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Control of paleoshorelines by trench forebulge uplift, Loyalty Islands

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ABSTRACT

Unlike most tropical Pacific islands, which lie along island arcs or hotspot chains, the Loyalty Islands between New Caledonia and Vanuatu owe their existence and morphology to the uplift of pre-existing atolls on the flexural forebulge of the New Hebrides Trench. The configuration and topography of each island is a function of distance from the crest of the uplifted forebulge. Both Maré and Lifou are fully emergent paleoatolls upon which ancient barrier reefs form highstanding annular ridges that enclose interior plateaus representing paleolagoon floors, whereas the partially emergent Ouvea paleoatoll rim flanks a drowned remnant lagoon. Emergent paleoshoreline features exposed by island uplift include paleoreef flats constructed as ancient fringing reefs built to past low tide levels and emergent tidal notches incised at past high tide levels. Present paleoshoreline elevations record uplift rates of the islands since last-interglacial and mid-Holocene highstands in global and regional sea levels, respectively, and paleoreef stratigraphy reflects net Quaternary island emergence. The empirical uplift rates vary in harmony with theoretical uplift rates inferred from the different positions of the islands in transit across the trench forebulge at the trench subduction rate. The Loyalty Islands provide a case study of island environments controlled primarily by neotectonics.

Introduction

Most island chains of tropical Pacific Oceania are either island arcs where volcanism builds alignments of islands parallel to subduction zones at oceanic trenches as magma rising from depth erupts through the overriding tectonic plates, or hotspot tracks of islands built across open seafloor by eruptions through the Pacific plate as it drifts across magma hearths in the mantle beneath. Variable arc and hotspot behavior influence the evolution of Pacific island chains (Scott and Rotondo, 1983; Dickinson, 1998, 2001), but the twin themes of arc and hotspot evolution dominate Quaternary history and govern analysis of evolving paleoenvironments over most of Pacific Oceania. The geodynamics of the Loyalty Islands between New Caledonia and Vanuatu (Fig. 1) are quite different.

The Loyalty chain owes its existence to Quaternary uplift of an alignment of pre-existing atolls on the flexural forebulge of the seafloor in front of the New Hebrides Trench (Dubois et al., 1974, 1975, 1977, 1988). The uplift of isolated islands on trench forebulges is known elsewhere in the world (Coudray and Montaggioni, 1982; Woodroffe, 1988; Nunn, 1988; Dickinson, 2001: 215–217), but the Loyalty chain is unique in displaying multiple uplifted atolls (Fig. 2) aligned obliquely to the crest of the trench forebulge (Carriére, 1987). The oldest limestones are of Miocene age on Loyalty paleoatolls (Chevalier, 1973), which crown the bathymetric Loyalty Ridge trending obliquely to the New Hebrides Trench and forebulge. South of the Loyalty Islands, the northeast flank of the Loyalty Ridge is currently colliding at the trench with the southern end of the New Hebrides island arc (Monzier et al., 1990). The Loyalty case of forebulge uplift is especially informative because each of the three main islands has a different morphology resulting from different Quaternary uplift and paleoshoreline histories stemming from the different positions of the islands with respect to the crest of the forebulge.

On Maré and Lifou, annular ridges rimming the flanks of the islands represent annular paleoatoll reefs that enclose nearly flat interior plateaus standing at lower elevations and representing the drained floors of paleolagoons. The outer slopes of the two islands are steep declivities, locally scored by marine terraces, representing the exterior walls of the paleoatoll reefs modified only slightly by erosion during uplift. On Ouvea, which has been uplifted less than either Maré or Lifou, the paleolagoon is still drowned by seawater.

Uplifted reef complexes in the Loyalty Islands are morphologically similar to uplifted reefs in other geotectonic settings but the geodynamic impulse for uplift is different. In the South Pacific Ocean, for example, uplifted fringing reefs on *makatea* islands of the Cook–Austral chain and uplifted atolls of Makatea Island and Anaa Atoll along the fringe of the Tuamotu Archipelago have been raised on annular flexural upwarps of the seafloor surrounding the cones of depression beneath the centroids of growing volcanic islands in positions far removed from any influence of plate subduction (Dickinson, 1998, 2001: 210–215). In forearc belts between island arcs and associated trenches, reef complexes can be uplifted along the edge of the overriding plate in response to deformation along the flank of the volcanic arc (Dickinson, 2000; Taylor et al., 2005;

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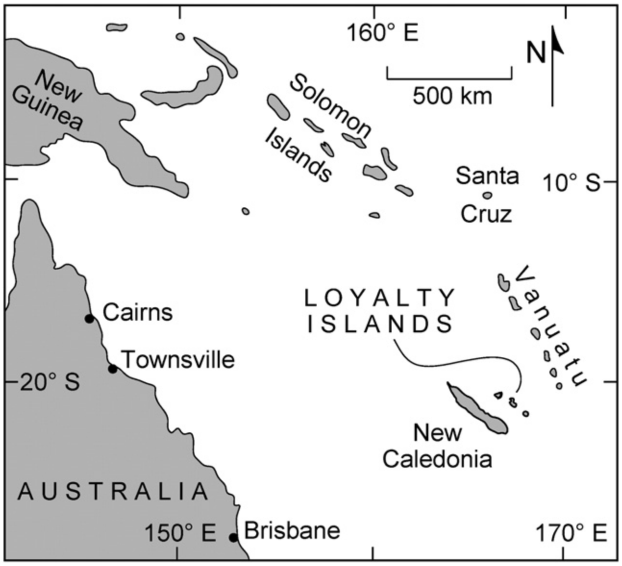

Figure 1. Location of the Loyalty Islands in the southwest Pacific Ocean east of Australia.

Dickinson and Burley, 2007) or to the growing crustal bulk of an accretionary subduction complex, as beneath Barbados in the Lesser Antilles (Speed and Larue, 1982). Analysis of paleoshoreline history related to forearc uplift near the edge of an overriding plate at a subduction zone differs in principle, however, from analysis of paleoshoreline history in the Loyalty Islands on the subducting plate. The only islands in the Pacific arena also uplifted on trench forebulges are isolated islands east of the Tonga Trench (Niue) and southwest of the San Cristobal Trench bounding the Solomon Islands (Bellona, Rennell).

Purpose and methodology

This paper has three purposes: (1) to report the differential elevations recorded for mid-Holocene and last interglacial paleoshoreline features exposed along island shorelines as empirical evidence for rates of late Quaternary uplift in the Loyalty Islands; (2) to evaluate the theoretical uplift rates predicted for each of the islands from the morphology of the trench forebulge and the rate of plate convergence at the New Hebrides Trench; and (3) to reconcile the empirical and theoretical uplift estimates in the context of the morphology of each island.

The empirical data for the elevations of Loyalty paleoshoreline indicators derive from a detailed reconnaissance of all shorelines accessible by road or by walking beaches on all three of the principal islands. My reconnaissance occupied a full elapsed month immediately following the International Lapita Conference held in Noumea, New Caledonia, in August of 2002. Good road access in detail on all three Loyalty islands (Maré, Lifou, Ouvea) allowed examination of paleoshoreline features on all coastlines not formed by steep declivities where no discernible paleoshoreline record is preserved (Fig. 3A). Many coastal flanks of the islands are precipitous because they are inherited from the steep outer walls of paleoatoll reefs. Discontinuous modern fringing reefs are uniformly narrow and typically present only within shoaling embayments between cliffed headlands forming shoreline promontories.

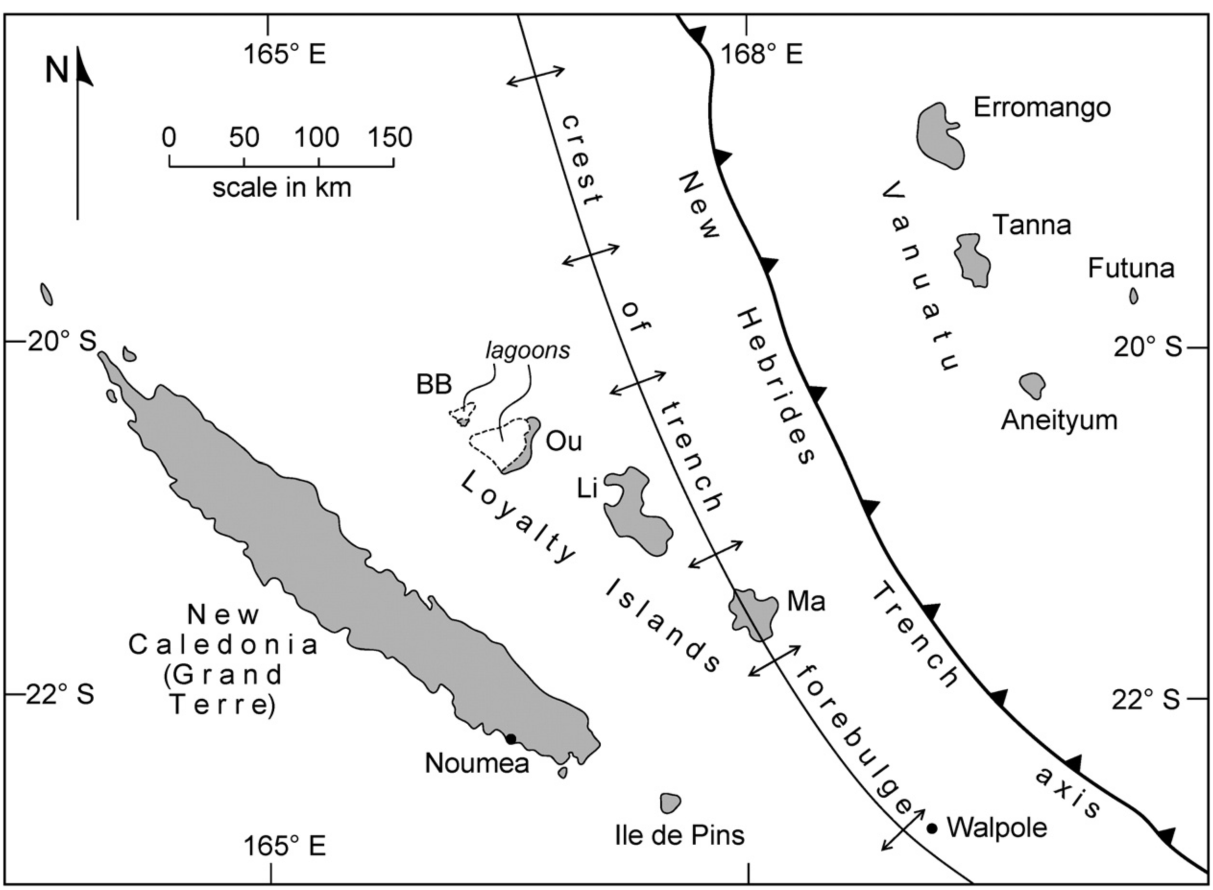

Figure 2. Tectonic setting of the Loyalty Islands (BB—Beautemps-Beaupré, Li—Lifou, Ma—Maré, Ou—Ouvea). From the configurations of flexural forebulge transects (Dubois et al., 1975, 1977, 1988), the crest of the trench forebulge is drawn parallel to the axis of the New Hebrides Trench where edge loading of the Australian plate, including the Loyalty Islands and New Caledonia, occurs beneath the overriding Pacific plate including Vanuatu.

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Past isotopic dating of limestones in the Loyalty Islands (Bernat et al., 1976; Marshall and Launay, 1978; Guyomard et al., 1996) is adequate for the identification of mid-Holocene and last-interglacial paleoshoreline features by analogy with relations elsewhere in Pacific Oceania (Dickinson, 2001). Lateral correlation of key paleoshoreline indicators allows extrapolation of age relations from selected localities where isotopic dating is available to other coastal reaches of the same island. Comparative elevations of the key paleoshoreline indicators on different islands shed light on the uplift history of the island chain as a whole.

Paleoshoreline indicators

Emergent paleoshoreline indicators of the late Quaternary positions of higher relative sea levels on limestone coasts of Pacific islands include records of both paleolow tide and paleohigh tide (Fig. 4). Paleoreef flats of emergent fringing reefs accreted to the flanks of islands record past higher levels of paleolow tide, above which paleoreef growth was arrested. Paleoreef remnants cannot be used as paleoshoreline indicators unless they are capped by smooth flat surfaces of paleoreef flats because coralline organisms can thrive at various depths below low tide level. Paleonotches incised into the bases of limestone cliffs well above the present sea level record past positions of high tide where bioerosion by littoral organisms created tidal notches at higher relative sea levels. Where intertidal beachrock is present on beach faces associated with modern tidal notches, the notches are incised at an elevation comparable to the upper limit of the sloping beachrock armor mantling the beach sand (Fig. 3B). It is important to appreciate that tidal notches on limestone coasts do not reflect wave attack, but bioerosion that is as effective in sheltered embayments as on exposed headlands (Hodgkin, 1970).

The elevations of paleoshoreline indicators relative to modern counterparts can be used to estimate past relative sea levels without detailed knowledge of current mean sea level, which is commonly poorly known for island locales far removed from tide gauges. For

Figure 3. Shoreline and paleoshoreline features in the Loyalty Islands: A, steep declivity displaying no discernible paleoshoreline features on the northeast face of Cap Coster on easternmost Maré (seacliff is ~60 m high); B, modern shoreline notch between Wabao and Cap Wabao (locality M3 of Table 1 and Fig. 7) on Maré (note that the apex of the notch is at the elevation of the upper limit of modern intertidal beachrock armoring the beach face in the foreground); C, mid-Holocene paleoreef flat (horizontal bedding) emergent above a modern shoreline notch at the inland edge of a modern fringing reef at Col de Casse Cou on Ouvea (locality U3 of Table 1 and Fig. 10); D, view southwest across the bay at Mou on the southeast end of Lifou showing the even surface of a last-interglacial paleoreef flat aligned with the camera position (locality L3 of Table 1 and Fig. 8 is on the far side of the bay in view); E, speleothem-ornamented last-interglacial paleoshoreline notch on the inland edge of a degraded last-interglacial paleoreef flat on southeast Lifou off the road from We to Mou (Fig. 8); F, view east at low tide on Ouvea across a modern reef flat in the foreground to a last-interglacial paleoshoreline notch (note speleothem ornamentation) emergent above the modern shoreline notch at the foot of the seacliff (locality U6 of Table 1 and Fig. 10).

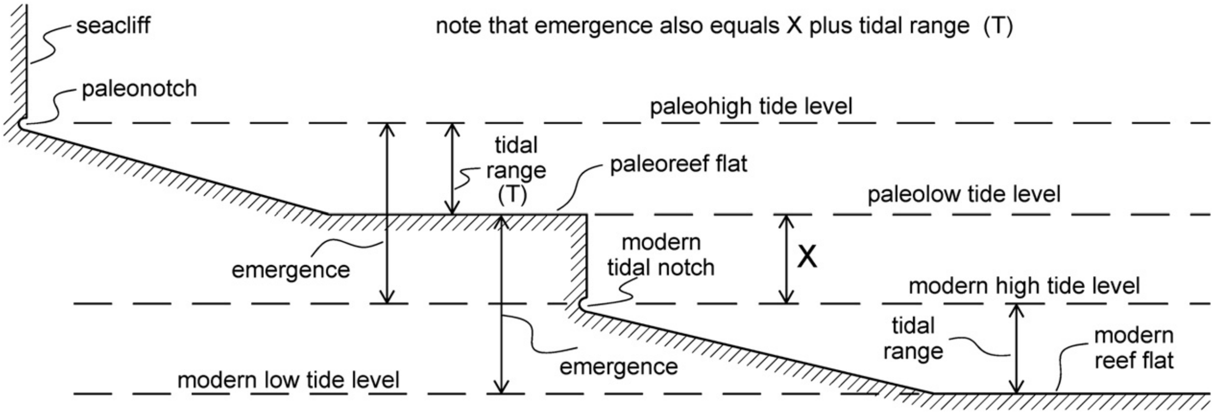

Figure 4. Determination of island emergence from key paleoshoreline indicators (paleoreef flats and paleonotches). Not to scale.

example, the differential elevations in the same seacliffs of the apices of paleonotches and active modern tidal notches cut at the present high tide level are reliable measures of changes in relative sea level (Fig. 4). Equivalent estimates of changes in relative sea level are provided by differential elevations of emergent paleoreef flats and modern offshore fringing reef flats that rise to low-tide level (Fig. 4). Where wave conditions or the timing of the tidal cycle makes wading on modern fringing reefs hazardous, satisfactory estimates of differential reef elevations can be determined by measuring the elevations of paleoreef flats relative to modern tidal notches cut into their flanks at modern high-tide level and adding the spring tidal range (Fig. 4), which is ~1.5 m for the New Caledonia region (Cabioch et al., 1995). For this study, all elevation differences between modern shoreline and paleoshoreline features (Fig. 4) were measured on outcrop using a hand level.

Because both tidal notches and reef flats are topographically irregular, differential elevations of paleoshoreline indicators cannot be measured in the field to a closer tolerance than ~0.1 m. Uncertainties of ±0.2 m in differential elevation are therefore a realistic appraisal of the precision that can be achieved with confidence by field observations (Table 1). Because some minimum duration of a higher relative sea level on island coasts is required to produce either persistent paleoreef flats or paleonotches resistant to erosion, emergent paleoshoreline indicators are effectively restricted to determinations of relative sea levels at the times of mid-Holocene and last interglacial highstands in tropical Pacific sea level (Dickinson, 2001, 2004). In the Loyalty Islands, the geomorphic record of older paleoshorelines is too fragmentary and too masked by thick vegetation to assess with confidence.

Last interglacial highstand

The last interglaciation peaked at ~125 ka (Edwards et al., 1987; Chen et al., 1991; Stirling et al., 1995), and was effectively terminated by ~115 ka (Muhs, 2002; Muhs et al., 2002). The global magnitude of the last interglacial highstand in eustatic sea level is most traditionally estimated to have been 6–7 m above modern sea level (Spencer et al., 1987; Jones and Hunter, 1990; Neumann and Hearty, 1996; Israelson and Wohlfarth, 1999). Uncertainties in the tectonic stability of proxy sites and in global isostatic adjustment (GIA) to changing interglacial sea levels make for a somewhat wider estimated range of 5–9 m above modern sea level (Lambeck and Nakada, 1992; Kopp et al., 2009; Dutton and Lambeck, 2012). For determining post-last interglacial uplift of the Loyalty Islands, the present elevations of paleoshoreline indicators ascribed to the last-interglacial highstand are compared to expected elevations of 7 ± 2 m relative to modern shoreline features, and implied uplift rates are calculated from an inferred age of 120 ± 5 ka for the last-interglacial features.

Mid-Holocene highstand

The mid-Holocene highstand across tropical Pacific Oceania was a hydro-isostatic facet of global isostatic adjustment (GIA) to the removal of Pleistocene ice loads from the polar regions. After meltwater raised eustatic sea level globally, slow mantle flowage rebalanced global isostasy by withdrawing seawater from equatorial oceans to fill space vacated by the delayed collapse of isostatic uplifts that had surrounded the loads of polar ice fields (Mitrovica and Peltier, 1991; Montaggioni, 2005), and by the continued subsidence of continental shelves tilted seaward by the augmented load of offshore meltwater that flexurally depressed the margins of continental blocks (Mitrovica and Milne, 2002). The resulting mid-Holocene highstand of regional sea level in Pacific Oceania was controlled by early Holocene rise in eustatic sea level followed by late Holocene decline in hydro-isostatic sea level (Dickinson, 2001).

Table 1
Relative elevations of paleoshoreline indicators in the Loyalty Islands listed by distance (to the nearest 5 km) from the axis of the New Hebrides Trench (the forebulge crest is ~100 km from the trench). Site code: L—Lifou, M—Maré, U—Ouvea. Age code: MH—mid-Holocene, LIG—last interglacial. Indicator type: pf—paleoreef flat (emergence is the differential elevation between a preserved paleoreef flat and the surface of a modern offshore fringing-reef flat constructed to modern low-tide level), pn—paleotidal notch (emergence is the differential elevation between the apices of a paleonotch and of a modern shoreline notch incised into the same seacliff at modern high-tide level). The spring tidal range is assumed to be 1.5 m, the modern range for New Caledonia (Cabioch et al., 1995) and a measure of the differential elevation between modern reef flats and modern shoreline notches, or between paleoreef flats and associated paleonotches (Fig. 3). See Figs. 7, 9, and 10 for locations of paleoshoreline sites on Maré (M1–M5), Lifou (L1–L3), and Ouvea (U1–U6), respectively.

Site	Location	Distance (km)	Age	Indicator Type	Emergence (m)
M1	Kurine	95	LIG	pf	8.9
M2	Wabao	105	MH	pn	2.2
M3	Plage de Kawé	110	LIG	pf	8.8
		110	MH	pn	1.8
M4	Plage de Pédé	110	LIG	pf	8.9
M5	Cap Wabao	115	LIG	pf	8.7
L1	Mou	130	MH	pn	2.3
L2	Wé	135	MH	pn	2.4
L3	Falaises de Xodé	135	LIG	pf	14.0
U1	Baie d'Ognat	175	MH	pn	1.8
U2	Saint Joseph	175	MH	pn	1.8
U3	Col de Casse Cou	180	LIG	pf	9.7
		180	MH	pf	1.8
U4	Trou Bleu d'Anawa	180	MH	pn	1.8
U5	Baie de Fayaoué	185	MH	pn	1.8
U6	Falaises de Lekinny	195	LIG	pn	7.2

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Theoretical calculations based on assumptions of globally uniform mantle rheology retrodict the peak of the mid-Holocene highstand in the range of 4 ka (Mitrovica and Peltier, 1991) to 5 ka (Mitrovica and Milne, 2002). For the Loyalty Islands, the latter age is preferred here because empirical age data for mid-Holocene paleoreefs fringing mainland New Caledonia (Grand Terre) indicate an age of 5.25 ± 0.45 ka, the mean of a dozen ages ranging from 5.8 to 4.6 ka (Cabioch et al., 1989). Depending upon local mantle rheology, the peak of the highstand varied areally, and highstand conditions apparently persisted until 2.5–2.0 ka in the atoll provinces of the open Pacific Ocean (Dickinson, 2009). There is no indication, however, that highstand conditions persisted after ~3.5 ka in the island arc provinces along the southwestern fringe of the Pacific Ocean including the region surrounding the Loyalty Islands (Dickinson, 2003).

From empirical data, the magnitude of the mid-Holocene highstand also varied areally across Pacific Oceania within the range of 1.0 to 2.5 m (Dickinson, 2009), but highstand magnitudes <1.75 m are known only for regions of Micronesia 3500 + km northwest of the Loyalty Islands and of Polynesia 2000 + km northeast of the Loyalty Islands. The theoretical estimate of highstand magnitude for New Caledonia, ~125 km from the Loyalty Islands, is ~2.0 m, with an uncertainty of ±0.5 m depending upon the varying mantle parameters that are assumed for model calculations (Mitrovica and Peltier, 1991). Empirical data from mid-Holocene paleoreefs on mainland New Caledonia (Grand Terre) yield a comparable estimate of 2.0 ± 0.3 m, the mean of a dozen observations ranging from 1.55 m to 2.55 m (Cabioch et al., 1989). In general accord with that estimate, Carson (2008) showed that relative sea level on the New Caledonia mainland (Grand Terre) has declined ~1.5 m since occupation by peoples of the Lapita culture at ~3 ka. With the assumption of a monotonic and linear post-highstand decline in hydro-isostatic sea level for the southwest Pacific region near Australia (Chappell, 1983; Harvey et al., 1999; Woodroffe et al., 2000), the observations for Lapita settlements on Grand Terre retrodict a mid-Holocene highstand of ~2 m for the New Caledonia region at ~4 ka, within the range of theoretical calculations for both magnitude and timing. That inference is compatible with the knowledge that littoral plains on New Caledonia were converted at ~3.5 ka from marine embayments to freshwater swamps by a decline in relative sea level (Wirrmann et al., 2011).

For estimating post-mid-Holocene uplift of the Loyalty Islands, the present elevations of paleoshoreline indicators ascribed to the mid-Holocene highstand are compared to an expected elevation of 1.75–2.25 m relative to modern shoreline features, and implied uplift rates are calculated from an inferred age of 5.25–3.75 ka for the mid-Holocene features. For deriving post-mid-Holocene uplift rates, the lowest paleonotches that are present on limestone seacliffs above active modern tidal notches are assumed to be mid-Holocene in age. The gradual flexural uplift of the trench forebulge precludes modulation by coseismic events that might give rise to post-mid-Holocene paleonotches. Where older paleonotches occur higher on seacliffs or on inland limestone bluffs, their significantly greater ages are revealed by columnar speleothems that ornament the older paleonotches to bridge the space between paleonotch visors and floors (Fig. 3E).

Theoretical uplift rates

Theoretical uplift rates for the Loyalty Islands can be calculated from the morphology of the trench forebulge (Fig. 5) and the subduction rate at the New Hebrides Trench. In effect, the islands ride sequentially up the western slope of the forebulge as they approach the trench (Fig. 2). The configuration of the forebulge is controlled by the maximum observed elevations of the uplifted atolls forming the several Loyalty Islands and further constrained by calculations assuming a flexural wavelength of 58 km and an elastic plate thickness of 22 km (Dubois et al., 1988). Those rheological parameters are within ranges observed (Bodine et al., 1981) for oceanic lithosphere with an estimated age of 42–55 Ma rejuvenated to an effective thermal age of ~25 Ma by later magmatism associated with construction of the volcanic edifices upon which Loyalty paleoatolls were built. Structural lineaments in the Loyalty Islands with modal orientations subparallel to the strike of the trench forebulge are controlled by extensional jointing normal to extensional stresses produced by the elastic plate flexure that formed the forebulge (Bogdanov et al., 2007, 2011). The slope of the forebulge uplift (Fig. 4) which the Loyalty Islands are transiting is ~0.0011 (1.1 m/km) but the subduction rate at the New Hebrides Trench is contentious.

Trench subduction rate

From global plate kinematics, the rate of convergence of the Pacific and Australian plates across the New Hebrides Trench is 79–83 (±1) mm/yr opposite Tanna (Fig. 2) in Vanuatu (DeMets et al., 1990, 1994). Direct GPS (global positioning system) measurements of convergence between Tanna and the Loyalty Islands (Lifou and Maré) or Noumea (Fig. 2) during the interval 1990–1994 yielded a much

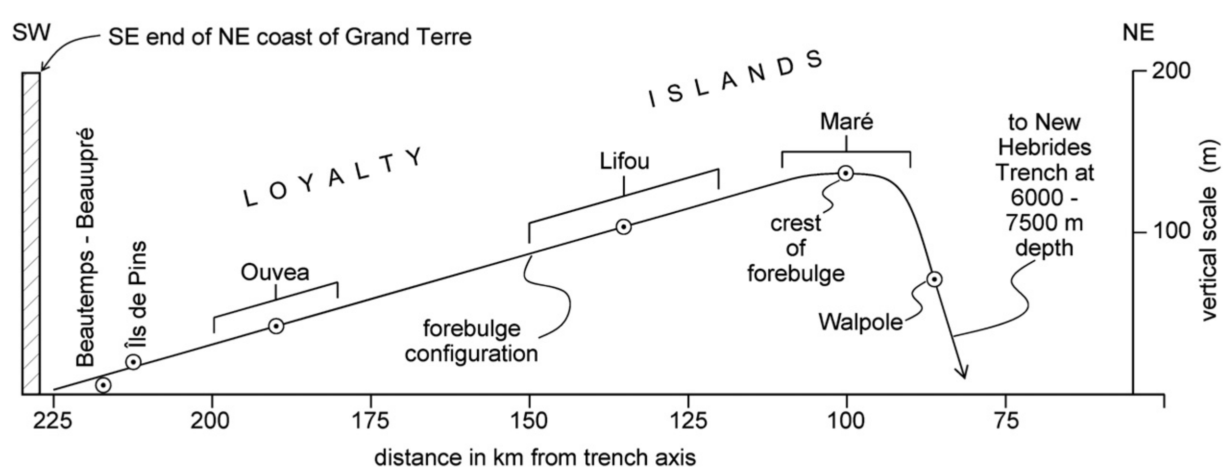

Figure 5. Composite topographic transection of the New Hebrides Trench forebulge showing the net Quaternary uplift of the Loyalty Islands projected parallel to the forebulge axis into the plane of the transect oriented normal to the forebulge crest (Fig. 2). Maximum island elevations (circled dots) after Dubois et al. (1988). Depth of the New Hebrides Trench after Chase and Seekins (1988). Vertical exaggeration 250×.

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higher convergence rate of 117–118 (±8–10) mm/yr (Calmant et al., 1995; Taylor et al., 1995). Farther north in Vanuatu, however, GPS measurements imply subduction rates as low as 39–47 (±2–4) mm/yr at the New Hebrides Trench. The contrasting GPS results for subduction rates at different locations along the New Hebrides Trench may reflect tectonic segmentation of Vanuatu (Taylor et al., 1995), or may be transient artifacts of measurements made at different stages of the earthquake cycle for different segments of the island arc system (Calmant et al., 1995).

The vector of relative plate motion for the calculated convergence or trench subduction rate of 81 ± 2 mm/yr is oriented at 80° to the trend of the trench and its parallel forebulge (Taylor et al., 1995), meaning that the velocity of the Loyalty Islands is inferred to be ~80 mm/yr with respect to the crest of the trench forebulge (80 mm/yr = sin 80° × 81 mm/yr). A subduction rate of 81 ± 2 mm/yr at the trench thus predicts an uplift rate of ~0.09 mm/yr for those of the Loyalty Islands positioned on the slope of the trench forebulge, whereas the faster GPS convergence (subduction) rate of 108–128 mm/yr oriented normal to the trench (Taylor et al., 1995) would predict an uplift rate of 0.12–0.14 mm/yr. The slower rate would produce enhanced emergence of mid-Holocene paleoshoreline features by 0.3–0.5 m and of last-interglacial paleoshoreline features by 10.8 m, whereas the faster rate would produce enhanced emergences for the two ages of paleoshoreline indicators by 0.5–0.7 m and 14.4–16.8 m, respectively. Given the inherent irregularities of paleonotches and paleoreefs, the expected difference in the positions of mid-Holocene paleoshoreline indicators (means of 0.4 m and 0.6 m for enhanced emergence) might not be detectable with confidence in the field, but the contrast for last-interglacial features (means of 10.8 m and 15.6 m for enhanced emergence) should be apparent on outcrop. For an analysis of Loyalty paleoshorelines, it is thus important to select the more realistic subduction rate governing the evolution of the trench forebulge.

Previous workers have suggested that backarc spreading in the North Fiji Basin east of Vanuatu (Fig. 6) has distended the Pacific plate adjacent to the New Hebrides Trench and thereby augmented the subduction rate at the trench by adding an increment of backarc plate extension to the calculated convergence rate of the Pacific and Australian plates at the trench. Past estimates of the subduction rate at the trench adjacent to the Loyalty Islands have been in the range of 120–124 mm/yr (Dubois et al., 1974, 1977; Louat and Pelletier, 1989; Pelletier and Louat, 1989; Lafoy et al., 1995; Pelletier et al., 1998), coordinate with the faster of the two GPS measurements. The seafloor spreading system in the North Fiji Basin, however, including a single ridge to the south and twin ridges to the north (Auzende et al., 1988; Tanahashi et al., 1991; Auzende et al., 1995b), actually separates southern Vanuatu from an integral prong of the Australian plate that extends northeast to Fiji (Fig. 6), and not from the Pacific plate. From GPS studies, the major islands of Fiji are moving only 12 ± 8 mm/yr (Viti Levu) and 12 ± 13 mm/yr (Vanua Levu), or negligibly, with respect to either New Caledonia (Grand Terre) or the Loyalty Islands on the Australian plate (Taylor et al., 1995). Extension in the North Fiji Basin cannot logically augment the convergence rate of the Pacific and Australian plates at the New Hebrides Trench adjacent to the Loyalty Islands.

That conclusion is underscored by the fact that net extension between Pacific and Australian plates within the North Fiji Basin is ~80 mm/yr (Auzende et al., 1994, 1995a), the same as the calculated convergence rate of ~80 mm/yr between the two plates at the southern New Hebrides Trench, as regional plate kinematics would seemingly require (Fig. 6). Moreover, if spreading within the North Fiji Basin were additive to the Pacific–Australian convergence rate at the New Hebrides Trench, one would logically expect a convergence rate near 160 mm/yr (80 mm/yr + 80 mm/yr), rather than the 120–124 mm/yr favored by previous authors or the ~80 mm/yr favored here. The twin spreading system of the North Fiji Basin is currently propagating northward into the Pacific plate (Tanahashi et al., 1991; Tiffin, 1993; Auzende et al., 1994, 1995a, 1995b; Pelletier et al., 1998), beyond the North Fiji Fracture Zone (Fig. 6). The northward propagation of backarc seafloor spreading may influence subduction rates at the New Hebrides Trench well north of the Loyalty Islands, but cannot logically impact subduction rates at the trench opposite the Loyalty Islands.

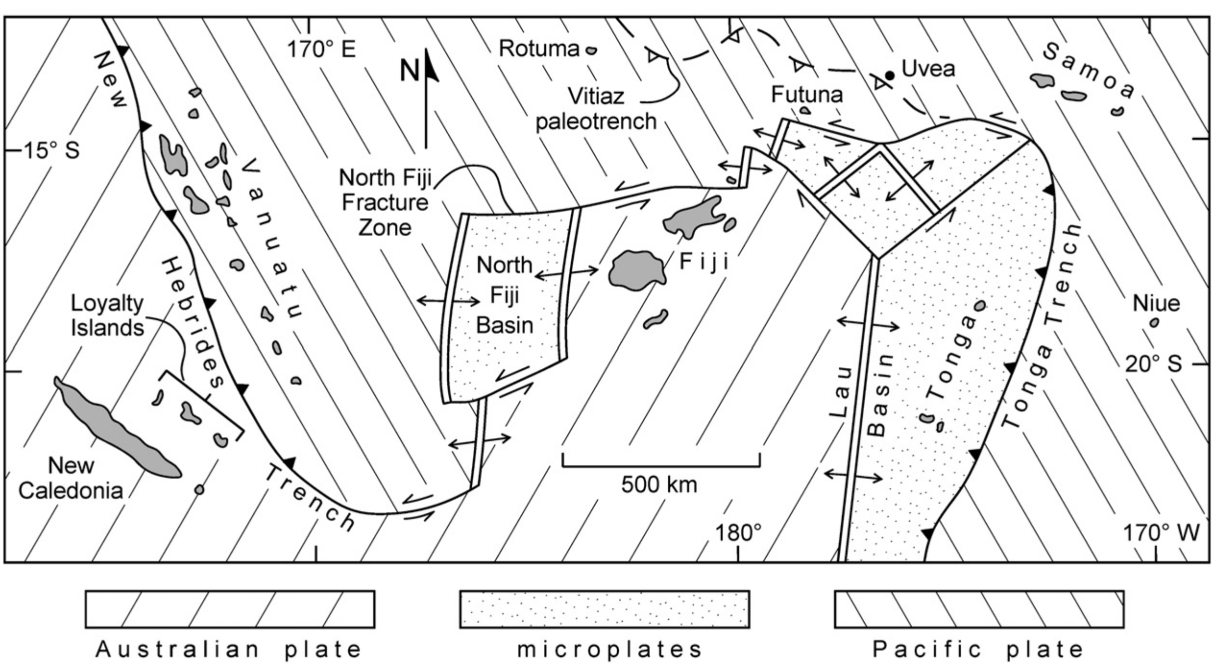

Figure 6. Schematic active plate boundaries (kinematically balanced) in the region northeast of the Loyalty Islands after Dickinson (2006). Barbed lines (plate convergence) are oceanic trenches (barbs on overriding plate). Double lines with opposed arrows are oceanic spreading centers (plate divergence). Single lines with half arrows (denoting lateral sense of motion) are transform faults. Major islands are shaded.

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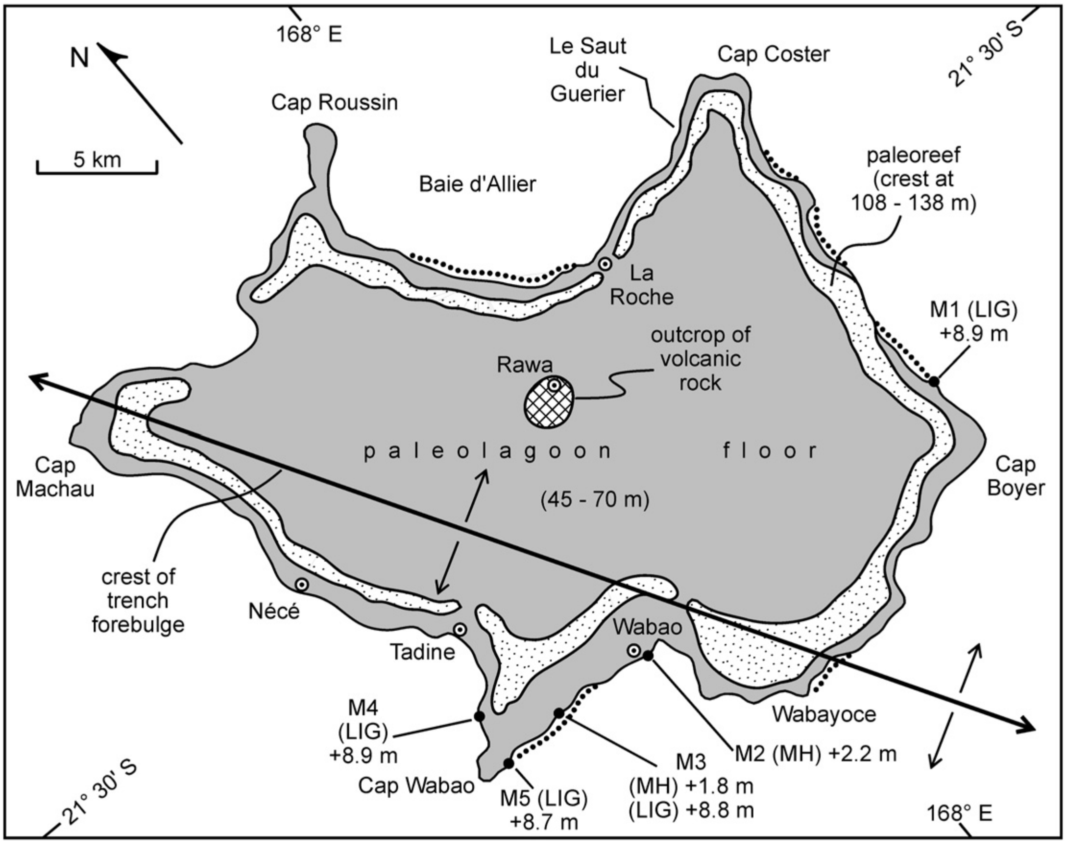

Figure 7. Paleoshoreline features (MH—mid-Holocene, LIG—last-interglacial) on Maré (Institut Géographique National, 1981). See Fig. 2 for location of Maré and Table 1 for paleoshoreline localities (M1–M5) and paleoshoreline emergence (+). Annular paleoreef after Aïssaoui (1988). Elevation of the paleolagoon floor after Chevalier (1973). The areal extent depicted for heavily weathered volcanic outcrop at Rawa is schematic. Dotted lines offshore denote seaward edges of local fringing reefs.

Loyalty Islands emergence

For analysis of Loyalty Islands paleoshoreline indicators, movement of the islands toward the trench and the crest of the trench forebulge at a rate of 80 mm/yr is favored here, dictating a maximum uplift rate of 0.09 mm/yr for the Loyalty Islands, but convergence and uplift rates of 120 mm/yr and 0.13 mm/yr, respectively, are also considered to test previous inferences. As outlined in detail below, analysis of paleoshoreline indicators in the Loyalty Islands clearly favors the lower subduction rate over the faster subduction rate.

Maré relations

Near the crest of the trench forebulge, uplifted paleoreef remnants reach an elevation of 138 m (Marshall and Launay, 1978; Carriére, 1987; Dubois et al., 1988; Guyomard et al., 1996) inland from Wabayoce on the southern tip of Maré (Fig. 7), and stand at elevations of 110–130 m elsewhere on the island (Institut Géographique National, 1981). Topographic gaps interrupting the continuity of the annular paleoreef ridge are interpreted as inherited paleopasses through the paleoatoll barrier reef leading into the paleolagoon floor forming the central plateau of Maré (Aïssaoui, 1988). The elevation of a paleopass at La Roche near the northeastern coast is 43 m (Institut Géographique National, 1981), slightly below the general elevation (Chevalier, 1973) of the paleolagoon floor (Fig. 7). Other prominent paleopasses through the paleoreef ridge provide easy road access from the interior paleolagoonal plateau to Tadine on the west coast and to Wabao on the south coast (Fig. 7). Subdued outcrop of volcanic rock projecting upward through onlapping paleolagoonal deposits in and near Rawa (Fig. 7) has yielded K–Ar ages of 11.2 ± 0.5 to 9.3 ± 0.5 Ma (Paris, 1981; Guyomard et al., 1996), implying that growth of the Maré carbonate platform did not begin until Late Miocene time. No ages are available for the buried volcanic edifices thought to underpin Lifou and Ouvea, but their carbonate platforms are assumed here to date from the same Late Miocene time frame.

Limestone stratigraphy

The magnetostratigraphy of Maré limestones (Guyomard et al., 1996) exposed in seacliffs and on steep slopes flanking the island at Le Saut du Guerrier ("Warrior's Leap") and near Tadine (Fig. 8) indicates that deposition of Maré limestone began by 9.0–8.7 Ma during Late Miocene magnetochron A4n (Cande and Kent, 1995). Initial sedimentation formed a flat carbonate platform composed of bioclastic calcarenite containing abundant algal nodules encrusted with foraminiferal laminations. The growing carbonate platform overtopped a subsiding volcanic edifice that contributed basalt clasts to basal limestone horizons.

Selective karstic erosion of the carbonate platform (Purdy and Winterer, 2001) produced a saucer shape in profile, with a central depression and an elevated peripheral rim (Carriére, 1987). The barrier reef of the Maré paleoatoll nucleated on the raised peripheral rim, which stood ~10 m above the central platformal depression (Aïssaoui, 1988). Growth of the paleoatoll barrier reef enhanced the relative relief between the peripheral paleoreef ridge around the margins of the island and the interior plateau formed by the paleolagoon that occupies the interior of the island. Around the periphery of the island (Aïssaoui, 1988), a marine hardground marks the base of a depositional hiatus at an unconformity between platform and paleoatoll strata (Fig. 8) that lasted for 1.8 ± 0.1 Ma

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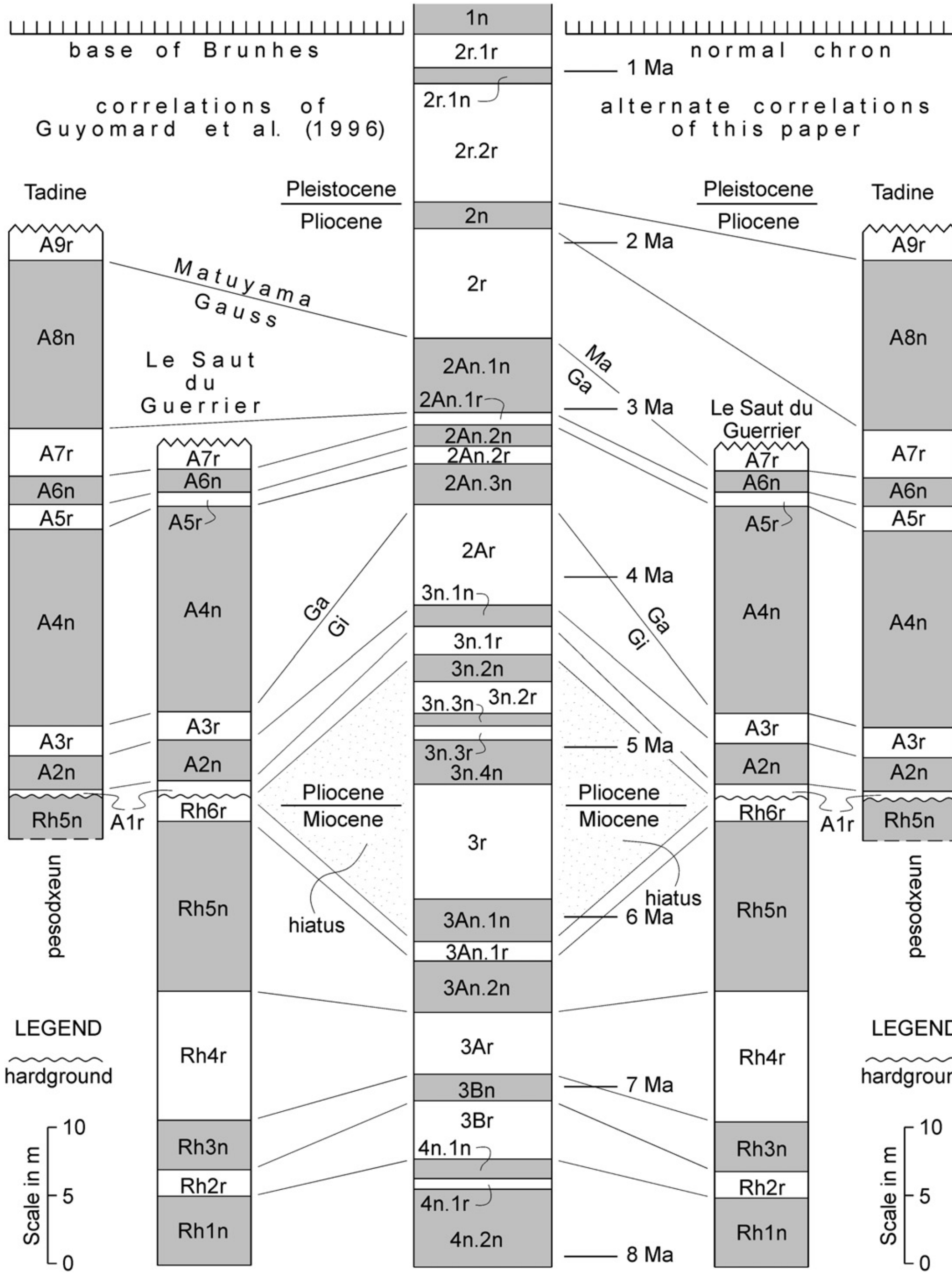

Figure 8. Alternate correlations of Maré limestone magnetostratigraphy. Polarity timescale (center) after Cande and Kent (1992, 1995). Normal polarity magnetochrons shaded. Reversed polarity magnetochrons blank. Short intervals of normal polarity within magnetochrons 2r and 3Br of dominantly reversed polarity are not plotted for reasons of scale. Thicknesses of strata deposited during normal and reversed magnetochrons at Tadine and Le Saut du Guerrier after Table 2 of Guyomard et al. (1996). Named Pliocene–Pleistocene chrons older than Brunhes normal chron (0–0.78 Ma): Ma—Matuyama reversed chron (0.78–2.58 Ma), Ga—Gauss normal chron (2.58–3.58 Ma. Gi—Gilbert reversed chron (3.58–5.89 Ma).

spanning the Miocene–Pliocene time boundary (Guyomard et al., 1996). A decline of 20 m in the elevation of the subatoll hardground from Tadine to Le Saut du Guerrier documents tilt of the Maré paleoatoll downward toward the northeast at ~0.8 m/km (~0.045°) as the northeast flank of Maré is depressed tectonically toward the trench on the foreslope (eastern side) of the forebulge (Figs. 5 and 7). Before transiting over the crest of the forebulge, the Maré paleoatoll was tilted downward toward the southwest on the backslope (western side) of the forebulge (Carriére, 1987).

Guyomard et al. (1996) suggested that differential ages of the uppermost horizons of the paleoreef successions exposed at Le Saut du Guerrier and at Tadine (Fig. 8) reflect different times of initial forebulge uplift on eastern and western flanks of Maré. The two study sites are located, however, only 25 km apart in the direction normal to the trend of the forebulge (Fig. 7). The relatively slow (80 mm/yr) and fast (120 mm/yr) estimates for subduction rate at the New Hebrides Trench imply that only ~250,000 ± 50,000 yr elapsed between initial uplift of eastern and western flanks of Maré (Fig. 4). Termination of the paleoreef stratigraphic sections at Le Saut du Guerrier and Tadine at horizons that differ in age by ~600,000 yr (Fig. 8) is inferred here to reflect local vagaries of truncation by post-uplift karstic erosion of emergent paleoreef crests rather

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than differential timing of initial island uplift. A trench subduction rate as low as ~50 mm/yr would be required to explain the truncation of paleoreef stratigraphy at the different horizons observed at the two sites from initiation of forebulge uplift at different times.

Given the configuration of the trench forebulge, the trench subduction rate of 80 mm/yr favored here could not have arrested paleoreef growth on Maré by initiation of forebulge uplift until ~1.55 Ma, long after the youngest paleoreef increments preserved on Maré are thought by Guyomard et al. (1996) to have accumulated during the interval 3.1–2.5 Ma (Fig. 8 left). The discrepancy is unexplained because the trench subduction rate of 80 mm/yr calculated from global plate motions (DeMets et al., 1990, 1994) is based on relative plate velocities integrated over the full time span since mid-Gauss magnetochron 2An.2n (3.2–3.1 Ma), which is present in both the Tadine and Le Saut du Guerrier paleoreef successions (Fig. 8). The faster subduction rate of 120 mm/yr postulated by others would not have arrested paleoreef growth by the same mechanism until even later, near 1.05 Ma (Fig. 5).

Recorrelation of Maré magnetostratigraphy (Fig. 8 right) allows coordination with initial forebulge uplift at ~1.55 Ma, as implied by a trench subduction rate of 80 mm/yr. The alternate correlation positing the presence of limestone as young as 1.55 Ma at Tadine (Fig. 8 right) assumes that reversed magnetochron 2An.2r was not detected in Maré limestone outcrops within dominantly normal magnetochron 2An, much as reversed magnetochron 4n.1r was missed on outcrop within dominantly normal magnetochron 4n. The two reversed subchrons each had a duration of only ~100,000 yr, and would be represented on outcrop by only ~1.5 ± 0.1 m of stratigraphic section if sedimentation was continuous at a constant rate. Moreover, neither short lacunae in sedimentation nor limestone accumulation at varying rates is precluded by the lithology of the cores studied for geomagnetic polarity (Guyomard et al., 1996). The Brunhes normal interval (<0.78 Ma) is missing at the top of the Maré paleoreef succession for either magnetostratigraphic correlation (Fig. 8), but magnetochrons exposed near the top of the Tadine paleoreef succession thought by Guyomard et al. (1996) to be of Gauss age (Fig. 7 left) are inferred here to be of Matuyama age instead (Fig. 8 right). Marine fossils collected near the top of the paleoreef succession on Maré may be as young as early Pleistocene (Guyomard et al., 1996), which is compatible with a Matuyama age but not a Gauss age.

Marine terraces

On the outer slopes of Maré (Fig. 6), a flight of 15 marine terraces is present between the modern shoreline and the crest of the paleoreef ridge surrounding the paleolagoon floor of the interior plateau (Chevalier, 1973; Marshall and Launay, 1978), but most are undated. By analogy with marine terrace flights in Papua New Guinea (Bloom et al., 1974; Chappell, 1974a; Chappell et al., 1996) and Indonesia (Pirazzoli et al., 1991), successive formation of the Maré terraces during progressive island uplift reflected multiple fluctuations in eustatic sea level associated with alternating Pleistocene glaciations and interglaciations. At a trench subduction rate of 80 mm/yr, Maré was in transit up the trench forebulge at a mean uplift rate of 0.09 mm/yr for 1.55 Ma, resulting in a predicted peak elevation of ~140 m (maximum observed elevation is 138 m). The alternate trench subduction rate of 120 mm/yr and mean uplift rate of 0.13 mm/yr for 1.05 Ma would produce essentially the same peak paleoreef elevation of ~135 m. A choice between the two alternate models for terrace development during transit of Maré up the foreslope of the trench forebulge cannot be made firmly without reliable dates for the older terraces because the reasoning that links trench subduction rate to uplift rate is circular, keyed to maximum observed paleoreef elevation.

For the preferred trench subduction rate of 80 mm/yr, the Maré terrace flight should provide a geomorphic record of the spacing of interglaciations since 1.55 Ma during transit of Maré up the forebulge slope, or only since 1.05 Ma for a trench subduction rate of 120 mm/yr. For the past million years, prominent interglaciations have recurred at a mean frequency of ~100 ka (Bintaja et al., 2005; Berger, 2008; Rohling et al., 2009; Tzedakis et al., 2009), but before then their frequency was ~50 ka and their amplitude was generally less (Lisiecki and Raymo, 2005; Raymo et al., 2006; Raymo and Huybers, 2008). The marine terraces on the outer slope of Maré are too numerous (N ~ 15) to find ready explication from formation in just a million years but too few to account for all the interglaciations (N ~ 20) since 1.55 Ma. It seems likely that the higher frequency but lower amplitude interglaciations older than a million years have not all been discriminated in the observed Maré terrace flight, in part because the detailed morphology of seaward slopes of Maré is largely masked by thick tropical vegetation. Given the steady uplift of Maré on the forebulge slope where complicating effects of coseismic uplift (Ota et al., 1993; Ota and Chappell, 1999) can be excluded, further study of Maré terrace ages might double or triple the duration of Pleistocene time for which observational control for interglacial frequency can be inferred directly from marine terrace flights (Bull, 1985).

Paleoshoreline indicators

The first prominent terrace above the modern shoreline notch around the coastline of southern Maré (Fig. 7) is emergent by 8.8 ± 0.1 m where measured at four favorable localities (M1 and M3–M5 of Table 1). The feature is interpreted as a last-interglacial terrace because it is topped by a paleonotch standing 9 m above mean sea level and dated to 125 ka (Guyomard et al., 1996). The measured elevation of the last-interglacial terrace implies late Pleistocene emergence of Maré at a mean rate of only ~0.015 mm/yr (calculated range from essentially nil to 0.033 mm/yr). The slow rate of uplift reflects the position of Maré near the crest of the trench forebulge (Fig. 5) where neither uplift nor subsidence is rapid as Maré arcs over the lithospheric flexure during transit toward the trench. At the preferred trench subduction rate of 80 mm/yr, Maré has moved only 10 km relative to the forebulge crest since the last interglaciation (15 km if the faster trench subduction rate of 120 mm/yr is assumed), or not far enough to place it at last interglacial time on the slope of the forebulge where uplift rates would have been much higher during earlier phases of Maré geologic history.

A paleonotch associated with the first prominent marine terrace above the last interglacial terrace on Maré stands 12 m above mean sea level and dates to 205 ka (Guyomard et al., 1996), hence is presumably of penultimate interglacial age. If last interglacial and penultimate interglacial sea levels were comparable (Siddall et al., 2003), the differential paleonotch elevations imply an interstadial uplift rate of ~0.04 mm/yr, or more than double the mean uplift rate inferred since the last interglaciation. At the preferred trench subduction rate of 80 mm/yr, Maré has moved ~16.5 km toward the trench since the penultimate interglaciation (~24.5 km if the faster trench subduction rate of 120 mm/yr is assumed). During the interval between the last and penultimate interglaciations, Maré may have been located near the inflection point between the forebulge slope and the forebulge crest (Fig. 5), in a position compatible with a faster pre-last interglacial than post-last interglacial uplift rate.

Of uncertain significance for Maré uplift is a $^{230}Th/^{238}U$ age of 98 ± 15 ka for a sample of aragonitic coralline limestone collected 3.2 ± 0.3 m above mean sea level (Bernat et al., 1976). From the best estimate of the coral age and an estimated global sea level of −15 m at ~105 ka (Chappell, 1974b), Marshall and Launay (1978) inferred an uplift rate of ~0.17 mm/yr for Maré. Using the same data, their inferred uplift rate is adjusted here to ~0.23 mm/yr using an updated estimate for an interstadial sea level of −20 m at ~100 ka (Siddall et al., 2003). Either inferred rate seems excessive for Maré from any other standpoint. It is assumed here that the U-series age, with an uncertainty almost overlapping the timing of

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the last interglaciation, is a degraded age for last interglacial limestone exposed on the eroded face of the last interglacial terrace, and is dismissed as an unreliable control point for estimating the Maré uplift rate. If an uplift rate of 0.20 ± 0.03 mm/yr were sustained during the full time that Maré was in transit up the trench forebulge for a trench subduction rate of 80 mm/yr, the paleoreef crest on Maré should have reached an elevation of 310 ± 46 m, which is at least double the maximum elevation actually observed.

At two localities on the south coast of Maré (M2–M3 of Table 1 and Fig. 7), the lowest preserved paleonotches exposed at elevations higher than modern shoreline notches at the same localities are emergent by only 1.8–2.2 m (2.0 ± 0.2 m), which is indistinguishable from the post-mid-Holocene emergence (2.0 ± 0.3 m) of paleoshoreline indicators on New Caledonia (Grand Terre) unaffected by forebulge uplift (Fig. 5). The uplift rate of ~0.015 mm/yr inferred here for Maré from late Pleistocene paleoshoreline features would enhance post-mid-Holocene emergence by only 0.055–0.075 m, an amount that could not be detected with confidence on outcrop from measurements of differential elevations that have an inherent uncertainty of at least ±0.1 m. Although Maré has experienced more net uplift than any other of the Loyalty Islands, its current uplift rate is the lowest because it has reached the crest of the trench forebulge and is no longer rising. Elevation measurements for last interglacial paleoshoreline indicators on Maré detected no systematic contrast in behavior between the west coast, still on the rising flank of the forebulge, and the east coast, subsiding now toward the trench (Figs. 5 and 7). That observation supports the conclusion that any continuing vertical movements of Maré are quite slow, probably ≤0.025 mm/yr either up or down, and undetectable from observation of mid-Holocene paleoshoreline indicators that have thereby changed elevation by ≤0.1 m.

Lifou relations

The geology of Lifou (Fig. 9) has been studied in less detail than that of Maré but the two islands are similar in morphology, with an annular paleoreef complex rimming an interior plateau, and the barrier reef of the Lifou paleoatoll was also constructed on a substratum of pre-atoll platform carbonate (Aïssaoui, 1988). On Lifou, the maximum elevation of the paleoreef is only 104 m (Marshall and Launay, 1978; Aïssaoui, 1988; Dubois et al., 1988), 75% of the elevation of its Maré counterpart, as befits an island that has progressed only 75% of the way up the trench forebulge (Fig. 5). Spot elevations on the annular Lifou paleoreef crest (Institut Géographique National, 1981) are compatible with tilt of the island toward the southwest at a slope of 0.0011 (1.1 m/km) parallel to the slope of the trench forebulge.

Bernat et al. (1976) reported last interglacial $^{230}Th/^{238}U$ ages of 120 ± 5 ka, 120 ± 6 ka, and 122 ± 7 ka for reef limestone collected 11–12 (±2) m above mean sea level on Lifou. The uranium-series ages for last interglacial limestone provide a minimum uplift rate of 0.04 ± 0.04 mm/yr for Lifou. A well preserved limestone terrace at the Falaises ("cliffs") de Xodé (or Xodré) near the south end of Lifou (Fig. 9), and interpreted here as last interglacial in age (Fig. 3D), is emergent by 14.0 m (locality L3 of Table 1). Emergence of the Falaises de Xodé terrace indicates post-last interglacial uplift of Lifou at a mean rate of 0.06 ± 0.2 mm/yr, a rate nearly congruent with the theoretical uplift rate of 0.09 mm/yr inferred from a trench subduction rate of 80 mm/yr, but only half the uplift rate (0.13 mm/yr) inferred from a trench subduction rate of 120 mm/yr. The contrast favors the slower trench subduction rate over the faster one advocated by other authors. The faster trench subduction and derivative island uplift rates would dictate emergence of last-interglacial paleoreef-flat terraces by 20–25 m, but there are no indications that last interglacial limestone reaches such high elevations on Lifou.

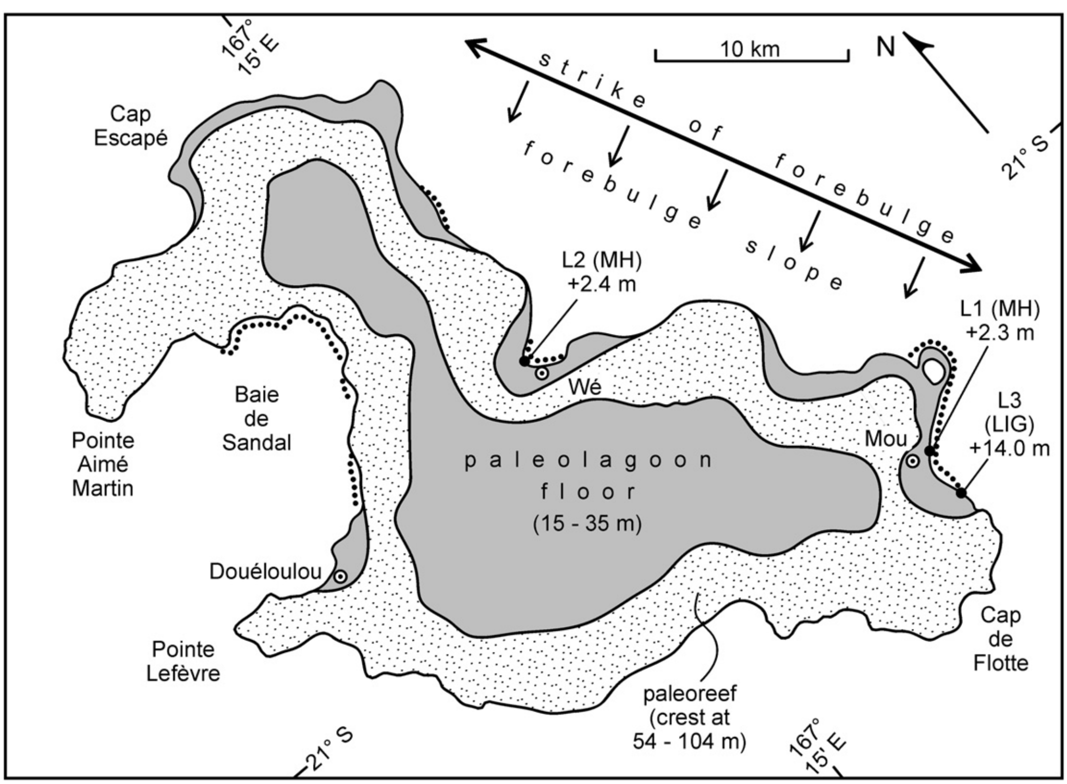

Figure 9. Paleoshoreline features (MH—mid-Holocene, LIG—last-interglacial) on Lifou (Institut Géographique National, 1981). See Fig. 2 for the location of Lifou and Table 1 for paleoshoreline localities (L1–L3) and paleoshoreline emergence (+). Extent of annular paleoreef complex inferred from gross island topography. Dotted lines offshore denote seaward edges of local fringing reefs.

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At two localities on Lifou (L1–L2 of Table 1 and Fig. 9), paleonotches interpreted here as mid-Holocene paleoshoreline features are emergent by 2.3–2.4 m, slightly in excess of the mean emergence of 2.0 m recorded for mid-Holocene paleoreef flats on mainland New Caledonia (Grand Terre) unaffected by forebulge uplift (Fig. 5). Continuing forebulge uplift of Lifou by 0.06–0.09 mm/yr would enhance the emergence of mid-Holocene paleoshoreline indicators by 0.2–0.5 m, to 2.2–2.5 m above modern tidal notches, an amount in satisfactory agreement with paleoshoreline observations on Lifou. The faster uplift rate of 0.13 mm/yr associated with a greater trench subduction rate of 120 mm/yr would predict the enhanced emergence of mid-Holocene paleoshoreline features by 0.5–0.7 m, to 2.5–2.7 m above modern tidal notches, an amount which is not observed.

Of uncertain significance for Lifou uplift are two imprecise ^{230}Th/^{234}U ages of 189 ± 17 ka and 174 ± 16 ka for coralline limestone collected 3.5 m above mean sea level on Lifou (Marshall and Launay, 1978). By adopting a mean age of ~180 ka for the two samples, and citing Chappell (1974a, 1974b) for interstadial global sea level at −20 m to −25 m for 180 ka, Marshall and Launay (1978) calculated an uplift rate of 0.13–0.16 mm/yr for Lifou. A slightly higher uplift rate of 0.19 mm/yr is implied by the same age-elevation data from the updated interstadial sea-level curve of Siddall et al. (2003) showing sea level near −30 m at 175 ka. An uplift rate in the range of 0.16–0.19 mm/yr would dictate emergence of last-interglacial paleoshorelines by 23–33 m and of mid-Holocene paleoshorelines by 2.6–3.0 m, but those expectations exceed the emergences observed empirically for both last interglacial and mid-Holocene paleoshoreline indicators on Lifou. It seems likely that the pre-last interglacial coral ages reported by Marshall and Launay (1978) from not far above sea level on Lifou are degraded ages for penultimate interglacial limestone ~205 ka, preserved as an underpinning for the last interglacial reef complex after interstadial karstic erosion (Dickinson, 2004), and are unreliable as a guide to the Lifou uplift rate.

Ouvea relations

Net forebulge uplift at Ouvea (Fig. 10) has been so slight that the paleolagoon is still drowned by seawater, although the eastern rim of the paleoatoll reaches elevations of 42–46 m (Marshall and Launay, 1978; Institut Géographique National, 1981; Dubois et al., 1988), and has spot eminences >25 m in elevation for 40 km of its length. The western rim of the paleoatoll is still largely submerged, however, with only chains of small reef islets spaced at intervals along the remnant reef crest. The morphology of Ouvea indicates that the paleoatoll is tilted downward toward the west-southwest at a slope of 0.011 (1.1 m/km), which is coordinate with the tilt of Lifou located farther up the forebulge slope.

Coralline limestone exposed at an elevation of 7.5 m above mean sea level on Ouvea has yielded a ^{230}Th/^{234}U age of 117 ± 6 ka indicative of last-interglacial age (Marshall and Launay, 1978). The uranium-series age implies a minimum uplift rate of <0.02 mm/yr for Ouvea. A prominent limestone terrace interpreted here as last-interglacial in age on northern Ouvea (at locality U3 of Table 1 and Fig. 10), the part of the island closest to the crest of the trench forebulge, records a slightly greater total emergence of 9.7 m, but implies a mean post-last interglacial uplift rate of only 0.01–0.04 mm/yr for Ouvea. A paleonotch ornamented with speleothems incised into the Falaises ("cliffs") de Lekinny on southern Ouvea (locality U6 of Table 1 and Fig. 10), is interpreted here as also last interglacial in age. The paleonotch is emergent by only 7.2 m above the modern tidal notch (Fig. 3F) and provides no evidence for significant post-last interglacial uplift of southern Ouvea, which is located downslope on the trench forebulge from northern Ouvea with respect to the forebulge crest (Fig. 10).

Mid-Holocene paleonotches measured at four localities on Ouvea (U1–U2 and U4–U5 of Table 1 and Fig. 10) are emergent by only 1.8 m, providing no evidence for any detectable post-mid-Holocene

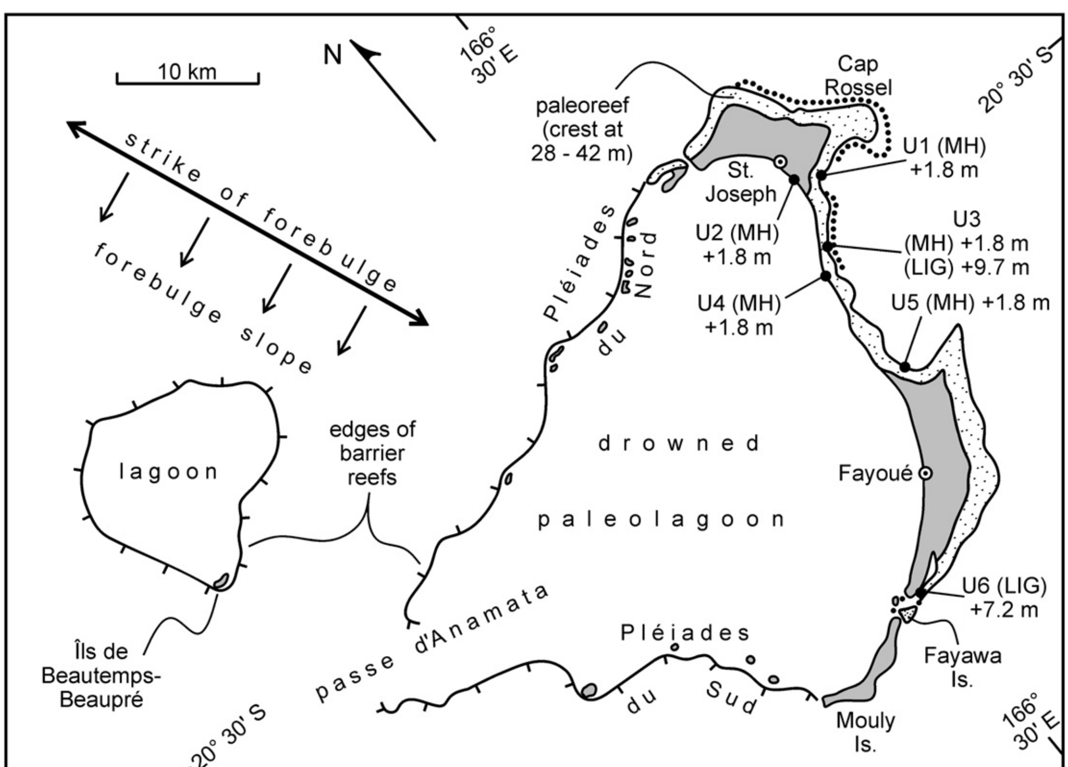

Figure 10. Paleoshoreline features (MH—mid-Holocene, LIG—last-interglacial) on Ouvea (Institut Géographique National, 1981). See Fig. 2 for the location of Ouvea and Table 1 for paleoshoreline localities (U1–U6) and paleoshoreline emergence (+). Paleoreef remnants after Aïssaoui (1988). Beautemps-Beaupré (west of Ouvea) included for clarity. Dotted lines offshore denote seaward edges of local fringing reefs.

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uplift of Ouvea. An emergent mid-Holocene paleoreef (Fig. 3C) flat exposed at one locality (U3 of Table 1 and Fig. 10) documents the same post-mid-Holocene emergence of ~1.8 m.

Contrasting emergence of the two last interglacial paleoshoreline features apparently reflects the tilt of Ouvea on the slope of the trench forebulge, but the consistently low uplift rates inferred for Ouvea are nevertheless unexpected. Restoration of the uplifted eastern flank of Ouvea to a position ~10 km farther west at last-interglacial time, by recovering motion of the island toward the trench at 80 mm/yr, may imply from the present morphology of Ouvea that significant uplift was delayed until after the last interglaciation, thereby reducing the mean post-last interglacial uplift rate. Mouly Island (Fig. 10) and smaller islets on the Ouvea paleoatoll rim, in the same position with respect to the forebulge crest as the eastern rim of the paleoatoll during the last interglaciation, are only slightly emergent today.

West of Ouvea, the tiny islet (1000 m × 500 m) of Beautemps-Beaupré, located as far from the crest of the trench forebulge as the submerged western limit of the Ouvea paleoatoll at Passe d'Anamata (Fig. 10), rises to an elevation of only ~5 m above mean sea level (Marshall and Launay, 1978) on the rim of an otherwise flooded small atoll with its barrier reef entirely awash. Six coral samples collected by Marshall and Launay (1978) on Beautemps-Beaupré from the level surface of a coralline terrace standing 2 m above mean sea level are uniformly >200 ka in age (200 ka being the effective limit of reliable $^{230}Th/^{234}U$ ages), and perhaps as old as 400 ka to 1 Ma based on $^{234}U/^{238}U$ ages. Such old coral at the surface is unexpected on atoll barrier reefs. Its presence directly beneath a modern subaerial surface may imply that penultimate interglacial and older paleoreef limestone deposited on the Beautemps-Beaupré barrier reef during interglacial highstands was never worn down enough by karstic erosion during synglacial lowstands (Dickinson, 2004) to provide any accommodation space for additional reef growth after the penultimate interglaciation.

The minimal uplift rate inferred empirically for Ouvea from the elevations of mid-Holocene and last interglacial paleoshoreline indicators and the seemingly excessive age of exposed paleoreef limestone on nearby Beautemps-Beaupré raise pointed questions about the geologic history of the northwestern Loyalty Islands, but do not negate inferences reached independently for Lifou and Maré farther to the southeast. Nor do they alter the conclusion drawn here and previously that the contrasting morphologies of the different islands are a function of position with respect to the crest of the trench forebulge. Minimal net uplift of Ouvea reflects its position near the foot of the trench forebulge slope (Fig. 5).

Conclusions

Maré at the crest of the New Hebrides Trench forebulge has reached its maximum expected elevation, and for that reason has not risen appreciably during latest Pleistocene and Holocene time. Lifou is still in transit up the forebulge slope and is rising at the uplift rate expected for a subduction rate of ~80 mm/yr at the New Hebrides Trench. The higher subduction rate of ~120 mm/yr favored by other authors is dismissed as unrealistic from joint consideration of regional plate kinematics and empirical observations of paleoshoreline emergence in the Loyalty Islands. Ouvea near the foot of the forebulge slope has only recently begun to climb the forebulge at a mean post-last interglacial uplift rate less than for Lifou, located farther up the forebulge slope.

Both Maré and Lifou are entirely emergent atolls exposing emergent paleoreefs, the barrier reefs of ancient lagoons, which form annular ridges standing atop high limestone cliffs or steep vegetated declivities on the flanks of the islands. The marginal paleoreef ridges enclose extensive flat interior plateaus that represent exposed paleolagoon floors. By contrast, the paleolagoon of Ouvea is still drowned as a vestigial modern lagoon. A strongly emergent paleoreef is confined to the eastern side of Ouvea closest to the crest of the trench forebulge, with only small reef islets present on the western side of the Ouvea paleolagoon. To the west of Ouvea, which has clearly been tilted by incipient forebulge uplift, and located as far from the crest of the trench forebulge as the still-drowned western side of the Ouvea paleolagoon, the tiny islet of Beautemps-Beaupré is sited on the rim of an otherwise flooded small atoll not yet affected by forebulge uplift.

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