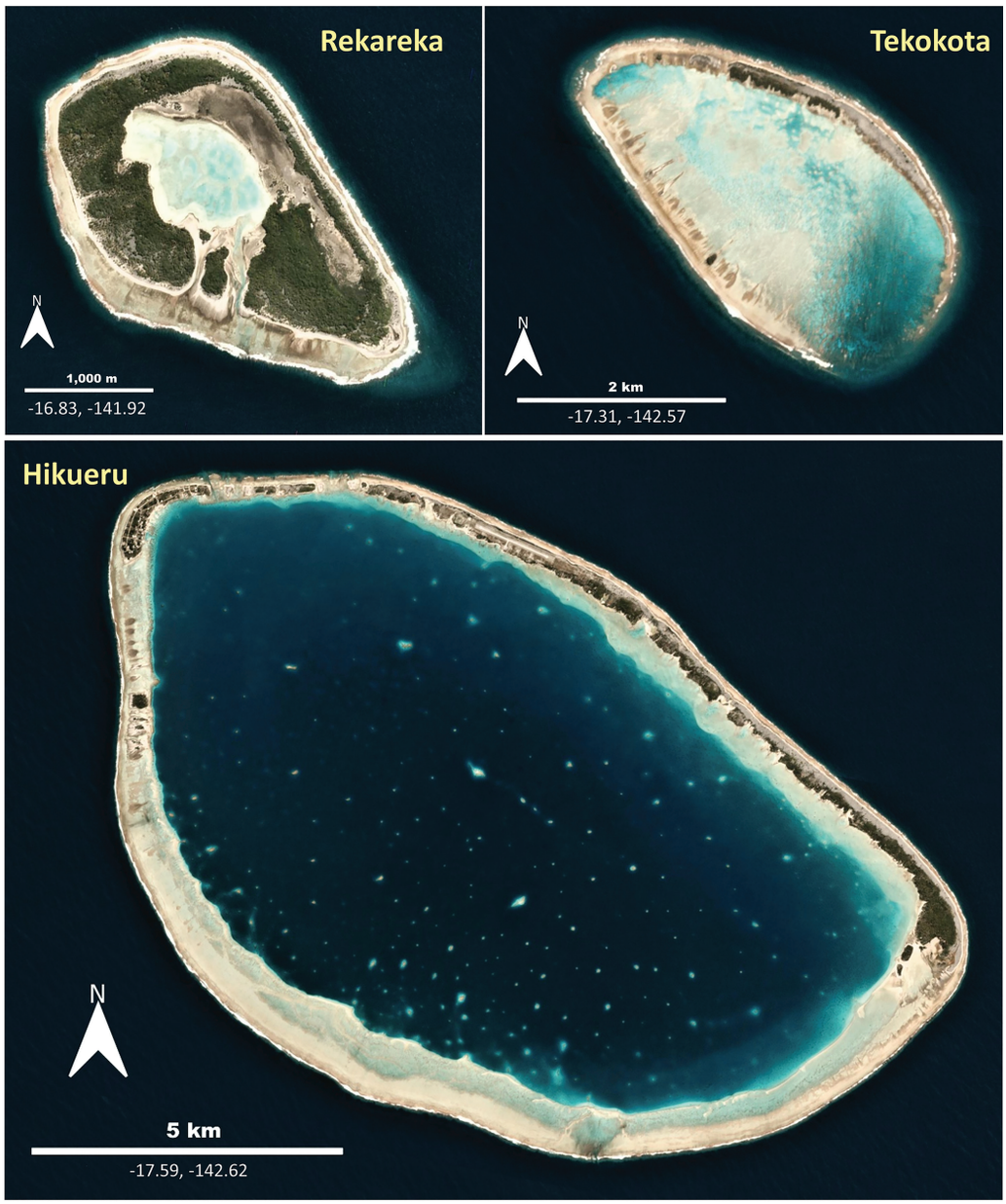

Figure 3.13 Remote-sensing images of the atolls of Rekareka, Tekokota, and Hikueru. Images © 2021, Planet Labs PBC.

Hikueru Atoll (Figure 3.13) is located 24 km southwest of Tekokota. It is ovoid, about 15 km long by 9 km wide, and has the same northwest to southeast orientation as the others described above. The platform covers 107 km^2 (Dufour et al., 2001; Torréton et al., 2002) and it is surrounded by an outer reef that ranges from 150–250 m wide. The northeast rim is about 400 m wide and includes an island about 6 km long that widens to roughly 700 m wide to the southeast. The trend of this island continues west and northwest along the entire eastern rim, where a gray ridge of sand and rubble forms the seaward edge of the vegetated island, smaller islands, and then motu and hoa at the northwest corner of the atoll. The rim of the northwest, the west, and the southeast parts of the atoll is open to southerly swells and is a reef flat, with few islands. There are scattered coral/algal patches on the reef flats along the east and north segments of the rim, including within the confines of a narrow, artificial channel located immediately east of the northwestern island. The rim is semi-closed.

The shallow lagoon is enveloped by a submerged sand apron that is 250–400 m wide along the northeast, 600 m wide to the southwest, and less than 50 m wide in the northwest. The lagoon covers 82 km^2, the mean depth is 25 m, and the estimated renewal time is 37 days (Pagés and Andréfouët, 2001). The primary reef material in the lagoon is associated with the many pinnacles, most of which occur on the broad lagoon slope that is especially prominent in the center and the southwest parts of the atoll. Several

pinnacles reach the surface. Despite the semi-closed morphology, this lagoon has been the site of several mass mortalities that have had a serious effect on its biota, likely due to exceptionally calm weather and a large phytoplankton bloom (Adjeroud et al., 2001).

Reitoru (Figure 3.14) is a reverse D-shaped atoll about 50 km southwest of Hikueru. The platform is 3 km wide bisecting the east-facing base, reaching 5 km at the widest, and occupies an area of 16.1 km^2. The outer reef surrounds this atoll and most of it extends 125–160 m from the rim, although it is about 225–325 m wide to the south. The rim from the northwest and the east is capped by islands that lie on a gray-colored ridge of sand and rubble. There is a shallow gap about 20 m wide in the rim just north of the southwestern-most island on the east, and another one ~1.7 km south that is about 30 m wide. A reef flat that is 30–60 m wide occurs along the entire eastern rim, oceanward of the islands and ridges. The remainder of the rim extending west–southeast is a reef flat that exceeds 300 m width at the south tip of the atoll. The rim is semi-closed.

The lagoon area is 9.1 km^2 and includes a broad expanse of shallow sand apron that is 700 m wide in the southwest and more than a kilometer wide in the south. This submerged sand area is reduced to 70–160 m wide along the east and is essentially absent to the north. Inside the shallow sand belt, a deeper lagoon covering 5.1 km^2 corresponds to the area given by Salvat (2009), who also found that this lagoon is a favorable environment for giant clams of the genus *Tridacna* described in more detail below. The lagoon slope contains a scattering of reefs. We do not have a maximum depth for this lagoon.

Tauere Atoll (Figure 3.14) is a square with rounded corners that is just over 4.3 km across. Its nearest neighbor is Tekokota 109 km to the west. The platform area is 20.5 km^2 and it has an uneven distribution of the outer reef around its borders. The outer reefs range from 170–240 m wide and is broadest at the southeast corner. A spur and groove system surrounds this atoll. The rim along the northeast side is a 3.9-km-long island. Counterclockwise, this is followed by a hoa and another smaller island in the north, a 540-m-wide gap that appears to be at sea level, and another small island at the northwest corner of the atoll. A reef flat occupies the western rim where there are motu and hoa, but at least a kilometer-long section appears to be near sea level. The southwestern and southern rims are composed of low islands, interrupted by a 23-ha island at the south corner. There are a few small and scattered reef patches seaward of these islands.

The lagoon is 8.1 km^2 and the rim is closed, but Andréfouët and Chauvin (2005) found that nearly 6% of the rim is open to exchange. Both the shallow lagoon on the southwest and the lagoon slope are convoluted with plateaus, and both areas develop a considerable reef system. We suspect that wave and tide activity may be sufficient to quickly renew the water in the lagoon, but we are unaware of the lagoon depth or data that would confirm this expectation. We mark this lagoon as semi-closed.

Marokau Atoll (Figure 3.15) is located 72 km southeast of Reitoru and 46 km southeast of Hikueru. It forms a warped triangle with a depressed base facing northwest. It is about 16 km from mid-base to the opposite, southeast-facing apex, and roughly 22 km at its widest parallel to the base. The

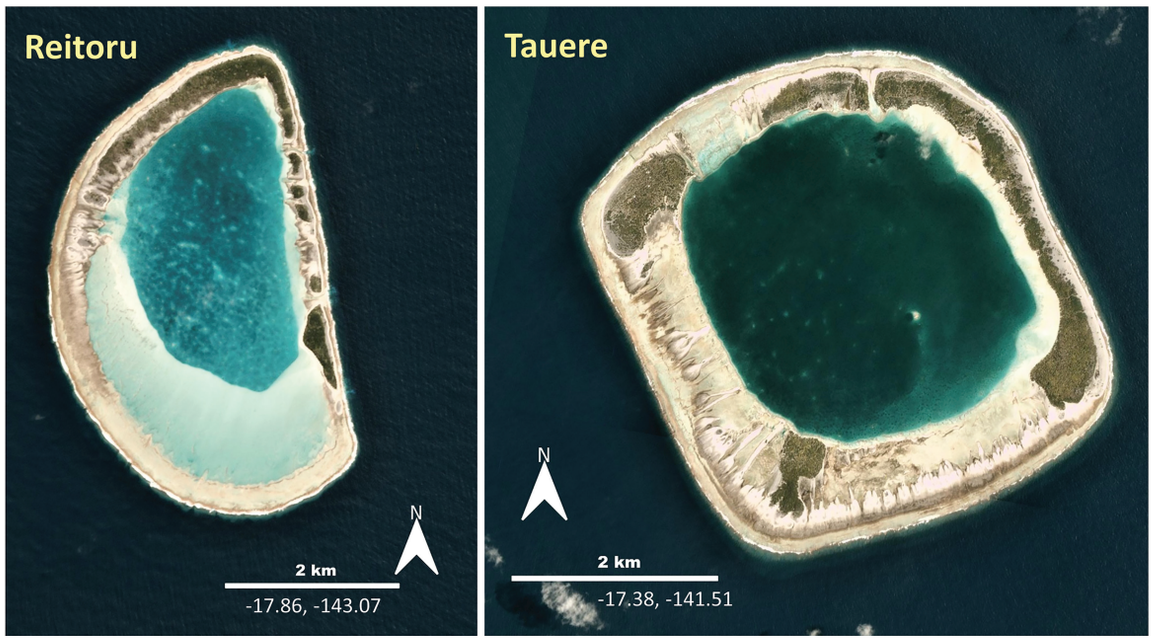

Figure 3.14 Remote-sensing images of the atolls of Reitoru and Tauere. Images © 2021, Planet Labs PBC.

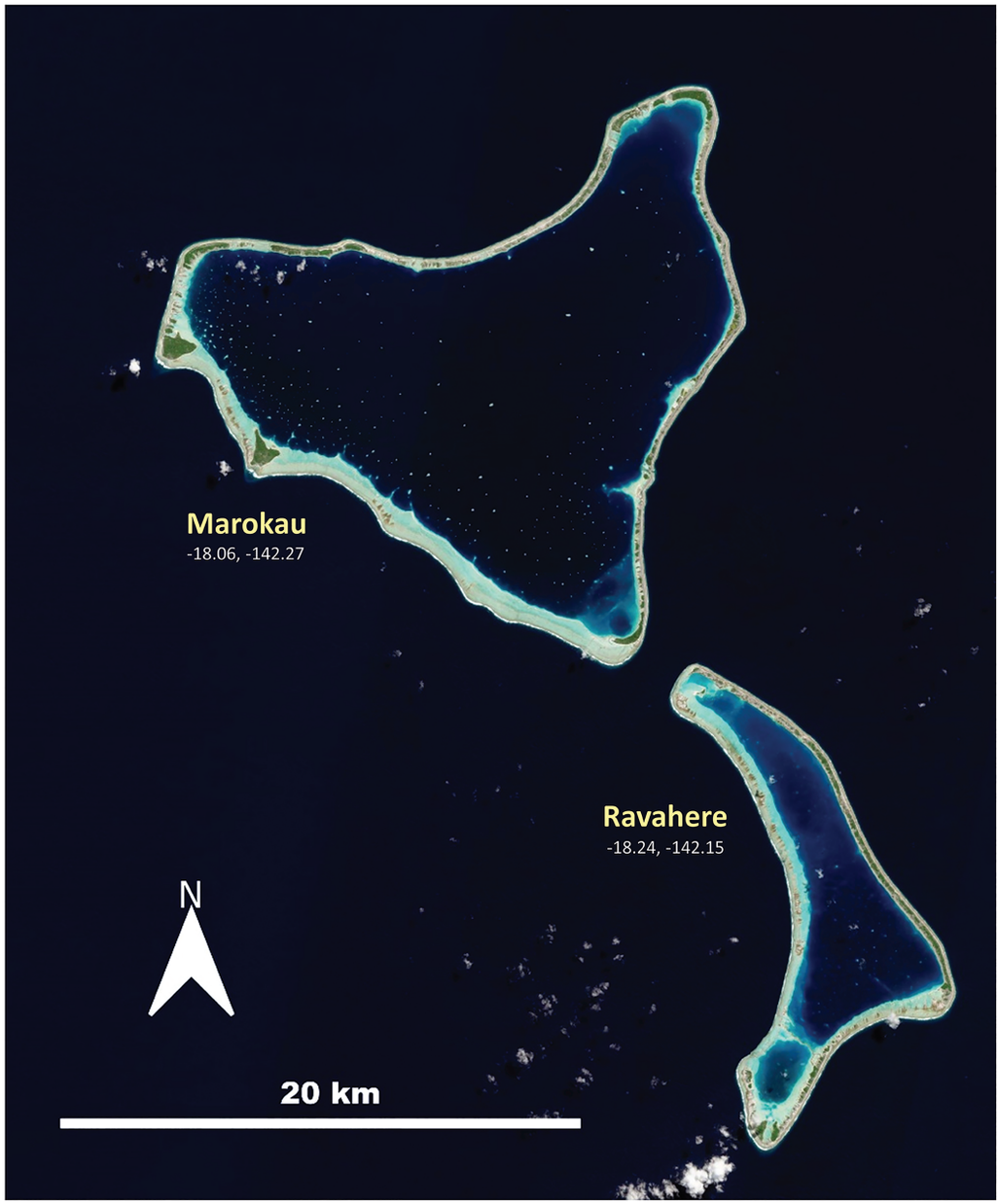

Figure 3.15 Remote-sensing images of the atolls of Marokau and Ravahere. Images © 2021, Planet Labs PBC.

platform area is 256 km^2 (Adjeroud et al., 2000; Dufour et al., 2001) and the broadest outer reef area is the southwest where it ranges from 235 m to as much as 630 m. The remaining reef areas are commonly 135–175 m wide.

The rim extending from the northwest-facing side to the northeast and southeast sides is occupied by small islands and hoa formed atop a ridge of gray-colored rubble and sand. The island-bearing portion of the rim ranges from about 350 to 520 m at its widest point near the northeast apex of the triangle. There are two narrow, shallow channels through the eastern islands and numerous hoa among the north and northwest islands. A reef flat about 40–60 m wide occurs along the eastern rim oceanward of the islands. A reef flat up to a kilometer wide extends along the southwest side of the atoll, where only a few motu occur, near the middle of that side. The rim is semi-closed.

A pronounced reef sand apron up to 500 m wide flanks the southwestern reef flat but is reduced to 80–200 m wide on the east/northeast atoll side and narrows even more at the northwest-facing rim. The lagoon covers 213 km^2 with an average depth of 30 m and has a renewal time of 55 days (Pagés and Andréfouët, 2001). Pinnacles with reef development occur along the northwestern, western, and southern lagoon slopes, but are most common towards the southwest and south margin. The deep lagoon at the atoll center and northeast displays fewer pinnacles. Salvat (2009) described a diverse bivalve community from here.

Ravahere (Figure 3.15) is a boomerang-shaped atoll just over 2 km southeast of Marokau. It is about 6.5 km at its widest, from the southeast-facing apex to the west-facing base, and 21 km long in a curved sweep from the southwest to the northwest. The platform area is 74.2 km^2 and it is surrounded by a nearly continuous deep outer reef, except for a 1.8 km gap in the southwest and a 550 m gap in the northwest. The outer reef is continuous around the atoll and is up to 330 m wide to the south–southeast and ranges from 110–210 elsewhere. The rim between the northwest and the southeast apices is composed of a stretch of about 5 km of motu followed by a single island nearly 12 km long. Most of this part of the rim is about 300 m wide, but its southern terminus expands to about 500 m. A reef flat, mostly 40–60 m wide, flanks the islands along the eastern rim. The southeastern to the southwestern rim is composed of islands and motu. Most of the rim northwest and west is a reef flat less than 400 m wide with motu and hoa along much of its length. The rim is without passes, but because the reef flats are weakly developed along the southernmost 5 km of the west, we regard it as semi-closed.

The lagoon area is 45.4 km^2 including two enclosed pockets, one in the north with an area of 4.3 km^2 and the other measuring less than 0.25 km^2. Both are isolated by a narrow rock and sand ridge. A broad reef sand apron that is 250–450 m wide occurs in the western shallow lagoon; the sand apron widths are narrower elsewhere. Sporadic, small reef patches are found along the west lagoon, although more occur in the lee of the eastern islands. Some pinnacles occur in the deeper lagoon, but fewer than 15 of them are associated with reef development. We do not have a depth for the lagoon. From Ravahere, we move west where we encounter Hao and Amanu.

Hao Atoll (Figure 3.16) is interesting for several reasons including the question of who among the European explorers discovered it. Pedro Fernándes de Quirós is often quoted as its discoverer in 1606, but as pointed out earlier in this chapter, Captain Quirós was not at all certain where he was at the time, and he logged the wrong latitude for Hao (e.g., Salmond, 2010), making credit for its discovery difficult to ascertain. There is no doubt that Louis-Antoine de Bougainville discovered Hao on March 24, 1768, and he named it Île de la Harpe in his belief that it resembled the musical instrument. However, Bougainville was given a decidedly unfriendly reception by the resident Polynesians (who likely arrived more than 800 years earlier) and being unable to find bottom by sounding to 100 fathoms (more than 180 m), even when close to shore, he was persuaded not to land (Dunmore 2002). Captain James Cook sailed by Hao in the following year and named it Bow Island, thinking it resembled the arrow-launching device (Young, 1899; Buck, 1953). Hao is a large atoll and neither captain could have seen it all, especially *en passant*, hence the misnomers. When viewed from space, Hao looks more like a shoe, but the one we described previously (Tahanea) is more masculine. This one is longer, more elegant, and more feminine like a ballerina slipper.

The long axis of Hao is oriented northwest–southeast, and it is a little more than 57 km from heel to toe and about 15 km at its widest. Hao is located 111 km from Ravahere. The platform area is 578 km^2 including a narrow outer reef that is generally 150–200 m wide but expands to 250–300 m wide along parts of the west. The windward, northeast rim is composed of a single island nearly 26 km long (across the opening of the slipper) and includes an airstrip. Another island occurs from the toe 16 km along the top of the slipper. The widest part of the rim is 1.7 km at the toe. Between the two islands, the windward rim is composed of motu. The windward side is typically about 200 m wide, although it is about 340 m wide where the main settlement of Otepa is located.

The northern rim, about 10 km from east to west, is composed of small islands, and between them is a pass, about 300 m wide, reaching a depth of at least 6.4 m (Sailing Directions, 2017). The remainder of the rim (from heel to toe) is a reef flat with motu, which is about 500 m across. The rim is open.

The lagoon is 497 km^2 with a mean depth of 40 m and a residence time estimated to be 90 days (Pagés and Andréfouët, 2001). The maximum known depth is 61 m (Purdy, 2001). Reefs occur through the pass in the northwest and continue around the shallow lagoon for 5 km to the west and more than 10 km to the east and south. More reef ribbons occur along the eastern just south of the slipper opening and flanking both sides of the lagoon northwest from the toe. There are numerous coralliferous pinnacles in the deep lagoon including those that are elongated along the sole and toward the toe.

Amanu Atoll (Figure 3.16), Hao's neighbor 19 km to the northeast, is sausage shaped and exhibits a northeast-southwest orientation, which is distinct from the other atolls described thus far in the Tuamotu Islands. There are seven atolls that have arisen from erupting fissures generated by fracture zones within the main Tuamotu line and Amanu is one of them. The remaining six will be described in the next section. This atoll is about 31.5 km long and 9.5 km wide. The platform area is 244 km^2 (Andréfouët et al., 2001). Outer reefs are widest to the east–southeast where they are 220–285 m wide but are otherwise narrower and become are more poorly developed

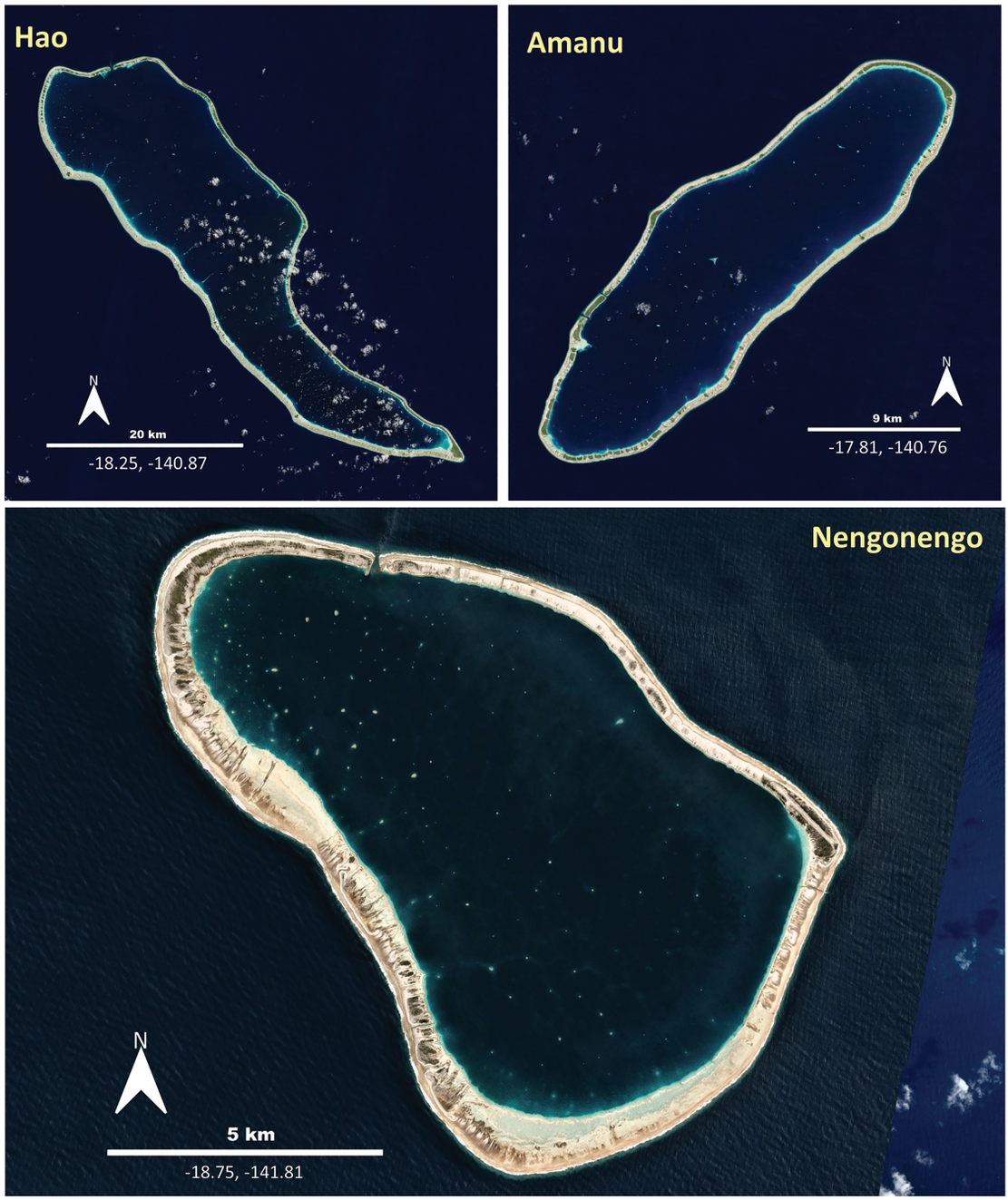

Figure 3.16 Remote-sensing images of the atolls of Hao, Amanu, and Nengonengo. Images © 2020-2021, Planet Labs PBC.

to the northeast. The rim includes vegetated islands on all sides. The northeast rim develops the largest island, which is about 6 km long and 570 m at its widest. The northwest-facing rim of the primarily consists of small, closely spaced islands and motu. Toward the southwest on this margin, two passes are separated by a small island. The more southerly of the two is 45 m wide and is about 5 m deep; the more northerly one is narrower 'and is not recommended' for passage (Sailing Directions, 2017). Both are encroached by shallow outer reef growth. The southeastern rim is primarily composed of reef flat with hoa and motu and is about 500 m wide. There are small ribbons of reef growth along the central portion of this rim. The rim is open.

The lagoon area is 210 km^2, with a mean depth of 30 m, a maximum depth of 62 m, and an estimated renewal time of 39 days (Pagés and Andréfouët, 2001; Purdy, 2001). The shallow lagoon is rimmed by sand northwest–southwest clockwise where it is mostly about 100 m wide. The lagoon slope in the southwest develops patch reef ribbons.

Nengonengo Atoll (Figure 3.16) is located 54 km southeast of Ravahere and 102 km from

Hao. It is ovotriangular with one apex pointing toward the northwest and its short base facing the southeast. The distance from base to apex is about 14 km, and the atoll is about 9 km at its widest, near its base. The platform covers 91 km^2 and is completely encircled by an outer reef that is generally 225–275 m wide although it narrows to 200 m wide to the northwest and expands to 325 m to the east. The northwestern rim is capped by a 6-km-long island and is separated by a channel from a second island that is a little more than a kilometer long. The channel is roughly 160 m wide and ~2 m deep. However, coral growth accounts for that depth along nearly half of the extent of the pass (Sailing Directions, 2017) and the Allen Atlas clearly shows the outer reef penetrating and spreading as if to fill the channel. A low area of the rim that is about 80 m wide flanks the smaller northeastern island and appears to be sufficient to allow additional exchange. There is a limited area of coral/algal growth on the reef flat adjacent to this low area. The rim is open. A third island 2 km long at the southeast bears an airstrip. The distance between this island and the pass is 6.8 km, most of which is a low, sand and rubble ridge, 200–300 m wide composed of motu. The remaining rim of the west and south is a combination of reef flat and motu and is up to a kilometer wide.

The lagoon is 67 km^2 in extent and reef growth especially near the pass. Reef development is also associated with pinnacles on the lagoon slope, especially in the northwest. Additionally, there are scattered pinnacles rising from deeper water. We are unaware of any depth data for this lagoon.

Manuhengi (Figure 3.17) is a small, egg-shaped atoll that lies about 68 km southeast of Nengonengo. It was discovered by the English navigator Samuel Wallis in 1767 and it is currently uninhabited and privately owned. Manuhengi is oriented northwest–southeast and is 5.6 km long and about 3.4 km at its widest. The platform is 16.6 km^2 in extent and is surrounded by an outer reef system that is widest to the west where it is generally 200–285 m wide. The eastern reefs are about 135–170 m wide but narrow to the northeast and south. The shallow reefs extend onto the reef flat around most of the atoll. The rim is capped by a gray sand and rubble island that is vegetated between the north and the southeast; it ranges from 250 to 550 m wide. There is an apparent coconut plantation in the north. The rim of the west side has about the same range of widths, with less vegetation. The southern rim is composed of motu, but there are two shallow gaps in the rim divided by a single motu in the southeast. The largest is 30 m wide and the other is perhaps 20 m wide, and both may be partly occluded by rock, rubble, or sand. The lagoon area is 8.7 km^2 with reef growth along its shallows and slope, and small pinnacles are present in the center of the lagoon. We do not have any depth information for this lagoon system.

Paraoa (Figure 3.17) is a small ovotriangular atoll with a south-facing apex and a north-facing base located about 54 km east of Manuhengi. It is about 4.4 km from apex to mid-base and 6.8 km at its widest. The platform covers 27.2 km^2 and it is surrounded by an outer reef up to 330 m wide to the southeast that narrows to about 100 m wide to the east. The rim is dominated by a single island on the north-facing base that extends northwest–southeast more than 10 km. The remainder of the rim at the south to the west is composed of motu and reef flats. The outer reef flats in the east and along the southwest have motu and are associated with patchy coral/algal reef. There are no passes, and the rim is closed. The lagoon is 15.8 km^2. A narrow band of submerged sand and reefs are found to the west in the lagoon shallows. A well-developed reef system is also present as extensions along the north and south lagoon slope. Pinnacles with coral are found in the deeper middle lagoon. Pinnacles are also present in the deep eastern lagoon, but fewer of them are associated with reefs. We are unaware of depth data for the lagoon, but Salvat (2009) indicates that giant clams (genus *Tridacna*) are abundant. We tentatively mark this lagoon as semi-closed.

Ahunui (Figure 3.17) is a rounded atoll with a flattened side facing northeast, and that lies 94 km southeast of Paraoa. It is 5.4 km bisecting the base and 6.3 km at its widest. The 30.6- km^2 platform develops an outer reef that is generally about 200 m wide but narrows to about 100 m to the east. However, a spur and groove system between 30 and 50 m wide is found around the atoll. The east-facing rim is occupied from north to south by a single island that is 8.9 km long and mostly about 200 m wide, but which expands to 400 m at the southern tip. The remainder of the rim is composed of motu, but there are no obvious functional hoa or passes. The rim is closed. There are also no settlements or air facilities. The lagoon is 19.2 km^2 in extent and develops eight reef-rimmed pinnacles in the lagoon center. Salvat (2009) indicates that there are appreciable *Tridacna maxima* and pearl oysters, among other bivalves, but we are not aware of any quantitative data or depth information.

The next three atolls form a triangle northeast of Ahanui. **Vairaatea** Atoll (Figure 3.18) is about 121 km northeast of Ahunui and is teardrop shaped with the single apex pointing west. From there, the longest axis is 6.8 km; the north-to-south axis across the drop is 4.8 km. The 25.3 km^2 platform is surrounded by outer reefs that vary from 150–250 m

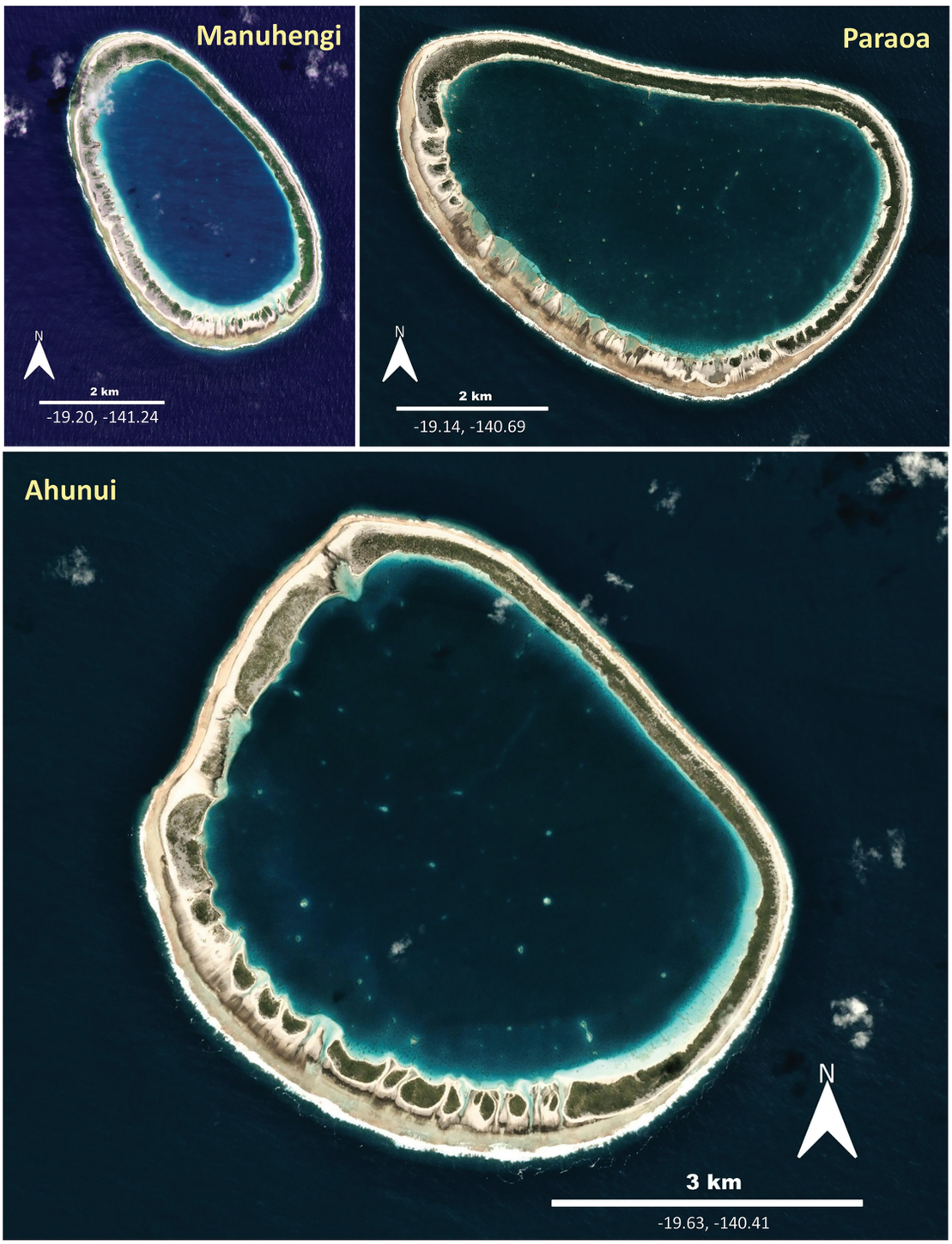

Figure 3.17 Remote-sensing images of the atolls of Manuhengi, Paraoa, and Ahunui. Images © 2021, Planet Labs PBC.

wide north–west to 35–400 m wide east–southwest, becoming narrow (100–135 m) through part of the northwest. The rim is composed primarily of two islands. The largest is C-shaped, extends from north to south along the bottom of the drop, and is 7.2 km long. There is a small settlement on the north of this island, but there is no airstrip. The second island is 4.1 km long and extends from the north to the west where it curves, forming a reverse J-shape. A reef flat that is 1.1 km long occurs between the islands on the northwest-facing rim. The southern rim is composed of a 3.5-km-long reef flat with scattered motu and hoa. Reefs are clearly developed on the outer reef flats here. The rim is closed but is open to exchange through both reef flat areas.

The lagoon area is 12.8 km^2. Reefs encircle the basin and are best developed to the north and northeast where they form pinnacles rising from the deep lagoon floor. We have no depth information for this lagoon.

Vahitahi (Figure 3.18) is located about 71 km northeast of Vairaatea. It forms an elongated oval shape that is oriented east–west. Its long axis is 8.4 km, and it is about 2.8 km at its widest toward the east. The platform is 22.5 km^2 and is surrounded by an outer reef about 125 m wide and the entire atoll is surrounded by a spur and groove system. An island 5.7 km long forms on the northeastern rim and curves around the eastern side. West of this, motu and hoa occur on the northern rim, along with two shallow channels 200–600 m wide. A small island occurs on the west tip, where there is a small settlement and an airstrip. The lagoon is 8.1 km^2 in extent and is generally shallow and reticulated. Reefs occupy the shallows to the east and west. Most of the lagoon includes reef-rimmed pinnacles. The western lagoon is sandy and develops a few reef areas. We do not have any depth records for this atoll.

Pinaki Atoll (Figure 3.19) is round, about 2.2 km in diameter, and is located about 54 km east–southeast of Vairaatea. An outer reef up to 350 m wide to the south surrounds the 4.9 km^2 platform. The rim is composed of one island of 1.3 km^2 that circumscribes the lagoon, but for a west-facing 200-m-wide hoa that appears elevated above sea level and is blocked at least partially by rock and rubble. It likely does not permit oceanic exchange with normal tides and is closed, although there are populations of *T. maxima*, as described below. The lagoon covers 0.60 km^2, and most of it is very shallow although no specific depths have been reported to our knowledge. Most of the lagoon is mapped

Figure 3.18 Remote-sensing images of the atolls of Vairaatea and Vahitahi. Images © 2021, Planet Labs PBC.

Figure 3.19 Remote-sensing images of the atoll of Pinaki. Image © 2021, Planet Labs PBC.

as sandy, replete with ridges and associated with islands that break the surface, suggesting mapiko, a Polynesian term for high density shell mound aggregations formed by *Tridacna* that often can be seen in satellite imagery. Van Wynsberge et al. (2016) report 4–12 *T. maxima* per m^2, a lower density than for neighboring, *T. maxima*-rich atolls. Coding by the Atlas indicates reefs are present in the shallows and on the margins of the lagoon entrance.

The northern and northeastern Tuamotu Islands

We introduce the 13 northernmost of the Tuamotu Islands here, starting with the northwesternmost pair, Ahe and Manihi, and then to another pair of atolls, Takaroa and Takapoto. These four are sometimes referred to as the King George Islands as explained below. Rarioa and Takume are the last of the paired atolls. All three pairs are elongated northeast–southwest rather than the more typical orientation of the Tuamotu Archipelago. As mentioned in the description of Amanu, Hao's neighbor, this orientation is due to eruptions from fissures generated by fracture zones that formed at right angles to the main Tuamotu trend (Montaggioni et al., 2019). This position changes their waveward sides to the west and northwest and the leeward side to the east and southeast. We then encounter Napuka and Puka-Puka, which are occasionally lumped together as the Disappointment Isles, as further explained below. These are followed by a chain of five including Fangatau, Fakahina, Takatoto, Pukarua, and Reao, the outermost of the Tuamotu group in the northeast and a convenient place to draw a boundary.

Ahe Atoll is at the northwestern edge of the Tuamotu group. It is ovoid with an elongated southeast end; it is about 24 km to the northeast side and about 10 km at its widest expanse (Figure 3.20). The platform is 171 km^2 in extent (Purdy, 2001) and develops an outer reef that is commonl6y 200–250 m wide although some areas narrow to 90–150 m wide, especially to the southwest and southeast. A narrow band of spur and groove occurs along the eastern and the western parts of the platform. A 14-km-long island extends along the northern rim from the northwest to the northeast, reaching about 550 m wide where the airstrip is located. A few reefs occur on the reef flats to the northwest. A 200-m-wide pass about 11 km from the airstrip on the western rim is up to 11 m deep

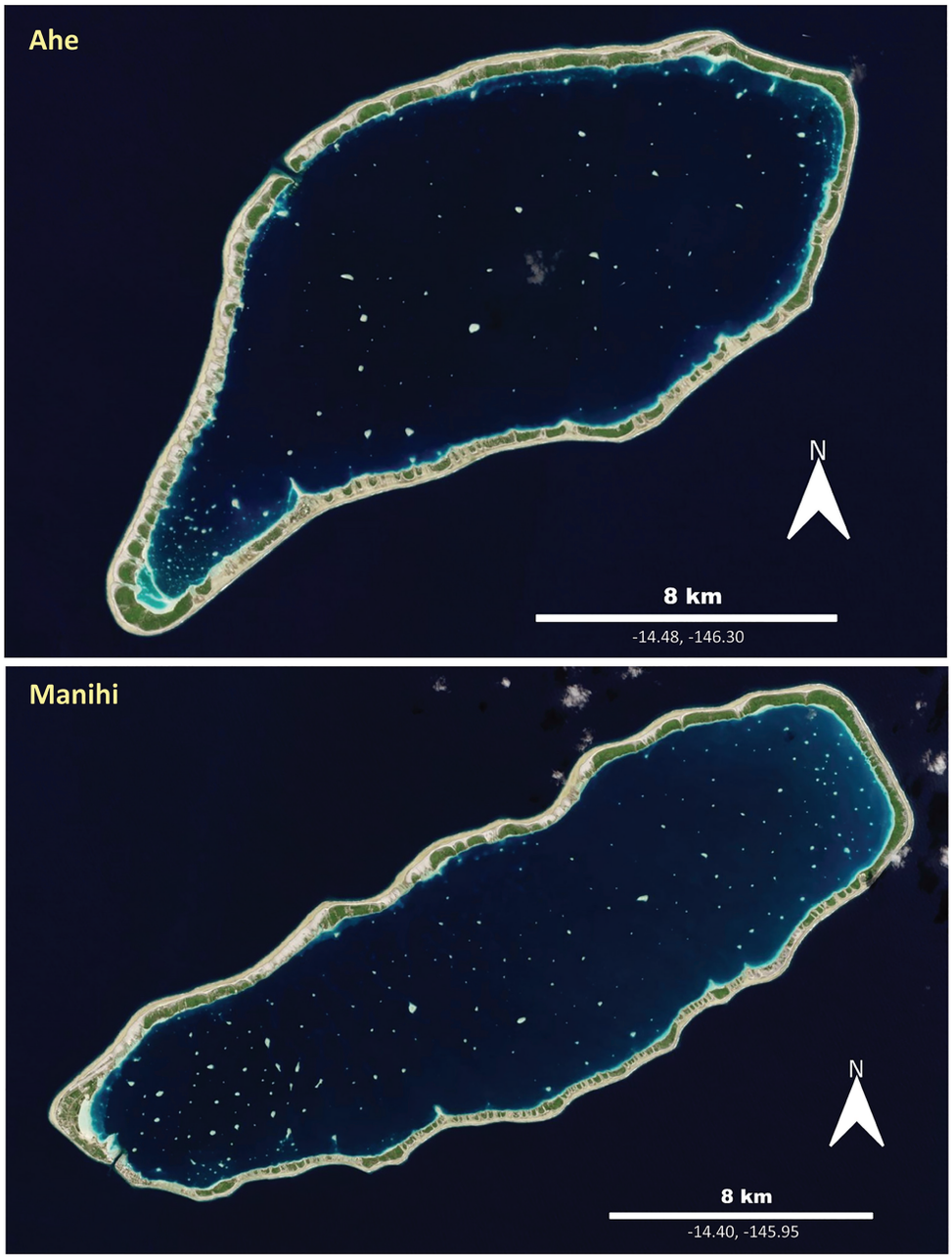

Figure 3.20 Remote-sensing images of the atolls of Ahe and Manihi. Images © 2021, Planet Labs PBC.

(Dumas et al., 2012). The remainder of the rim from the west consists of motu with hoa, some of which are blocked, as well as several that are 10–300 m wide and less than a meter deep (Dumas et al., 2012); some are open to ocean exchange with the lagoon. There is a 1.1-km^2 arcuate island on the southwestern rim that is followed to the east along the southern margin by small islands (one of which includes a village) and motu separated by hoa. The eastern rim is closed.

The lagoon area is 145 km^2, with an average depth of 41 m, a maximum depth of 71 m, and a renewal time of 34 days (Pagés and Andréfouët, 2001; Andréfouët et al., 2020). Oceanic exchange with the lagoon has been studied intensively owing to the importance of Ahe in pearl oyster aquaculture (Andréfouët et al., 2012). Most of the circulation is driven by tides that force water in and out of the lagoon through the northwest pass. Even though the tidal range reaches only 30 cm, strong currents at 2 m/sec (more than 7 km/hour) create a jet-like circulation that rapidly renews the lagoon waters. However, the lagoon volume can be viewed as a three-cell system that does not respond to wind and tide forcing uniformly or as forcefully as it does in the vicinity of the pass. The overall lagoon renewal time is estimated to be 252 days, but this figure does not consider all the dynamics of wind, wave, and tide or the response of basin morphology to these forces as described in detail by Dumas et al. (2012).

The lagoon area includes a shallow, 47-ha sandy basin (excluding inner reef flat) at its southwestern point that is partly isolated from the main lagoon by a rock and rubble ridge. The shallow sand continues from this small basin along the lagoon margins for 2 km to the northeast and 4 km to the east. Patch reefs occur as ribbons in the shallow lagoon and on the reef flats along the north and northwest and continue to the northeast, where they are associated with plateaus. The lagoon slope is studded with numerous plateaus and reef pinnacles that are especially prominent to the southwest. However, most of them (141) are associated with the lagoon deeper than 20 m that extends throughout most of the basin (Andréfouët et al., 2020). Many of these break the surface where they are rimmed with coral/algae and topped with rock and rubble. It should be noted that Andréfouët et al. (2020) found 65 deep reticulated basins using bathymetry in Ahe lagoon, but these are too deep to be visible in optical satellite imagery.

Manihi Atoll (Figure 3.20) is located 30 km east of Ahe. It is elongate with a point at its southwest (toward Ahe) and a short, flattened northeast-facing side. The atoll is 28 km long and 8 km wide covering an area of 201 km^2 (Purdy, 2001). The outer reefs are quite variable in extent. Along the northwest platform for example reefs extend from 200–285 m wide but narrow to about 100 m wide to the southwest; long sections of reef to the southeast are narrower than 100 m. The distribution of islands is similar to Ahe. There is a narrow 9-km-long island lying on a gray sandy ridge forming the northeast part of the atoll. A low point in the rim that is 260 m wide occurs in the northwest and appears to be a point of oceanic exchange. This area is flanked by smaller islands and motu (some with possibly functional hoa) on the northwest-facing margin. A west-facing arcuate island that is 4.3 km long and 1.7 km wide at the southwest extent includes an airstrip, and a village is established on a smaller, adjacent island. Between the two is a narrow pass about 60 m wide that shoals at the lagoon entrance, leaving a navigable channel about 40 m wide, with a depth of 3 m (Sailing Directions, 2017). The shoaling and narrowing are due primarily to coral/algal growth. The southeast-facing rim is composed of small islands and motu with numerous hoa 40 to more than 400 m wide. It is not clear if these hoa permit ocean water exchange with the tides or only occasionally. The rim width here is about a kilometer.

The lagoon extends across 165 km^2, with a mean depth of 30 m, a maximum depth of 37 m, and an estimated renewal time of 130 days (Pagés and Andréfouët, 2001). The northwest lagoon is lined with reef ribbons which extend from the inner reef flat to the shallow lagoon, as on Ahe. The lagoon shallows are flanked by a narrow edge of sand extending from the northeast lagoon more than half the length along the southeast flank and about 6.5 km along the northwest side of the lagoon. Most of the lagoon slope displays reef development with pinnacles rising from the deep lagoon. As on Ahe, many of these reefs reach the surface and they are rimmed with coral/algae and are topped with sand, rock, and rubble. We are aware of no studies of lagoon dynamics comparable to Ahe, but the stock of pearl oysters is comparatively poor and limited to the upper 10 m of pinnacles (Andréfouët et al., 2016).

Takapoto Atoll (Figure 3.21) is located about 70 km southeast of Manihi and it is about 20 km long by about 7 km wide at the center. The platform area is 104 km^2 and an outer reef mostly about 200 m wide occurs along the northwestern flank. The platform from north–southwest appears to be less well developed and are most often 100 m wide or less. However, a continuous spur and groove system about 20–40 m wide occurs here, and consistent with the mapping, these are evident in the Allen Atlas along the northwestern rim. About 2/3 of the northwestern rim is occupied by a 21-km-long island that extends around the south and about 1/3 of the way along the southeast coast. The island is 300–480 km wide and includes a village and an airstrip at the southeast corner. A second island 1.6 km long is separated by a 40-m-wide gap that is spanned by a causeway and connects to the village. There are reef areas on the flats seaward of this settlement. A third island that is 10 km long curves around the northeastern rim. These islands are extensively planted with coconut palms. Motu are interspersed among these islands, a few of which are separated by gaps 20–40 m wide along the east that may allow oceanic exchange with the lagoon. There are no passes, and the rim is closed.

The lagoon is 81 km^2 in extent, with an average depth of 25 m, a maximum depth of 43 m, and the estimated renewal time of 268 days (Pagés and Andréfouët, 2001). This long interval of time corresponds to a higher salinity in the lagoon that ranges between 37‰ and 39.5‰, depending on precipitation. The average salinity here is 38.2‰ (Charpy, 1996) which is about 7% higher than the surrounding ocean but this does not seem to be an impediment for high lagoon densities of the giant clams and pearl oysters (Salvat, 2009). Ribbons of patch reefs occur flanking the northwestern islands facing the lagoon, although some are associated with the shallow lagoon accompanied by a narrow band of sand. Plateaus along part of the southeastern flank of the lagoon slope and in the south occur where the lagoon is partly partitioned into a reticulated basin. Most

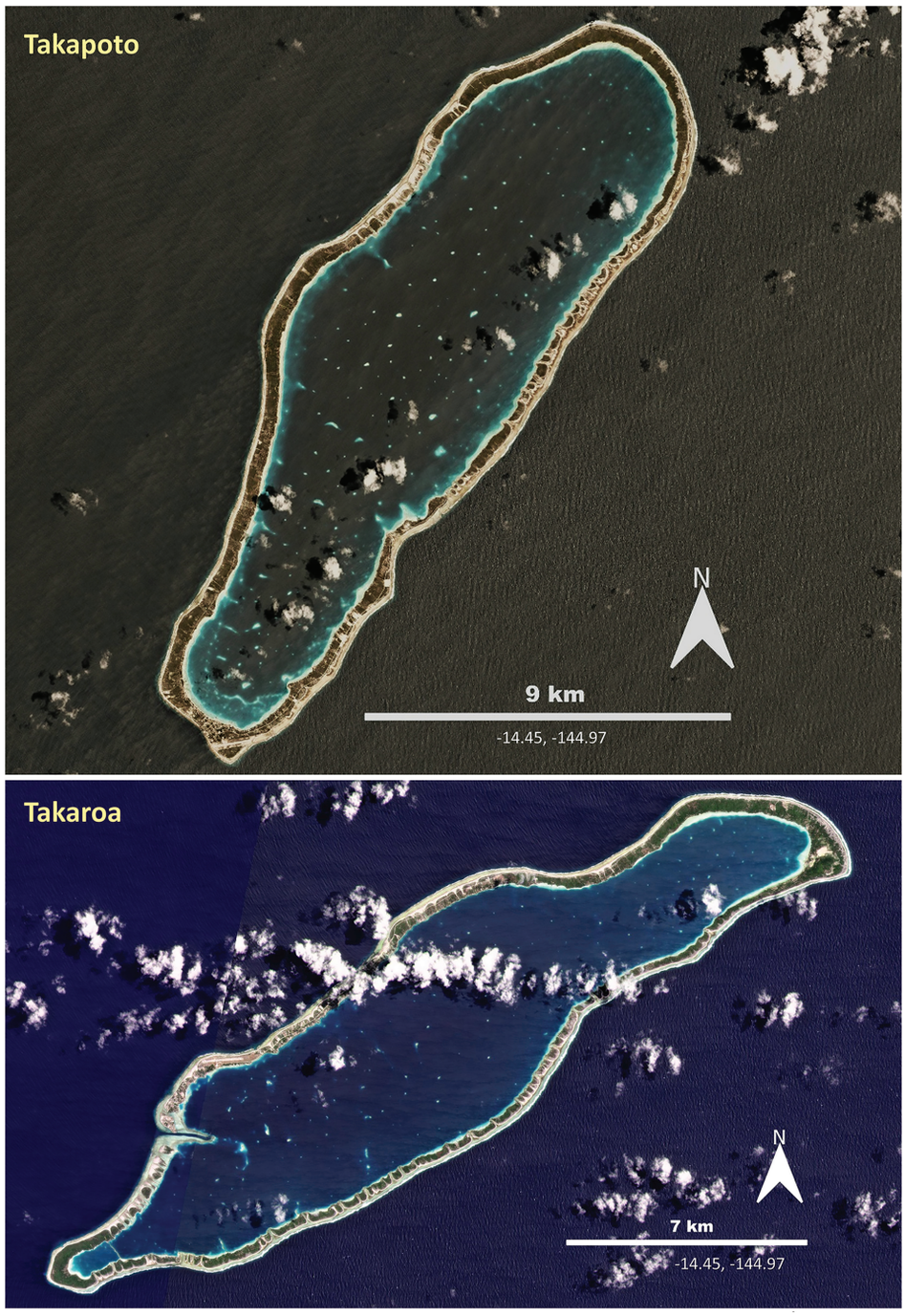

Figure 3.21 Remote-sensing images of the atolls of Takapoto and Takaroa. Images © 2021, Planet Labs PBC.

reef development associated with the lagoon is in the 194 pinnacles that occur in waters deeper than 20 m (Andréfouët et al., 2020). The lagoon currently has developed a substantial population of oysters (Andréfouët pers. com.).

Takaroa Atoll (Figure 3.21) is just over 9 km northeast of Takapoto. It is elongated northeast–southwest like the others in this group, but it is also polygonal, about 26 km long and about 6.5 km at its widest. The platform covers 114 km^2 (Purdy, 2001). A deep and shallow outer reef occurs along its northwestern side and extends onto the reef flat in several places. In the Allen Atlas thematic maps, the outer reefs to the north-northwest are generally 180–200 m wide, whereas those to the southeast are more often 100 m wide or less, similar to Takapoto.

A spur and groove system 20–30 m wide occurs close to shore along the northwest, and continues around the southern platform and all the way along the southeast. As is typical for this group, the northeastern rim includes a single island, which in this case is over 11 km long and about 1.2 km wide at its widest. The northwest-facing rim is composed of smaller islands and motu extending about 12 km,

some with accompanying hoa, after which there is an airstrip and a village. A pass 55 m wide with a depth of at least 12 m occurs about 2.3 km south of the airstrip, which shoals to about 3 m toward the lagoon (Sailing Directions, 2017). The Allen Atlas shows that the pass narrows and includes coral/algae on the south flank, and the lagoon entrance (which requires a sharp turn to port) is further obstructed by coral growth. A 3.3-km-long interval of motu separates the pass from a second island, 1.2 km long, that curves around the southwest rim back toward the southeast. The southeast-facing rim is composed of island and motu with about 20 hoa that are mostly 20–50 m wide.

The lagoon covers 86 km^2, with a mean depth of 26 m, a maximum depth of 48 m (rounded from Andréfouët et al., 2020), and a renewal time of 76 days (Pagés and Andréfouët, 2001). This lagoon is about the same size and depth as its neighbor Takapoto, but exchanges ocean water 3.5 times faster, and it is a more welcoming habitat for the pearl oyster, although the stocks are relatively low and are found predominantly in shallow water between 1 and 10 m depths (Andréfouët et al., 2016). The southwest lagoon is partitioned by a sand and coral-bearing outer reef flat into an 82-ha shallow basin that terminates as a sandy shore. Reefs in the lagoon center include 246 reef-rimmed pinnacles rising from the deeper (>20 m) lagoon. Many of these break the surface where they appear as rock with sand and rubble. Pinnacles are also habitat for pearl oysters although they are still recovering from a mass mortality that occurred in 2014 (Monaco et al., 2021).

The four atolls just described are those that are the farthest north in the Tuamotu Islands and were named the King George Islands by John Byron in 1765. As Commodore Byron headed to the northwest with the copper-bottomed HMS *Dolphin*, he had been chased away from more than one island (see below) but was finally successful in landing on two of them, which he promptly named King George's Islands in honor of King George III (Hawksworth, 1775). It should be noted for the purpose of clarity that the island of Tahiti was also briefly titled for King George in 1767 by another English captain, as was an island in the South Shetland group near the Antarctic Peninsula. The coordinates given in Byron's logbook do not help determine which of the Tuamotu Islands were King George's, but Gallagher (1964) suggests they were Takapoto and Takaroa, although Ahe and Manihi are also possible. Perhaps in the spirit of historical compromise, all four of these atolls have been accorded the royal eponym.

Raroia is located about 315 km from Takaroa, although its nearest neighbor is Nihiru, which lies 56 km to the southwest. This atoll is ovoid, 40 km long, and about 13 km at its widest (Figure 3.22). The platform area is 421 km^2 and its outer reefs are about 150–200 m wide except to the south where they extend 100 m or less from the rim. Although the waveward, side is to the northwest, an account by Newell (1954) indicates that this atoll is surrounded by a conspicuous spur and groove zone that is 50–100 m wide.

The northeastern rim is capped by motu with hoa that extend 20 km around the rim and may be

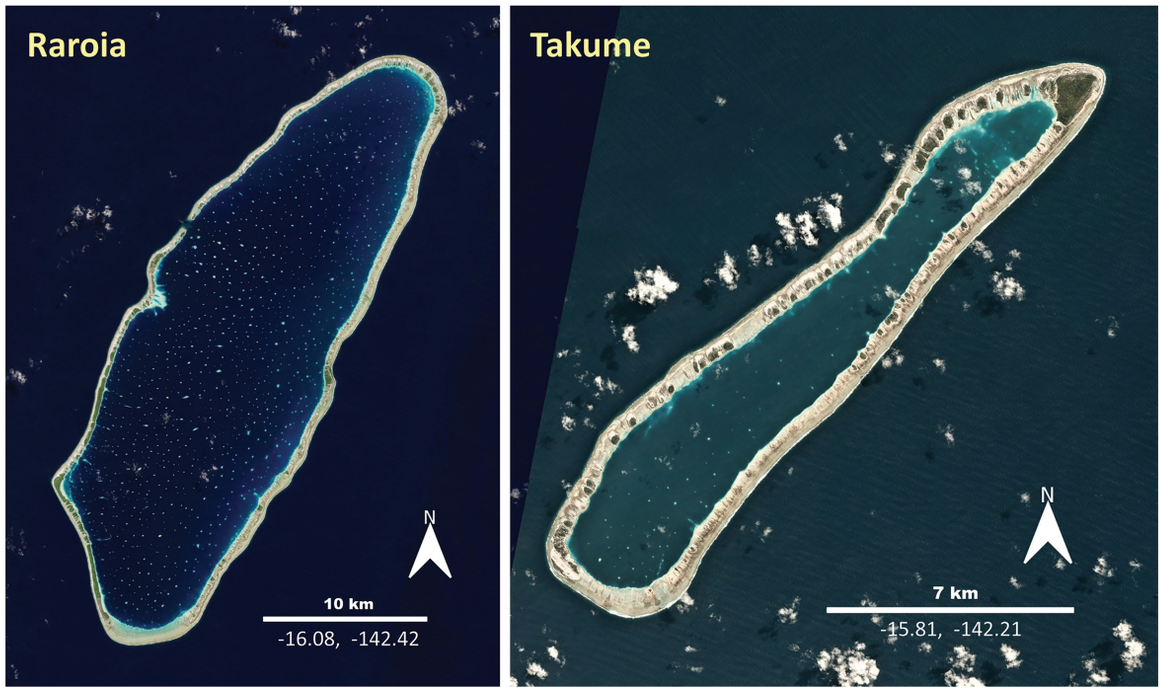

Figure 3.22 Remote-sensing images of the atolls of Raroia and Takume. Images © 2021, Planet Labs PBC.

functional only during storms. The mid-northwestern rim is the location an airstrip with a pass located about 3.5 km to the north of it. The pass is 20 m wide and 6.2 m deep (Sailing Direction, 2017). South of the airstrip and around a west-facing elbow, the rim is punctuated by islands and motu, some of which may be functional. A 4.7-km-long island completes the western rim and is followed by a reef flat at the south that is about 5 km long and 650–850 m wide. There is some reef development on the flats at the middle of the eastern rim associated with an island.

The lagoon is 368 km^2 in extent (rounded from Andréfouët et al., 2020). The northeast and southwest ends of the lagoon contain sand deposits that are about 450 m wide. The slope is narrow. The average depth of the lagoon is 32 m, whereas the maximum recorded depth is 68 m. Depths greater than 20 m are skewed toward the western flank although numerous coralliferous pinnacles, 1,434 of them as assessed by Andréfouët et al. (2020), populate much of the lagoon basin. However, there are an additional 184 pinnacles have bases in shallower water.

The atoll of Raroia also is of broader, popular science note, as the Pacific landing place of Thor Heyerdahl in 1947. Heyerdahl was a Norwegian adventurer knowledgeable in ethnology, zoology, and geography. To demonstrate the plausibility of an east-to-west pattern of ancient settlement of remote Pacific Islands, following the trade winds, he set out from South America on a small, balsa wood raft, *Kon-Tiki*. Over 100 days and 8,000 km later, the raft crashed onto the reef at Raroia, simultaneously fulfilling and shocking Heyerdahl, who had nearly drowned twice as a child and was fearful on the water. A 1951 documentary captured the essence of the voyage, and although physical, cultural, and DNA evidence demonstrate a west-to-east migration and settlement, counter to his hypothesis, Heyerdahl is remembered as a colorful explorer.

Takume Atoll (Figure 3.22) is about 9 km northeast of Raroia. That atoll and the nearby Takume were known as Napaite, which means 'the twins,' by the locals prior to European exploration. It is 21 km long and a bit more than 4 km at its widest on a platform of 72 km^2. Similar to the other atolls with a northeast–southwest orientation, the outer reefs along its northwestern margin are 150–200 m wide and are better developed than the southeast where they are commonly less than 100 m wide. The rim supports two relatively large islands. The one in the southwest, Ohomo, covers 81 ha and includes an airstrip. The other, at the northeastern end, is Taheto, covers 1.3 km^2 on a rim that is 1.6 km wide. The northwest-facing rim is composed of motu and hoa as well as reef flats from 400 to more than 900 m wide that likely permit ocean exchange with the lagoon. The southern rim is a 3-km-long reef flat that extends from the airstrip in the southwest to the northeast. The eastern rim is composed of motu and hoa, some of which may be functional. Reefs on the flats along southeast flank of the rim occur in association with motu, as well as close to the reef crest.

The lagoon is 41 km^2 in extent (rounded from Andréfouët et al., 2020). The shallow areas are lined with reef ribbons that merge onto the inner reef flat. Such reefs are less common in the southwest lagoon and northeast lagoon, where sand is prominent in the lee of Taheto and adjacent islands. The lagoon depth averages 20 m, and this depth extends through most of the center of the basin to the maximum of 58 m. Most reef development is associated with 56 pinnacles in lagoon found at depths greater than 20 m (Andréfouët et al., 2020).

Napuka is polygonal, oriented west–east, and is a distant atoll, 193 km northeast of Takume (Figure 3.23). It is about 11.5 km long and 5.8 km at its widest; the platform extent is 42.4 km^2. It is bordered by outer reefs about 150 m wide along all sides accept the south, where they are 50–100 m wide although there is a spur and groove system along this edge. The rim is dominated by a 4.7-km^2 island about 11 km long that extends from the northwest to the southeast. Another island in the west is 1.5 km^2 in extent and is the site of a small village with an airstrip. A 1.5-km-wide gap separates the two northwestern islands, reflecting a reef flat with a rubble bottom and some nearshore reef ribbons. The south rim is composed of islands and motu with reef flats 60–600 m wide. The reef flat of the southeast is 370 m wide.

The lagoon area is 20.3 km^2. About 1 km^2 of the western lagoon is partially closed by a ridge that is part of the shallow lagoon. The lagoon center supports a series of plateaus and reef-bearing pinnacles. Some of these features are elongated and others widen as they reach the surface, where they become flattened and sparsely vegetated; a few reach an area of up to 3 ha. Pinnacles diminish in extent but continue toward the eastern lagoon that ends in a sandy cul-de-sac with little reef development. We have no depth information on this lagoon.

Although there are no passes, the lagoon has been characterized as semi-closed due to the high densities of giant clams found in this lagoon, as they are in several other closed atoll lagoon systems in this area (e.g., Van Wynsberge et al., 2017). However, these same atolls are often susceptible to mass mortalities due to events such as prolonged periods of low wind or swell from the south that diminish or impede lagoon water renewal.

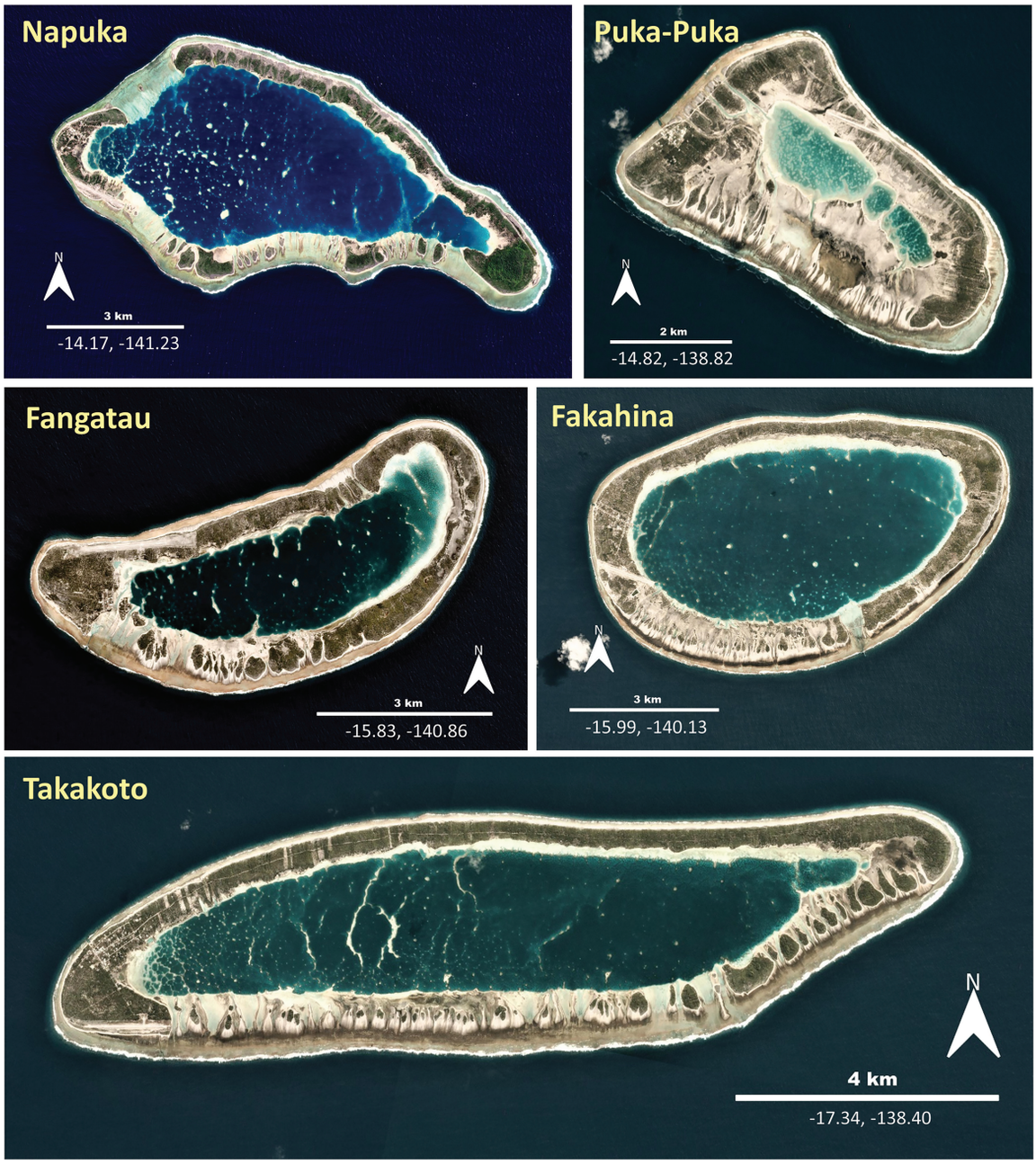

Figure 3.23 Remote-sensing images of the atolls of Napuka, Puka-Puka, Fangatau, Fakahina, and Takakoto. Images © 2021, Planet Labs PBC.

Puka-Puka Atoll (Figure 3.23) is northeasternmost of the Tuamotu Archipelago and there is some evidence that Magellan may have encountered this island en route to Asia on January 24, 1521, but it could have been Fangahina or Fangatau just as easily (Fitzpatrick and Callaghan, 2008). This atoll occasionally is included as one of the Disappointment Islands, although it is doubtful that Byron ever sailed near it. The first Europeans to describe Puka-Puka without doubt were two Dutch merchants, LeMaire and Schouten, who followed the footsteps of Quirós exploring the Pacific. In 1616, they landed on a remote island and reported seeing three dogs there that neither barked nor made any noise. These were Tahitian canines, now extinct, but Dog Island, as they named it (Honden Eiland in Dutch), is generally regarded as Puka-Puka (Young, 1899; Douglas, 2014).

Puka-Puka is ovotriangular with a rounded apex facing the southeast. From there to the center base that faces northwest, it is about 6.6 km long and 4.3 km at its widest. The platform area is 23.1 km^2. There are some outer reef areas to the northwest that are separated as ridge-like projections 100 m or more from the outer reefs. These were not included in calculating the platform area. The outer reefs are typically 200–275 m wide except to the southwest where

they extend to more than 300 m. Reef development also occurs on the outer reef flats, especially northeast–south. A spur and groove system appears to surround this atoll but is somewhat obscured to the east by wave activity. The rim is composed primarily of a 7-km-long island that extends on the northern margin from the northwest to the southeast, where it becomes wider and curves, as it does on Napuka. The island is about a kilometer wide to the north, where an airstrip is located. This island is separated by a 1.5-km-long reef flat from a second island with a village on the west. The remainder of the rim along the south is about 8 km long and is composed of reef flats interspersed with islands, motu, and apparently non-functional hoa. The reef flat on the southeast rim is about 400 m wide, similar to Napuka. There are no passes, and the rim is closed.

The lagoon is about 1.9 km^2. It is skewed toward the northeast rim, and it is very shallow, perhaps only a few meters deep (Rougerie, 1995). It is divided into three pools that have an extensive and dissected apron. The northwestern pool is 1.4 km^2 and has four stream-like spillways from the southwest, where water from storms appears to have overtopped the rim. The middle lagoon is the smallest (0.15 km^2) and is separated from the others by ridges. There are no spillway connections. The third, southeastern pool covers an area of about 0.3 km^2 and has 2–3 spillways facing the south. There are numerous ridges and pinnacles, many of which break the surface.

Fangatau is about 130 km east of Takume and 183 km southwest of Puka-Puka. This atoll is a D-shaped atoll with the 8-km-long flat side facing north and it is just over 3 km wide bisecting the base (Figure 3.23). The platform area is 25.2 km^2 and it is surrounded by outer reefs that are generally 170–180 m wide. Small areas to the southeast and southwest are 300 m wide, whereas adjacent areas develop reefs that are 100 m wide or less. Reef material occurs on the reef flats around the atoll with less widespread occurrences on the north than elsewhere. The rim is composed of two large islands that are separated by a 3.8-km-long stretch of motu and hoa along the southern rim and a 400-m-wide gap with two motu and three hoa on the north-facing rim. The 10–12-m-wide artificial channel through the reef flat on the southwest includes no passes. The lagoon could be regarded as closed (Salvat, 2009) or semi-closed, due to hoa along the south, which are sufficient to exchange seawater with the lagoon and thereby support a very large giant clam population (see below).

The lagoon is 8.7 km^2 in area and about 20 m deep. Andréfouët et al. (2005) found that 40% of the lagoon (4.1 km^2) is less than 6 m deep. These sandy shallows are home to an estimated population of more than 20 million giant clams that attach their shells to the substrate, and by constructing mounds (Gilbert et al., 2006a) or ridges, they have become the primary reef builder in this lagoon. Indeed, the shallow northeastern part of it (about 1.6 km^2) is separated from the rest by a large deposit of shells, and most of the main lagoon is isolated from the shoreline by another such deposit. Reef-rimmed pinnacles and ridges occur in the deeper lagoon.

Fakahina (Figure 3.23) is an egg-shaped atoll located about 73 km southeast of Fangatau. It is 8.6 km long and 5 km at its widest. The platform is 38.1 km^2 and is surrounded by an outer reef that is about 160–200 m wide northwest–east clockwise. The remainder is quite variable and mostly narrower. A spur and groove system around rings most of the atoll. Coral/algae occur on the reef flat between the northeast and the southwest, with more occasional patches along the north rim. The rim is dominated by a single island nearly 14 km long, up to 860 m wide to the east, and 810 m wide to the west where there is an airstrip. The island is separated by a 4.4-km-long series of motu and hoa. The hoa do not appear to be functional daily, but there is a 300-m-wide low point in the rim (traversed by a causeway) where oceanic exchange clearly takes place.

The lagoon area is 18.6 km^2. An apron extends from the airstrip at the west to the east, becoming widest in the north where it extends up to 200 m. The apron is submerged along the southeast and south atoll, where it becomes part of the shallow lagoon. A relatively small number of pinnacles occur in the lagoon center. Salvat (2009) reported substantial populations of giant clams and pearl oysters in the lagoon here, but we have no depth reports.

Tatakoto Atoll (Figure 3.23) is 274 km south of Puka-Puka and 228 km southeast of Fakahina. It is an elongate ovoid atoll and oriented west–east. The 45.7-km^2 platform is surrounded by an outer reef that is generally 150–200 m wide, although parts of the southern reef are 275–325 m wide whereas the eastern reef is quite narrowly developed. A spur and groove system occurs around most of this atoll's perimeter. The rim is composed of a C-shaped, 7-km^2 island that is open to the south and widens as it wraps around the east and west ends of the atoll. A village and an airstrip are found to the west, where the island is a kilometer wide. The eastern side is 580 m wide, otherwise, the island is 300–400 m wide. The southern rim is 12 km long and is composed of motu and hoa, several of which at the center and westward, toward the airstrip, appear to be open. There are no passes, and the rim is closed, but see below. There are reefs that appear on the flats at the southwest and small ribbons near the island to the northeast.

The lagoon covers 17.5 km^2. It is shallow and is being infilled by sand from the south (Pirazzoli et al., 1988b). Several reticulated basins appear as plateaus and reef flat ridges in the western half of the lagoon. In addition, there is a 36-ha shallow area in the eastern lagoon that is mostly sand. Reefs can be found in areas on the lagoon slope along the shallow areas at the margins. As described for Fangatau in the previous section, this lagoon is a major habitat for large numbers of giant clams, *T. maxima,* whose shells contribute to the carbonate production of the lagoon and are especially prominent as shell mounds (mapiko) on shallow ridges and in the shallow eastern and western ends. Dense populations of these bivalves, as many as 544 individuals per m^2, were recorded from this lagoon, although they were later devasted by a mass mortality that reduced the population considerably (Gilbert et al., 2005; Andréfouët et al., 2013). The lagoon depth has neither been reported to our knowledge nor have the lagoon dynamics, but the center is greater than 10 m deep (Van Wynsberge et al., 2017), and the openings through the southern rim that support the coral and giant clam communities suggest that the lagoon is semi-closed. However, the closed rim and its effect on water exchange during calm weather likely was a factor in the mass mortality as well (Van Wynsberge et al., 2017).

Giant clams, *T. maxima,* are common in the Tuamotu group, especially within the closed atolls of Fangatau and Tatakoto described above and many others in the southeastern Tuamotu group described below. The bivalves are shown wedged into cracks and crevices of the reef, often in high densities one next to the other (Figure 3.24a). The ridged shells eventually become incorporated into the reef framework and contribute, in some cases significantly, to the process of reef building. They are particularly abundant in closed lagoon systems where they build shell mounds and what appear as dotted ridges in satellite imagery as in the shallow lagoon of Tenararo Atoll (Figure 3.24b). There are ten species in the genus *Tridacna*, and despite the name 'giant clam' *T. maxima* typically grows to about 20 cm, its larger cousin *Tridacna gigas* grows to a meter or more. Thus, *T. maxima* often is called the 'small giant clam.'

Giant clams attach to the substrate by means of a tangle of high-strength proteinaceous threads located at the shell hinge that faces the rocky substratum. Juveniles secrete compounds near the byssus that enable them to bore into rock, becoming completely embedded in the process, but older individuals outgrow their borings. Their multicolored and greatly enlarged mantle tissue is oriented toward the sun where their single-celled photosynthetic symbionts (zooxanthellae) produce dissolved organic matter, especially glucose and amino acids, as well as oxygen for their hosts. Because of their dependence on sunlight, these species are restricted to waters less than 10 m deep. In addition, giant clams can absorb dissolved nitrogen and particulate matter from seawater (Fitt, 1992).

How *T. maxima* achieves high abundance in many of the closed atolls in the Tuamotu Archipelago is unclear. There are many structural, hydrodynamic, and nutritional variables within closed systems, as well as exploitation by fishers for food. Thus, their conservation is often a concern. For more information, see the review by Neo et al. (2015, 2017).

Pukarua is an elongate, ovoid atoll with a flattened side facing the northeast (Figure 3.25). Its nearest neighbor is Tatakoto, 169 km to the northwest is similar in many respects. It is about 16 km long and 4.4 km wide bisecting the flattened northeast-facing side. The platform is 56.9 km^2 and is surrounded by an outer reef that is mostly 150–250 m wide and a spur and groove system. The reef flats along the northeast rim have a few coral patches, but they become numerous on the southwest rim. The rim is dominated by a single island covering 6.3 km^2. It is 16.7 km long and generally 250–350 wide but expands as it wraps around the northwest and southeast margins, like the large island of Tatakoto. There is an airstrip near the center-north part of the island and a small village in the northwest. The southwest side is composed of motu and hoa, most of which are functional at high tide (Salvat, 1971), and there are reefs closely associated with those islets on the outer reef flats. There is also an open reef flat that is more than 500 m wide to the southeast, which includes a rubble bottom. There are no passes, and the atoll appears to be closed; nonetheless, like Tatakoto, Fangatau, and other *Tridacna*-rich environments, the lagoon may also be considered semi-closed based on its biological characteristics.

The lagoon is 29.1 km^2 and up to 35 m deep (Salvat, 1971) with reticulations that subdivide it into numerous basins. The reticulated ridges and pinnacles among them are rimmed by reefs and break the surface forming a few (<20) small islands that suggest shell accumulations of *T. maxima.* The northwestern basin (1.7 km^2), the southeast basin (~4 km^2), and the lagoon margins are shallow and display small mounds that also indicate mapiko like those at Tatakoto (Gilbert et al., 2006b; Van Wynsberge et al., 2016). The southeast basin is mostly a sandy outer reef flat.

Reao is an elongated oval atoll about 54 km southeast of Pukarua (Figure 3.25). It is 22 km long and roughly 4.6 km at its widest in the southeast. The

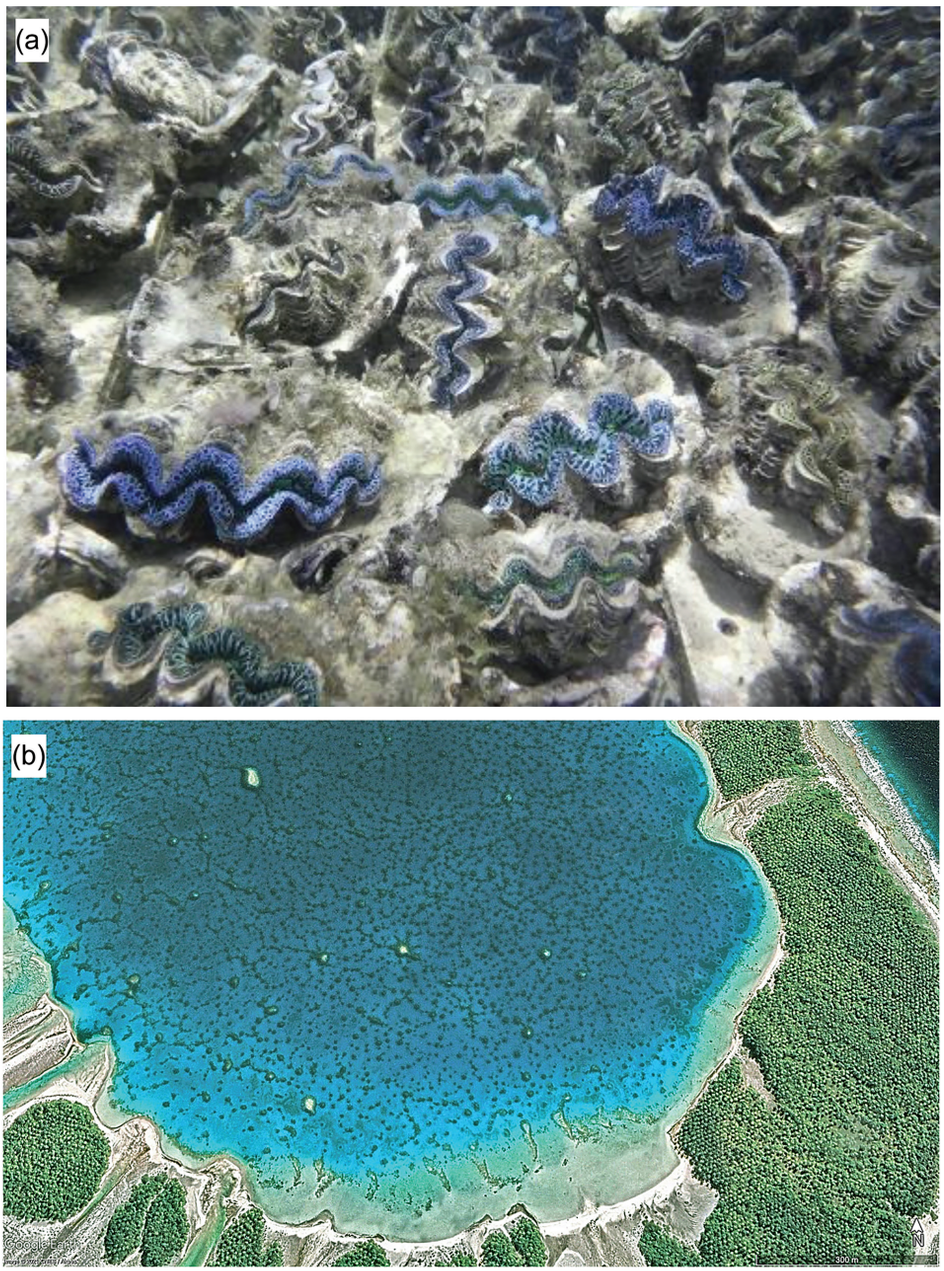

Figure 3.24 Giant clams, *Tridacna maxima*, are common in the Tuamotu group, especially within many of the closed atolls to the southeast. The bivalves are shown wedged into cracks and crevices of Tatakoto Atoll as shown (Figure 3.24a). (Photo courtesy of Direction des Ressources Marines (DRM), Papeete.) The ridged shells eventually become incorporated into the reef framework and, in some cases, contribute significantly to the process of reef building. They are particularly abundant in closed lagoon systems where they build shell mounds and what appear as dotted ridges in satellite imagery as shown in the shallow lagoon of Tenararo Atoll (Figure 3.24b).

platform area is 77.3 km^2 and is flanked by an outer reef roughly 250 m wide along the southwest side of the atoll whereas the northeastern reefs are narrower, most often 125–175 m. Reefs on the rounded ends appear to be diminished. A shallow outer reef occurs all around the island, as well as on the reef flats along the southwest. A spur and groove system surrounds the entire atoll. The rim is dominated by a 25-km-long island that extends across the entire northeast, then curves around the west and east sides. This island lies atop a foundation of gray sand and rubble. An airstrip is in the northwest and a settlement is established on the west end of this island. The southwest rim is composed of motu and hoa associated with patch reefs. The rim has no passes and is closed, but it also may be considered semi-closed as described below.

The lagoon is 40.2 km. The hoa function occasionally at high tide, but like the other closed atolls in this area, including Fangatau, Pukarua, Napuka, and Tatakoto, the lagoon supports a large *T. maxima* population (224 per m^2) in shallow water, especially along the lagoon border and other shallow areas 0–6 m deep (Salvat, 2009). Mapiko are present at the northwest lagoon and continue along the south

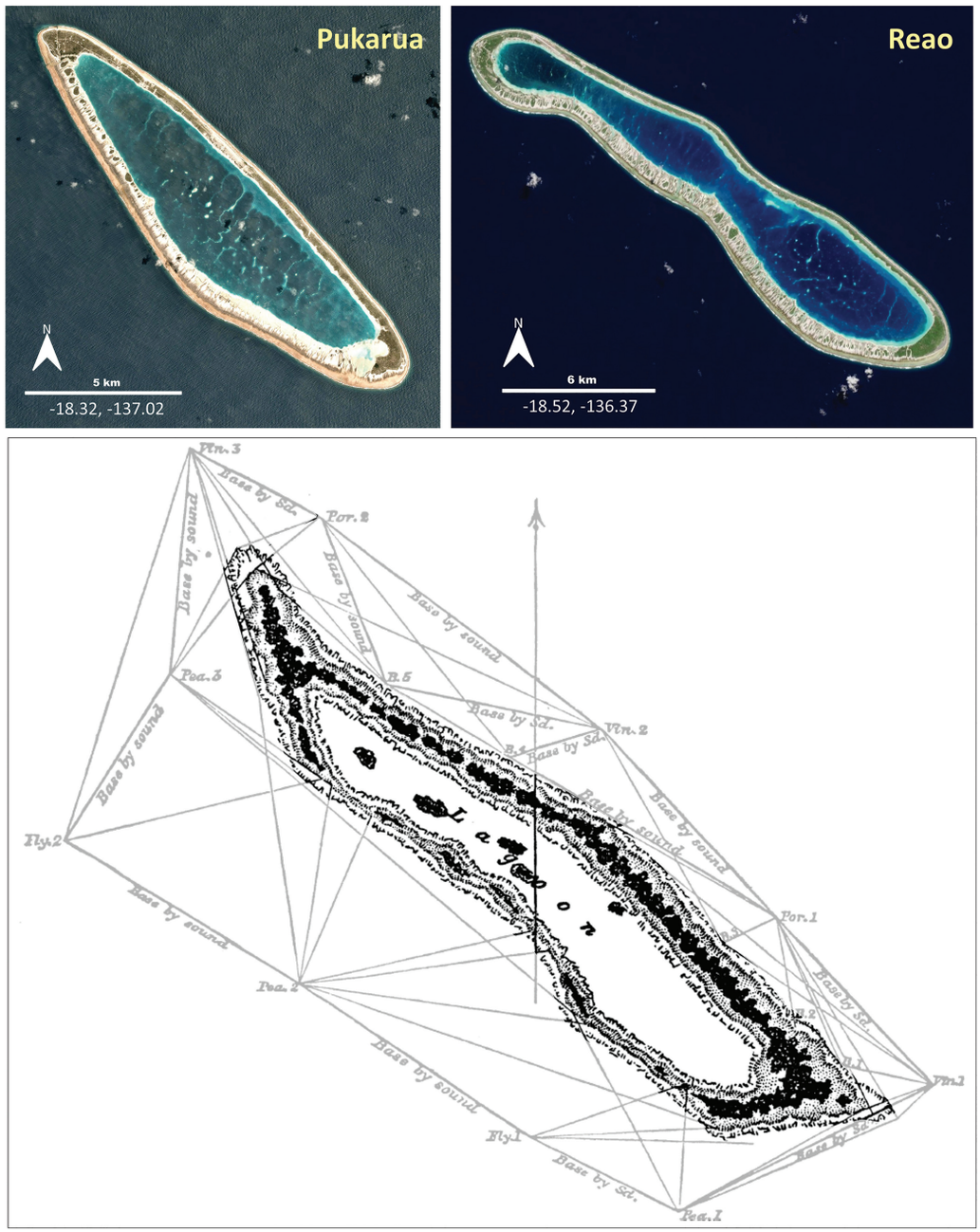

Figure 3.25 Remote-sensing images of the atolls of Pukarua and Reao. (bottom): Lieutenant Charles Wilkes explored the Tuamotus in 1839 and included mapping as an explicit mission objective. One example, from Reao (then known as Clermont de Tonerre), illustrates their rigorous technique using spider-like sight lines described in the text.

border for more than 5 km. They are also present elsewhere along the margins but in general appear to occur at a lower frequency. The lagoon is reticulated throughout, and it is 10–12 m deep in the northwest, 18 m deep in the center, and reaches a maximum depth of 29 m in the southeast. (Salvat, 1971). The basins are partially isolated by plateaus and are encircled by reefs on the lagoon slope. Several of these ridges break the surface as islands, possibly representing mapiko.

The Allen Atlas demonstrates how far technology has advanced since these atolls were first systematically examined and mapped globally. Although most of the explorers mentioned thus far made maps of various sorts, the U.S. South Seas Exploring Expedition stands out as especially meritorious in their mapmaking. Although perhaps best known for discovery of Antarctica, this voyage, led by Lieutenant Charles Wilkes, explored the Tuamotu group in 1839 and included systematic, scientific observations and mapping as an explicit mission objective. One example, from Reao (then known as Clermont de Tonerre), illustrates their rigorous technique.

Upon encountering a new atoll, two larger ships of the expedition sent out smaller boats to positions on the reef or on an island. One of the larger ships raised

a flag, then set off a shot. Personnel on the other ship and the smaller boats measured the time from seeing the shot to hearing the shot, then calculated distances. The scientists on the boats then measured angles between the two offshore ships as well as the altitude and azimuth of the ship's masts. Then, one of the ships moved to a new location, and the process repeated, as the ships and boats made their way around an atoll. After this process, the head ship collected the data, made calculations, and plotted the survey. An atoll ten km long would take less than 4 hours to map.

The results for each island included a map, such as the one shown in Figure 3.25 for Reao (Clermont de Tonerre), with the survey sight lines forming what appear to be spider webs around the atoll. Although not as pretty or colorful as a satellite image or thematic map, these charts were so accurate that they remained in use as primary navigational tools for years.

The southeastern Tuamotu group

The next set of atolls is an array of nine widespread, small, and mostly closed or semi-closed atolls at the end of the Tuamotu Archipelago, plus two more that continue the chain but are outside of French Polynesia. The first of these is **Vanavana** (Figure 3.26), a small egg-shaped atoll located 155 km south of Vairaatea. It is 3.2 km from north to south and 2.3 km east to west through the center. The platform covers 8.9 km^2. An outer reef surrounds this atoll and extends to more than 300 m to the south-southwest. In many places, the reef extends to the reef crest, which is well developed northeast–south clockwise, and onto the outer reef flats as well. The rim is dominated by two C-shaped islands, each about 3.3 km long, that face each other and are separated by two motu on both the east and west sides. The motu in turn are separated by hoa; only one on the west appears to be functional, but is limited to a width of 20 m. There are no settlements and no airstrip. The rim is closed.

The lagoon area is 3.0 km^2 and develops a wide slope to the south and a narrower one to the north, both of which are coded as reef. The lagoon also presents numerous reefrimmed pinnacles rising from the deeper basin. We are not aware of any depths or further information for this lagoon.

Tureia Atoll (Figure 3.26) is a diamond-like polygon 57 km southeast of Vanavana. The long, northwest–southeast axis is 14.1 km, and the atoll is 7.6 km wide through the center. The platform is 79.4 km^2 in extent and is surrounded by outer reefs that are about 190–250 m wide to the west and 140–180 m wide to the east. The shallow reef is quite narrow but a well-developed spur and groove system occurs around the entire atoll. The rim has a narrow single island that extends 21.9 km from the northwest to the southwest. There is a settlement and an airstrip on this island in the northwest. The remainder of the rim is composed of motu and hoa that are functional at high tide, but the rim is described as closed (Salvat, 1971). Reef patches form on the reef flat of the southwest rim, associated with the motu.

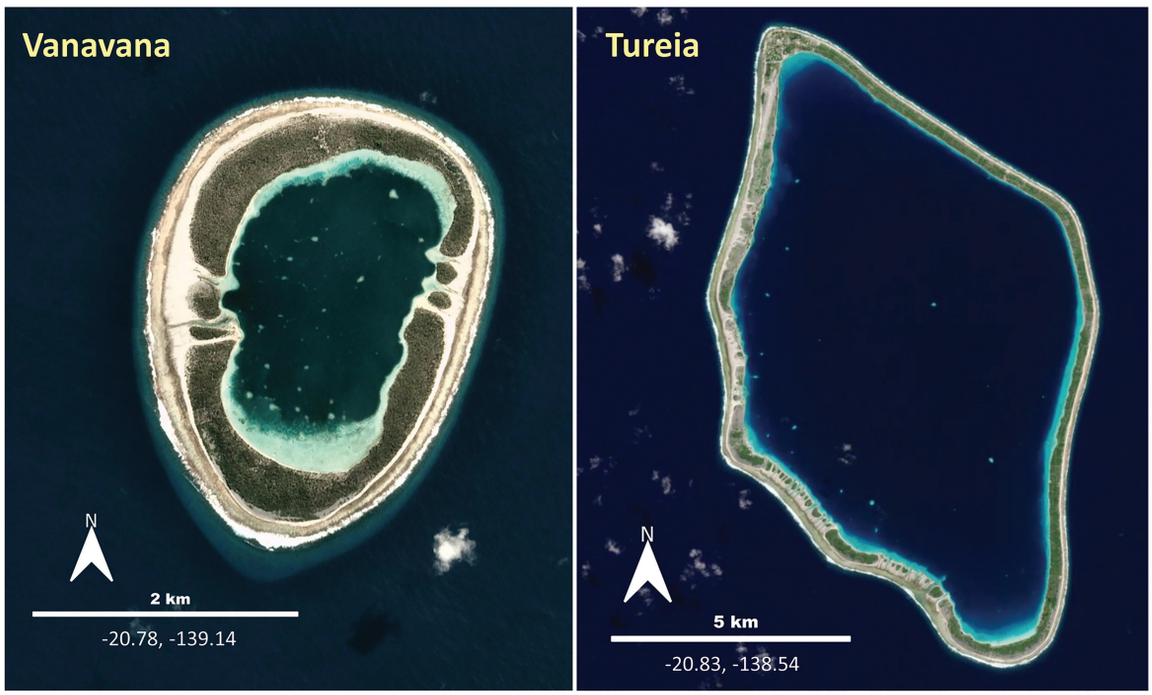

Figure 3.26 Remote-sensing images of the atolls of Vanavana and Tureia. Images © 2021, Planet Labs PBC.

The lagoon area is 59.0 km^2. Reef ribbons follow along the northwest shallow lagoon, but more generally, the lagoon margin is sandy and narrow, mostly 60–70 m wide, with little coral development. The sand areas expand to 200–300 m wide at the northwest and southeast ends of the lagoon. A few reef-rimmed pinnacles project from the deep lagoon, but most occur close to the west side. The lagoon has a maximum depth of 65 m (Salvat, 1971).

A cluster of four uninhabited atolls follows Tureia to the southeast: Tenararo, Vahanga, Tenarunga, and Matureivavao. The first three are only 7–8 km apart and represent volcanic peaks on the same plateau 650–800 m deep (SHOM Hydrographic chart 6692). The fourth is somewhat more isolated, an additional 16 km from the other three. These four sometimes are referred to as the Actéon Group, named after HMS *Actaeon*, a ship that charted these atolls in the 1830s.

The first atoll in this quadruplet is egg-shaped **Tenararo** (Figure 3.27), which is oriented with the long axis running northwest–southeast where it is 3 km long. It is 2.5 km at its widest, parallel to the northwestern side. The platform area is 7.3 km^2 and is surrounded by outer reefs 150 m wide to the north and east, and 250–300 m wide to the south and west. A spur and groove system occurs to the northeast where it is about 50 m wide. Spurs and grooves surround the rest of this atoll as well and are at least 110 m wide on the southwest side of the platform. Shallow reefs also extend a considerable distance onto the outer reef flats and follow the two open hoa into the reef flats of the lagoon where they extend among rock

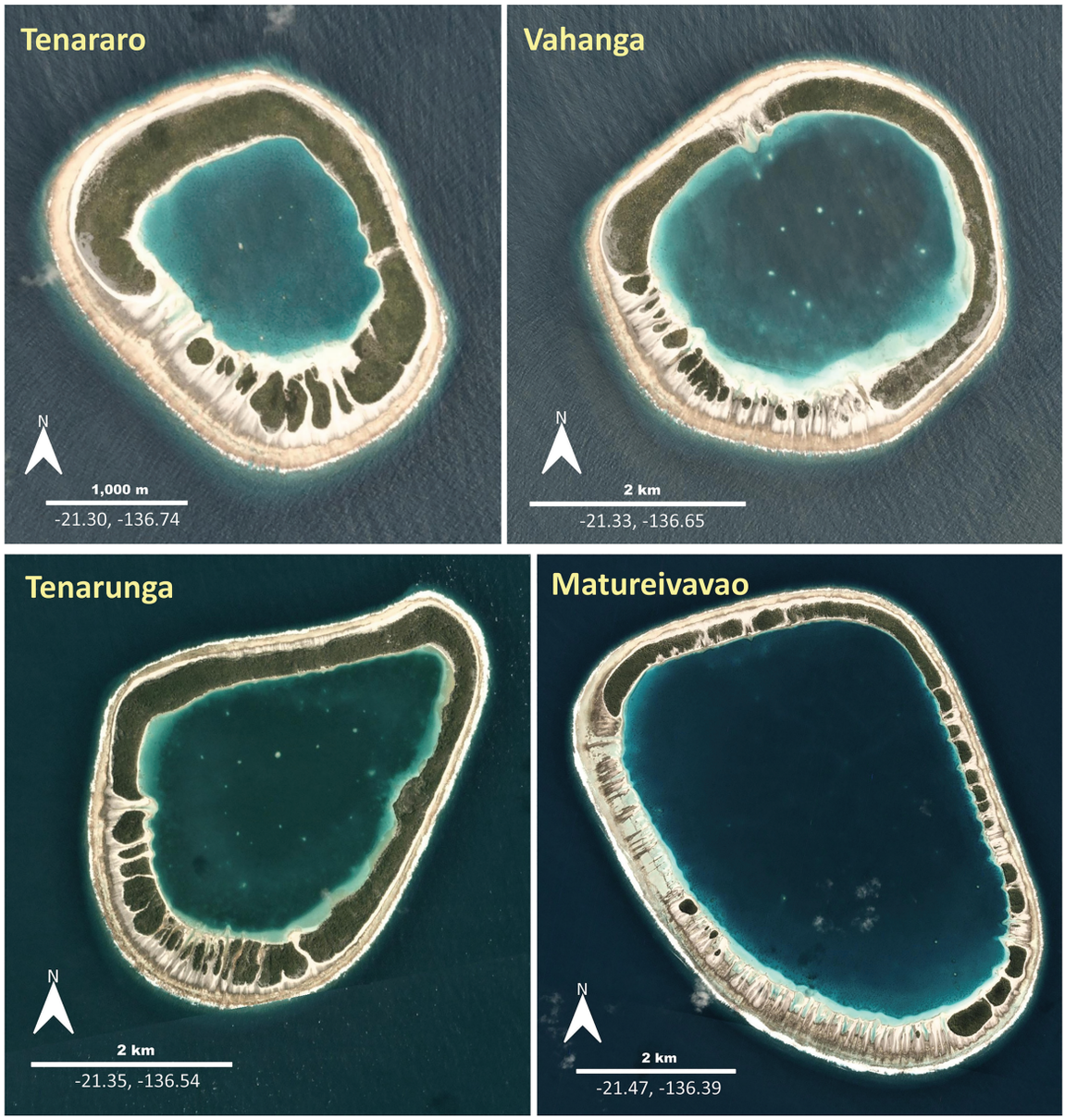

Figure 3.27 Remote-sensing images of the atolls of Tenararo, Vahanga, Tenarunga, and Matureivavao. Images © 2021, Planet Labs PBC.

and rubble along the west, north, and south margins. A C-shaped island 1.5 km^2, 4.5 km long, and 250–450 m wide dominates the north-facing rim from the northwest to the south and is densely planted with coconut palms. The remainder of the rim between the west and south is composed of motu and reef flats. Hoa are present, but with the exception of two that are 10–20 m wide on the west, they do not appear to be functional except during wind or swell events. We tentatively mark this atoll as semi-closed as further explained below.

The lagoon area is 1.8 km^2, and apart from 0.8 km^2 which may be more than 15 m deep, the majority maps as a shallow lagoon slope with a wide area of reef development. The deeper lagoon appears to have few such reefs, but the bottom of the entire lagoon appears to have mapiko-like mounds and ridges, as well as several islands that break the surface, most of them rising from shallow lagoon water. However, Salvat (2009) found that there are no important stocks of giant clams here and suggests that higher temperatures and low oxygen levels due to lagoon exchange with the ocean may be a reason for this observation. On the other hand, reef development in the two western hoa and the lagoon would appear to be rather substantial for an environmentally marginal environment. Andréfouët and Chauvin (2005) found that a bit more than 2% of the rim is open to exchange. Otherwise, we are aware of no biological or bathymetric studies, or ocean exchange estimates for this lagoon.

Vahanga (Figure 3.27) is a round atoll about 7 km southeast of Tenararo. The platform is 3.7 km from north to south and 4.0 km from west to east, covering an area of 12.9 km^2. An outer reef mostly about 200–300 m wide occurs to the west–southwest compared with about 150 m wide to the east. The outer reef to the north–northeast also is narrow, but a reef crest is better developed in that location. As on Tenararo, the entire atoll is rimmed with a spur and groove system. The rim is also similar to Tenarao by the presence a C-shaped 2.0-km^2 island, 6.8 km long, and mostly 250–350 m wide, that extends from the northwest to the south on the north-facing rim of this atoll. The island lies on a gray sand and rubble ridge. A partial break in the island faces the northwest, and the remainder of the rim from the southern to the western flanks is composed of motu. Many of the intervening hoa appear to be raised and may be functional only during storm or swell events. Correspondingly, Andréfouët and Chauvin (2005) found that only about 1% of the rim is open to oceanic exchange.

The lagoon area is 5.9 km^2, and we estimate the shallow lagoon to account for 1 km^2 of that area, about 2.5 km^2 is apportioned to the slope, and 2.4 km^2 is likely deeper than 15 m where most of the approximately 12 reef-draped pinnacles occur. Salvat (2009) reported a high diversity of bivalves in this lagoon including *T. maxima*. We mark this lagoon semi-closed.

Tenarunga Atoll (Figure 3.27) is 8 km east from neighboring Vahanga Atoll. The platform is 14.2 km^2 and is ovotriangular or teardrop shaped with an apex facing northeast. The distance from the apex through the rounded southwestern face of the atoll is 5.0 km. The widest part of the platform of the perpendicular, northwest–southeast axis is 3.5 km long. The outer reefs surround this atoll and extend from about 200–350 m northeast–south, narrowing to less than 200 m wide elsewhere. As with many of its neighbors, there is a well-developed spur and groove system surrounding this atoll. The rim is composed of a single island, 7.8 km in area and 16.7 km^2 long, that accounts for 73% of the perimeter. The remaining rim at the southwestern flank is composed of motu and hoa that may be functional only during wind and storm events. Andréfouët and Chauvin (2005) recorded zero openings in the rim for oceanic exchange. Nonetheless, the lagoon supports a large and diverse population of bivalves (see below). We mark the rim semi-closed.

The lagoon area is 6.3 km^2, and the lagoon slope is very steep and narrow along the western and eastern margins, becoming gentler and wider to the northeast and southeast. A limited shallow area is favorable for large numbers of *T. maxima*, but the lagoon supports a diverse population of other bivalves as well (Salvat, 2009). The deep central lagoon is relatively large and accounts for roughly half of the total area where about 15 reef-covered pinnacles rise, a few of which break the surface. We are not aware of any bathymetric data for this lagoon.

Matureivavao (Figure 3.27) is an ovoid atoll with a flat northwestern flank. The platform area is 28.9 km^2, 6.4 km long bisecting the flat side from the southeast, and 4.9 km at the widest, parallel to the northwest flank of the atoll. An outer reef about 150–200 m wide is found surrounding most of the rim along with a spur and groove system. Patch reefs occur on the reef flats southeast–southwest. A continuous island 5.1 km long with an area of 1.1 km^2 occurs on the northern rim. Compared with the drawing provided by Renaud-Mornant and Salvat (1971), there appears to have been some erosive changes to this island, especially in the central 2 km where several areas are now without vegetation, compared with the rest of the island that is fully vegetated. The eastern and southeastern rims are composed of motu and hoa that appear to be elevated above high tide to some degree. The southern

and western rims are 6.5 km long and are composed of several motu with hoa and adjacent reef flats with a rubble bottom. Reef patches occur at several places on the outer reef flats and on the lagoon side of the hoa. The sandy inner reef flat exceeds 300 m wide locally on this waveward margin. There are no passes, but the presence of reefs on the flats as well as the lagoon fauna (see below) suggests that oceanic exchange occurs with the highest tides (Salvat, 1971); the rim is semi-closed.

The lagoon area is 17.5 km^2. The northern and eastern margins of the shallow lagoon are rimmed with reef ribbons. Satellite imagery shows that the shallow eastern and western lagoon flanks display a more precipitous descent into the deep lagoon compared with the northern or southern flanks. The northern lagoon slope is 5 m deep about 25 m from shore, gradually descends to 14 m about 1700 m from shore, then drops precipitously to 40 m. The bottom of the shallow southern lagoon is sand, zone up to 180 m wide. It then slopes gradually and descends to 45 m, the deepest part of the lagoon (Renaud-Mornant and Salvat, 1971). Sand persists along the shallow water of the western lagoon although it mostly 50–60 m wide. Seven pinnacles can be seen on the images in the s lagoon slope. The upper parts of these structures support *T. maxima*, among other bivalves, in large populations (Renaud-Mornant and Salvat, 1971; Salvat, 2009).

Three additional atolls are found to the southeast of Matureivavao, including Marutea South, Maria Est, and Temoe, the last of the Tuamotu atolls.

The form of **Marutea Sud** (Figure 3.28) is that of a warped rectangle located 75 km east of Matureivavao. The platform area is 142 km^2 and extends 20.8 km from the northwest to the southeast corner and 11.6 km northeast–southwest. The outer reefs are variable and range from about 130–160 m wide to the northeast near a reef crest, about 175–200 m wide to the west, and up to 400 m to the southeast and southwest. As with all these isolated atolls in the southeastern Tuamotu Archipelago, Marutea Sud is surrounded by a well-developed spur and groove system that extend 120 m from shore, compared with about 80 m wide at the northeast. Islands on the four corners of the rim lie atop gray ridges of sand and rubble. The northwesternmost island, Viatutaki, includes an airstrip. A distance of 1.2 km^2 separates Viatutaki from Arumu, which curves in the northeast and is 2.1 km long. This 47-ha island contains a small area where buildings dedicated to a pearl farming are located (Marutea Sud Atoll is privately owned by Robert Wan, the 'Pearl King,' as a commercial black pearl operation). Amanu is separated from the next island, Teupukahaia, by a 100-m-wide hoa. This island is the longest on Marutea Sud and begins on the eastern flank where it is about 200 m wide and expands to about 550 m wide at its southeastern terminus. Another hoa about 100 m wide is found on the southeastern end of this island. From the terminus of the long island to the southernmost 66-ha island, Vainono, is a 10-km-long expanse composed of islands, motu, and hoa, as well as reef flat segments. There are additional buildings on Vainono. The southern and western rims from Vainono to Viatutaki on the north cover 15.5 km and are composed primarily of motu and hoa with a single island about 1.8 km long in the middle; the rims there can exceed 500 m width. There are numerous points of oceanic exchange with the lagoon through hoa and reef flats, especially on the southern rim, but there are no passes. This atoll is semi-closed.

The lagoon area is 111.5 km^2. The outer reef flats and the shallow lagoon are predominantly sand, although patch reef ribbons are also found on the outer reef flats on the west and southwest. The widest expanse of sand in the shallow lagoon is in the northwest in the lee of Viatutaki where it extends more than 200 m. The shallows are narrow at all points and the lagoon slope descends precipitously except in the lee of Vainono in the south where it extends about 500 m wide before reaching the deepest part of the lagoon, where i is at least 50 m deep. Numerous pinnacles are reef-rimmed and several of them break the surface. Very large stocks of the black-lipped pearl oysters, estimated to be more than 10 million individuals, are found at depths of between 30 and 50 m in this lagoon (Andréfouët et al., 2016) and stocks of *T. maxima* occur as well (Salvat, 2009), although they may be more limited by the extent of shallow-water habitat.

Maria Est (Figure 3.28) is a small ovoid atoll with a flat side facing the east, located 75 km southwest of Marutea Sud. The northeast–southwest axis is 5.8 km, and the perpendicular axis is about 2.9 km at its widest. The platform extent is 15.9 km^2, including an area to the southeast where Allen Atlas coverage is missing. An outer reef extends around the platform and is about 150–200 m wide, extending to about 280 to the southwest. A well-developed spur sand groove system extends 60 m from the eastern reef crest here and everywhere else around this atoll, especially at the waveward southwest, where it extends to 120 m from wave break (Figure 1.9a). The rim forms a reef crest to the east and is composed of four islands, one facing north, followed by another, 2.1 km long on the east that curves toward the southeast. It appears that natural vegetation is absent on the southeastern point, exposing a gray sand and rubble ridge that underlies this and other neighboring islands. A narrow

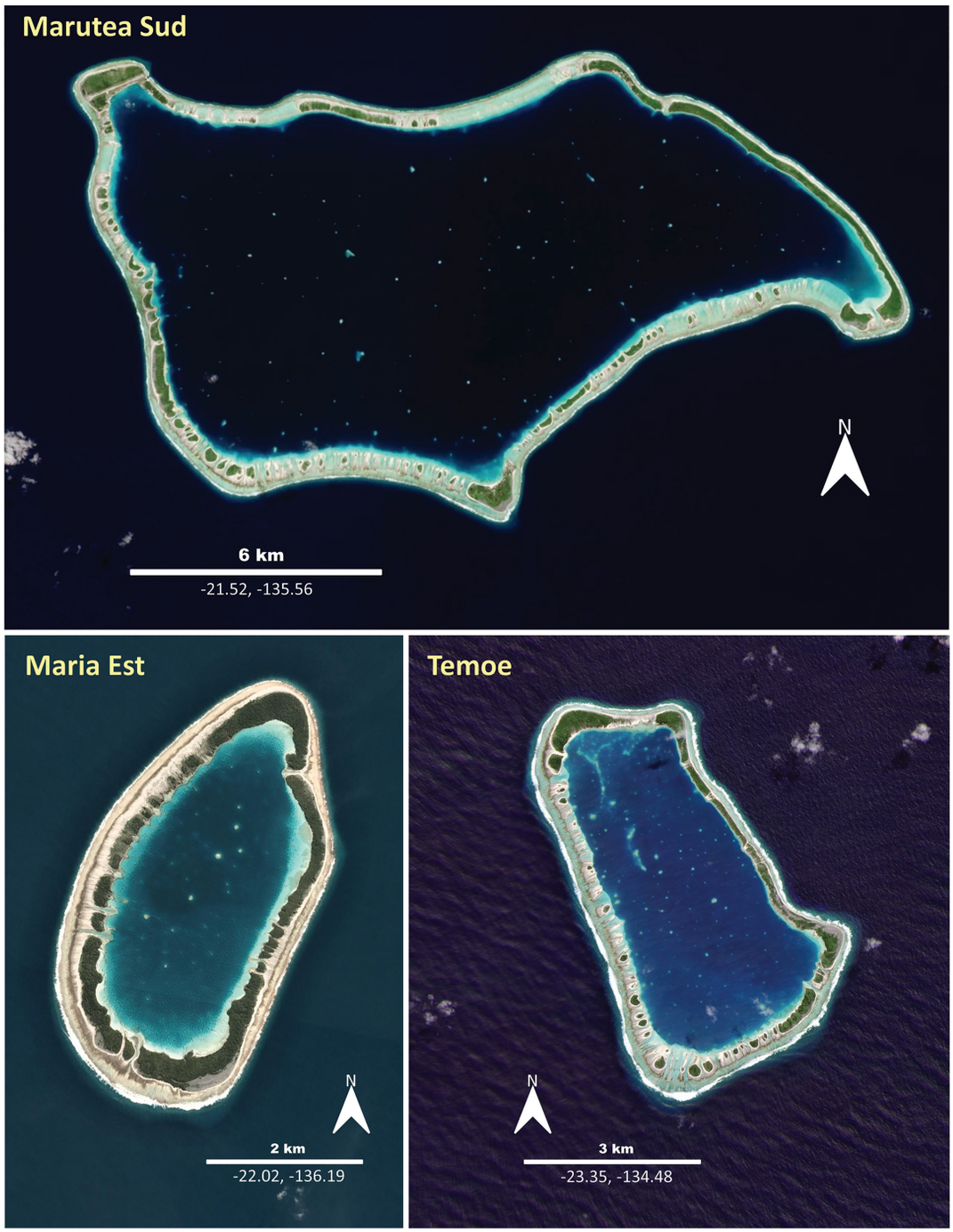

Figure 3.28 Remote-sensing images of the atolls of Marutea Sud, Maria Est, and Temoe. Images © 2021, Planet Labs PBC.

(30-m-wide) channel separates the two islands at the middle of the flat eastern side. Five motu and hoa follow in the next 690 m of the rim, running to the southwest. None of the hoa on the eastern rim are at sea level, and all appear to be non-functional. A third island about 2.3 km long extends from the southeast and curves around to the south. The fourth island, 1.7 km long, occupies the southwest and west rim, and it is separated by narrow channels on both ends. The remaining 2.7 km of the rim on the west is composed of motu with hoa that are blocked by sediment and are unlikely to exchange ocean water with the lagoon except with assistance from wind or swells. Conversely, the lagoon biota (see below) suggest that the rim is semi-closed.

The lagoon area is 7.1 km^2. Reef development that occurs on the reef flats along the west is limited to the outer reef flat on the western lagoon margin. A sandy perimeter up to 250 m wide forms the shallow lagoon, which extends down part of the lagoon slope on the southeast and the west as the lagoon drops rapidly into deeper water. By contrast, it does so more gradually on the northeastern and southwestern boundaries. Several pinnacles rise from the

lagoon slope in the southwest although fewer do so on the northeastern slope. Both areas appear to develop mapiko, as do the narrow shallow water areas on the eastern and western lagoon. Large stocks of *T. maxima* are known to occur here (Salvat, 2009) despite only 1.2% of the rim being open to exchange (Andréfouët and Chauvin, 2005). About a dozen pinnacles rise from the deeper lagoon, most of which are reef rimmed; some break the surface as well. We do have any details of the depth or renewal time for Maria Est lagoon.

Temoe (Figure 3.28) is the southeasternmost atoll of the Tuamotu Islands. It is oblong and about 38 km southeast of Mangareva, an almost-atoll containing 14 volcanic islands in its lagoon, several of which rise 130–400 m above sea level. Its nearest neighboring atoll is Maria Est, 224 km to the northwest. The platform area is about 28 km^2 with uncoded reefs to the south. The longest axis is 7.3 km northeast–southwest, and it is 4.5 km at its widest, across the southern part of the rim. The outer reefs encircle the entire atoll and are widest to the southwest where they exceed 750 m in width, and 200–400 m wide elsewhere. The shallow outer reef follows suit and overlaps with the reef crest and outer reef flats. Pirazzoli (1987) reported a spur and groove system on the south and west of the platform. The eastern flank of the rim is essentially a single island that is 5.6 km long with 3–4 breaks in continuity, possibly representing closed and elevated hoa. The available imagery is insufficient to assess those details. Most of this island is about 200 m wide, but it expands at its southern terminus to 370 m. The southeastern point has been stripped of vegetation leaving an exposed ridge of gray sand and rubble as on Maria Est. Two smaller islands occur on the rim including one at the southeast atoll corner with an area of 21 ha and the other in the northwest that occupies 44 ha. The remainder of the rim is composed of motu with narrow hoa and reef flats in the south and west. The rim here approaches 800 m wide at the southern atoll tip but is mostly around 400 m wide. The most hoa are narrow or occluded by sand and, except for a few that are functional, are inactive with normal tides, but likely become active with austral swells (Pirazzoli, 1987). Andréfouët and Chauvin (2005) calculate that 10% of the rim is open to oceanic exchange. The rim is semi-closed.

The lagoon area is 13.6 km^2, the average depth is about 13 m, and the maximum depth is 23 m (Pirazzoli, 1987). Sand occupies much of the shallow lagoon but most of the lagoon slope is steep. Reef development on plateaus, ridges, and numerous pinnacles that are found here, a few of which reach the surface. Large stocks of *T. maxima* have been reported from this lagoon (Salvat, 2009).

Two atolls, Ducie and Oeno, lie outside the boundaries of French Polynesia but represent young formations that lie closer to a hotspot now located about 80 km east of Pitcairn Island than to the Tuamotu group (Figure 3.2). This pair has a different and more recent origin than those atolls described thus far and are perhaps only a few million years old, whereas the atolls at the southern end of the Tuamotu group are about 6.5 million years old (Delavault et al., 2016). The first of the Pitcairn group is **Oeno** (Figure 3.29), a round atoll that lies 383 km southeast of Temoe and 139 km northeast of volcanic Pitcairn Island (Figure 3.2). The platform area is 13.1 km^2 as mapped by Allen Atlas, but the satellite imagery shows a deep outer reef that extends 200 m or more seaward of the coded reefs. A platform map that includes those areas covers 15.3 km^2, 3.2 km from north to south and 4.2 km west to east. The outer reef is variable in extent but is commonly more than 300 m wide to the north including uncoded areas; the rest is mostly 150–250 m wide. High-resolution imagery shows a spur and groove system around most, if not all, of this atoll. The rim is submerged and is composed of rock and rubble. A single 62-ha Oeno Island extends northeast into the lagoon from the southwestern inner reef flat. The northeast 3 ha of the island shows signs of erosion with some vegetational loss and extends farther northeast as a sand spit (area not included).

The mostly sandy outer and the inner reef flats extend well into the lagoon, especially in the southern half. There are a few small areas mapped as reef in the lagoon on these flats, but none that are clearly within the lagoon shallows. The irregular extent of the inner reef makes it difficult to estimate the lagoon area. Two areas of shallow lagoon occupy the northwestern and eastern areas and these two combined occupy approximately 3.7 km^2, mostly coral rubble and sand, none of which is more than 3 m deep (Devaney and Randall, 1973; Pandolfi, 1995).

The second atoll in the Pitcairn hot spot chain is **Ducie** (Figure 3.29), which is egg shaped and canted somewhat southwest–northeast, where it is 3.2 km long and 2.4 km at its widest on the west. The platform as mapped by the Allen Atlas is 6.4 km^2, but like on Oeno, there is a considerable area that apparently is deeper than 15 m and is unmapped. If included, the platform area measures 8.6 km^2. The outer reef surrounds Ducie and becomes best developed to the northeast where it reaches a width of 175 m. Devaney and Randall (1973) found that corals on the outer reef to a depth of at least 30 m were dead and covered by coralline algae, although we cannot be certain if that is still the case. A spur and groove system surrounds most of the atoll although available imagery lacks sufficient detail to observe the entire periphery.

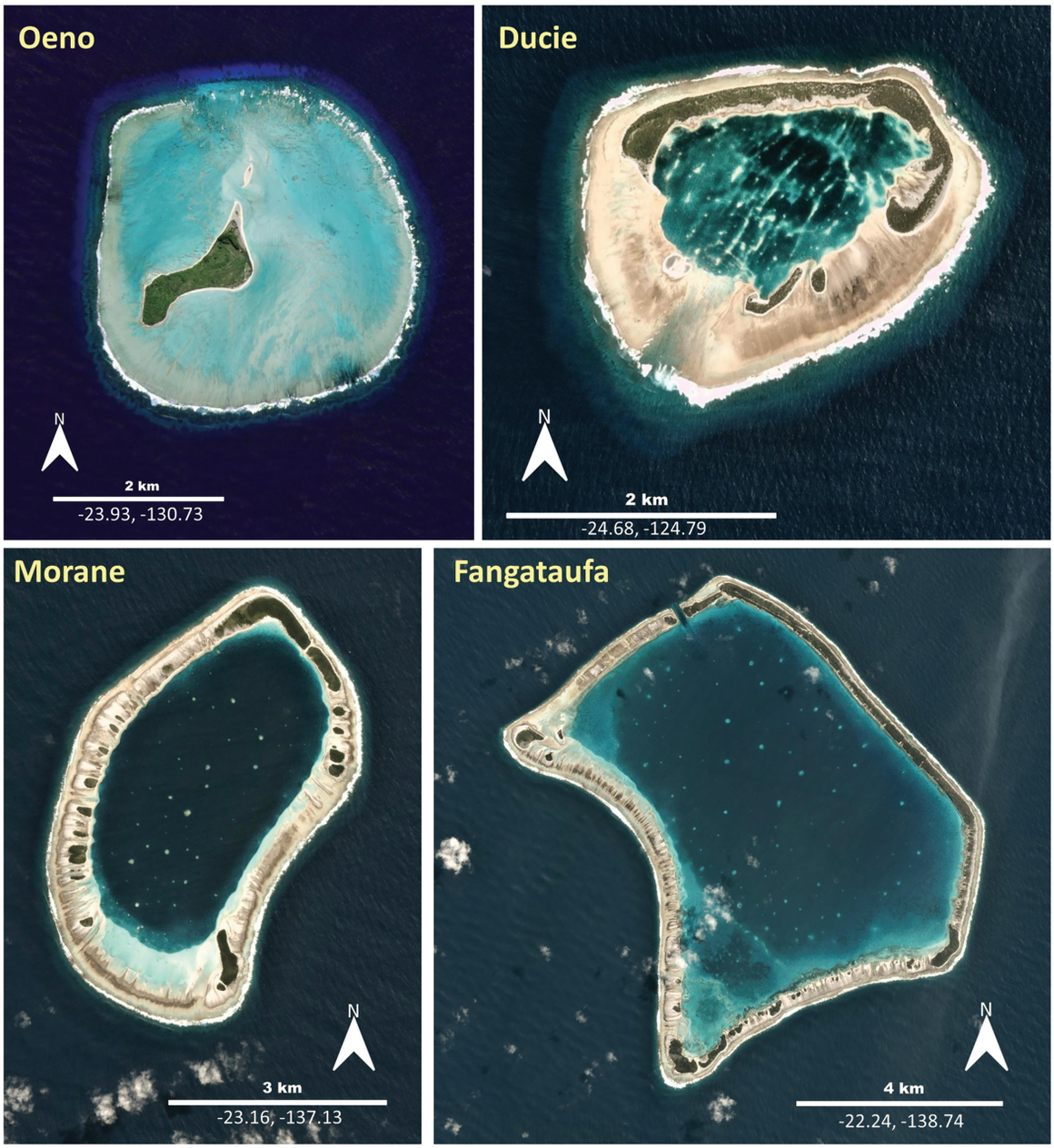

Figure 3.29 Remote-sensing images of the atolls of Oneo, Ducie, Morane, and Fangataufa. Images © 2021, Planet Labs PBC.

The rim is dominated by 68-ha Ducie Island on the north rim that curves on the east. Most of it is less than 200 m wide, but the island expands at the ends to 290 m wide. There is some vegetative erosion on the curved section on the northern and eastern lagoon sides, where the island ridge composed of gray sand and rubble is exposed. The remainder of the south-facing rim extending 2.9 km from the southeast to the northwest is mapped as a submerged outer reef flat, except for two small islands on the southern rim. Most of the flats are rock and rubble but the outer edges are rimmed by reef on the west, north, and northeast sides. There is a shallow channel about 250 m wide on the southwest side of the rim that according to Devaney and Randall (1973) can be negotiated by a small boat, except at low tide. This small channel is the main exchange route for the lagoon, although some water passes between two islets on the south side during high tide. Devaney and Randall found this channel with a moderate amount of small but live coral colonies, in contrast to the lagoon.

The lagoon is 1.8 km^2 and is reticulated, and the Atlas shows that reefs occur on many of the ridges. Devaney and Randall found the lagoon is at most 16 m deep with irregular coral heads that are interconnected at their bases. Many of them reach the surface, but the corals were completely dead. The water

in the deeper lagoon had a dark greenish cast, likely reflecting the low level of flushing by ocean water. The Devaney and Randall study suggested that coral death was recent, perhaps only a year prior to the early 1970s, but no cause was given. We are unaware of any investigations that might address more recent conditions on this small atoll, one of the most isolated in the world and the southernmost in the hemisphere. Given this single report, we regard this atoll as closed.

Turning west from the Pitcairn group and Temoe, we encounter **Morane** Atoll (Figure 3.29) located within the boundaries of the Tuamotu group. This is an ovoid atoll oriented from northeast to southeast where it is 6.1 km long and 3.8 km at its widest. It is located about 154 km southwest of Maria Est and 268 km west of Temoe. The platform is 20.9 km^2 and it is surrounded by outer reefs that generally range from 225–290 m wide. Patch reefs occur associated with islands and hoa in the southeast and southwest. Two islands occupy the north and northeast rim, and these are followed by about a kilometer of motu and closed hoa on the northeast-facing rim and 2.7 km of reef flats that complete the southeastern rim. Two small islands of about 15 ha occur at the southeast corner of the atoll, followed by a reef flat 2.3 km long on the southwest rim, the eastern half of which may be above sea level, whereas the western half is at or below sea level. The remainder of the rim on the west is composed of motu and hoa. The rim is semi-closed.

The lagoon area is 10.1 km^2 and is rimmed by sand in the shallows where it overlaps with the outer reef flats. The sandy rim is least developed on the western flank and reaches its greatest extent in the shallow southwest lagoon where it is up to 500 m wide. The outer reef slope is surrounded by reef including its pinnacles. Many of the pinnacles that rise from the deep lagoon break the surface and are also reef rimmed. Although we know of no bathymetric data or specific studies on the lagoon biota, analyses strongly suggest a high genetic diversity and a large population of *Pinctada margaritifera*, the black-lipped pearl oyster here (Lemur and Planes, 2014).

Mururoa and Fangataufa atolls are found to the northwest of Morane and lie on volcanic basements about 10–11 million years old. Even though they are in the Tuamotu group geographically, they are derived from the same hotspot and are much younger than their Tuamotuan neighbors (Buigues, 1997). By extension, the Duke of Gloucester Islands, 435–660 km northwest of Moruroa, should be about 25 million years old, although that age has not been confirmed. This entire chain of 11 atolls from Pitcairn to Hereheretue (Figure 3.2) is sometimes inharmoniously referred to as the Duke of Gloucester-Mororua-Pitcairn volcanic alignment (Neall and Trewick, 2008; Bonneville, 2009).

The Muroroa volcanic alignment to the west of Morane includes Fangataufa and Mururoa. **Fangataufa** Atoll is about 188 km northwest of Morane and 146 km south of Tureia. Its closest neighbor and sister atoll is Mururoa, located 37 km to the southeast, described below. Fangataufa forms a warped rectangle with a concave western side (Figure 3.29). The platform is 10.1 km northeast–southwest and the same distance northwest–southeast. The platform is 55.3 km^2 in extent and is surrounded by an outer reef that varies considerably, but covers 375–400 m to the west-northwest, 100–250 m wide to the east and up to 380 m to the southwest. The rim on the northeast is composed of a single island 6.9 km long although there are a few partial hoa on its ends. Motu with blocked hoa occur on the southeast rim, followed by an island and additional motu on the south rim, all of which are traversed by a causeway. Some of the hoa may be functional, but most are blocked. The rim in the west is composed of motu and hoa that are associated with well-developed patch reefs and face the prevailing swells (Villiers and Bodiou, 1996). A small island protruding west separates the rim at the northwest, which is at sea level and is open to exchange. Fangataufa's lagoon was closed, but in 1966, an artificial channel 60 m wide was dredged to a depth of 6.5 m. However, entry here (and on Mururoa) is prohibited without permission of French military authorities (Sailing Directions, 2017).

The lagoon area is 37.3 km^2 and the maximum depth is 45 m (Villiers and Bodiou, 1996). It is surrounded by reefs in the shallow lagoon. Reefs are also present at the southwest 'apex' area and partially enclose the lagoon slope. Reef-associated pinnacles are scattered throughout the deep lagoon. The *Tridacna* population was destroyed by atmospheric testing of nuclear weapons, especially after Conopus, a 2.6 MT blast set off at low tide in 1968. There appears to be no substantive population in Fangataufa's lagoon (Legendre and Salvat, 2015). The rim is closed.

The considerable geological information available concerning **Mururoa** is summarized by Montaggioni et al. (2015). This atoll formed from a volcano that ceased activity about 10.5–11 million years ago and has since accumulated a carbonate cap that varies between 130 and 570 m thick. It is located 105 km south of Tureia and 173 km east of Temitangi, and it has an irregular, elliptical shape, 28 km long and 11 km wide (Figure 3.30). This configuration is no doubt due to its foundation composed of two volcanic peaks joined by an isthmus. The platform is 172 km^2 and is surrounded by outer reefs that are 150–400 m wide. However, reefs become 1,300 m

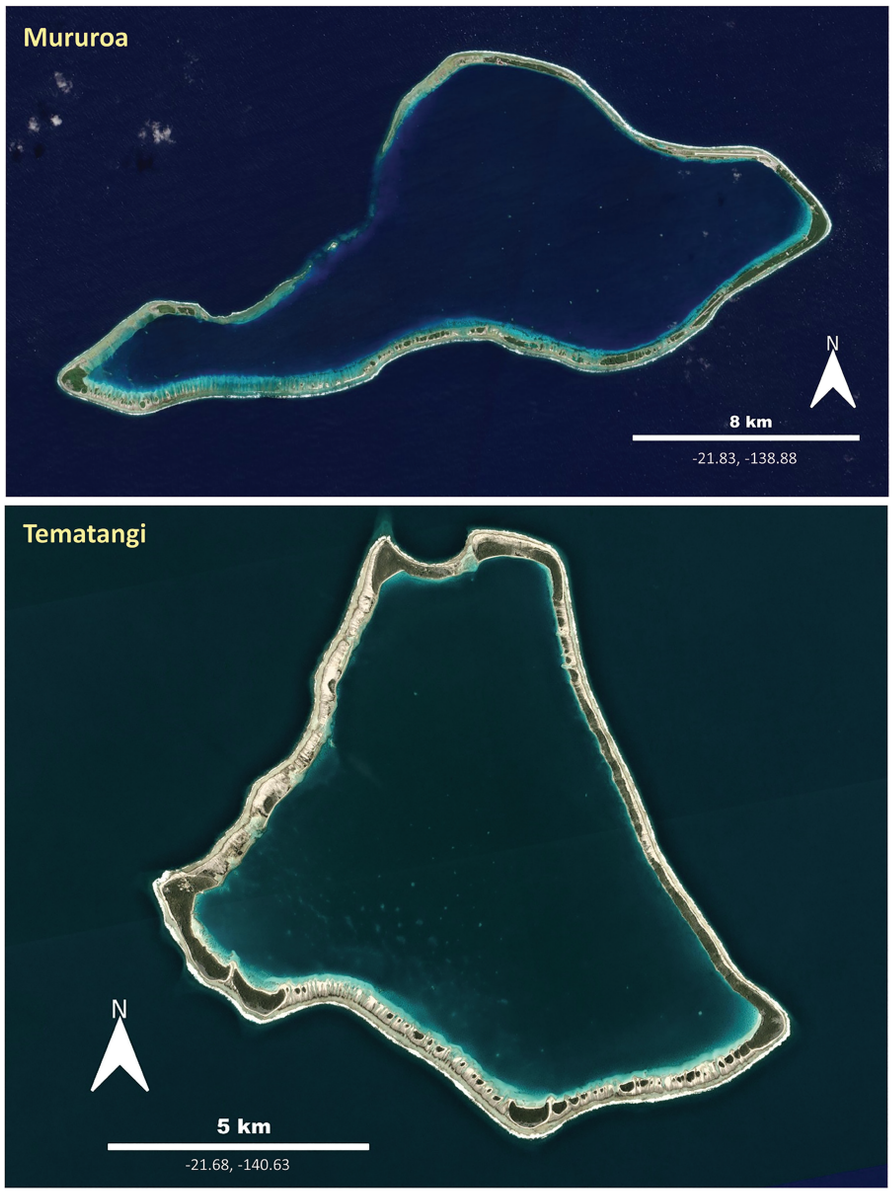

Figure 3.30 Remote-sensing images of the atolls of Mururoa and Tematangi. Images © 2021, Planet Labs PBC.

wide on the south side in the direction of the dominant southeasterly winds and southerly swells that typically roll in at less than 3 m (Montaggioni et al., 2015). The shallow outer reef continues onto the outer reef flat to the south. The rim is most strongly developed along the eastern half where a single island about 13.2 km long is found. There are two airstrips, one to the north and the other on the southeast part of this island. The southern rim is composed of islands and motu as well as an extensive submerged reef flat at the southwest that allows oceanic swell to directly enter the lagoon (Montaggioni et al. 2015). A 62-ha island marks the western rim. We refer to the rim northeast of this island as the northwest side. The northwest rim follows a curved path about 19 km long toward the north. This section is primarily a reef flat interrupted by two small islands. A 5-km-long section in the middle is submerged to a depth of 9 m, saves one 30-ha island in the center, and constitutes a pass (Montaggioni et al., 2015). As we detail below, not all of this pass is natural. The rim is open, and we note among all the closed and semi-closed atoll in this region, that the nearest open atoll is Nengonengo, 445 km to the northwest. The northern rim is composed of motu that are collectively about 2 km long and a 57-ha island that is 3.5 km long.

The lagoon area is 136.4 km^2 with a mean depth of 33 m, a maximum depth of 52 m, and a renewal time of about 100 days primarily due to wind stress rather than tidal currents (Tartinville et al., 1997; Montaggioni et al., 2015). Patch reefs along the reef flats occur in the lagoon, near the western island, and adjacent to the airstrips. These reefs pass to the sandy shallow lagoon to the south where they extend

west–east and the deepest lagoon areas are near the center (Montaggioni et al., 2015), where many pinnacles are found. A majority of these are rimmed by reef.

The broader focus on Muroroa stems not just from a curiosity about atolls but also from an interest in a place where France might test a few nuclear weapons. From 1975 to 1996, a total of 127 underground tests were conducted at Mururoa (along with ten at nearby Fangataufa) in sealed shafts drilled 500–1,000 m under the rim or in the lagoon (Muslow et al., 1999). This number does not include at least 41 atmospheric tests during the period of 1966–1974. Many of these were conducted on small islands at the west and north of the atoll, although some were conducted on barges in the lagoon, or were dropped from bombers, or were exploded over the atoll from platforms suspended by helium-filled balloons (Drozdovitch et al., 2020). One of the underground tests in 1979 was to be conducted in an 800 m shaft on the northwest rim, but the device became stuck halfway down. A decision was reached to detonate it anyway, and the result was a major underwater landslide with an estimated volume of between 75 and 220 million cubic meters that not only submerged the rim at the test site but also generated a tsunami with wave heights of 5–6 m. The wave completely submerged the south rim of Mururoa, the north rim of Fangataufa, and much of Tureia 105 km away (Morrison et al., 2013; Poupardin et al., 2017). The political fallout from these nuclear tests is outlined by Goldberg (2018).

Tematangi (Figure 3.30) is a polygonal atoll located about 159 km west–northwest of Mururoa. The distance from the center of the depressed northern face to the center island on the south of the atoll is about 11 km, and it is approximately 12.5 km at its widest from the westernmost apex to the easternmost apex. The platform area is 88.1 km^2,and is surrounded by outer reefs that are widest to the south and southwest where they extend 500–750 m; elsewhere they are 150–190 m wide with smaller areas where they are narrower. The atoll is also surrounded by a spur and groove system.

The rim is composed of two crescentic islands at the north separated by a reef flat 250 m wide, much of which is at sea level. An island in the center part of the east-facing rim is 2.3 km long and is followed by another 2.1 km long island that wraps around to the southeastern rim. These islands appear to have been joined and low areas between them may have been created by storms. The south and southwest rim is composed of motu and hoa, some of which are functional judging from the presence of reefs between motu. The western rim bears two crescentic islands, the northernmost of which has a settlement, but there is no airstrip on this atoll. The northwest rim is composed of low islands with two reef flats between them, the first is 290 m wide and the other is 130 m. Both may be open to oceanic exchange. There are no passes, and the lagoon is semi-closed as described below.

The lagoon is 60.9 km^2 in extent. The shallow lagoon develops a sand deposit to the southeast that is up to 250 m wide but become narrower where they are present elsewhere. Reefs are present scattered in the lagoon There are a few mapiko in the shallows on the west, and Salvat (2009) indicates that there are large stocks of *T. maxima* in this lagoon. Sand about 200 m wide forms the shallow lagoon of the south and southeast, narrowing to about half that width elsewhere. We are aware of no data on lagoon biota, bathymetry, or hydrodynamics.

Continuing to the northwest from Tematangi, three closely spaced islands are encountered, and these are sometimes referred to as the Duke of Gloucester Islands, named by Philip Carteret in 1767. However, they are also likely to be the same islands sighted by Pedro Fernandez de Quir*ós* in 1606 who saw all four and named them Las Quatro Coronados (Wallis, 2011). The first of these four is **Nukutepipi**, a small atoll in the shape of a truncated triangle 267 km northwest of Tematangi (Figure 3.31). The platform area is 8.0 km^2 and is 3.9 km from the southeastern 'apex' as it bisects the base, and the platform is 2.6 km at its widest. The Atlas suggests that the atoll is surrounded by reefs 300–350 m wide northwest–southeast, and 175–225 m northwest–east.

The rim supports two islands. The first is 1 km^2 that extends from the north to the southeast parts of the atoll; an airstrip is present here. The second island is 28 ha and faces northwest. A channel about 150 m wide separates the two islands and is one meter deep. The southwestern rim is primarily sand on an inner reef flat about 1.5 km long mixed with a shallow lagoon no more than 2 m deep. Scattered corals are found here, but there is no reef development. However, this is the typical entry point for ocean water entering the lagoon with southerly winds and exiting through the hoa (Salvat and Salvat, 1992). The rim is closed.

The lagoon area is 1.2 km^2. If the sandy reef flat is excluded from the shallow lagoon, the lagoon area is 92 ha. Salvat and Salvat (1992) found pinnacles or patch reefs that rise from the deepest lagoon, which reaches its maximum depth of 17 m.

Anuanurunga is 23.5 km northwest of Nukutepipi. The atoll is egg shaped, with a north–south axis 3.3 km long and 2.7 km through the middle from west to east (Figure 3.31). The platform extent is 8.9 km^2 and it is nearly surrounded by a deep outer reef, except for about 400 m in the southeast.

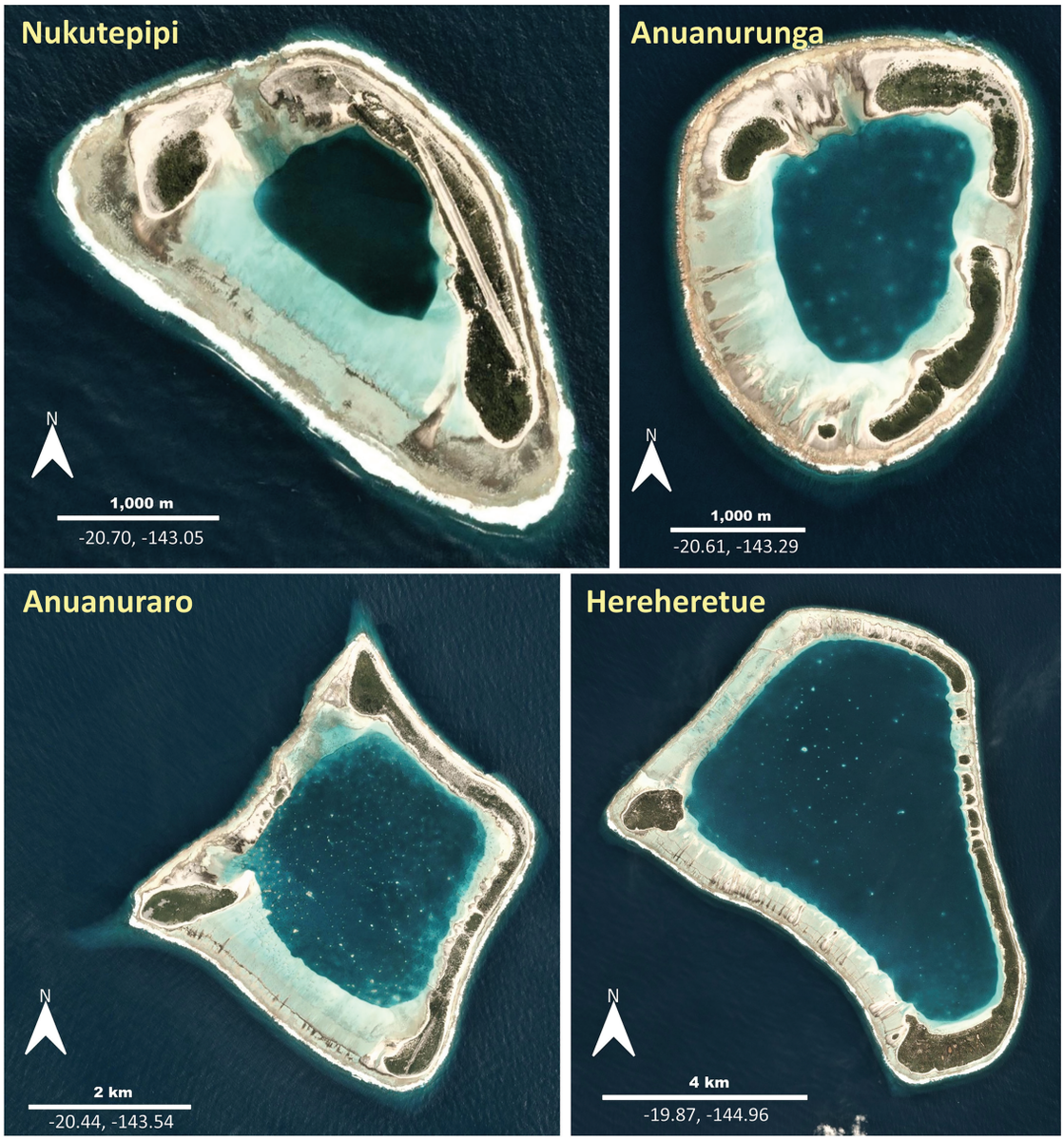

Figure 3.31 Remote-sensing images of the atolls of Nukutepipi, Anuanurunga, Anuanuraro, and Hereheretue. Images © 2021, Planet Labs PBC.

The outer reefs surround this atoll and extend up to 300 m southeast–southwest, and about 200 m wide elsewhere. Patchy reef occurs on the reef flats to the north, but elsewhere they are sparsely distributed. The rim includes three islands, two of which are on the northern rim. The smaller is 32 ha; the other curves around the northeast and covers about 53 ha. A channel between the two islands has been sealed by sediment at the entrance, but there is a reef ribbon area on its eastern flank. The largest island is on the east to southeast rim and covers 43 ha. A 280-m-wide channel occurs between the second and third island. A single motu occurs in the southern rim. The western rim is open and is composed primarily of shallow lagoon intermingled with inner reef flats of sand and rubble.

The lagoon is 3.2 km^2. Sand covers part of the shallow lagoon. The deeper lagoon is 2.0 km^2 in extent, and numerous small pinnacles rise from the deep lagoon. We have no information on the biota or the bathymetry of this lagoon and tentatively mark it as closed. This atoll is privately held, and it is currently for sale.

Anuanuraro is the last of the Duke of Gloucester Islands. It is square shaped with two rounded corners to the east and south and is located about 59 km northwest of Anuanurunga (Figure 3.31). The platform is 18.6 km^2 in extent and it is surrounded by an outer reef that is 110–160 m wide northwest–southeast clockwise, and 270–390 m wide south–southwest. In addition, there is a 900 m wide reef extension that extends spurlike to the west. Shallow outer reefs

occur as localized reefs to the northeast. A 6.7-km-long island extends from the north to south on the eastern rim and includes an airstrip at the southern end. All these islands are on a gray sand and rubble ridge. A 3-km reef flat separates the southern island from the westernmost island of 45 ha that is oriented east–west. The northwestern rim is 3 km long and is composed of motu and reef flats.

The lagoon area is 8.3 km^2. The inner reef flats, shallow lagoon, and part of the slope are covered by a sand apron more than 900 m wide on the waveward southwest that narrows to about 100 m wide to the northeast behind the island. A few patch reefs are on the lagoon slope and on the edges of the deep lagoon there appear to be some mapiko associated with the western island in the lagoon shallows, as mapped by the Allen Atlas and on numerous small pinnacles that rise from the deep lagoon, which has been reported to be up to 12 m deep (Devaney and Randall, 1973), all of which are coded as reef rimmed. We have no other information on the lagoon biota or bathymetry. Until there are data to suggest otherwise, we classify this lagoon as closed.

Hereheretue is an ovotriangular atoll with a platform area of 49.1 km^2 (Figure 3.31). Its longest, northwest–southeast axis is 9.7 km, and it is 7.7 km at its widest, bisecting the westernmost island and extending to the eastern platform. The atoll is surrounded by an outer reef that is generally 180–260 m wide except for the southwest where it extends to 400 m. Three islands are found on the rim. The first is 2.4 km long on the northeast, followed clockwise by a chain of motu and hoa that are 2.9 km long. The largest island extends from the middle of the eastern rim, where it is 250–350 m wide, and then expands to 890 m wide on the south rim in a J-shape, ultimately covering an area of 2.6 km^2. The southwestern rim is a reef flat 5.9 km long, with low, elongated motu; the northwest rim is a more open and is a submerged reef flat, with motu only at the north. A single island of 79 ha that includes a few buildings occurs on the west and divides these two reef flat areas. There is no airstrip on this atoll.

The inner reef flats and the shallow lagoon on the northwest and southwest here as on the other atolls of this group are covered with sand and are more than 300 m wide to the southwest. If the reef flats are eliminated from measurement as much as possible, the lagoon area becomes about 30 km^2. Many reef-rimmed pinnacles rise from the northwestern lagoon, a few of which reach the surface. Small patches of coral are detected by the Allen Atlas on the pinnacles here and elsewhere in the lagoon. We are not aware of any depth information or studies of renewal time, but Salvat (2009) indicates that there is a *T. maxima* population of some significance here and a genetically differentiated population of the black-lipped pearl oyster *P. margaritifera* (Amaud-Haond et al., 2008). We tentatively refer to this lagoon as semi-closed.

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