The diversity of New Caledonia coral reef geomorphology and genetic processes: a synthesis from optical remote sensing, coring and acoustic multi-beam observations

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Introduction

The New-Caledonia (NC) exclusive economic zone (EEZ) includes a large variety of oceanic and continental coral reef formations. This geomorphological diversity provides a rich framework which itself supports a large diversity of shallow modern habitats and communities. As a background to the description of the marine check-lists published in this volume, we describe here for each of the main coral reef complexes (bank, atolls, uplifted reefs, drowned reefs, fringing reefs, barrier reefs, patch reefs), a review of their geomorphological diversity and genetic processes.

There is a long history of scientific research on the formations of NC coral reefs. First, datations from corals from a variety of locations in uplifted and subtidal positions provided a general idea of the intensity and timing of the dynamic processes that resulted in the modern morphology (Dubois *et al*. 1974; Collot *et al*., 1975, Coudray 1976; Debenay 1986; Carriere 1987). With the generalization of drilling programs and the possibility to assess the vertical structures of a reef (succession of episodes of reef growth), genetic processes have been locally refined (Coudray, 1976; Cabioch, 1988; Degaugue-Michalsky 1993; Castellaro; 1993), especially around Grande-Terre (Cabioch 2001, 2003). Drilling provided a huge mass of information relevant to establish models of reef settlement and development during the last interglacial ages in the Indo-Pacific region (Montaggioni, 2005). However, drilling provides only point data, spatially limited, and inferences must be made for larger spatial scales.

Synoptic data come with remote sensing observations, which include shipborne, airborne and space-borne data. Using Landsat satellite images, Grande-Terre, Ile des Pins, Entrecasteaux, Loyalty and Chesterfield reefs were recently mapped using the geomorphological typology proposed by Andréfouët *et al*. (2006). The resulting atlas provides a quasi- exhaustive detailed two-dimension (2D) view of modern NC reefs (Andréfouët & Torres-Pulliza, 2004) (Fig. 1, plate 3/1). Finally, multi-beam acoustic data were collected between -20/-40 to -1000 m along the New-Caledonia and the Loyalty Ridges using the EM1002 echosounder of the R/V Alis (Pelletier *et al*., 2004). Data were processed using the software CARAIBES TD (© IFREMER) (Flamand, 2006). Bathymetric multi-beam data provided a 2D/3D vision of the outer slopes of several NC reef complexes (Flamand *et al*., 2004). The internal structure provided by coring is not accessible, but marine terraces and faulting became visible with the fine-resolution bathymetric data. These features helped drawing the evolution of the Grande-Terre barrier reef system (Flamand, 2006).

In this review, we use the synoptic exhaustive description provided by optical satellite images as the primary guideline to describe the main NC reef complexes. In the Background section (next) we also briefly describe the main forcing oceanographic, tectonic and eustatic processes occurring in the region. Then, for each reef complexe, when the information is available by datations and coring, we provide the current interpretation of the local dynamics across times. As much as possible, given the existing data, we consider the 125 ka (1ka=1000 years)-Present time-period. This period includes the last interglacial period (125 ka, mean sea level 6 meters above present level), crosses the last glacial maximum (at 23-20 ka, lower sea stands at around -120m and beginning of the end of aerial exposure for interglacial reefs), and eventually crosses the postglacial periods of rising (~20-6 ka), quickly falling (~6-5.5 ka) and stable (~5.5 ka-Present) sea levels.

Forcing processes and their significance for reef and lagoon modern morphologies

The three main axes of reef complexes: Chesterfield-Bellona, Ile-des-Pins-Grande-Terre-Entrecasteaux and Loyalty Islands.

New Caledonia EEZ's tectonic framework is made of a succession of basins and ridges (Fig. 2). From West to East, NC modern reefs have for foundation the Chesterfield/Bellona plateau, the Lord Howe Ridge, the Fairway Ridge, the Norfolk Ridge (or New Caledonia Ridge in its northern part) and the Loyalty Ridge. These ridges respectively support the Chesterfield banks, the -Fairway banks and drowned atolls, the Grande-Terre, Ile des Pins, and d'Entrecasteaux reef complexes, and the Loyalty uplifted-reefs and banks (Fig. 2). A prominent dynamic regional feature is the subduction zone between NC and Vanuatu, where the -Australian plate dips underneath the Vanuatu arc-North Fiji Basin microplates and Pacific plate Plate. The lithospheric deformation (bulge) before its dip explains the uplifted reefs of Grande-Terre, Ile des Pins and Loyalty islands (Dubois *et al*.; 1974).

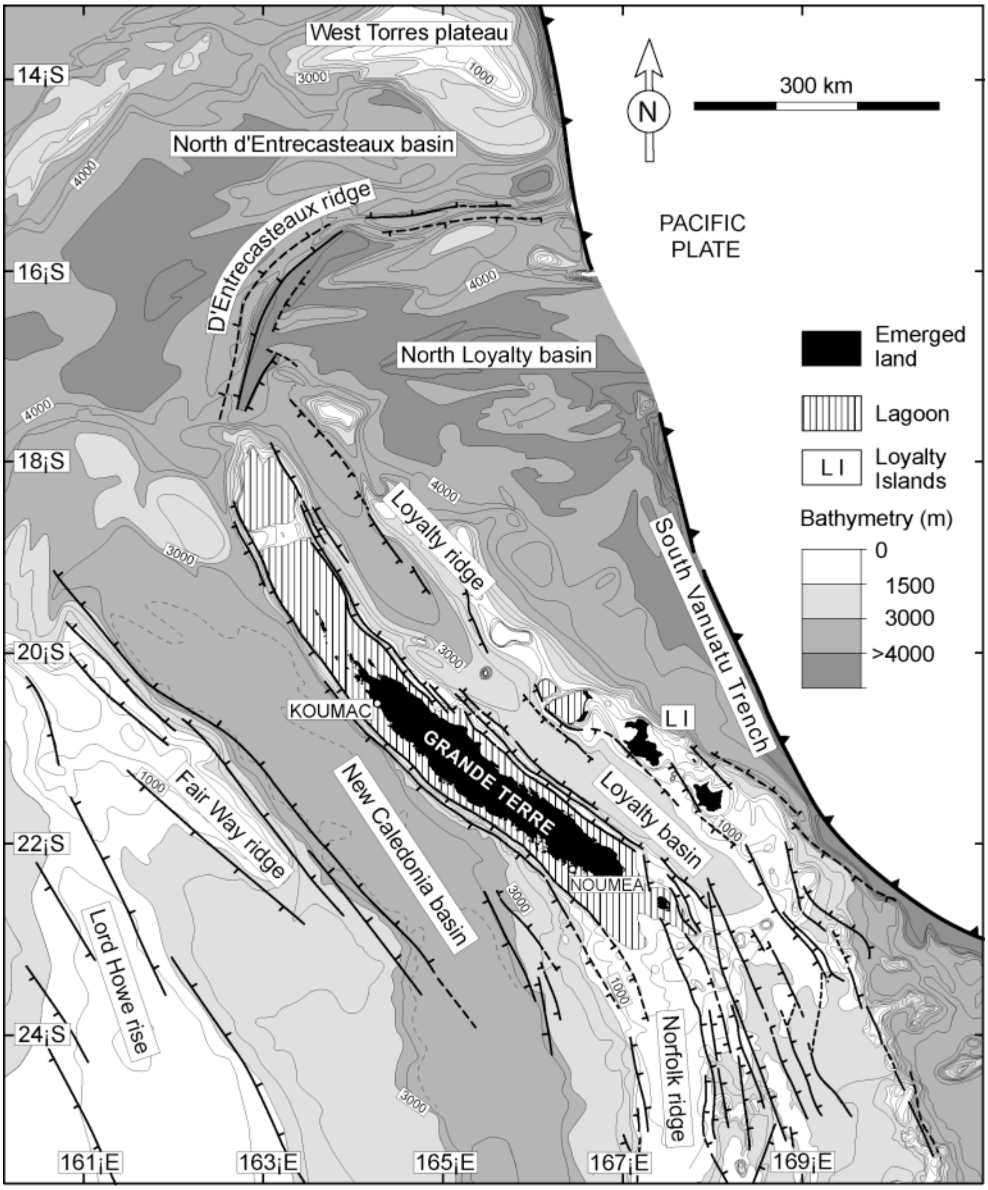

Figure 2: Morphology and main structures of the peri-caledonian domain. Modified from Flamand (2006). Data compiled by Chardon & Chevillotte (2006), from Maillet *et al.* (1983), Mignot (1984), Rigolot (1989), Lafoy *et al.* (1995) and Dupont *et al.* (1995).

Tectonics processes

Local equilibrium and differential motions (or movements) between subsidence and uplift explain largely the modern reef morphology (Fig. 3). Differences in depth, or altitude, between 125 ka-old reefs and post-glacial reefs highlighted the differential vertical processes. In a general way, subsidence dominates around Grande Terre, although some parts (especially in southeast) have been subjected to uplift (Cabioch *et al*., 1996). For instance, Cabioch (2001) shows that Amédée Reef subsided at a rate of 0.14 mm.y^{-1} at least, while the reefs close to Nouméa, on the coast, subsided at 0.07 mm.y^{-1}. Similarly, near Bourail, the subsidence is low (0.03 mm.y^{-1}) which explains the proximity to land of the outer reef flat in this section of coast. The highest subsidence rate offshore explains the formation of the vast and large Southwest and North lagoons. Therefore, offshore postglacial barrier reefs will be also much thicker than coastal ones. The antecedent topography is located much deeper and is more difficult to reach with coring techniques.

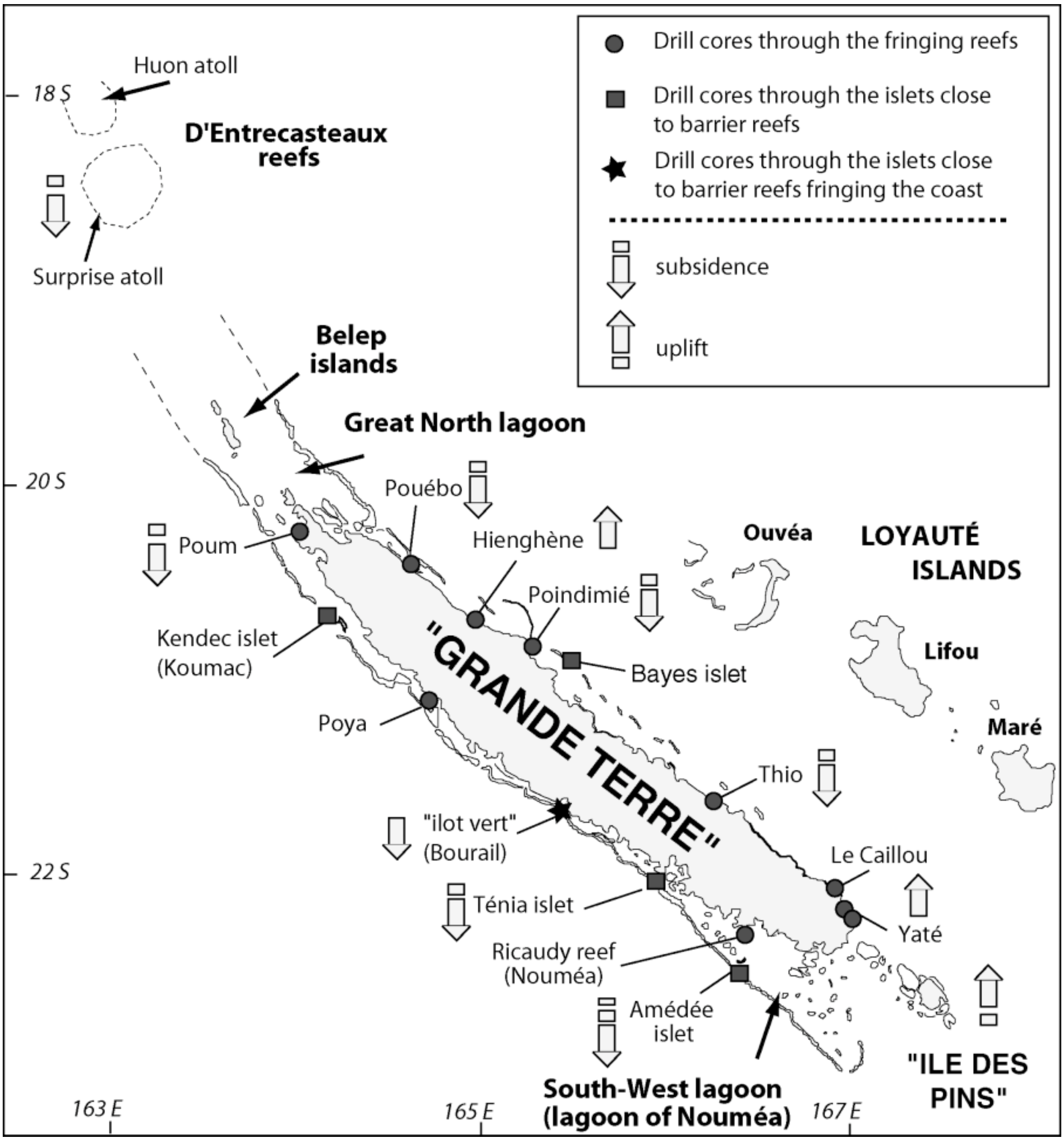

Figure 3: Locations of cores drilled through New Caledonia coral reefs and neotectonic behavior of Grande-Terre and Ile des Pins (modified from Cabioch *et al*. 1996, Cabioch 2003).

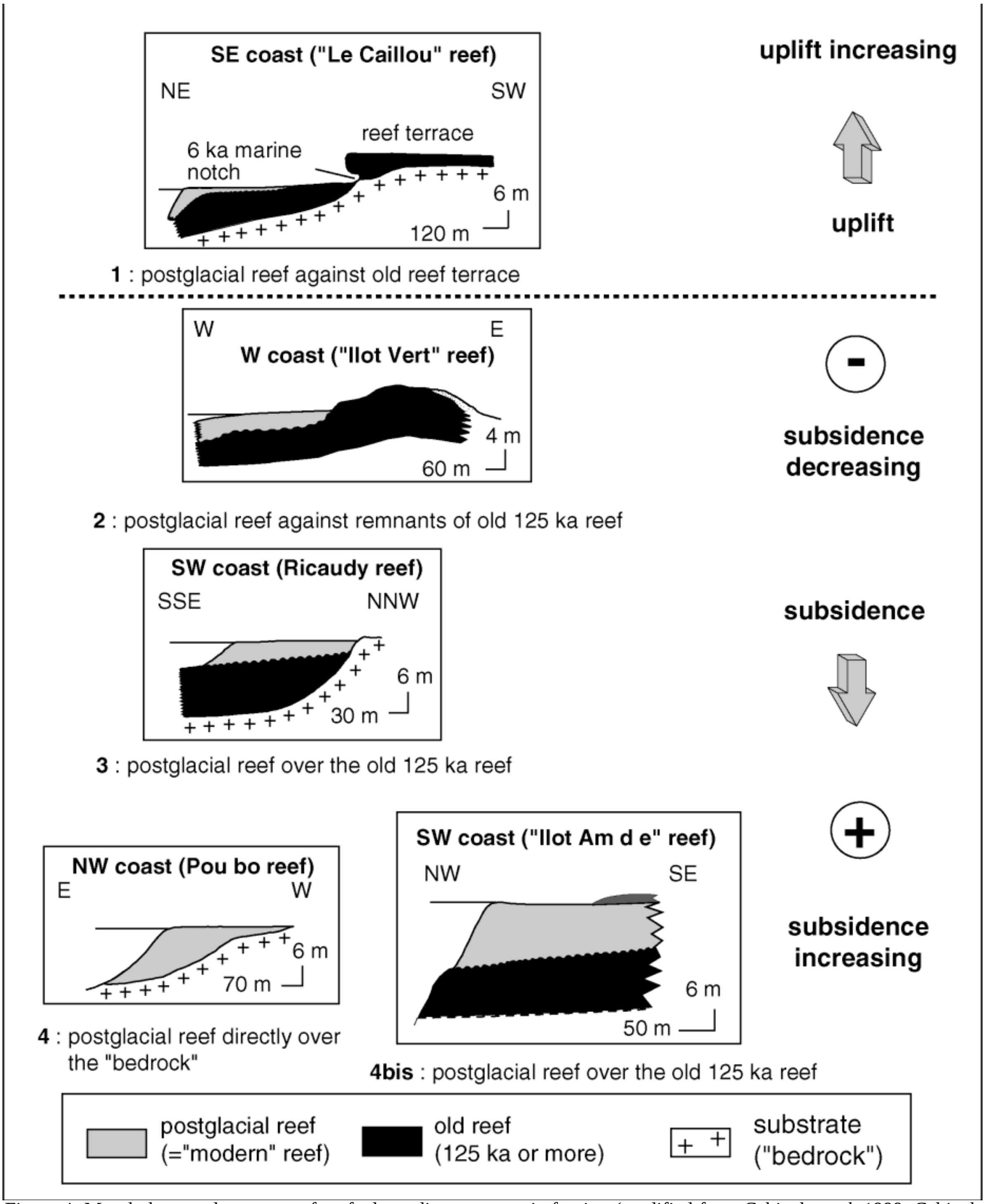

Figure 4: Morphology and structure of reefs depending on tectonic forcing (modified from Cabioch *et al*. 1999, Cabioch 2003).

Uplift occurred during the last 125 ka in the South of Grande-Terre, around Yate, providing terraces at an altitude of up to 10m. Thus, postglacial reefs are narrow in this region. They are also thin and developed above an antecedent platform (reef or continental) which is at short vertical distance from present sea-level (Fig. 4). Ile des Pins has also been uplifted in the same way. Simultaneously to the uplifting of the coast, the barrier reef of the south-east coast drowned (Dugas & Debenay 1978, Cabioch *et al*. 1996), creating a very open and deep lagoon from Yate up to about Port-Bouquet.

Yate and Ile des Pins uplifts reveal the beginning of the influence on Grande-Terre of the lithospher-

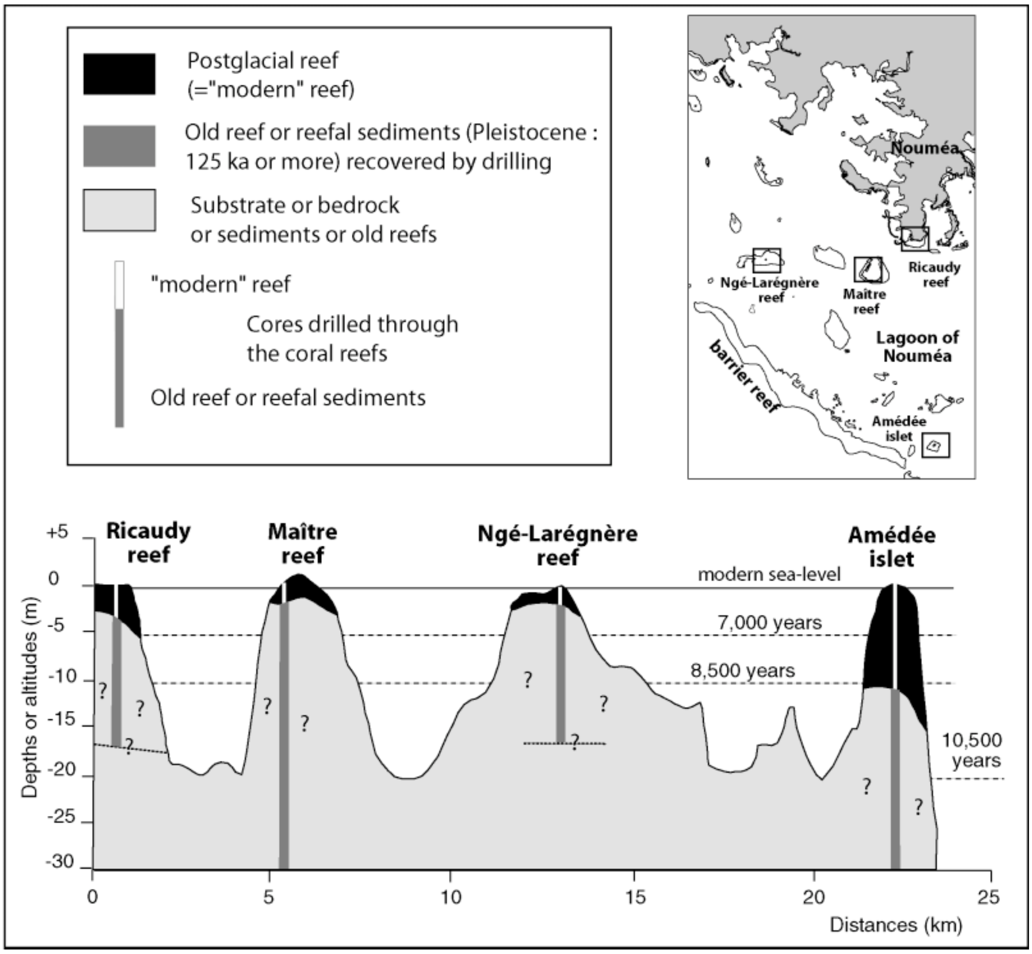

Figure 5: Relationships between the timing of the flooding and available substrates and age of the coral reef formations of the Noumea lagoon inferred from core data (modified from Castellaro *et al.* 1999, Cabioch *et al.* 1999 and unpublished data).

ic bulge of the Vanuatu subduction zone. Its influence had also strongly modeled the Loyalty Ridge reefs. From South to North, Maré (+138m) has just passed the top of the bulge, Lifou (+104m) is ascending the bulge, and Ouvéa and Beautemps-Beaupré are only partially uplifted, just starting the process. Uplifting rates vary from +0.12 to +0.17 mm.y^{-1} in the last 125 ka. In contrast, Walpole is now slowly drowning towards the subduction zone.

The amplitude of the hydro-isostatic readjustment induced by the sea-level rise of the last 23 ka following the last deglacial sea level rise depends on the underlying mantle viscosity. Consequently, raised beach-rocks, emerged marine notches and abraded reef flats from 0 up to 2±0.5 m dated of mid-Holocene characterize this process in New Caledonia (Cabioch *et al*., 1989).

Antecedent topography

The antecedent topography and the type of substrate is one of the factors that explains modern reef geomorphology (Purdy, 1974; Cabioch, 2003; Montaggioni, 2005). Small-scale erosional or depositional topographic features and hard surfaces (e.g. paleorivers, karstic basins, lava beds, previous reefs) are suitable for reef-builders settlements. NC cores reveal that reef growth started late in the past postglacial period, about around ~7.5-7 ka for the fringing reefs and 8.2 ka for Amédée Reef (Cabioch *et al*., 1995, 1996). This period was optimal in terms of temperature regimes and sea-level stabilization. In Grande-Terre, settlements occurred on the southwest and southeast coasts, over both karstified 125 ka old reef platform and over non-carbonated substratum. They occurred at different

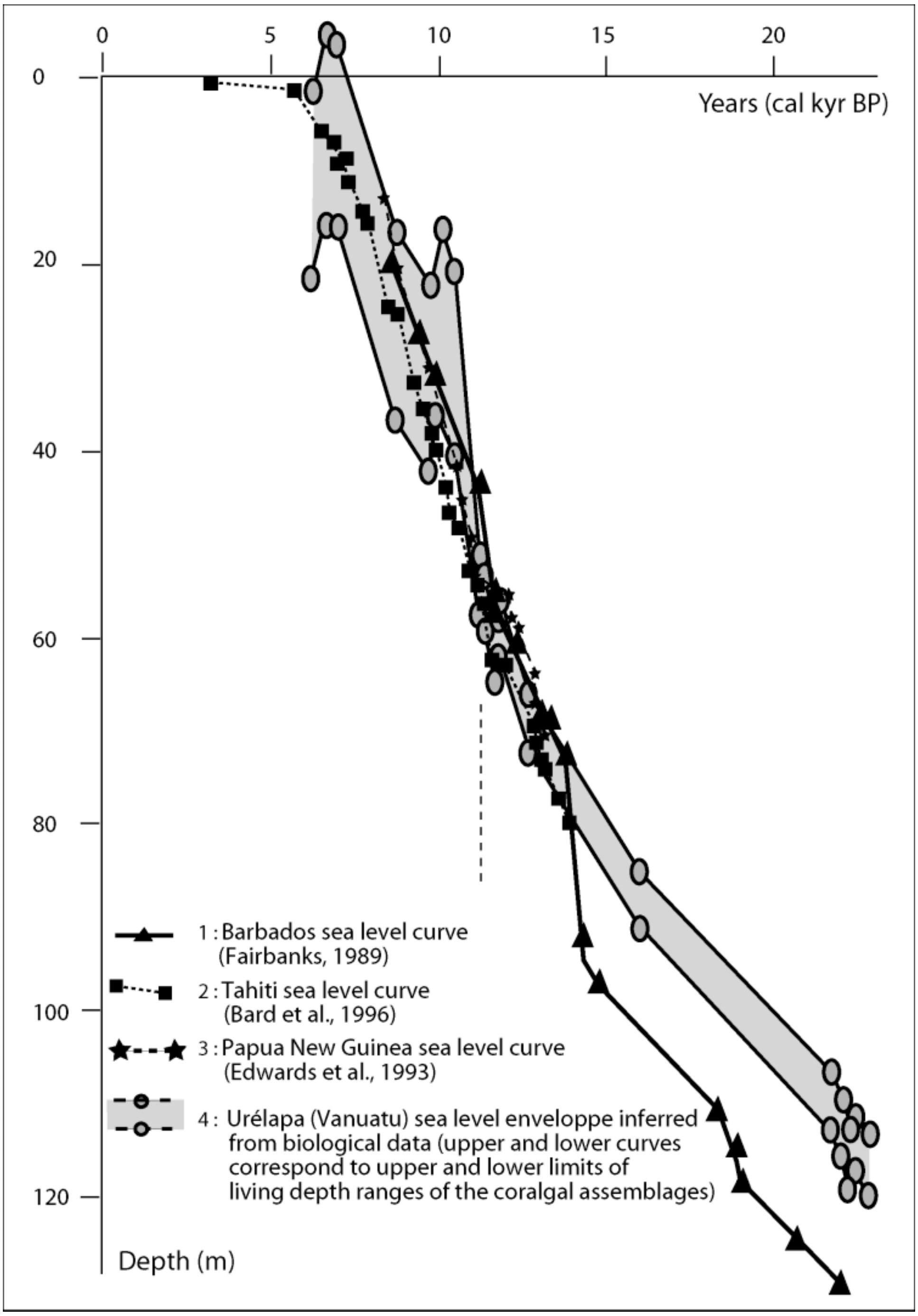

Figure 6: Deglacial sea-level curves for different reefs worldwide (modified from Cabioch, 2001).

depths likely favored by an energetic hydrodynamic regime. A variety of antecedent topographic forms (slopes, flat areas) were colonized as soon as the substrates were flooded (Fig. 5). The Loyalty islands reefs are developing above a substratum made of carbonate from Miocene to Quaternary, which were subsequently uplifted.

Sea-level variations

The postglacial rate of sea level variations is a key parameter to understand reef modern morphology. Obviously substratum need to be flooded before a reef can start growing, but after the initialization has started, the speed of the sea-level rise and the type of living communities (fast or slow growing) concur to provide a variety of reef-growth strategy (keep-up, catch-up or give-up, see Neumann & MacIntyre, 1985) which may result in different reef morphologies for the same antecedent substrate. The timing of the flooding and substrate availability explains the geometry and patterns of reef development (Fig. 5). Between 125 and 23 Ka, sea level variations followed cycles of glacial-interglacial periods. These dates correspond to maxima and minima respectively, with sea levels between +4 to +6m (125 ka) and around -120 m (20 / 23 ka) compared to present mean sea-level (Waelbroeck *et al*. 2002). In New Caledonia, highest levels, up to +2 m, were reached at 5.5 Ka (Fig. 6) due to the isostatic readjustment.

Paleo-oceanography

Sea Surface Temperatures (SST), salinity, nutrients, upwelling regimes**,** turbidity, atmospheric CO_2, circulation and hydrodynamic energy can contribute to explain the patterns of reef growth (Chappell, 1980; Davies & Montaggioni, 1985). Even though this is not completely demonstrated, the most obvious oceanographic factor that can explain the late (8.2 ka) formation of postglacial reefs in New Caledonia is SST (Cabioch, 2001). SST may not have been suitable for corals before that period. Paleo-SST before 8 ka were probably similar to today's SST at 30 degree South of latitude, which is the modern limit of significant reef development. Alternatively, lack of suitable substrates can also explain the youngest settlement of the New Caledonian reefs.

Specificity, diversity and extent of New Caledonia reef complexes

If we follow the typology of reef units proposed by Andréfouët *et al*. (2006) to map all reefs worldwide, New Caledonia presents a high diversity of structures. This typology will be referred hereafter as the "Millennium" typology, since it was designed for a remote-sensing based mapping project called "Millennium Coral Reef Mapping project".

The Millennium typology is a hierarchical scheme whose main nodes are provided Fig. 7 (plate 3/2). The Millennium classes were designed to reflect, not just geological processes, but principally habitat diversity for several applications. Thus, the terminology is specific to these applications (Andréfouët *et al*., 2006), and may not match perfectly the usual geodynamic and geologic definitions since it considers also hydrodynamic and biological factors. For instance, the word "drowned reef" refer to a deep reef location, in contrast with nearby subtidal formations of the same type (e.g. atoll, or barrier reef). The process involved (slow subsidence or quick tectonic event) is not known most of the time.

The Millennium typology proposes a frame allowing consistent interpretation for reefs worldwide. Generally, the interpretation, based only on remote sensing images, is clear and unambiguous. However, highly-complex reefs and environments can be interpreted in different ways and there may be more than one solution (see Balabio Island further). Grande-Terre was considered as a continent, and not a continental island. Conversely, Ile des Pins, Balabio, Yandé and Belep are classified as continental islands, since they are satellites of Grande-Terre. D'Entrecasteaux reefs were considered as oceanic islands even if their basement could be partly of continental origin ridge. Within the Millennium typology, since they don't have a lagoon, Mare, Lifou, Tiga and nearby platform reefs were considered as oceanic islands. In contrast, Ouvea, with its wide lagoon and uplifted rim and islets was considered as an oceanic uplifted atoll.

Grande-Terre, Ile des Pins, D'Entrecasteaux, Loyalty and Chesterfield reefs provide 161 Millennium classes (150 classes defined in Andréfouët & Torres-Pulliza 2004, plus 11 classes specific to Chesterfield banks and atolls). NC reefs include both oceanic (D'Entrecasteaux, Loyalty and Chesterfield) and continental reefs (Grande-Terre, Ile-des-Pins). In comparison, the continental eastern Papua New Guinea alone includes 180 classes. The oceanic French Polynesia includes 64 classes. In the Caribbean, the Meso-American Reef System which is the most developed and rich system, includes 100 continental and oceanic classes. Thus, NC is clearly an area of high complexity, a hotspot of reef diversity, though it is not the most complex area.

The prominent, almost emblematic, feature of NC is its barrier reef. If we include the deeper south-east section from Poindimie to Yate, it is a 1500 km long system. The subtidal domain is a 1300 km long system, from, clockwise, the "Corne Sud" till Poindimié. It is cut by deep passes though they are not numerous. This is the longest stretch of barrier reef worldwide, since the Great Barrier Reef (GBR) in Australia is for most of its length a dense, or diffuse, matrix of platform reefs of various sizes and shapes and not a linear barrier reef. Only the northern part of the GBR, the Ribbon Reefs, have a morphology similar to NC barrier reef (Hopley, 1982).

The Millennium typology provides two main types of barrier reefs: outer shelf and intra-shelf barrier, both are found in NC. Intra-shelf barrier are continuous lines of reefs making a barrier in the lagoon well separated from the outer shelf barrier, like the line of Bogota reefs north of Canala. These two types of barrier reefs can be broken as (regular) barrier, multiple-barrier, imbricated-barrier, coastal-barrier and fringing-barrier types. Except the later, all are found in New Caledonia. Multiple-barriers are made of series of parallel reef flats that are developed closed to each others and some times connect together (see Guilcher, 1988). An imbricated-barrier is a section of barrier which is turning around itself, thus changing completely the degree of exposure and the types of habitats, the outer side turning to the inner side when bending. This configuration marks the termination of the southern end of Récif de Cook, or the termination of Corne du Sud in the South lagoon. An imbricated-barrier can also be a barrier that terminates in the lagoon of a second separate barrier. This configuration also occurs in Hienghene according to Andréfouët & Torres-Pulliza (2004) interpretation. A coastal-barrier is an intermediate configuration between a (regular) barrier and a fringing reef, i.e. there is no deep lagoon, but a shallow sedimentary terrace that clearly separates outer reef flats habitats from fringing-like habitats. This configuration is found in Bourail on the central-west coast. A fringing-barrier is a section of barrier that harbors large islands, thus displaying fringing-type habitats in an outer barrier environment. This is not present in NC (but see the case of Balabio Island in the *Continental Reefs* section), but it occurs for instance in Palau, Mayotte and frequently in Papua New Guinea and Solomon Islands. Examples of these barrier reef types are provided Fig. 8 (plate 3/3)

In contrast with other wide Indo-Pacific continental areas (Eastern Australia, Indonesia but especially Eastern Papua New Guinea), or oceanic areas with large shallow shelves (Fiji), the spatial organization of Grande-Terre reefs is not very diverse since it provides a onshore-offshore sequential zonation of fringing-patch-barrier reefs for most of its perimeter. The wide south lagoon and the uplifted Ile des Pins provide some variations with more complex gradients of spatial organizations due to higher abundance of patch reefs and wide shallow lagoons.

Surface areas of the main reef complexes of New Caledonia are provided Table 1. The inventory shows that there are 8 times more lagoonal and sedimentary areas (~31300 km^2) than reef areas (~4500 km^2). Among the reef areas, 1/3 (1450 km^2) comes from the Chesterfield-Bellona reef complex. However, it is worth noting that most of this surface includes drowned atoll rims and banks, and not shallow areas of active biological construction. The lagoonal areas of Chesterfield-Bellona (~12200 km^2), which are completely open to the ocean for the most part, also account for more than 1/3 of the total non-reef area (~31300 km^2). Detailed assessment of reef surface, itemized per individual reef types are available in Andréfouët & Torres-Pulliza (2004) at the exception of Chesterfield-Bellona which were computed afterwards.

Table 1: Surface areas and number of reef classes (*sensu* Millennium Mapping Project) of the main reef complexes of New Caledonia. Barrier reefs include here, for simplification, atoll and bank peripheries. Total reef area including only hard-bottom areas (forereefs, reef flats, reticulated areas, etc..). Non-reef areas include lagoons (deep and shallow), terraces (deep and shallow), enclosed basins and passes. Land includes the main land, uplifted land and islets. Grande Terre statistics include Balabio, Yandé and Belep continental islands. The New Caledonia statistics include each reefs from each region, except Walpole, Banc de la Torche, Matthew and Hunter. The number of Millennium classes includes the land classes (mainland, islets, etc.).

	Barrier reefs reefs (km^2)	**Fringing reefs (km^2)**	**Patch reefs (km^2)**	**Total reef area (km^2)**	**Non-reef area (km^2)**	**Land (km^2)**	**Number of Millennium classes**
D’Entrecasteaux	154.00	0.00	11.60	165.59	812.29	0.68	16
Chesterfield	1324.01	0.00	133.92	1457.93	12241.64	2.31	20
Loyalty	126.15	147.68	0.50	274.33	1037.61	1962.41	27
Ile Des Pins	104.12	10.82	13.68	128.62	370.53	161.98	34
Grande Terre	1744.06	391.18	376.22	2511.47	16874.25	16641.77	108
New Caledonia	3452.34	549.68	535.93	4537.94	31336.32	18769.15	162

Oceanic reefs: islands, banks, atolls, uplifted atolls, drowned reefs

Introduction

Oceanic reefs in New Caledonia includes a large variety of reef structures encountered on oceanic islands (Maré, Lifou, Tiga, Nié, Dudun, Léliogat, Hua), banks (Beautemps-Beaupré, Astrolabe, Petrie, Portail), atolls (most of D’Entrecasteaux reefs, Chesterfield and Bellona), uplifted atoll (Ouvéa) and drowned reefs (between Chesterfield and Bellona atolls). The presence of a drowned rim along the eastern perimeter of the Chesterfield/Bellona platforms justified that they were classified as atolls and not banks in the Millennium typology.

Chesterfield and Bellona

The two very large Coral Sea systems of Chesterfield and Bellona include intertidal structures on their western and southern flanks. The deep patches that are at the limit of visibility in satellite images of the deep lagoons may not be high relief patches. Instead, they are probably the top of low relief mounds (Richer de Forges *et al*., 1988). High relief pinnacles occur in Chesterfield, interpreted as the possible signature of karstic processes by Degauge-Michalski (1993). The eastern drowned paleo-rim systems are well visible on remote sensing imagery, showing drowned reef flats cut by passes.
The Chesterfield/Bellona are supported by five guyots (drowned atolls) that constitute the northern and oldest volcanoes along the Lord Howe hotspot track (Missegue & Collot, 1987). Volcanic activities possibly took place in the Late Oligocene time (28 Ma) when the Australian plate and the western side of the Lord Howe ridge moved above a hot-spot. The thickness of the carbonate layers are 200-300 m. Drilling till -14 m on the inner slopes and -9 m on the reef flat, the limit between 125 ka-Pleistocene/Holocene reefs was still not reached. However seismic data suggest that this limit is 2 to 3 m below the lagoon floor (40 to 60 m depth), and 7 m along the shallower inner slope. The origin of the antecedent rim-like structure that support the Holocene reefs is not elucidated and the different scenario are discussed in Degauge-Michalski (1993, p.190 and 198). Holocene reef growth as interpreted from cores data reveal that vertical growth was initiated around 6 ka, and stopped around 3.5 ka. Horizontal growth started shortly after the definitive sea level stabilization around 3000-2500 years B.P. The sequences of postglacial reef formation is described by Degauge-Michalski (1993) from cores drilled in the south central part of Bellona, near the “Caye de l’Observatoire”, in the southern tip of the Bellona atoll, and from the southern tip of Chesterfield atoll, around Loop islet. Subsidence rates were estimated at 0.1-0.15 $mm.y^{-1}$, slightly higher than d’Entrecasteaux and the west coast of Grande Terre.

Entrecasteaux

D’Entrecasteaux reefs supported by the northern extension of the NC ridge is the complex of reefs, including atolls and banks, separated from Grande-Terre by the 600-800 m deep “Grand Passage” (Collot *et al*., 1988a).

D’Entecasteaux reefs are arranged in three parallel ridges (Collot *et al*, 1988b). The main structures are Huon and Surprise which are two 60 m deep-lagoon atolls supported by a central NW-SE trending ridge of ultramafic rocks in the extension of the eastern ridge of the Grand Lagon Nord . East of Huon, the shallow atolls from the Guilbert’s group are supported by the northern end of a ridge which may include ultramafic rocks and thin imbricate slices of oceanic crust. West of the Huon-Surprise-Pelotas ridge, the Portail atoll is supported by a small N140°E ridge. Postglacial reefs have established upon antecedent karstified atoll structure around 6 ka. Drillings were performed on Surprise and Huon atolls on the inner slopes and reef flats. On Huon atoll, the limit between 125 ka-Pleistocene/Holocene reefs is at -7.90 m. On Surprise, the limit was not reached, but neo-tectonic processes may have occurred, putting the actual limit deeper (Degauge-Michalski 1993 p. 191). For Huon, assuming a sea level at 5 m higher than present around 125 ka, this provides a subsidence rate of 0.1 $mm.y^{-1}$, which is comparable to Grande-Terre rates (Degauge-Michalski 1993) and slightly lower than Chesterfield and Bellona’s atolls.

Loyalty

We include in the Loyalty reefs all the reefs supported by the Loyalty Ridge, from Maré up to Petrie Reef. The largest islands are the uplifted Pleistocene carbonate platforms of Lifou and Maré. Several small islands dot the ocean between Maré and Lifou (Nié, Dudune, Léliogat, Hua and Tiga). The largest of them is Tiga. The geomorphological diversity of these islands is low, since they mostly have fringing slopes and narrow fringing reef flats. Maré and Lifou also display small shallow lagoons. Northward, the complexity increases with Ouvea, a partially uplifted atoll, and the suite of banks that include Beautemps-Beaupré, Astrolabe and Petrie reefs.

Loyalty islands have been the focus of many geodynamic and geological studies. The Australian plate where are located the New Caledonian (a part of the Norfolk) and Loyalty ridges is subducting underneath the Pacific plate. This subduction induces a bulge of the Australian plate, that culminates in the Loyauté islands (Dubois *et al*., 1973, 1974). The various degree of uplift between islands and degree of terrace inclinations in Maré (Carriere,1987), due to the lithospheric flexure before the Vanuatu subduction zone provided an indirect way to measure and model the dynamics of this zone.

Walpole, Banc de la Torche, Matthew, Hunter

These four systems from the southern part of NC EEZ are presented together due to their extremely simple geomorphological structure, mapped with only one Millennium class. However their origins largely differ (uplifted reefal plateau, drowned atoll and active volcanoes).

Walpole island, located south of Maré and supported by the Loyalty ridge, is a 3 km-long and 200 to 500 m-wide reefal plateau which culminates at 70 m altitude and is surrounded by vertical cliffs cut by notches. A narrow reef terrace culminating between +4 and +8 m is located at the bottom (foot) of the cliffs. This island displays a succession of Pleistocene reef terraces due to the combination of eustatic sea level variations and tectonic movements induced by the bulge. The narrow reef terrace from +4 to +8 m is 125 ka-old while the surface of the plateau is probably older than 500 ka (dating by L.K. Ayliffe in Cabioch and Genthon, 2002). Multibeam bathymetric map, achieved in 2002 (Cabioch *et al*., 2003), reveals several submarine platforms, probably corresponding to low sea levels, and several landslides, probably induced by the location of the island on the bulge near the subduction zone.

The Banc de la Torche, located south of Ile des Pins, is a 120 m high and 5 km wide circular shoal. Its summit corresponds to a tabular plateau reaching 32 m depth, partly topped by a few meters high annular ring. Thus, it may be a drowned atoll (Flamand, 2006).

Matthew and Hunter are active volcanoes in the southernmost segment of the Vanuatu arc. They are located on the Pacific Plate.

Continental reefs: islands, fringing, barrier and patch reefs

Introduction

The continental reefs of New Caledonia offer the largest diversity of reef formations, explained by the diversity of environmental forcing. Following geomorphologic criteria, the Millennium typology separates the lagoons, and the fringing, barrier and patch reefs. Four islands (Ile des Pins, Balabio, Yandé and Belep) were considered separately due to their distance to the main land and respectable sizes. They were classified as continental islands, i.e. islands around the Grande-Terre “continent”.

Grande-Terre reef diversity is variable depending on the considered sector. Clockwise, these are the north, northeast, southeast, southwest, central-west and northwest sectors. Each has its own particularity. The North sector is characterized by a very wide lagoon (Grand Lagon Nord) bounded by a continuous barrier reef (split between the Récif des Français and Récif de Cook) but depleted from patch reefs. Balabio and Belep islands are found here. The northeast sector, from Amoss Pass down to Houailou Pass has a narrow lagoon bounded by an intertidal barrier reef. In the southeast sector, the barrier reef becomes progressively subtidal and drowned and the lagoon gets wider. The southwest sector includes Ile des Pins and the highly-complex and wide southwest lagoon with numerous fringing and patch reef systems with different hydrodynamic exposure. The Millennium typology separates the oceanic, intra-seas and lagoonal patch and fringing reefs. Thus, highest reef diversity is found in this southwest sector. The central-west sector is characterized by coastal barrier reefs without deep lagoons but with large sedimentary shallow terraces. North of Népoui, the northwestern sector provides deeper lagoons bounded by continuous barrier reefs with large enclosed basins, and large lagoonal fringing reefs and patch reefs.

Balabio, Yandé and Belep

These three islands are found in the north lagoon. Balabio displays the widest formations in the continuity of the bended, imbricated Cook Reef south section. The habitat zonations and navigation channels justify the classification of Balabio reefs as a coastal barrier reef. Another possible interpretation could have been to consider Balabio reefs as the prolongation of the south Cook Reef merging with the fringing system of Balabio. Thus, the Balabio area would be classified as an imbricated fringing-barrier structure. This interpretation was eventually discarded because of the presence of a deep channel east of Balabio. Balabio has very large sedimentary terraces dominated by seagrass beds. Narrower fringing reefs and coastal barriers are found on Belep on Yandé. Yandé has a reticulated terrace on its southwest side.

Ile des Pins

Ile des Pins exhibits a large diversity of reefs, with gradients of exposure, distance to the shores and depth, with deep and shallow lagoons.
The system is dominated by two types of barrier reefs: an outer barrier reef system in the northwest (Jaré, Titia and Kuru Reefs), and two structurally contrasted coastal barrier reefs in the west and south sections. The Kangé Reef (west) has a wide shallow terrace dotted with numerous small patch and linear reefs. Large lagoonal patch reefs are found in the northwest lagoon. The vicinity of Ile des Pins includes several oceanic patch reef systems (e.g. Nokanhui, just north of the Banc de la Torche, and the Merlet reef system) as well. Finally, steep fringing slopes are on the oceanic east side.
The contrast between steep oceanic east slope and wide western terrace is an evidence of the influence of the lithospheric bulge on the island. The Pleistocene reef system was uplifted and tilted, but appears stable since 120 ka (Launay, 1985). Subsidence and uplift are in equilibrium in this part of

New Caledonia, but the subsidence dominates offshore southeastward (Cabioch *et al.*, 1996). This explains the morphology of Nokanhui reefs, and the presence in this direction of a small 20 m-deep bank and then the Banc de la Torche.

Grande –Terre

The reefs surrounding Grande-Terre are the most extensive and are by far the most studied. We detail hereafter the barrier, fringing and patch reef complexes.

Barrier reefs

The outer barrier reef system is made of four different types of Millennium-type barrier reefs (regular, imbricated, coastal, multiple) (Fig. 8, plate 3/3). The barrier reef has been drilled in several locations around Grande-Terre (Fig. 3) (Cabioch *et al.*, 2001, 2003). The deepest core reaches more than 220 m at Ténia (Coudray, 1976). More recently, cores were performed in Amédée Reef (south-west coast) and in Kendec reef (north-west reef) (Cabioch *et al.*, 2004). Additional cores were recovered at Ténia (Cabioch *et al.*, 2004). Data show that the barrier reef has been constructed layers by layers during the different episodes of reef accretion and sea level variations during Quaternary times.
Drowned terraces have been mapped all along the barrier reef slopes using multibeam data. Deep and wide marine terraces found along the slopes suggest reef flat formations (vertical catch-up growth followed by horizontal growth when sea level is reached) during high sea level stands anterior to the postglacial period (Flamand, 2006). Deepest terraces are interpreted as the oldest. Flamand (2006), in a detailed analysis of the slopes morphology, highlights five groups (T1 to T5) of few decameter width terraces. These five groups provide terraces in the -20 to -50 m, -50/-55 to -70/-75 m, -60/-70 to -85/-95 m, -95 to -105 m and -100 to -115/-120 m depth range (Fig. 9, plate 3/4). The vertical evolution of the largest terrace T3 (-60/-70 to -85/-95 m) reveals that the barrier reef is segmented, as previously observed in the fringing reefs (Cabioch, 1988), in blocks with independent vertical motions created by three groups faults striking N110°E, N-S, and N70ºE. The datation of these terraces and the correspondence with reef flat cores sequences is a work in progress that requires several hypotheses on subsidence rates, timing of high sea-levels, tectonic influences and homogeneity of reef growth rates (Flamand 2006). If the preliminary analysis is confirmed, it appears for instance that T3 was created around the marine isotopic stage 11 (~408) ka.
The modern shallow barrier reef is generally made of a high-energy outer reef flat that contrasts with a sedimentary back-reef terrace with or without presence of pinnacles on the inner slopes. This is the dominant facies of the southwest and north barrier reef. However, several reticulated terraces and basins probably from karstic origins (dissolution by aerial exposure of carbonate forms during period of low sea levels periods resulting in a rugose substrate) are adjacent to the reef flats and provide shallow segments of much higher structural complexity (for instance Tetembia, Gatope or Koumac Reefs). Variations occur along the barrier reef bounding the Grand Passage in the north which is drowned and partially imbricated, and fragmented on its eastern section. The north section of Cook Reef is fragmented, with numerous sections of subtidal reef flats. The tip of Grand Récif Sud, i.e. the most southern barrier reef, is also imbricated) and provides a specific inner-outer zonation with larger protected outer slopes. The largest extent of the south lagoon is due to faster subsidence rates. Subsidence rates in the far south is not exactly known but cores suggest a 0.14 $mm.y^{-1}$ rate at Amédée Reef. Further south of Ile des Pins, in Nokanhui and Banc de la Torche area, subsidence rates might be higher.

The shallow central western coastal barrier reefs between Moindou and Kone are also rich in reticulated and linear intermediate formations. The absence of lagoon, and the short distance between the outer reef and the coastline in this part of New Caledonia is explained by a lowest (double) rate of subsidence (0.03 $mm.y^{-1}$). Slow subsidence also explains why 125 ka-Pleistocene reefs are still visible above sea level in the present days in this area (e.g. Vert Islet in Bourail: Degauge-Michalski 1993; Cabioch *et al*. 1996).

The eastern barrier reef is partly multiple (double), partly drowned. In addition, alignments of lagoonal patch reefs could be also interpreted as barrier reef formations if they were more continuous (St Laurent Reef, offshore Canala). Coudray (1976, Fig. 23) provides several explanations for the presence of intra-lagoon barrier (e.g. Bogota Reef) or multiple barrier reefs (e.g. outer barrier off Thio and Poindimié) that are parallel to the coastline. First, reef growth may occur on opposite directions due to strong hydrodynamic on both faces of the reefs. Inner spur-and-grooves systems are present on inner sides of barrier reefs offshore Port-Bouquet confirming partly this hypothesis (pers. obs.). However, due to the size of the parallel structures, other most likely scenarios present the inner reefs as older reefs. Installation of younger, outer reefs have occurred parallel to older reefs due to a combination of subsidence, sea level variations and local tectonics processes that have locally created new parallel substratum for coral colonization in a stepping stone fashion.

The south tip of the eastern barrier reef is drowned. Optical remote sensing does not provide details on these deep structures below twenty five meters, but acoustic multi-beam data allows analyzing its detailed morphology and how this part of the barrier reef as evolved under the local tectonics and morpho-structural constraints. From Ouinné Pass to La Havannah Pass, the submerged barrier reef strikes to the N150°E. The eastern barrier reef has been mapped continuously from the lagoon to the open ocean just north of La Havannah Pass and southeast of Goro. Multibeam data revealed the structure of a N150°E striking ridge between -20 m and -100 m depth called the Coëtlogon Bank (Fig. 10, plate 3/5). The western slope is wider than its eastern counterpart. Several escarpments and numerous terraces have been recognized along these slopes (Flamand, 2006). Five terraces occur on the eastern slope, and three on the west. Assuming these terraces are synchronous, this dissymmetry suggests a 5-10m-amplitude northeastward tilt of the structure (Fig. 10, plate 3/5). Even if this drowned ridge related structure has been only mapped locally, one can expect that it may extend northward.

Fringing reefs

The variety of coastal environments around Grande-Terre and Ile Ouen has provided a large number of fringing configurations. They are found in oceanic, intra-seas, lagoonal, bay and coastal barrier reef environment. High-energy fringing reefs are found on the southeast coast, exposed to the ocean. In Voh, Pam, Pouébo and La Foa they make very large low energy terraces dominated by seagrass beds and bordered by mangroves. In Néhoue Bay and Port-Bouquet Bay, satellite images reveal reticulations.

The fig. 4 summarizes the different morphologies and settlement-growth sequences observed in the various drilling sites around Grande Terre. The drilling sites around Yaté provided cores from uplifted areas. The foundation of Holocene reefs consists in 125 ka-reefs (Ricaudy Reef, near Nouméa) or non-carbonate substratum (Pouébo). The horizontal growth and type of facies (coral-coralline-sediment matrix) of the forereef depends on the degree of hydrodynamic energy of the sites (Cabioch, 1988; 2003 ; Cabioch *et al*., 1995).

Patch reefs

The patch reefs around Grande-Terre are found in oceanic, intra-seas and lagoonal environment. They vary widely in size and habitat zonations. The richest areas are the southwest lagoon, and between Ile des Pins and Grande-Terre. In the north and east lagoons, patch reefs are also abundant, especially between Kaala-Gomen and Koumac, and next to Borindy.

Patch reefs are often ellipsoids and organized as alignments parallel to barrier reefs (e.g. N130ºE directions near Noumea). However, in the south lagoon, the shapes and directions vary significantly. The subtidal topography visible in satellite images show that intertidal lagoonal path reefs are connected by large common foundations and rims. This suggests similar structures than the faroes visible in Maldives atoll lagoons, where subaerial exposure of antecedent platforms have created new

karstic topography available for colonization and growth during the Holocene (Purdy & Bertram 1993). This interpretation is consistent with seismic reflection profiles collected in the south lagoon (Dugas *et al*. 1980) and with the timing of sea level variations. Sea-level variations amplitude during the last interglacial (125 ka), subsidence rates estimated in Amédée Reef and present average depth of the south lagoon (~20m) show that the submergence time of the lagoon was limited and aerial exposure frequent (Dugas *et al*., 1980, Chevillotte *et al*. 2005).
Lagoonal patch reefs have been drilled at Maitre, Larégnère and Mba islest near Nouméa. Cores performed in this reefs reveal that the modern reef (or Holocene reef) is particularly thin and cap the 125 ka reef. The old Pleistocene reefs are constituted by reefal sediments rich in molluscs, foraminifers and algae (Castellaro, 1999).

Conclusion

This review of New Caledonia reef structures is original since it comes from a unique synthesis of three different data sources. Remote sensing precisely shows, in a continuous 2D-field, the extent, diversity and complexity of reef geomorphological features. In addition, drilling and multi-beam data provide the 3D structure and help defining the dynamics of the system since the last interglacial, the time period we have considered here.
The review highlighted the high diversity of morphologies and processes that occur in New Caledonia EEZ waters. Considering the artificial nature of EEZ boundary, NC is not the most complex areas in the world in terms of reef diversity, but it is one of the most complex, and its paleodynamics is certainly one of the most studied worldwide.
Our goals were to present here the background of the rich biodiversity of New Caledonia coral reefs. We make here a first cut considering only the geomorphological units and their diversity in terms of structures and processes. But it would be necessary to also provide a description of the diversity of habitats found in the lagoons and reefs to finish the description of this background. This is a work in progress, also combining remote sensing and *in situ* data. Coral and algal communities are also an essential piece to solve the puzzle of reef formations in New Caledonia. Data on occurrences of paleo-communities, compared with modern communities, are essential for understanding the dynamics of the system. Further description of reef habitats and communities, both modern and fossil, and their comparisons are yet to be provided, but they will achieve in the future the description of the marine diversity described in this volume.

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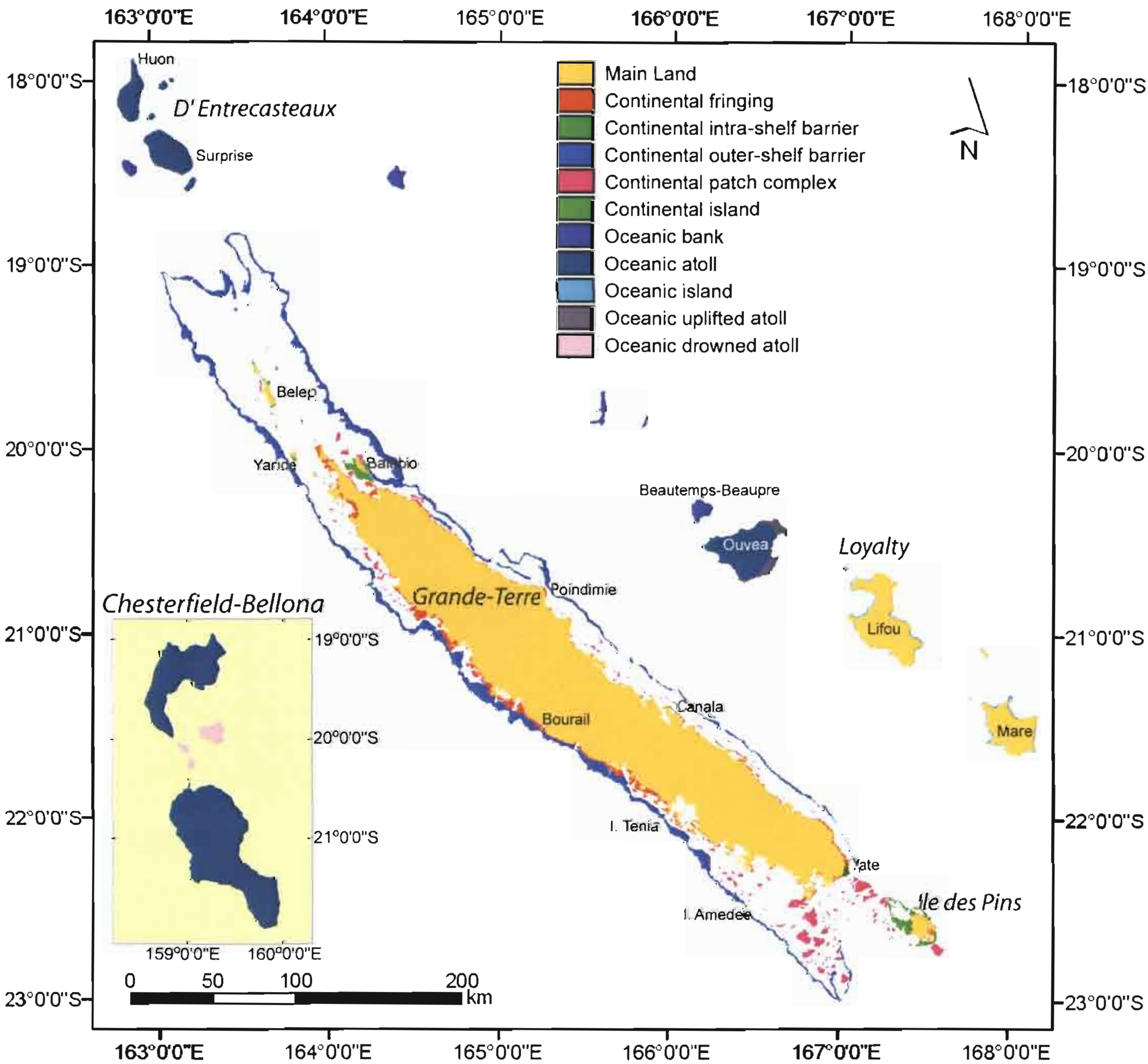

Figure 1: Reef geomorphology map of New Caledonia according to the Millennium Mapping Project typology (modified from Andréfouët & Torres-Pulliza, 2004).

Oceanic Reefs

- *Atoll*
  - Drowned atoll
  - Lagoon
  - Rim
  - Patch
- *Bank*
  - Drowned bank
  - Bridge
  - Lagoon
  - Barrier
  - Patch
- *Uplifted Atoll*
- *Island*
  - Land
  - Non reefal water bodies
  - Coastal Barrier
  - Outer Barrier
  - Multiple Barrier
  - Imbricated Barrier
  - Barrier-Fringing
  - Coastal/fringing Patch
  - Intra-lagoon Patch
  - Intra-seas Patch
  - Shelf Patch
  - Ocean Exposed Fringing
  - Intra-seas Exposed Fringing
  - Lagoon Exposed Fringing
  - Shelf Reefs

Continental (shelf) Reefs

- *Atoll*
  - Drowned atoll
  - Lagoon
  - Rim
  - Patch
- *Bank*
  - Drowned Bank
  - Bridge
  - Lagoon
  - Barrier
  - Patch
- *Uplifted Atoll*
- *Island*
  - Land
  - Non reefal water bodies
  - Coastal Barrier
  - Outer Barrier
  - Multiple Barrier
  - Imbricated Barrier
  - Barrier-Fringing
  - Coastal/fringing Patch
  - Intra-lagoon Patch
  - Intra-seas Patch
  - Shelf Patch
  - Ocean Exposed Fringing
  - Intra-seas Exposed Fringing
  - Lagoon Exposed Fringing
  - Shelf Reefs
- *Patch*
  - Coastal/fringing Patch
  - Intra-lagoon Patch
  - Intra-seas Patch
  - Shelf Patch
- *Intra-shelf Barrier*
  - Coastal Barrier
  - Outer Barrier
  - Multiple Barrier
  - Imbricated Barrier
  - Barrier-Fringing
- *Outer-Shelf Barrier*
  - Coastal Barrier
  - Outer Barrier
  - Multiple Barrier
  - Imbricated Barrier
  - Barrier-Fringing
- *Fringing*
  - Ocean Exposed Fringing
  - Intra-seas Exposed Fringing
  - Lagoon Exposed Fringing
- *Shelf*

Figure 7: Main nodes of the Millennium coral reef typology (from Andréfouët *et al.*, 2006).

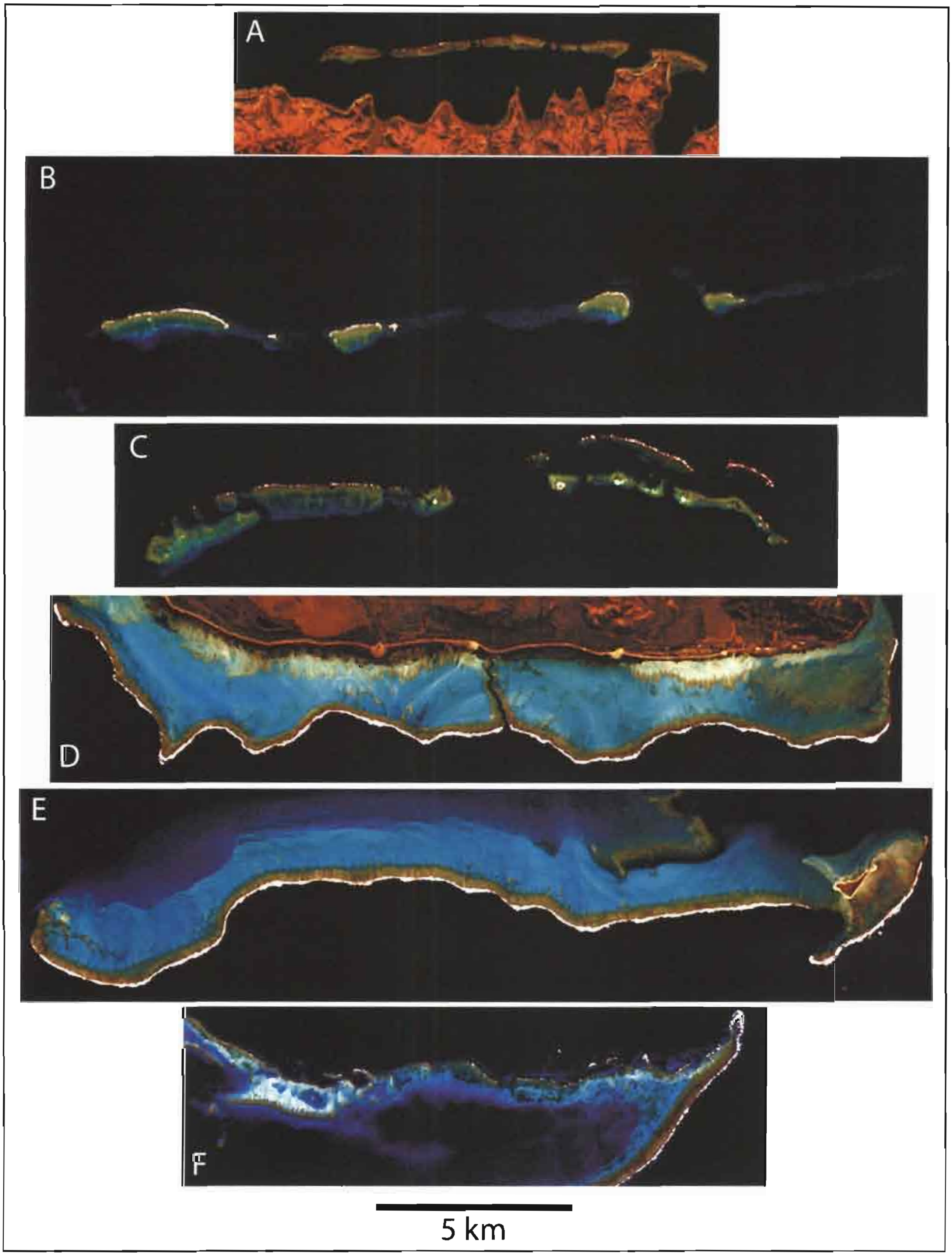

Figure 8: Examples of the diversity of New Caledonia barrier reefs (BR). Landsat images acquired between 1999-2003. Imges are at the same scale, but have been rotated for easier comparisons. On the East Coast: A: intra-shelf BR, Bogota Reef, Ouasse-Canala. B: outer-shelf outer BR, Canala, large portions of the reef are drowned. C: outer-shelf multiple (double) BR, Poindimié; Ilot Bayes, a drilling site, is visible. On the West Coast: D: outer-shelf coastal BR, Poe. E: outer-shelf outer BR, Grand Récif Extérieur, Boulouparis; Ilot Tenia, a drilling site is visible on the right side. F: outer-shelf imbricated BR, Corne Sud.

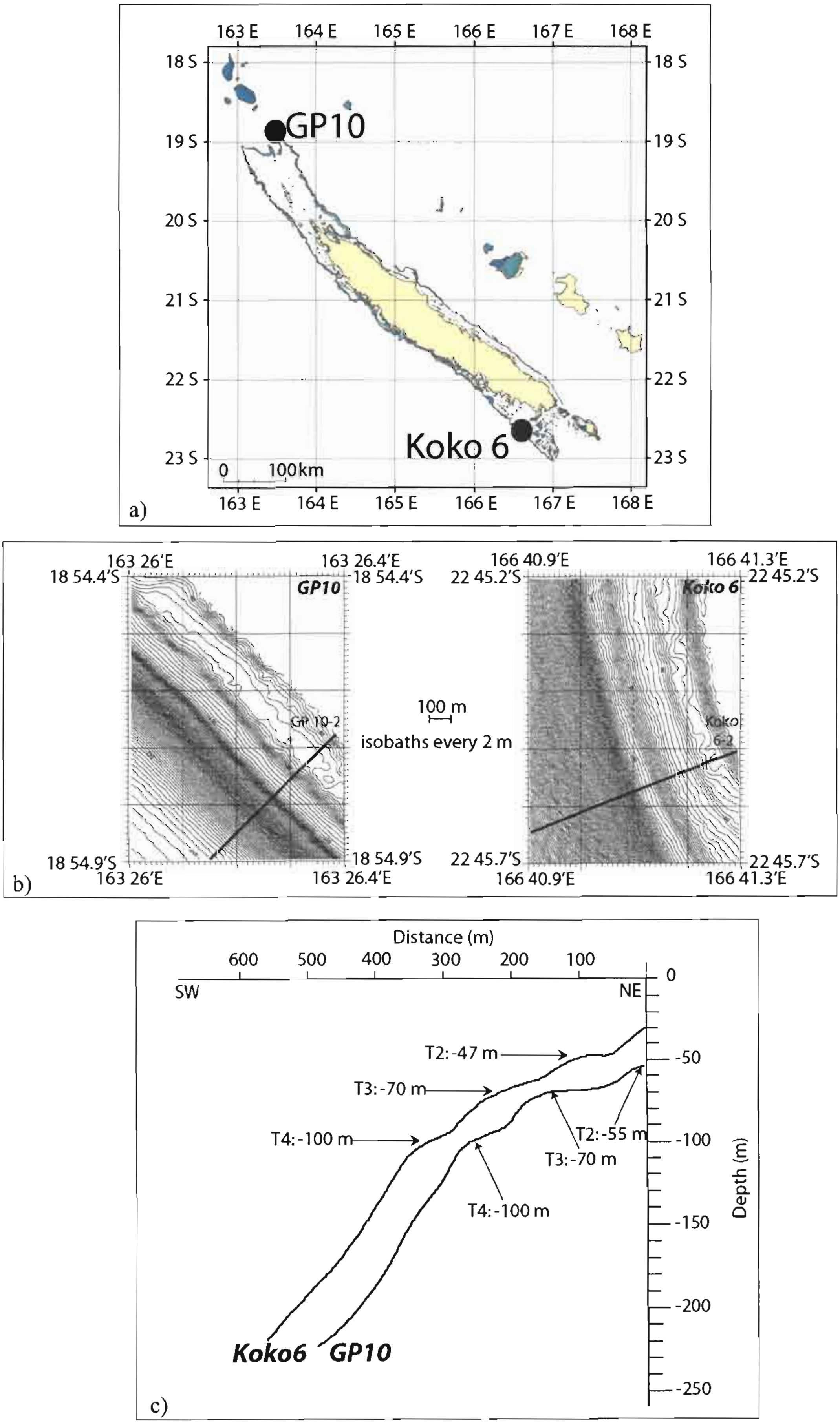

Figure 9: Detailed bathymetric maps from two different locations, in the north (Grand Passage 10) and South (Koko 6) of New Caledonia. The profiles show the depth and morphology of the marine terraces.

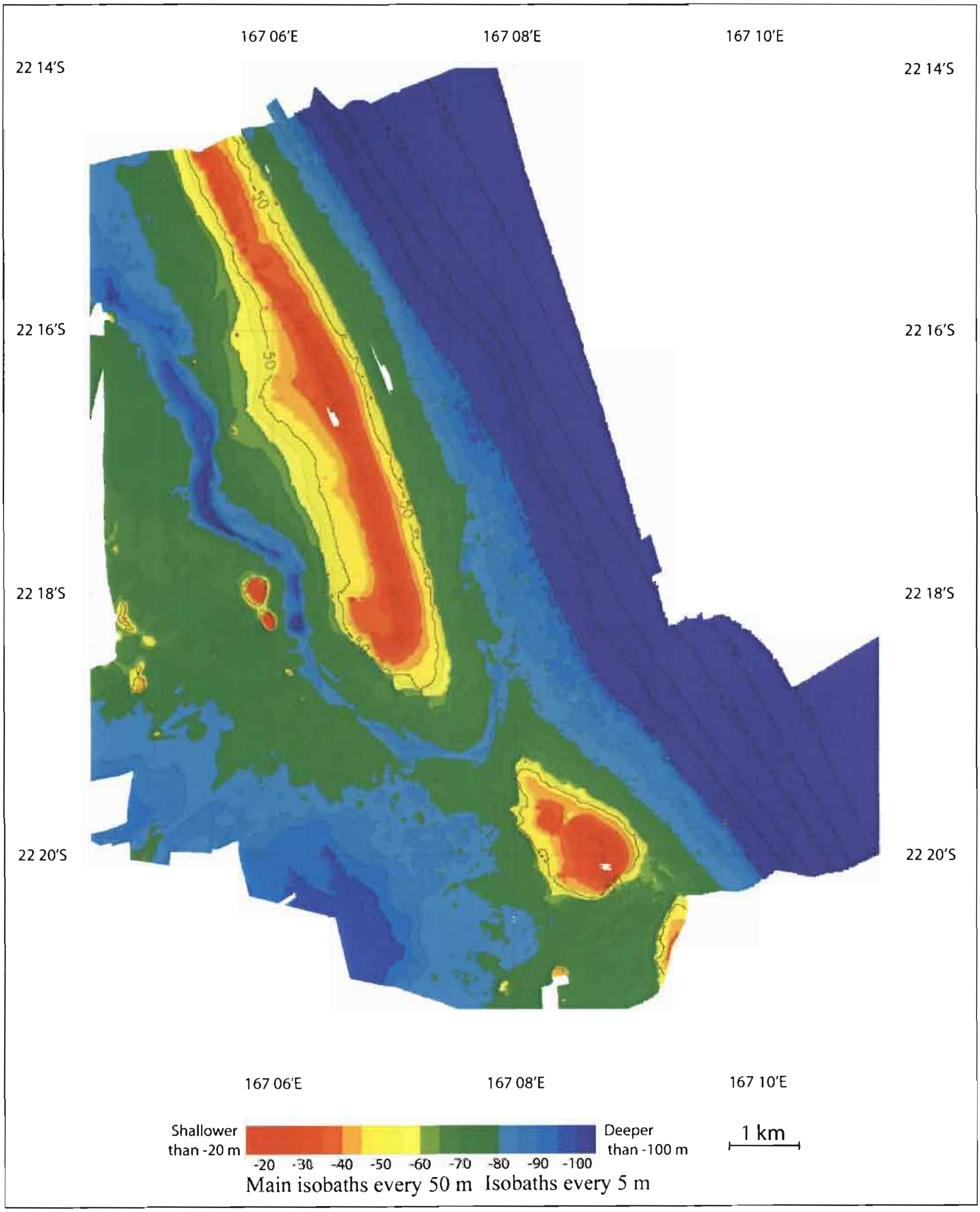

Figure 10: Bathymetric map of the Coëtlogon Bank area (modified from Flamand, 2006).

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Volume spécial

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