Chapter 1

The tales narrated by coral reefs

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Modern reef flat topped with an ancient reef, eroded at its base (notch) by present-day sea level, Maré. © IRD/S. Andréfouët

A large oceanic domain with numerous banks, atolls, islands and associated reefs

New Caledonia is located between Australia and Vanuatu, just north of the Tropic of Capricorn. It is known for its pristine reefs and beautiful lagoons, which are a dream destination for many. The exclusive economic zone of New Caledonia extends over 1,200 km from north to south (15°S to 26°S) and 1,800 km from west to east (157°E to 174°E), 1.4 million km^2 in total. It harbors a multitude of reefs associated with numerous banks, atolls and islands, and distributed over five ridges. These ridges are roughly parallel, mainly oriented north-south to northwest-southeast, and mostly submerged, separated by basins and deep trenches (Fig. 1).

The following reefs follow one another eastwards: (i) the large atoll-complex of Bellona-Chesterfield-Bampton that corresponds to the northern section of an alignment of seamounts on the northwest edge of the Lord Howe Ridge; (ii) the Fairway banks and reefs, and the Lansdowne Bank with its Néréus Reef at the northern extremity of the Fairway Ridge; (ii) the New Caledonia Ridge, a geographical extension of the Norfolk Ridge, along which the Antigonia and Torche banks, Isle of Pines, Grande Terre (the main island, 400 x 50 km), the Belep Archipelago, the d'Entrecasteaux Reefs, and

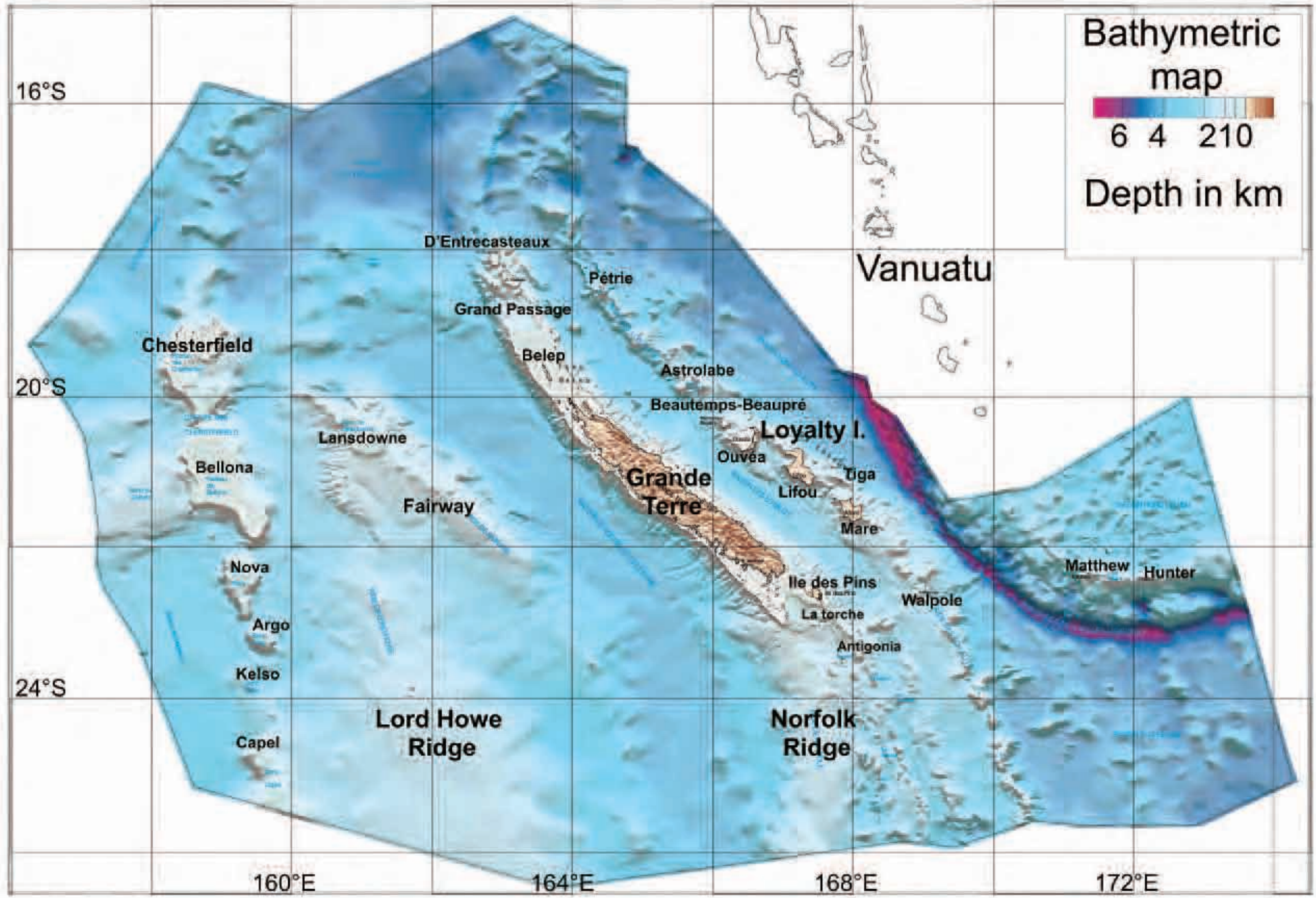


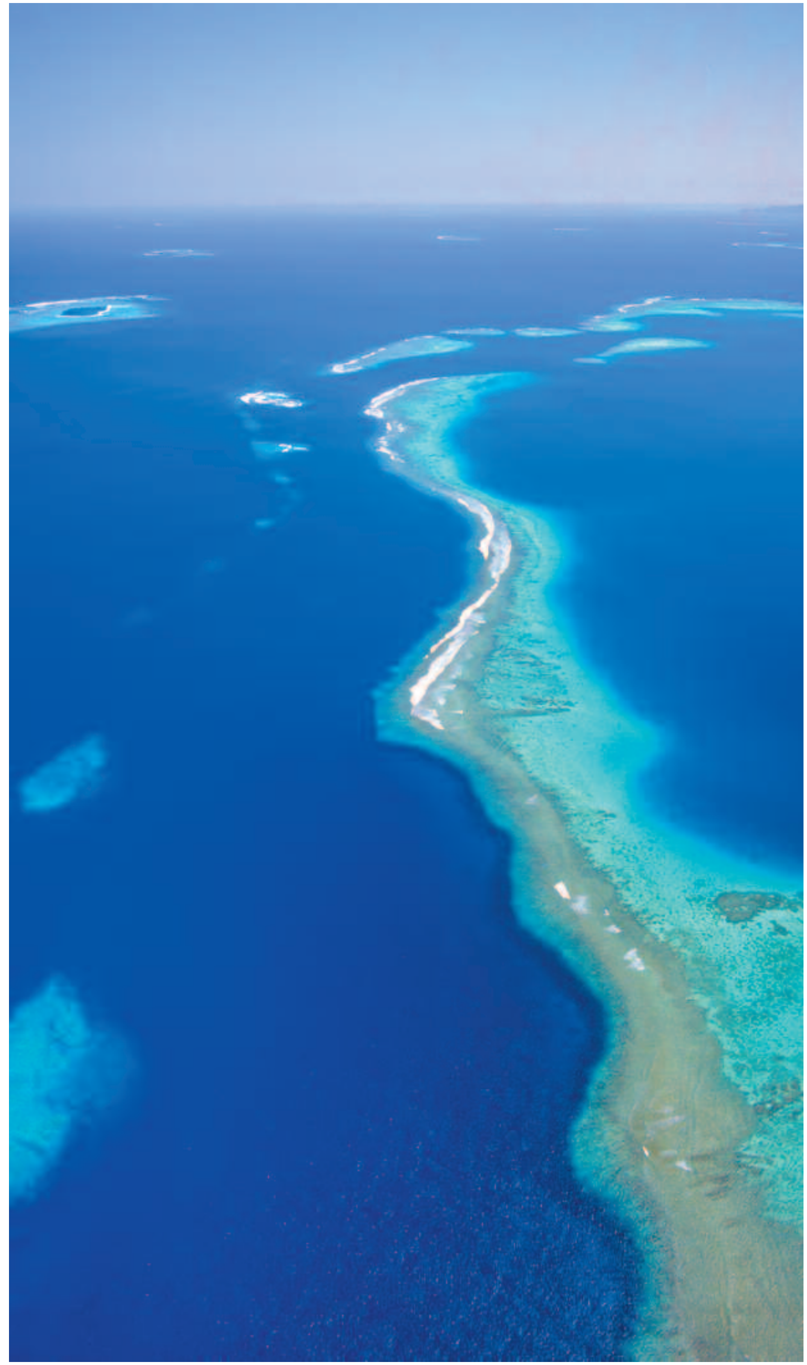
Figure 1: Exclusive Economic Zone (EEZ) of New Caledonia. Adapted from ZoNéCo program, 1998

the atolls beyond the Grand Lagon Nord (Northern Lagoon) succeed one another northward; (iv) the Loyalty Ridge, along which Walope Island, Orne Bank, Durand Reef, the Loyalty Archipelago with its main islands Maré, Tiga, Lifou, and Ouvéa, the Beautemps-Beaupré Atoll, Astrolabe Reefs, and further north Pétrie Reef succeed one another northward; (v) lastly, Matthew and Hunter Islands at the southernmost point of the Vanuatu Arc system, beyond the deep trench of the same name.

The result of a tumultuous geological evolution

The geological evolution that has shaped the New Caledonian oceanic domain into its succession of ridges (with banks and islands) and basins, can be divided into four main periods (Pelletier, 2007). From the late Cretaceous (100 Ma) to the early Eocene (50 Ma), the eastern margin of Gondwana (East Australian Margin) stretched, which led to the opening of oceanic basins and the release of continental strips eastward, such as the Lord Howe and Norfolk-New Caledonia ridges. The middle to late Eocene period (50-34 Ma) was marked by a contraction within this margin, which had previously been lacerated. This period ended with the formation, on the Norfolk-New Caledonia Ridge, of one of the largest outcrop plates of oceanic lithosphere in the world: The Peridotite Nappe of Grande Terre (large massif in the south, and klippes along the northwest coast), the Isle of Pines and the Belep Islands. The subsequent meteorite weathering of the latter led to the formation of one of the largest nickel reserves in the world. Significant vertical movements, substantial erosion, and volcanic activity characterize the period spanning from the Oligocene (34 Ma) to the late Miocene (12 Ma). The beginning of the late Miocene period was marked by the formation of the Vanuatu Subduction Zone, along which the eastern part of the domain, the Loyalty Basin, has largely disappeared.

Currently, ridges and basins surrounding New Caledonia are supported by the Australian plate, which plunges in subduction beneath the active Vanuatu Island Arc System. The relative east-northeast oriented motion of convergence is particularly fast: 12 cm/yr at the latitude of the Loyalty Islands (Dubois *et al.*, 1977; Pelletier and Louat, 1989). Closer to the subduction zone, the



Barrier-reef complex, Southern Lagoon. © P.-A. Pantz

Uplifted reef, Walpole Islet. © IRD/P. Tirard

plunging plate is deformed. It is first uplifted, and then collapses before subduction. This lithospheric bulge before its subduction, is well illustrated by the shapes and different altitudes of the Loyalty Islands, which are made of uplifted atolls and are located at different distances from the trench (Dubois *et al.*, 1974). Two atolls uplift and emerge: Beautemps-Beaupré and Ouvéa. The latter is partly exposed above sea level, has a large open lagoon, inclined westwards, and cliffs reaching 41 m high on the east coast. The ancient atolls, Lifou and Maré, are located on each side of the top of the bulge, and reach altitudes of 104 and 138 m, respectively. Walpole Island (70 m) has reached the top of the bulge and starts its subsidence. At 22°S, the Loyalty Ridge subducts and collides with the south end of the Vanuatu Arc. This collision leads to a fragmentation of the upper plate along an east-west trending left-lateral fracture zone, as well as a decrease in convergence speed south of the impact point (Pelletier et Louat, 1989). The plate, or rather the micro-plate, supporting the active volcanic islands of Matthew and Hunter, is therefore different from the plate supporting the rest of the New Caledonian Archipelago.

A high diversity of reefs

After Fiji and Papua New Guinea, New Caledonia has the world's third most diverse reef types (Fig. 2).

From the d'Entrecasteaux Reefs to those of the Isle of Pines, and from the Chesterfield-Bellona Reefs to those of the Matthew and Hunter Islands, New Caledonian reefs occupy an area of about 4,500 km^2. They form a mosaic of diverse shapes and structures, which results from the region's geological history and from the tectonic processes that still shape the terrestrial and submarine topography today (ANDREFOUËT *et al.*, 2009). The geomorphological development of the reefs is also impacted by recent environmental conditions, such as sea level change over the past hundreds of thousands of years, as well as more local and short term contemporary factors such as exposure to wind, swell, terrigenous inputs, freshwater runoff, and temperature. Besides these local and regional physical processes, reefs are also shaped by numerous short-term biological processes, such as coral growth.

Modern barrier, lagoon and fringing reefs

The reefs surrounding the main island, Grande Terre, are the most studied and also the most diverse. New Caledonia harbors the longest continuous barrier reef in the world, which extends over 1,500 km (1,300 km is intertidal reef) and covers about 1,750 km^2. It is interrupted by numerous narrow passes which are located up to 70 km off the coast and encloses Grande Terre (including the islands of Belep and Balabio) and an immense lagoon. This barrier reef displays a variety of structural configurations. For instance, the southern section of the east coast is made up of large portions of drowned reefs, and at some points a double barrier reef. In contrast, the northern section of the east and west coasts harbor relatively more typical barrier reefs. Near Bourail (on the west coast), the barrier reef is located very close to the coast and the lagoon is shallow. Besides these large groups, more unsual portions of barrier reef can be found - for example, in the north where the reef curves around Balabio Island, or at the southern end in the Corne Sud.

The lagoon surrounding Grande Terre covers 16,800 km^2 and harbors numerous shallow reefs (380 km^2). Some of these reefs are characterized by the presence of islets, built from carbonate debris that have accumulated on ancient reef reliefs. Although they can appear superficially similar, the reefs of these islets display an important diversity of shapes and structures, due to the different genesis.

Fringing reefs are contiguous to the main land mass. Around Grande Terre, they cover up to 400 km^2 and are found in places with contrasted environmental conditions: sheltered bays subject to terrigenous inputs; portions of coast exposed to trade winds but protected from the swell; and portions of coast directly exposed to the ocean, such as in the south of Grande Terre. These different environmental exposures lead to contrasted reef formations, which can be more or less developed.

Atolls

There are several atolls in New Caledonia. Chesterfield and Bellona, d'Entrecasteaux, and the Loyalty atolls have different origins. Their total reef and lagoon area (2,000 and 14,000 km^2, respectively) is almost equivalent to the reef and lagoon area surrounding Grande Terre.

The huge complex, formed by the Bellona and Chesterfield-Bampton atolls, represents a third of the lagoon and reef areas of the entire economic zone of New Caledonia. Its shape is asymmetrical with a drowned reef to the east, and a deep lagoon (40-60 m) with scattered pinnacles. These atolls rest on five seamounts, relics of ancient volcanoes - possibly dating back to the late Oligocene - which originated from the Lord Howe hotspot.

At the northern extremity of the New Caledonia Ridge, the d'Entrecasteaux Reefs are located beyond the Grand Passage to the north of the Grand Lagon Nord. They are spread out over three parallel ridges which extend the formations of Grande Terre and the Grand Lagon Nord. They include the large atolls and deep lagoons (60 m) of Huon and Surprise, and the smaller atoll of Pelotas, distributed along a central ridge. Portail Atoll and Gilbert Reef are located to the west and to the east, respectively.

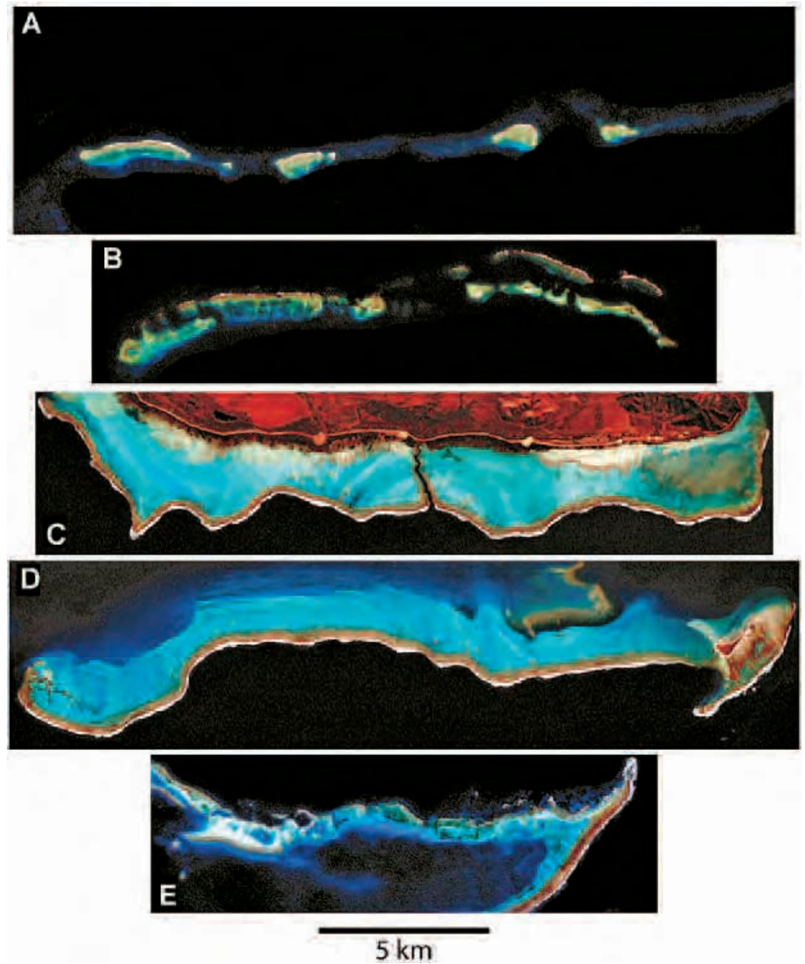


Figure 2: Diversity of New Caledonian barrier reefs. The same scale should be considered for landsat images (1999-2003), which have been rotated to simplify comparisons.
East coast:
A: Outer barrier reef, Canala; large portions of the reef are drowned;
B: Outer double barrier reef, Poindimié, Bayes Islet; West coast:
C: Coastal barrier reef, Poé;
D: Outer barrier reef, Grand Récif, Tenia Islet, Boulouparis;
E: Nested barrier reef, Corne Sud.
Adapted from ANDREFOUËT *et al.*, 2009

The atolls of Ouvéa (850 km^2) and Beautemps-Beaupré (120 km^2), supported by the Loyalty Volcanic Ridge, have shallow lagoons which open westward. The atoll of Ouvéa, bordered by the islands and reefs of the North and South Pléiades, is characterized by a lagoon floor that dips gently westward, and by the high cliffs of Ouvéa Island to the east. Unlike the other atolls, these are emerging.

When reefs inform us about vertical movements and climates

There is good knwolege of the sea level variations for the last two million years, with an alternation of warm periods with high sea level stands (interglacial periods such as present-day climate) that are favorable to coral constructions, and cold periods with low sea level stands (glacial periods). During the last interglacial period (125 ka), the sea level was 6 m higher than present. Since then, the sea level has gone down by 120 m during the last glacial maximum (20-23 ka), and then rose rapidly to remain relatively stable for the last 6 ka. Coral reefs are excellent markers of sea level variations. The past vertical movements of islands can be interpreted from sedimentological analyses, and the position and dating of ancient reefs which were built during interglacial periods and are now outcropping or buried.

Thanks to these techniques, recent vertical movements (since the late Pleistocene, 125 ka ago), and zones of uplift or subsidence have been identified and mapped. This has been done by the systematic sampling of reef formations dating back to Pleistocene and Holocene. These reef formations were either outcropping near the coast or have been reached by drilling cores into the fringing and barrier reefs, notably around Grande Terre (CABIOCH *et al.*, 1996) (Fig. 3).

Sedimentological and stratigraphic analyses of the cores also provide precious information about the resettlement processes of coral reefs during the last post-glacial sea level rise. Around Grande Terre, the age of the oldest Holocene reefs does not exceed 8.2 ka. Sea surface temperatures were probably too cold before this date (4°C lower than present) to allow the significant development of coral reefs.

Drilling of the barrier reef, Bayes Islet, east coast of Grande Terre (2002). © IRD/G. Cabioch

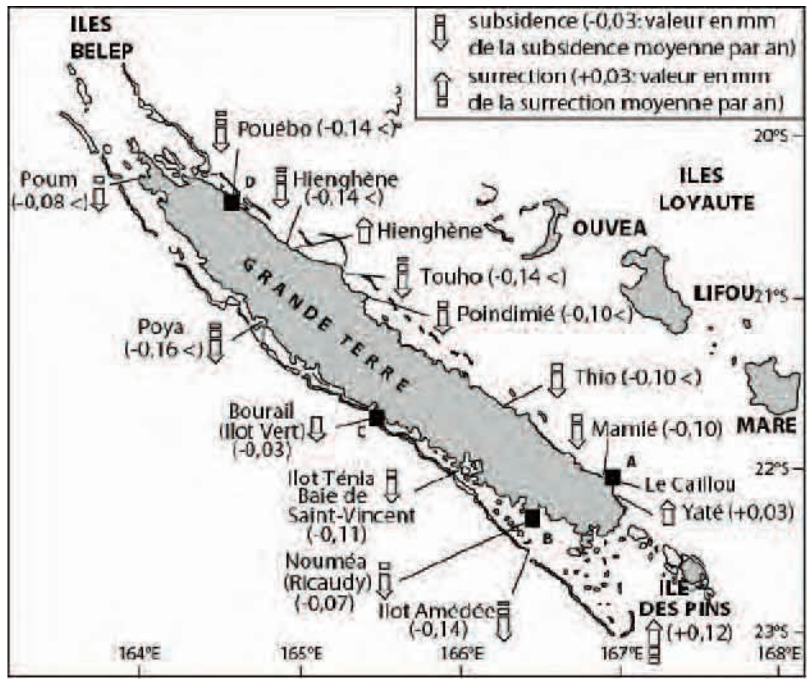


Figure 3: Vertical movements over the last 125 ka around Grande Terre.
Adapted from Cabioch *et al.*, 1996

Reef limestone cliffs and modern and ancient notch, north of Lifou, Joking. © P.-A. Pantz

Surrection zones with ancient and uplifted reefs and atolls

The ancient (middle Miocene to Pleistocene) atolls of the Loyalty Islands have been substantially uplifted and now reach an altitude of between 40 and 140 m above sea level. At the Isle of Pines, the reef complex matched with the high sea level stand of the last interglacial period, has revealed an uplift of 0.12 mm/yr during the last 125 ka. In the region of Tara/Yaté, southeast of Grande Terre, the fringing reef that was built 125 ka ago also emerged. It reaches a maximum altitude of 10 m, which indicates an uplift rate of 0.03 mm/yr, while in the same region, the current barrier reef is deeply submerged at 15 to 20 m. All these surrection zones point to the lithospheric bulge of the Australian plate before its subduction.

Subsidence zones with drowned or buried ancient reefs and atolls

Relicts of the 125 ka-old fringing reef also outcrop in the region of Bourail, on the west coast of the island. However, their altitudes (about 2 m) are less than those recognized for the high sea level stand (6 m higher than present), which suggests a slight regional subsidence (-0.03 mm/yr). Everywhere else around Grande Terre, the 125 ka-old fringing reef is located below the Holocene postglacial reef or is immersed further offshore. This indicates a subsidence of 0.1 to 0.16 mm/yr, which increases northward and southwestward on each side of a relatively more stable central zone. Near the barrier reef, the 125 ka-old fringing reef is capped by a Holocene formation, whose thickness depends on subsidence. It increases substantially with distance to the coast, such as in the lagoon near Nouméa or at the barrier reef near Yaté. This points to the double warping that the New Caledonian formation has undergone during the last 125 ka. This warping has been both longitudinal and transversal, with fault-flexures that are parallel to the island, and transversal faults, which divide it into large blocks.

Comparable subsidence rates have been measured or estimated for atolls of d'Entrecasteaux (0.1 mm/yr at Huon) and Chesterfield-Bellona Reefs (0.1 to 0.15 mm/yr) over the last 125 ka.

Drillings, on the barrier reef to the west of Grande Terre have also led to the identification of reef constructions dating back to anterior high sea level stands (last 1 Ma). Detailed morphological analysis of the outer reef slopes of the barrier reef revealed the existence of five submarine terraces between 20 and 120 m deep.

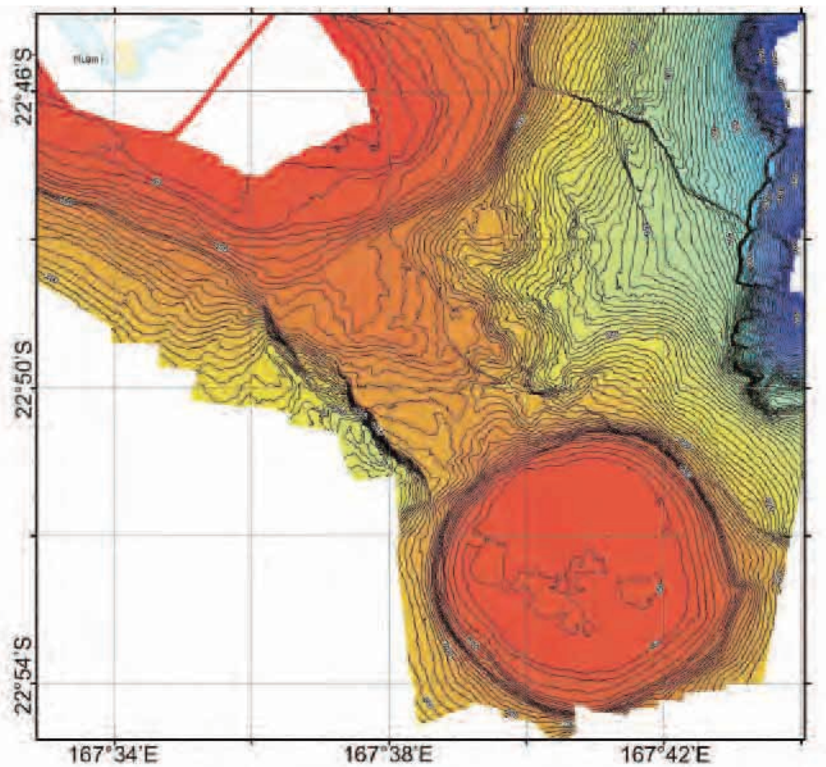


Figure 4: Map of the Torche Bank to the south of Isle of Pines. Isobaths every 10 m.
© IRD/ B. Pelletier

These have been interpreted as the morphological signature of reef units that developed during the last five high sea level stands. The largest terrace, located between 70 and 85 m deep, is thought to be the remains of a 408 ka-old high sea level stand. Its vertical distribution indicates a segmentation in displaced blocks and average subsidence rates of 0.13 and 0.20 mm/yr, which are in the same range as those of the last 125 ka.

Lastly, subsidence is also indicated by the presence of drowned atolls (such as those of the Torche Bank (Fig. 4) and Antigonia to the south of Isle of Pines), as well as seamounts on the Norfolk Ridge to the south of Grande Terre, on the Loyalty Ridge, and to the south of the Bellona-Chesterfield complex (Capel, Kelso, Argo and Nova banks, Fig. 1).

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