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Key Points:
- The New Caledonia Peridotite Nappe is confidently identified in offshore seismic lines over a 50,000 km^2 area
- Offshore, the Peridotite Nappe is clearly cut by postobduction, deeply rooted normal faults
- Speculatively, the continuation of the HP/LT Mt. Panie metamorphic complex lies east of the Peridotite Nappe, along the dome-shaped Félicité Ridge

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New Caledonia Obducted Peridotite Nappe: Offshore Extent and Implications for Obduction and Postobduction Processes

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Abstract One of the largest ophiolitic peridotite masses in the world covers a quarter of the island of Grande Terre, New Caledonia. The Peridotite Nappe was obducted during the Eocene, is weakly deformed, and corresponds to the highest of a structurally simple pile of thrust nappes. We present new marine seismic data that allow us to track the offshore continuation of the Peridotite Nappe along strike for a distance of more than 500 km south of New Caledonia and to image its preobduction, synobduction, and postobduction sedimentary records. Offshore, the Peridotite Nappe underlies a ~150 km wide and 2 km deep basin. Flat-topped horsts of peridotite are clearly bounded by major normal faults; in contrast, faults are obscure onland. To the east, the Peridotite Nappe roots along the eastern margin of the Félicité Ridge (new name), a ~300 × 25 km dome-shaped ridge, which we interpret as being the southern extension of the high-pressure/low-temperature metamorphic core complex observed in New Caledonia. Two alternative tectonic models address the relative timing and relationships between Peridotite Nappe emplacement, uplift of a metamorphic core complex, and extensional tectonics. These models provide new ideas for the understanding the formation of the eastern margin of the Zealandia continent. Our results contribute to an understanding of how oceanic mantle is emplaced onto continental margins.

1. Introduction

Obduction is a tectonic process by which mantle peridotite is emplaced at shallow crustal levels (Coleman, 1971). Obduction mechanisms and postobduction tectonic responses are mostly inferred from field studies of pre-Cenozoic ophiolites that are now isolated and embedded in continental orogenic belts. This presents difficulties as ancient ophiolites typically are totally disconnected from their original offshore oceanic basin and island arc sources and are often highly tectonized (e.g., Tethyan ophiolites). Consequently, obduction processes are commonly inferred and much debated.

In New Caledonia, on the ~500 × 80 km island of Grande Terre, a 7,000 km^2 nappe of ophiolitic mantle peridotite is exposed (Avias, 1967; Paris, 1981). Unlike many ophiolites, the New Caledonia Peridotite Nappe still lies close to a continent-ocean margin, immediately adjacent to the basins and arcs that likely played a role in its genesis. The offshore extent of the ophiolite has been explored in a limited way, via gravity and magnetic anomalies along strike to the NW (Collot et al., 1988) and via seismic profiles and rare dredges to the SE (Auzende et al., 2000; Daniel et al., 1976; Mortimer et al., 2014). Because much of the New Caledonia ophiolite is submerged, it provides a rare opportunity to study ophiolite structural style and geometry (and therefore obduction processes) with marine seismic methods. In May–June 2015 the VESPA scientific cruise, on the research vessel *l'Atalante* mapped seabed features, shot seismic reflection profiles, and dredged volcanic rocks between New Caledonia and New Zealand (Mortimer & Patriat, 2016; Mortimer et al., 2015). The new offshore seismic stratigraphic and structural data complement observations from onland New Caledonia, where outcrops commonly are degraded by tropical weathering and landsliding. In this paper, we present results from 3,400 km of shallow reflection seismic profiles from the cruise. Integrated with existing geophysical and geological data, these new seismic profiles provide significant revisions to the offshore extent of the Peridotite Nappe and associated New Caledonia high-pressure/low-temperature (HP/LT) metamorphic terrane. They also shed light on the synobduction and postobduction structures of the Norfolk Ridge and Félicité Ridge; the latter is a newly named undersea feature whose importance is highlighted in this paper.

Our results allow us to develop peridotite obduction models with more confidence, and we propose two end-member conceptual models of evolution from preobduction setup, through mantle peridotite obduction, to postobduction extension. Such new information from south of New Caledonia allows a more robust integration of geological and tectonic information along the Zealandia continental margin between New Caledonia and New Zealand (Figure 1) (Bradshaw, 2004; Brothers & Delaloye, 1982; Cluzel et al., 2010; Malpas et al., 1992; Mortimer et al., 2014, 2017). This holistic view of an ophiolite belt near a continent-ocean margin is relevant to more general aspects of the obduction process that may be applicable to ophiolites that are more deformed and isolated within continental orogenic belts.

2. Geological Setting

2.1. Onland Geology

The geological basement of New Caledonia consists of three allochthonous Permian-Early Cretaceous greywacke and schist terranes that were accreted along the East Gondwana margin during a Permian-Early Cretaceous subduction (Aitchison et al., 1995; Cluzel et al., 2002; Paris, 1981). Basement is unconformably overlain by an autochthonous Late Cretaceous to Paleocene sedimentary cover formed as Zealandia rifted from Gondwana, subsided and drifted north (Meffre, 1995; Paris, 1981).

From the Paleocene to the Late Eocene, the New Caledonia region underwent a period of renewed convergence that culminated in the emplacement of a stack of ophiolitic thrust nappes with the Peridotite Nappe at the top (Aitchison et al., 1995; Cluzel et al., 2001, 1994, 2012; Paris, 1981). Paleogene sedimentary rocks record the onset and infill of a foreland basin resulting from progressive thrusting, with consequent flexural subsidence of the foreland and progressive change of detrital sources as each nappe was emplaced (Aitchison et al., 1995; Cluzel et al., 2001). Detrital input from the Peridotite Nappe is first seen in the Late Eocene Nepoui Flysch, and this is considered to date the inception of Peridotite Nappe emplacement (Paris et al., 1979).

The Peridotite Nappe and the structurally underlying basaltic Poya Terrane nappe are both considered important igneous components of the New Caledonia Ophiolite. Gabbroic rocks are rare to absent, and mantle peridotite structurally overlies crustal basalts (Paris, 1981). As well as being the structurally highest allochthonous nappe, the Peridotite Nappe underlies most of the topographic highs of Grande Terre (Figure 2). It is not depositionally overlain by any strata other than rare Neogene and Quaternary shallow marine terrigenous and reef formations.

The structurally lowest geological unit on Grande Terre is an HP/LT metamorphic complex exposed in the northeast of the island (Clarke et al., 1997; Cluzel et al., 1994; Rawling & Lister, 2002; Vitale Brovarone & Agard, 2013). Peak metamorphism was eclogite facies (24 kbar, 600°C; Clarke et al., 1997) and is dated at 44 Ma with rapid exhumation from 40 Ma to 34 Ma (Baldwin et al., 2007; Blake et al., 1977; Rawling & Lister, 2002) (Figure 2).

Postobduction geology is characterized onland by a widespread Oligocene sedimentary hiatus and by small plutons and stocks of 27–24 Ma granodiorites that intrude the Peridotite Nappe (Cluzel et al., 2005; Paquette & Cluzel, 2007; Paris, 1981). The clastic Nepoui unit ranges up into the Miocene and is the only outcropping record of postobduction marine sedimentary deposition (Coudray, 1977; Paris, 1981; Sevin et al., 2014).

Numerous normal faults cut the Peridotite Nappe and the underlying units onland (Lagabrielle & Chauvet, 2008; Lagabrielle et al., 2005) as well as some Neogene deposits (Chardon & Chevillotte, 2006; Chardon et al., 2008). The age and origin of these faults are still debated. They could be related to synobduction tectonics, accommodating the final gravity sliding of the ophiolitic sheet (Genna et al., 2004; Lagabrielle et al., 2013), to postorogenic gravitational collapse of the nappe stack at various scales (Lagabrielle et al., 2005; Sevin et al., 2014; Iseppi et al., 2018) or to far-field plate boundary conditions (Chardon & Chevillotte, 2006).

2.2. Offshore Geology

In a general way, the onland geology of New Caledonia is thought to continue offshore with strike trends parallel to the Norfolk and Loyalty Ridges. As such, the Norfolk Ridge is likely to be underlain by pre-Late Cretaceous basement terranes and thin Late Cretaceous to Miocene sedimentary cover (Auzende et al., 2000; Dupont et al., 1975; Eade, 1988; Van de Beuque et al., 1998). The South Loyalty Basin is regarded as

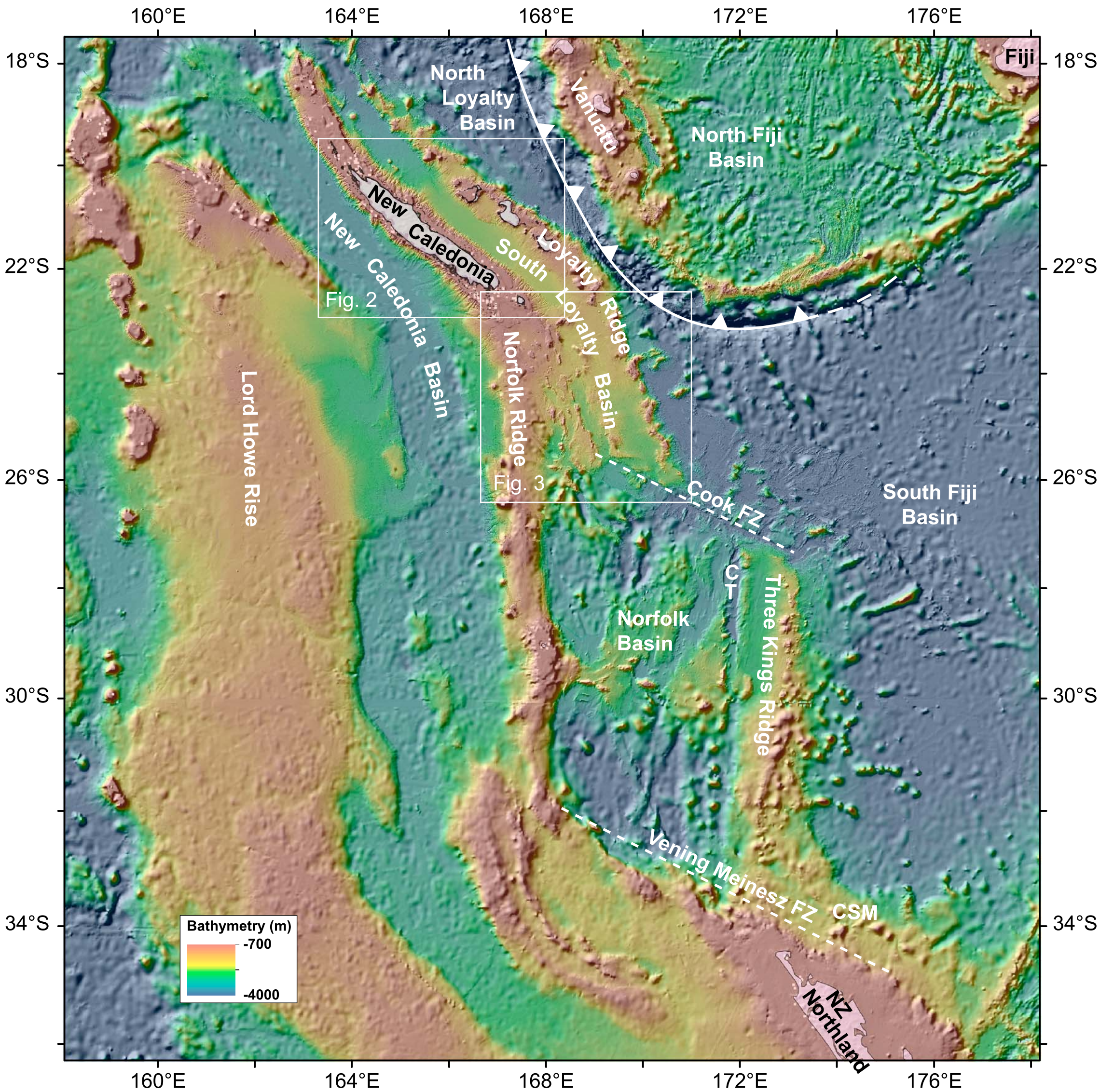

Figure 1. General physiography of the area between New Caledonia and New Zealand. CSM = Cavalli Seamount; CT = Cagou Trough.

Cretaceous to Paleocene oceanic crust (Auzende et al., 2000; Dupont et al., 1975; Van de Beuque et al., 1998), possibly the source of the Poya Terrane and Peridotite nappes (Cluzel et al., 2001). The present-day physiography of the South Loyalty Basin probably results from Late Eocene obduction, and its sedimentary cover is most likely a postobduction sequence (Bitoun & Recy, 1982).

The South Loyalty Basin is separated from the Oligocene-Early Miocene oceanic South Fiji Basin (Watts et al., 1977) by the Loyalty Ridge, a volcanic chain that is generally assumed to be an Eocene volcanic arc (Cluzel et al., 2001; Crawford et al., 2003). Near 26°S, the Loyalty Ridge is cut by the Late Oligocene-Early Miocene sinistral Cook Fracture Zone, and its southward continuation, the Three Kings Ridge, has been shifted 300 km SE (Herzer et al., 2011; Lapouille, 1977; Sdrolias et al., 2004).

From gravity and magnetic anomalies and seismic profiles it has been proposed that the onland Poya Terrane nappe continues along strike southward to 26°S (Rigolot & Pelletier, 1988) and the Peridotite Nappe to 24°S (Auzende et al., 2000; Rigolot & Pelletier, 1988). Some continuations of offshore geology have been confirmed with the dredging of pyroxenite and serpentinite from two seamounts in this region (Daniel et al., 1976; Mortimer et al., 2014). From seismic profiles, refraction experiments and gravity modeling, Collot et al. (1982, 1987) proposed that the onland Peridotite Nappe roots northeastward under the South Loyalty

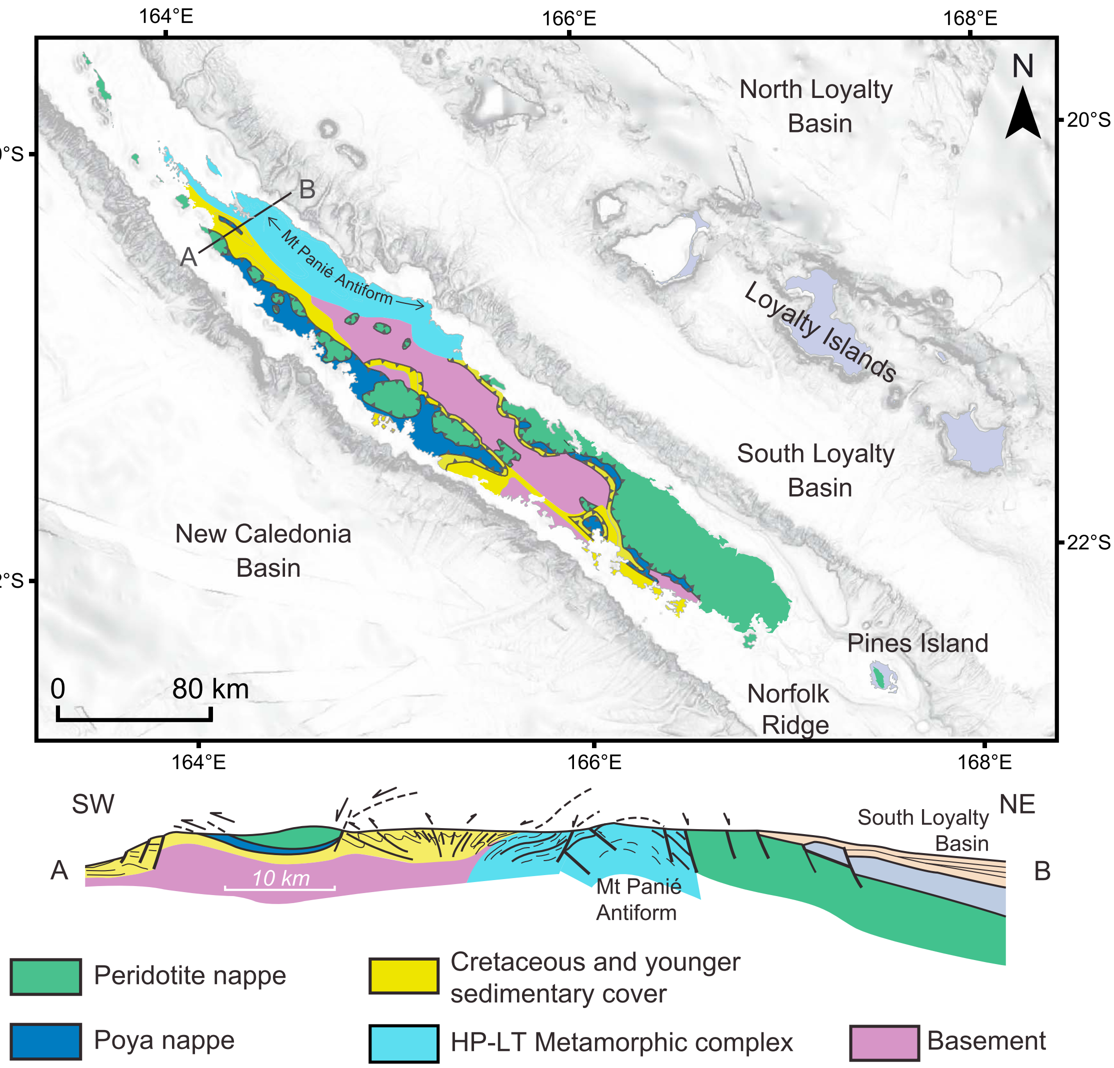

Figure 2. Simplified geological map and NE-SW general cross section of New Caledonia after Maurizot (2001). HP-LP = high-pressure-low-temperature.

Basin and merges with the lithosphere mantle of this basin. In the New Caledonia Basin, an obduction-related unconformity has been correlated with a regional unconformity dated as Eocene-Oligocene from nearby Deep Sea Drilling Project wells. (Collot et al., 2008; Kennett et al., 1975; Sutherland et al., 2010).

3. Methods

The structural and stratigraphic interpretations in this paper are based on the integration of 2-D seismic, bathymetric, magnetic, and gravity data, as well as seabed rock sampling. Seismic reflection data come from various sources acquired between 1972 and 2015, the bulk of which have been compiled in the Tasman Frontier database (Sutherland et al., 2012). In this paper, we especially make use of newly acquired data from the 2015 VESPA voyage on R/V *l'Atalante* (Mortimer & Patriat, 2016).

The VESPA voyage used a rapid seismic acquisition system (SISRAP) towed at 10 knots. The active part of the 600 m long streamer comprised 24 separate 12.5 m channels and 2 auxiliary channels. The sound source was produced by two GI guns with a total volume of 300 cubic inches, towed 25 m behind the ship. The shooting interval was 10 s. Due to the short length of the streamer, only basic processing was applied to the seismic data among which a stack and a Stolt migration used a constant water velocity (Mortimer & Patriat, 2016).

For seismic interpretation in this paper, we use the terms S for surface and U for unit, followed by a letter identifying the basin or ridge where the feature is defined, and a number identifying the relative age of the

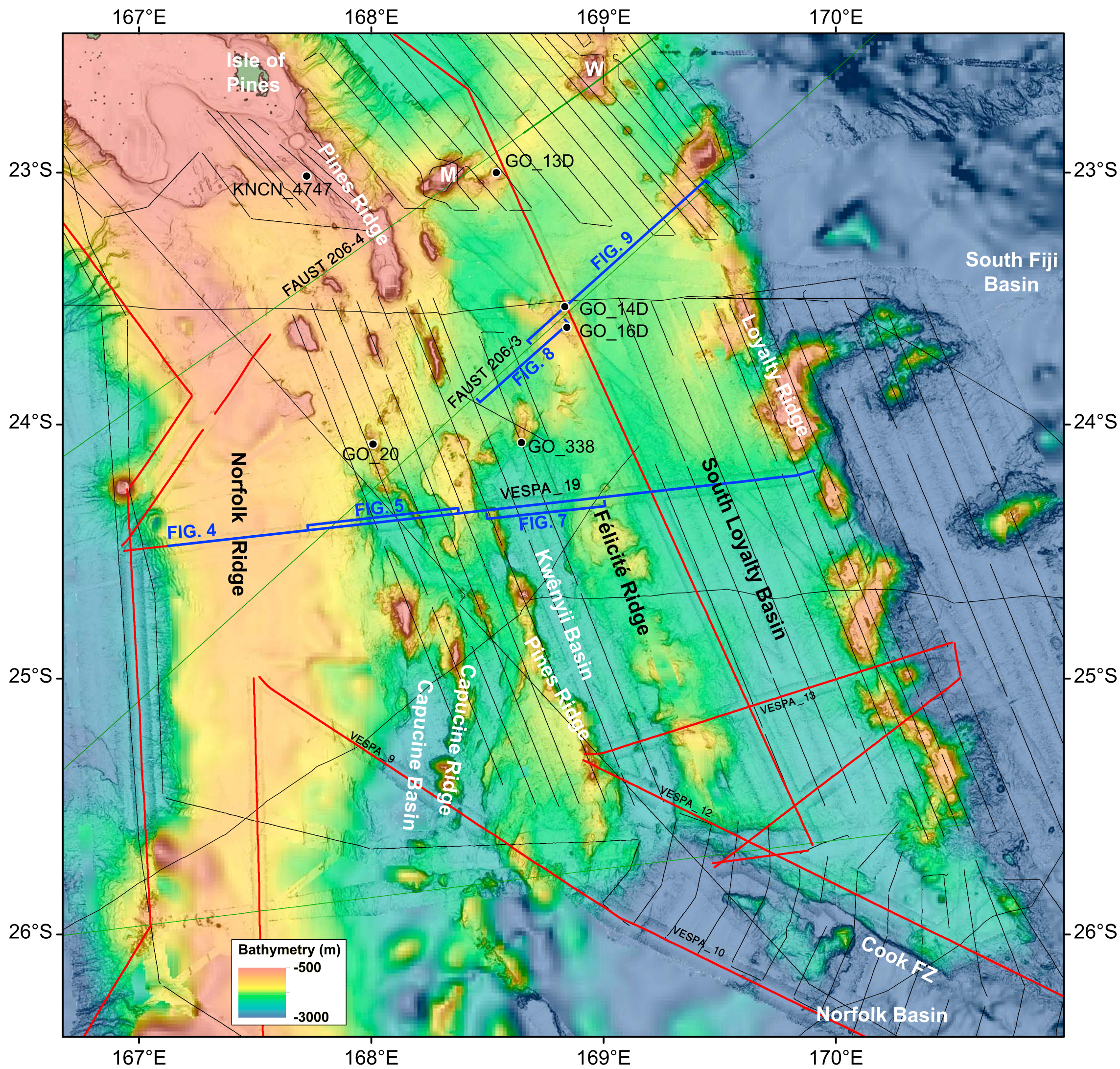

Figure 3. Location of seismic sections on multibeam bathymetry (blue lines = seismic lines shown in this paper; red lines = VESPA seismic lines; black lines = other seismic). Multibeam data from various cruises have been complemented by satellite data (Smith & Sandwell, 1997). Black dots correspond to sites of dredges discussed in the text (Mortimer et al., 2014). M = Munida Seamount; W = Walpole Island.

feature, for example, UN1 is the oldest sedimentary unit we identified covering the basement of the Norfolk Ridge, and UL3 is the youngest sedimentary unit we identified in the South Loyalty Basin. Units and surfaces cannot be correlated between areas.

4. Results

4.1. Overview

Two seismic profiles, VESPA_19 and FAUST_206_3, cross the entire area from the Norfolk to the Loyalty Ridges (Figure 3) and provide a useful overview of the regional bathymetry and structure. The area is characterized by several bathymetric highs and basins elongated in a NNW-SSE direction. This direction is subparallel to the Loyalty Ridge but at angle of ~20° to the N-S trending Norfolk Ridge.

4.2. Norfolk Ridge

The Norfolk Ridge is the southern bathymetric continuation of New Caledonia and corresponds to the western limit of our study area. It is bounded by steep flanks but has a large domed top (Figure 4).

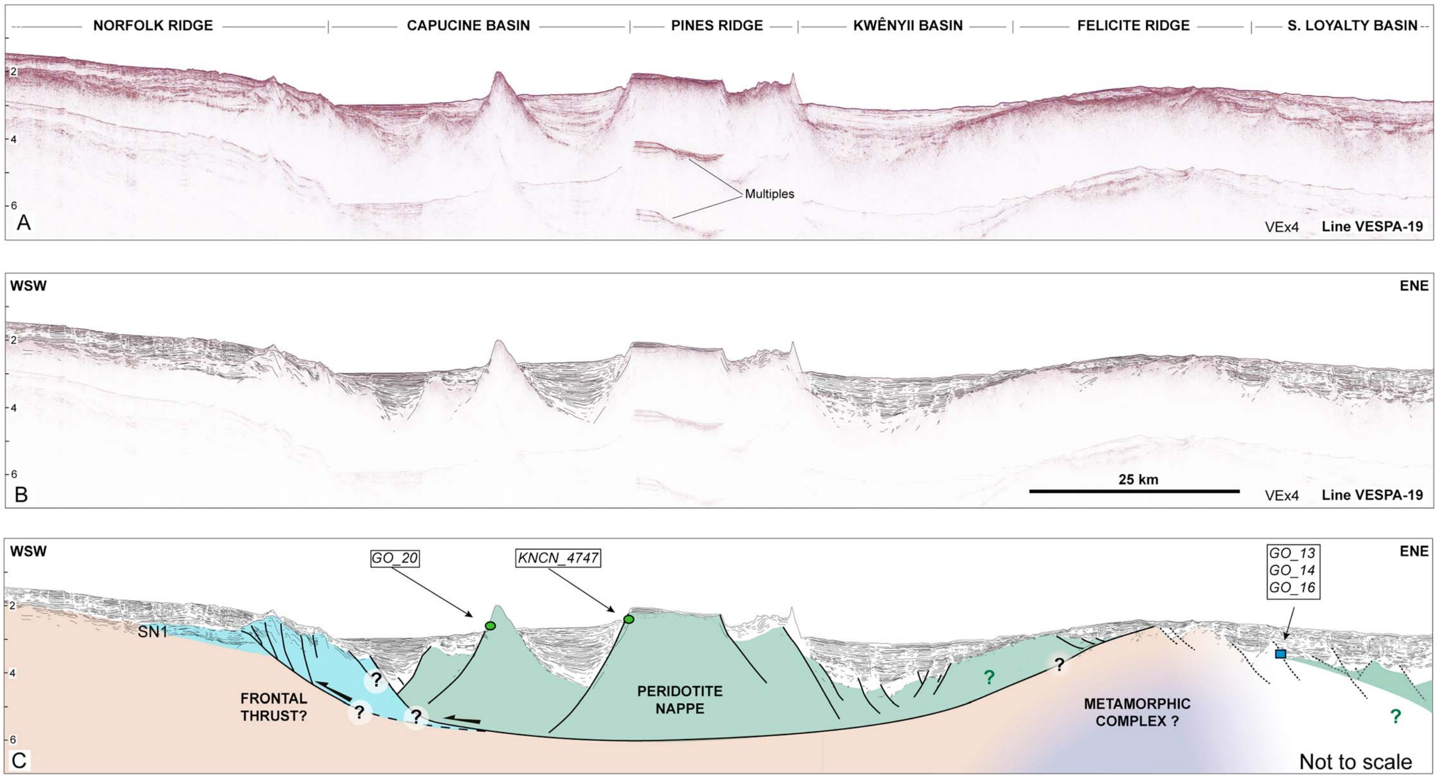

Figure 4. Seismic profile VESPA 19 (see location in Figure 3. Vertical exaggeration: x4). (a) Uninterpreted profile with location of main basins and ridges. (b) Line drawing. (c) Interpretation illustrating the conceptual model of the Peridotite Nappe/Metamorphic complex relationships (see section 5). Locations of ultramafic (green circles) and basaltic (blue square) dredges have been projected on the seismic line.

Seismic data show that the eastern flank of the Norfolk Ridge is underlain by a first-order compressional structure (Figures 4 and 5). An ENE dipping erosional surface SN1 separates underlying ENE dipping deformed strata with toplap (unit UN1), from an overlying sedimentary unit UN2. UN2 sediments are thicker in the east and progressively onlap/downlap onto SN1 to the WSW. Both flanks of the ridge are affected by N-S oriented normal faults. At the foot of the eastern flank of the Norfolk Ridge, lower sediments of UN2 (subunit UN2a) are deformed and form a series of faults and related folds thrust over UN2a sediments (Figure 5). The deformation of this local fold and thrust belt (FTB) seems to postdate the erosional surface SN1 but is sealed by upper sediments of unit UN2 (subunit UN2b).

4.3. Capucine Basin

The Capucine Basin (new name; Figures 4 and 5) is bounded to the west by the Norfolk Ridge and to the east by a major west dipping normal fault along the Pines Ridge. The Capucine Ridge (new name) is the apex of a block in the middle of the basin tilted along this fault. Subsidiary west dipping normal faults segment the basin into tilted blocks, horsts, and grabens and create numerous small ridges (Figure 3). In the northern Capucine Basin, these ridges trend NNW-SSE, whereas south of 25°S, they trend NNE-SSW, with the change in direction occurring over a short distance (Figure 3).

The stratigraphy of the Capucine Basin consists of a thin (<750 ms two-way travel time, TWT) fanning unit (UC1) overlain by a thick (>1 s TWT) unit (UC2). On both sides of the basin UC2 dips toward the center of the grabens, where the sedimentary cover is the thickest; we interpret this feature as resulting from differential compaction (Figure 5). The top of acoustic basement has a strong positive reflection. On rare, deep penetration seismic profiles such as FAUST1 or Noucaplac2 (8,000 cu source and 4.5 km long streamer), basement is seen to comprise some deep reflectors within crust of transparent to chaotic seismic character (Auzende et al., 2000).

Serpentinite and pyroxenite have been dredged at site GO20 on the Capucine Ridge (Figure 5; Bitoun & Recy, 1982; Mortimer et al., 2014).

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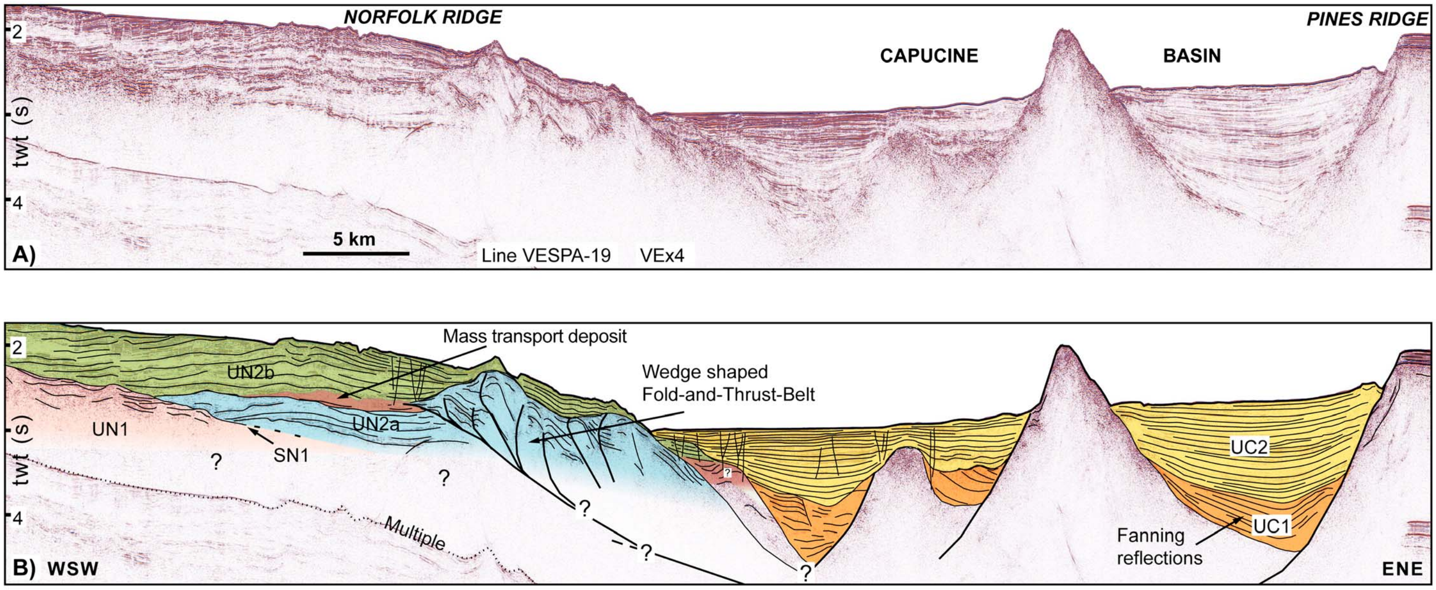

Figure 5. Detail of seismic profile VESPA 19 (See location in Figure 3. Vertical exaggeration: x4). (a) Uninterpreted profile. (b) Interpreted line drawing.

The stratigraphy and structure of the Capucine Basin is relatively simple: one major phase of extension that ended before the deposition of UC2 and was followed by the passive infilling of the resulting topography (Figure 5).

4.4. Pines Ridge

The Pines Ridge (new name) is a narrow and discontinuous ridge that differs significantly from the Norfolk Ridge in azimuth, width, and geological character. It is the structural prolongation south from the Isle of Pines to Antigonia Seamount and, along a series of seamounts and ridge segments, to the Cook Fracture Zone (Figure 3). In cross section, it is seen to be a SSW aligned horst bounded by major normal faults (Figures 3–5).

The seismic character of the Pines Ridge is distinctive (Figures 4 and 5). A highly reflective flat top comprises several high-amplitude subparallel reflectors, 0.1 to 0.6 s TWT thick, that are slightly tilted toward the center of the ridge; in places, lower-amplitude reflections are seen. The top of basement is marked by a subplanar, positive polarity, very high amplitude reflector and contrasts with the transparent internal character of basement.

The subplanar basement surface is interpreted as a wave base paleo–erosion surface. It is blanketed by a thin sedimentary cover that has aggrading to locally prograding geometries. Several horsts may be drowned reefs with associated lagoonal sediments and slope carbonate deposits. Miocene bioclastic carbonates dredged at the top of the ridge on several locations confirm this hypothesis (Daniel et al., 1976). Dredge KNCN-4747 during the recent *Kanacono* cruise (Figure 3; Puillandre & Samadi, 2016), sampled serpentinites, gabbros, and peridotites from the Pines Ridge.

The Pines Ridge can be followed on free air gravity and magnetic anomaly maps (Figure 6). The wavelength of the magnetic anomaly is significantly wider than the bathymetric ridge. This suggests that the magnetic anomaly is created by a deeper background feature rather than just the shallow Pines Ridge itself (Figure 6).

4.5. Kwênyii Basin

The Kwênyii Basin (new name) is bordered by the Pines Ridge and the Félicité Ridge (Figures 4 and 7). A large normal fault is present on its west side, and the entire basin is segmented into narrow half-grabens by NNW striking and east dipping normal faults, which break the seabed as a series of steep escarpments (Figure 3).

The top of acoustic basement, SK0, corresponds to a high-amplitude but irregular reflector. Below this, rare, isolated, high-amplitude reflections are seen within basement of otherwise bland to transparent character.

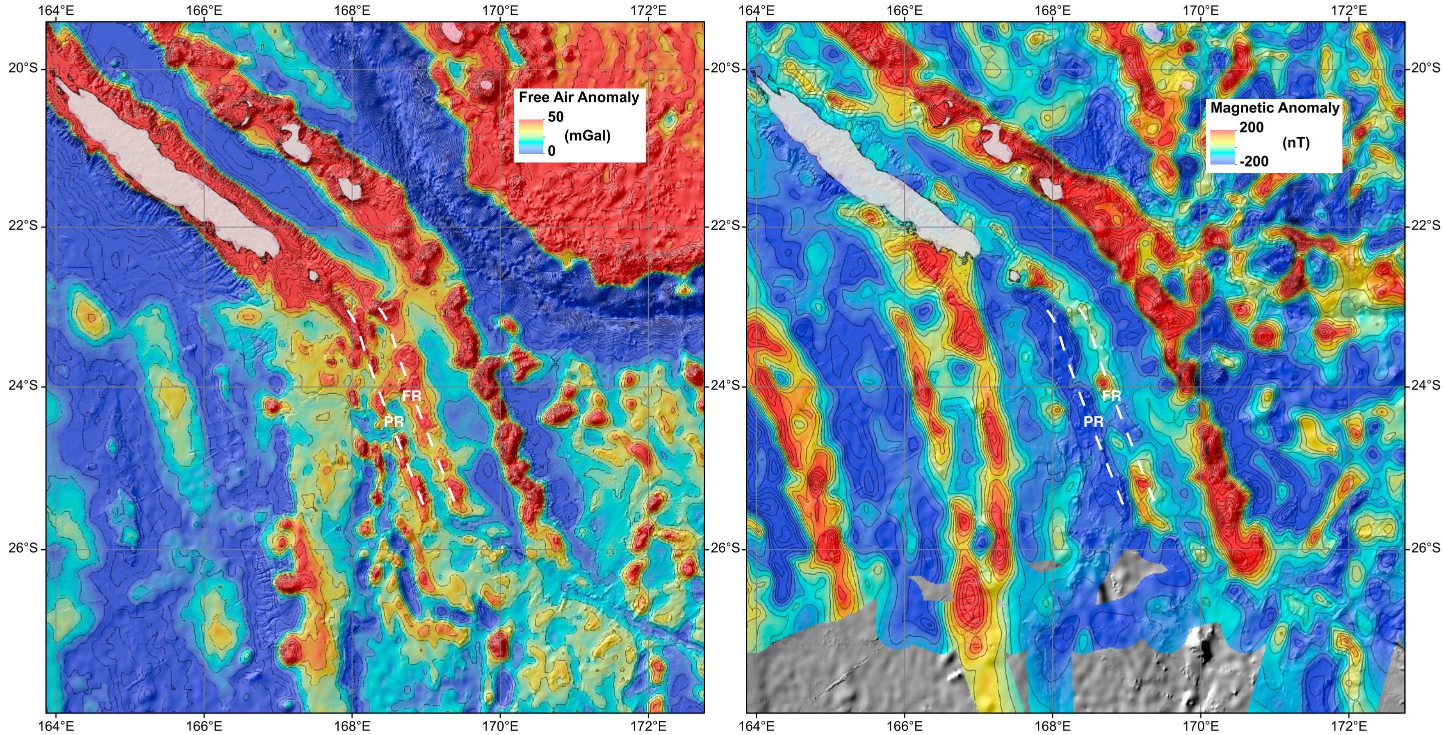

Figure 6. Gravity (isocontours 10 mGal) and magnetic (isocontours 50 nT) grids draped over topography. Left: free air gravity anomaly (Sandwell et al., 2014). Right: reduced to pole magnetic anomaly (Collot et al., 2009). White dashed lines mark the axes of the Pines Ridge and Félicité Ridge.

The seismic stratigraphy of the Kwênyii Basin consists of a fan-shaped sedimentary unit UK1, overlain by a subhorizontal, postrift UK2 unit. UK1 and UK2 onlap SK0.

UK2 can be divided into two subunits UK2a and UK2b separated by an unconformity SK1, which, on the eastern side of the basin, is possibly an erosion surface on which UK2a seems to toplap and UK2b onlaps (Figure 7). There, on the western flank of Félicité Ridge, SK0 is particularly flat and UK2a sediments seem to be conformable on it, both being tilted westward. This suggests that a general westward tilting affected the eastern side of the Kwênyii Basin after UK2a deposition, presumably after the end of rifting.

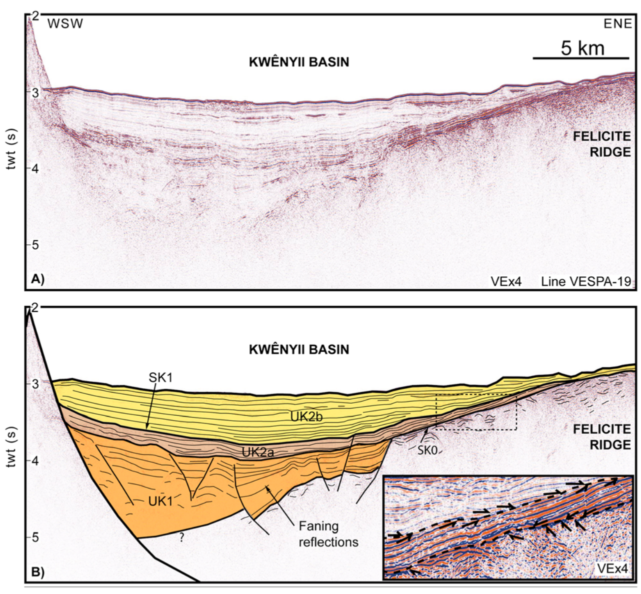

Figure 7. Seismic profile VESPA-19 over the Kwênyii Basin and eastern flank of Félicité Ridge showing chronological relations between sedimentation, normal faulting, and tilting. See location in Figure 3. (a) Uninterpreted profile. (b) Interpreted line drawing. The inset shown at the bottom right is an enlargement of the area of the dashed rectangle.

Further north, on seismic section 206-3, a series of normal faults is seen under the basin (Figure 8). These normal faults delineate several tilted blocks whose depth and width progressively increase toward the west. This suggests that they could be rooted on a westward dipping basal detachment. We propose two possible origins for the series of normal faults, either (i) they are antithetic normal faults resulting from a top-to-the-west bookshelf type of tectonics, in which case the basal detachment orientation may not have changed much, or (ii) they originally were synthetic normal faults resulting from a top-to-the-east sense of shear along a subhorizontal basal detachment, which has later been subsequently tilted toward the west.

The tilted block geometry is in better agreement with a top-to-the-east detachment, since normal faults are generally expected to be synthetic to the basal decollement (Faugères & Brun, 1984; Vendeville, 1987). Furthermore, as demonstrated from the stratigraphic relationships in Figure 7, a late tilting affected the western flank of the Félicité Ridge.

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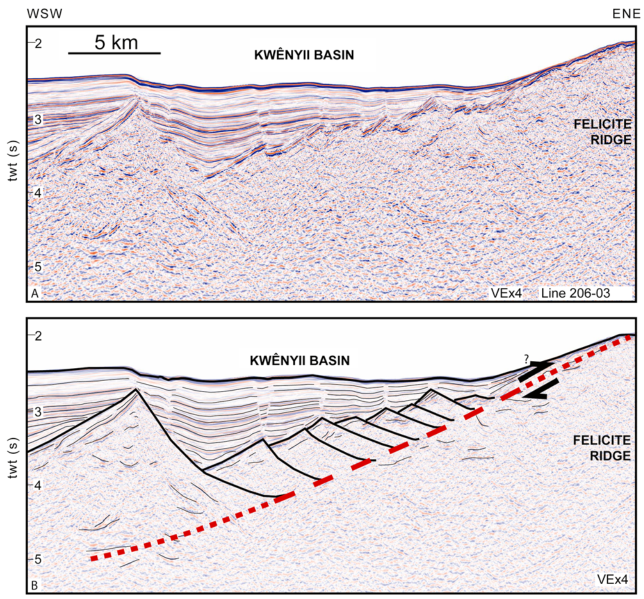

Figure 8. Seismic profile 206-03 over the Kwênyii Basin and eastern flank of Félicité Ridge showing chronological relations between sedimentation, normal faulting, and tilting. See location in Figure 3. (a) Uninterpreted profile. (b) Interpreted line drawing.

These stratigraphic and structural relationships suggest a fairly simple geological history for Kwênyii Basin, with one major phase of extension followed by the passive infill of the resulting topography. This is similar to the Capucine Basin, with an additional, postextension, westward tilt of the eastern Kwênyii Basin. We note that this margin corresponds with the western flank of the Félicité Ridge.

4.6. Félicité Ridge

The Félicité Ridge (new name) lies between the South Loyalty Basin and the Kwênyii Basin (Figures 4 and 7). The axis of the ridge trends NNW-SSE, with prominent highs and lows along its axis. In cross section, the ridge has a ~30 km wide arch-like shape. In stark contrast with the other ridges of the area, its flanks are gently sloping and there are no major normal faults on the ridge flanks. Some minor normal faults do exist, but they are not as significant in the shaping of the Félicité Ridge as they are for the Pines and Capucine Ridges. Instead, Félicité Ridge is delineated by sedimentary layers of opposing dips on both flanks (Figure 4).

The Félicité Ridge coincides with distinctive continuous gravity and magnetic anomaly highs (Figure 6). The magnetic anomaly can be followed not only from the Cook Fracture Zone to Munida Seamount but also further NW; the NNW-SSE anomaly trends NW-SE close to the Isle of Pines and continues off the east coast of New Caledonia (Figure 6).

A total of 12 dredges has been made on the Félicité Ridge but most of them sampled carbonates on the top of Munida seamount (Figure 3). Two dredges (GO14 and GO16) sampled Early Miocene intraplate basalts (Daniel et al., 1976; Mortimer et al., 2014) and one dredge (GO13) an enriched mid-ocean ridge basalt (E-MORB) lava of unknown age assigned tentatively by Mortimer et al. (2014) to the Poya Terrane of onshore New Caledonia. Numerous fragments of serpentine occur in the calcareous cement of some samples in dredge GO16 (Bitoun & Recy, 1982).

4.7. South Loyalty Basin

The South Loyalty Basin is more than 1,000 km long and about 100 km wide. It extends from north of New Caledonia, at 18°S, to the Cook Fracture Zone at 26°S (Figure 1). Near 22°S, its direction changes from NW-SE to NNW-SSE. At this location, the seabed in the basin axis is at its shallowest (~500 m deep). To the NW, the seabed deepens to ~4,000 m, and to the SSE, it deepens to ~2,500 m near the Cook Fracture Zone (Figure 3). In this study, we focused on the seismic stratigraphy of the southern part of the basin south of 22°S. (Bitoun & Recy, 1982, described the northern part of the basin.)

More than 3 s TWT of sediments are imaged in the southern South Loyalty Basin (Figure 9) with a depocenter located toward the foot of the Félicité Ridge. Seismic interpretation allows definition of three main units (UL1 to UL3), separated by two major unconformities (SL1 and SL2, Figure 9). Because it is generally buried below more than 2 s TWT of younger sediments, unit UL1 is only partially imaged by deep penetration FAUST1 profiles (206-3, Figure 9); it reaches more than 2 s TWT in thickness. UL1 is composed of an upper subunit UL1b of well-stratified reflections and a deeper subunit, UL1a, which has a more chaotic character. UL1a and UL1b are locally separated by chaotic high-amplitude reflections with notable depth shifts. Across the basin, UL1 is subhorizontal or gently dips toward the west except along the western side of the basin where the reflections remain subparallel but are progressively tilted toward the east, following the shape of the Félicité Ridge. The seismic character of these tilted reflectors becomes progressively fainter and more chaotic toward the ridges.

Surface SL1, the top of unit UL1, is a high-amplitude reflector, conformable with underlying reflectors and interpreted as a major unconformity surface. SL1 is tilted downslope along the eastern flank of the Félicité Ridge and along the western flank of the Loyalty Ridge (Figure 9).

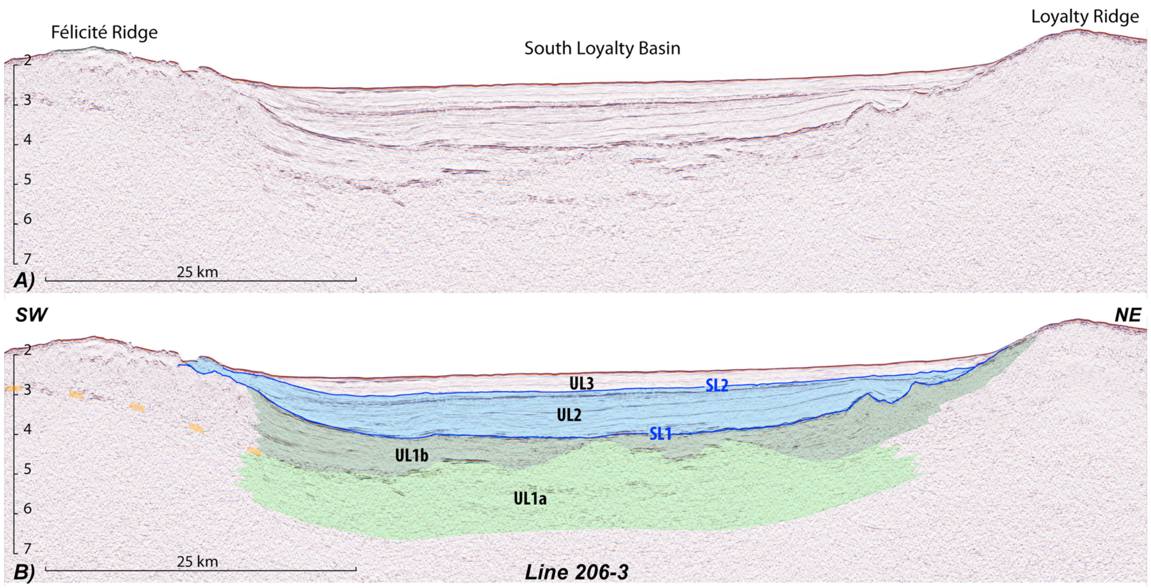

Figure 9. Seismic profile FAUST 206-3 across the South Loyalty Basin. Note the scale change from previous cross sections. (a) Uninterpreted profile. (b) Interpretation. See location in Figure 3.

Unit UL2 is 1 s TWT thick on average and consists of parallel low-amplitude and discontinuous reflections alternating with high-amplitude continuous reflections. UL2 reflectors onlap to locally downlap onto the SL1 surface. Unit UL2 and its upper bounding unconformity SL2 are both tilted downslope along the eastern flank of the Félicité Ridge. However, they are more gently folded than UL1 and SL1. More generally, folding increases with depth showing that the deformation has been progressive since UL1 deposition until the end of UL2 deposition, at least on the west side of the basin.

Surface SL2, the top of unit UL2, is generally conformable with underlying reflectors but is onlapped by the overlying UL3 unit. Unit UL3, the uppermost unit of the South Loyalty Basin infill, comprises high-frequency, low- to very low amplitude, more or less continuous, reflectors. UL3 is generally of similar thickness throughout, being 0.4 s TWT at its thickest. On both sides of the South Loyalty Basin, UL3 reflectors onlap onto SL2 and SL1 surfaces.

In stark contrast to the Capucine and Kwênyii Basins, very few normal faults are seen in the South Loyalty Basin. Some minor normal faults are mainly concentrated in the western side of the basin, at the foot of the Félicité Ridge (Figure 4). Except in the north part of the basin where deformation is recent and linked to the New Hebrides subduction (Dubois et al., 1974), in the South Loyalty Basin the normal faults disrupt only UL1.

4.8. Loyalty Ridge

The NNW-SSE trending Loyalty Ridge lies between the South Loyalty Basin and the South Fiji Basin (Figure 1). It consists of a series of seamounts with steep flanks. Some of these seamounts in the northern part of the ridge emerge as the Loyalty Islands (Dubois et al., 1974).

The flanks of the Loyalty Ridge are marked by a high-amplitude seismic reflector, which connects with surface SL1, the main South Loyalty Basin unconformity (see previous section).

Even though seismic imaging is poor below this strong reflector, a series of basinward dipping parallel reflectors can be seen, indicating the presence of tilted sedimentary rocks on both flanks of the ridge (Figure 9). On the western flank, they dip west and correspond to sedimentary unit UL1b of the South Loyalty Basin.

The Loyalty Ridge coincides with a strong positive magnetic anomaly that exactly matches its morphological expression (Figure 6). The ridge's magnetic anomaly can be explained by its igneous nature (Mortimer et al., 2015).

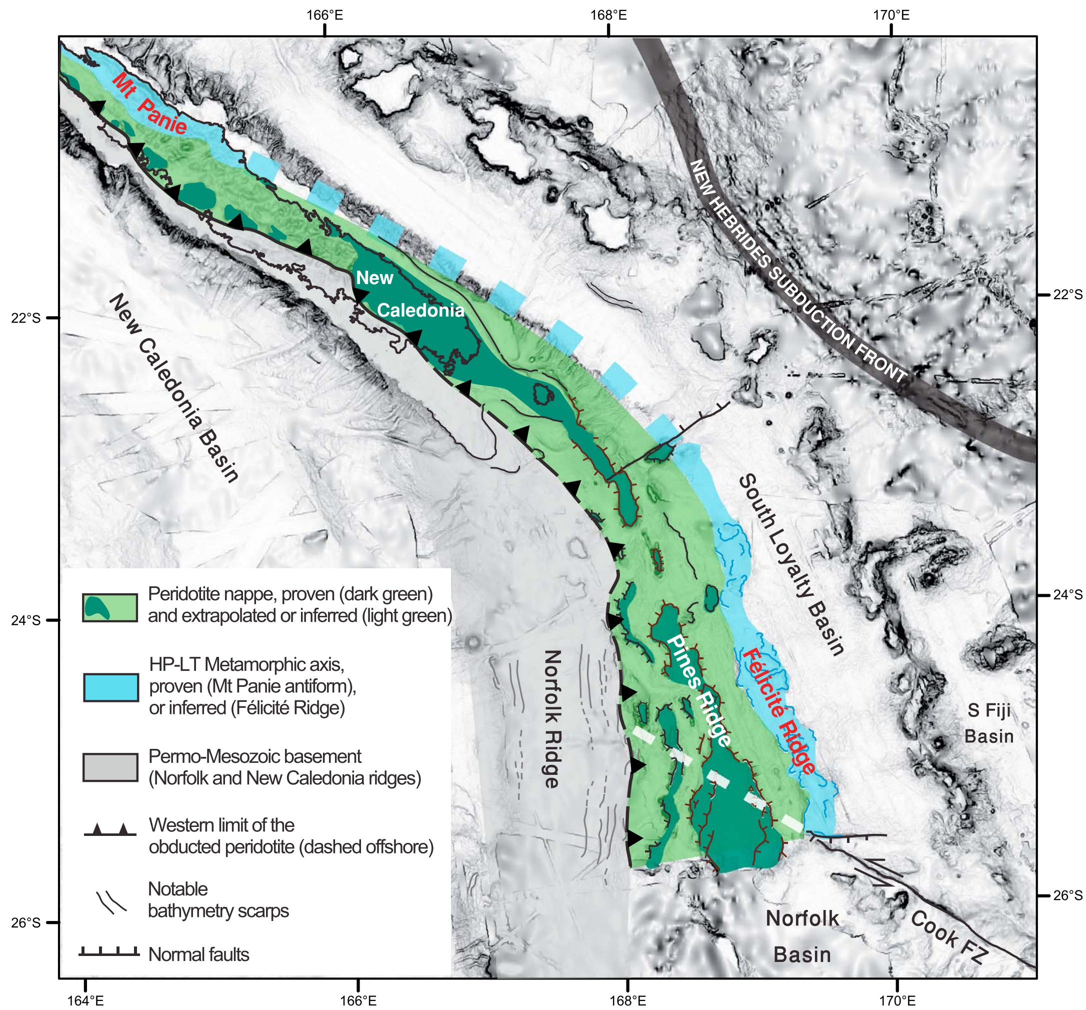

Figure 10. Basement map of the study area. White dashed line corresponds to the virtual prolongation of the Cook Fracture Zone to the NW, across which normal faults show different strikes. HP-LP = high-pressure-low-temperature.

5. Discussion

5.1. Offshore Extent of the Peridotite Nappe

The geophysical and seismic characteristics of the Pines Ridge (section 4.4) suggest that its basement is the same as that of the Isle of Pines, that is, the Peridotite Nappe (Figures 3 and 8, Paris, 1981). This hypothesis is supported by existing onland exposures of peridotite on the Isle of Pines and samples dredged along the western flank of the Pines Ridge at site KNCN-4747 (Puillandre & Samadi, 2016).

All the various highs, apexes of tilted blocks, and horsts located between the Norfolk and Félicité Ridges share with the Pines Ridge a distinctive seismically opaque basement with a very reflective and flat top. We interpret these reflective features, along with the strong reflective basement of the Kwênyii and Capucine Basins, as representing the top of the Peridotite Nappe. Serpentinite and pyroxenite dredged at sites GO20 (Capucine Ridge) and GO338 (Kwênyii Basin) corroborate this (Bitoun & Recy, 1982; Mortimer et al., 2014). Sediments capping the seamounts correspond to lagoonal deposits, reefs, and/or photic zone limestones deposited during subsidence after wave planation, notably on the relatively shallow seamounts south of Isle of Pines.

Identification of the seismic characteristics of the Peridotite Nappe in this study confirms the earlier work of Auzende et al. (2000) who mapped the offshore extent of the ophiolite SE from New Caledonia. However, our data set allows us to more reliably outline the lateral extent of the ophiolite. It can now be traced as far east as

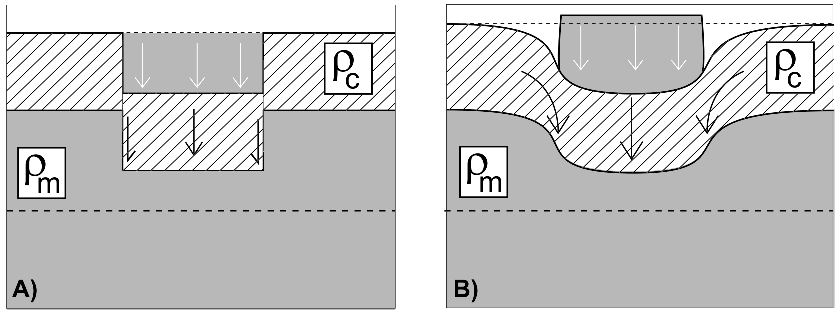

Figure 11. Schematic cartoon summarizing the effect of emplacing material with mantle density (ρm, in gray) over crust material (density ρc, hatched): All or most of the additional height due to the stacking is absorbed by the subsidence of the whole column. (a) For the case of purely local isostasy, once the crust has subsided so that isostatic equilibrium is achieved, there is no change in resulting topography. Note that in this case the mass of the lithosphere column above the asthenospheric mantle (dashed line) is everywhere the same (isostatic equilibrium). (b) In a more realistic situation, where the strength of the lithosphere supports a part of the load, the final topography is then slightly higher (and even more so if the lithosphere is strong) than before emplacement.

the Félicité Ridge and as far south as the Cook Fracture Zone (Figure 10). Seismic profiles show that the Peridotite Nappe is cut by major normal faults. It is important to state that due to the limited penetration of the seismic data available in this study, neither the structural base of the Peridotite Nappe nor any underlying units have been imaged.

It is notable that the magnetic anomaly map (Figure 6) does not help establish the extent of the Peridotite Nappe. This could indicate that the peridotite is not extensively serpentinized but could also just be a consequence of serpentinite being only weakly magnetized; magnetic properties of extensively serpentinized peridotites can vary significantly (Oufi et al., 2002).

Similarly, neither the free air gravity anomalies (Figure 6) nor the Bouguer gravity anomalies (not shown) help outline the offshore extent of the ophiolite. One reason is that the significant changes one might expect from the obduction of a Peridotite Nappe are extremely attenuated by isostasy because the obducted peridotite density and asthenosphere density are similar (Figure 11). In this particular case, the most spectacular consequence of isostatic adjustment is the destruction of any topography created by the overthrusting of peridotite. The subsidence accompanying the restoration of the isostasic equilibrium will not simply reduce the relief due to overthrusting, as in the case of crustal material, but in this rare case of peridotite obduction, where the load has the density of mantle, it will almost completely annihilate it (totally in the theoretical case of a local compensation).

Moreover, because of the large distances from the seabed at which gravity measurements are made, the gravity changes due to lateral density contrasts are smaller than the changes due to topography. If parameters like the thickness of the sedimentary cover or the true density of materials are unconstrained, it is impossible to distinguish the different causes of the gravity signal. This is the situation in our study area: the regional gravity map (Figure 6) does not show a marked gradients where peridotite is definitely known to be present (onshore Grande Terre and the Isle of Pines and offshore around the Isle of Pines).

5.2. The Félicité Ridge: An Exhumed Metamorphic Core Complex Along the Suture Zone of the Ophiolite?

The seabed expression of the Félicité Ridge is relatively subtle and discontinuous. Yet seismic reflection data show the underlying structure to be remarkably clear and continuous. The Félicité Ridge separates two areas with contrasting structural styles (Figures 4, 5, 7, 8, and 13). To the west, the Capucine and Kwênyii Basins are characterized by the presence of the obducted Peridotite Nappe and normal faults (see below). In contrast, to the east, the Loyalty Basin contains only minor normal faults and the Peridotite Nappe is either absent or deeply buried below the sediment cover. Hence, by analogy with the geology of New Caledonia, the east side of the Félicité Ridge marks the suture zone where the Peridotite Nappe roots at depth into the South Loyalty Basin whose oceanic lithospheric mantle would correspond to the in situ equivalent of the Peridotite Nappe (Cluzel et al., 2001; Collot et al., 1987).

The Félicité Ridge runs ~300 km from the Cook Fracture Zone as far north as 23°S. Further north, its expression on the seabed disappears, but its magnetic signature persists along with a subtle but uninterrupted gravity anomaly high (Figure 6). As such its presence is confidently located off the Isle of Pines and off the east coast of New Caledonia as far north as 22°S. The New Caledonia ophiolite suture zone may therefore be mapped from 22°S to the Cook Fracture Zone.

The antiformal shape, width and structural setting of the Félicité Ridge resemble that of the Mt. Panié Antiform, a domed HP/LT metamorphic complex, which outcrops as a fenster in NW New Caledonia (Baldwin et al., 2007; Clarke et al., 1997; Cluzel et al., 2001, 1995) (Figure 2, cross section). We suggest that these metamorphic rocks underlie much of the Félicité Ridge. As yet there are no dredges to ground truth this hypothesis.

5.3. Postobduction Extension of the Peridotite

Seismic observations complemented by multibeam bathymetry data indicate the presence of NNW-SSE striking normal faults between latitudes 23°S and 26°S, parallel to the Félicité and Loyalty Ridges. Dip directions of the faults are variable but are broadly symmetrical relatively to the Pines Ridge; that is, they dip west under the Capucine Basin and east under the Kwênyii Basin. A notable fault orientation change in strike, from NNW-SSE to NNE-SSW, is observed near 25°S, whereas the Pines and Félicité Ridges do not show any such change in strike. This change occurs across a line, which corresponds with the northwestward projection of the Cook Fracture Zone (white dashed line in Figure 10). Apart from the change in strike, the two groups of faults appear identical; that is, one set does not cut the other.

As mentioned above, the amount and nature of extension in onland New Caledonia is a matter of debate, notably because no indisputable normal faults or tilted blocks of the size of those we describe in this paper are known from Grande Terre (Chardon & Chevillotte, 2006; Chardon et al., 2008; Gautier et al., 2016; Iseppi et al., 2018; Lagabrielle & Chauvet, 2008; Lagabrielle et al., 2005, 2013). However, our data show that, west of the Félicité Ridge, the Peridotite Nappe is cut by prominent normal faults as shown by displacement and tilt of the top of the Peridotite Nappe, presence of graben or half-graben subbasins filled by syndeformation (fan-shaped) to postdeformation sediments, and upward deformation in the hanging wall of faults (Figures 4 and 5). Despite poor seismic at depth resolution, the normal faults appear to root deeply, below the sedimentary cover and in acoustic basement.

5.4. Vertical Motions Associated With Flexure and Relative Timing to Extension

An important first-order observation is that the entire Peridotite Nappe, including Kwênyii and Capucine Basins and the different ridges between and within these basins, occupies a large trough between the Norfolk and Félicité Ridges (Figure 4). Furthermore, the shallowest parts of the Peridotite Nappe are in the same water depth as the Norfolk Ridge.

5.4.1. Loading of the Norfolk Ridge

Because isostasy tends to erase the topographic effect of the overthrusting by a nappe whose density is that of the mantle, the topography before and after the nappe emplacement will theoretically remain mostly unchanged (Figure 11). In our case, the fact that the depth of the peridotite seamounts is not significantly different to that of the Norfolk Ridge (Figure 4) supports a hypothesis that the Peridotite Nappe was emplaced over the eastern edge of the Norfolk Ridge and that the whole area subsided under the peridotite load. Such subsidence is also suggested by the tilted unconformity surface SN1, on the eastern side of the Norfolk Ridge (Figure 5).

As shown by stratal relationships, this flexure occurred after deposition of unit UN1 and erosion of surface SN1 but before UC1 and UC2 sediment filling in the Capucine Basin. Except for compaction, UC2 sediments are untilted and the half-graben tilts on UC1 sediments are local and entirely due to rifting (Figure 5 and section 4.3).

The FTB on the eastern side of Norfolk Ridge is built over the lowermost part of unit UN2 (subunit UN2a, Figure 5) and is, arguably, topped by the Peridotite Nappe. The FTB occupies a structural position equivalent to the lower thrust nappes in onshore New Caledonia (Montagnes Blanches nappe and Poya Terrane of Cluzel et al., 2001; Maurizot, 2011; Maurizot & Cluzel, 2014). It is therefore tempting to consider this FTB as the offshore continuation of the latter and perhaps a new example of the widespread Eocene compressional episode described by Sutherland et al. (2017). However, deformation in the FTB occurred after the deformation of unit UN1, which suggests that the Norfolk Ridge had been flexured due to peridotite loading before being overthrust by the FTB. This is somewhat surprising as the emplacement of the Montagnes Blanches nappe and Poya Terrane is known to predate Peridotite Nappe emplacement by several million years (Maurizot, 2011; Maurizot & Cluzel, 2014). Resolving such a paradox is important but is beyond the scope of this paper.

5.4.2. Uplift of the Félicité Ridge

Seismic analysis shows a significant tilting affected the western flank of the Félicité Ridge, and this tilting could have happened during or after normal faulting (Figure 11 and section 4.5). Although the seismic stratigraphic relationships of UK2a with its lower and upper surfaces (SK0 and SK1) are not entirely clear, a late (postrift) westward tilt is supported by the aforementioned normal fault geometry seen on the western side of Félicité Ridge in seismic section 206-3 (Figure 8 and section 4.5). An important corollary of such a rift-followed-by-tilt evolution is that the uplift of the Félicité Ridge relative to the Kwênyii Basin would also have happened after rifting and a fortiori after the flexure of the Norfolk Ridge, suggesting a flexure-then-rift-then-uplift evolution.

5.5. Obduction to Postobduction Structural Evolution

Because of the uncertainty on the relative timing between extensional tectonics and uplift of the Félicité Ridge we propose two end-member schematic models of the evolution from preobduction setup, through mantle peridotite obduction, to postobduction extension (Figure 12). Both models honor relatively early overthrusting and flexure of the eastern side of the Norfolk Ridge, followed by extension of the Peridotite Nappe and uplift of the Félicité Ridge.

Absolute ages indicated in Figure 12 are derived as follows. (1) Tectonic emplacement of the Peridotite Nappe over preobduction sediments is dated as Bartonian-Priabonian (41–33 Ma) (Cluzel, 1998; Lagabrielle et al., 2013); (2) Exhumation of HP-LT metamorphic rocks of the Mt. Panié Antiform to relatively shallow crustal levels is dated as post Early Oligocene (< 34 Ma) (Baldwin et al., 2007); (3) Extension affecting postobduction sediments is pre-Early Miocene to late Middle Miocene (Chardon & Chevillotte, 2006). These age constraints are derived from three very different crustal units in Grande Terre and do not represent a coherent or comprehensive chronology of ophiolite emplacement and extension.

5.5.1. Model A. Uplift of Félicité Ridge Predates or Is Synchronous With Extension

In this model, extension of the Peridotite Nappe and uplift of the Félicité Ridge happened mostly simultaneously (Figure 12a). This could have resulted from the following chronological succession of events: (1) obduction and flexure of the eastern side of the Norfolk Ridge and (2) postorogenic collapse of the Peridotite Nappe and, simultaneously, related extension accompanied by the uplift of the Félicité Ridge. In such a scenario, normal faulting of the Peridotite Nappe corresponds to postorogenic collapse, as proposed by Lagabrielle et al. (2005) or to far-field boundary conditions and plate tectonics as proposed by Chardon and Chevillotte (2006). Our Model A is compatible with the model of passive obduction from Lagabrielle et al. (2013) where the uplift of the Mt. Panié Antiform would have triggered a late gravity sliding of the nappe which would correspond to its final westward emplacement. Our offshore seismic observations do not enable us to confirm or refute this mode of emplacement.

5.5.2. Model B. Extension Mostly Predates Uplift of Félicité Ridge

In this model, the postobduction extension took place after the tilting of the eastern flank of the Norfolk ridge but before the tilting of the western flank of the Félicité Ridge (Figure 12b). This could have resulted from the following chronological succession of events: (1) obduction and flexure of the eastern side of the Norfolk Ridge, (2) postorogenic collapse of the Peridotite Nappe with any related extension predominantly top to the east, and controlled by the slope of the former peridotite thrust ramp, and (3) cessation of the postorogenic collapse with separate uplift of Félicité Ridge. In this scenario, the top-to-the-east collapse of the peridotite corresponds kinematically with an inversion of the motion on the main thrust plane at the base of the Peridotite Nappe. In the literature, such inversion is usually referred as eduction and is recognized as an effective means of denudation and exhumation of HP-LT units (Andersen et al., 1991; Dixon & Farrar, 1980; Duretz et al., 2012; Fossen, 2000). The density contrast between the overriding and underriding plates explains the buoyancy of the lower crustal root (Duretz et al., 2012). In our case, as eduction follows obduction and the overriding plate is almost entirely made of high-density mantle peridotite, the density contrast is extreme, and the processes of denudation and buoyant exhumation are expected to be particularly active.

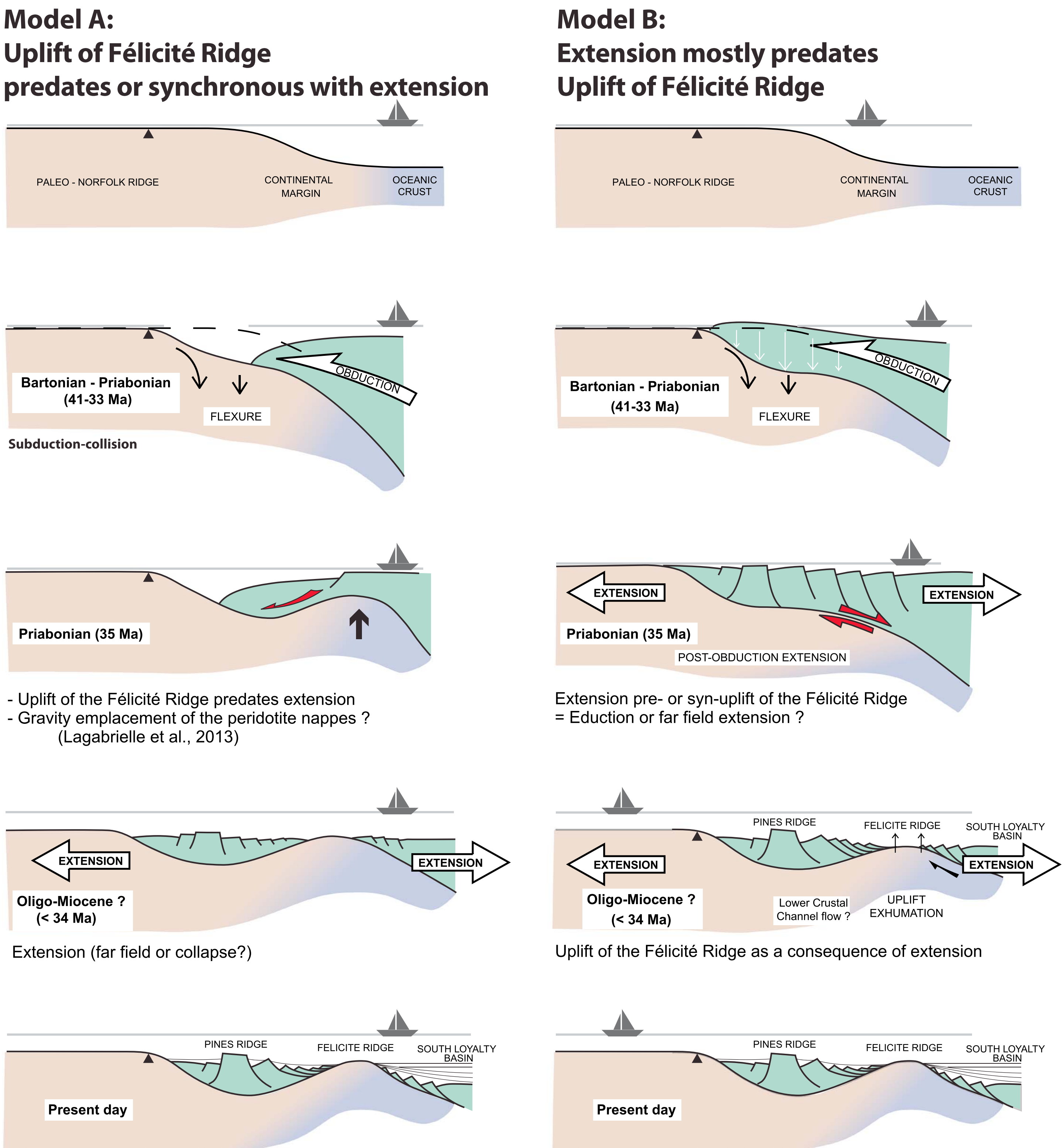

Figure 12. Two schematic models of obduction to postobduction evolution.

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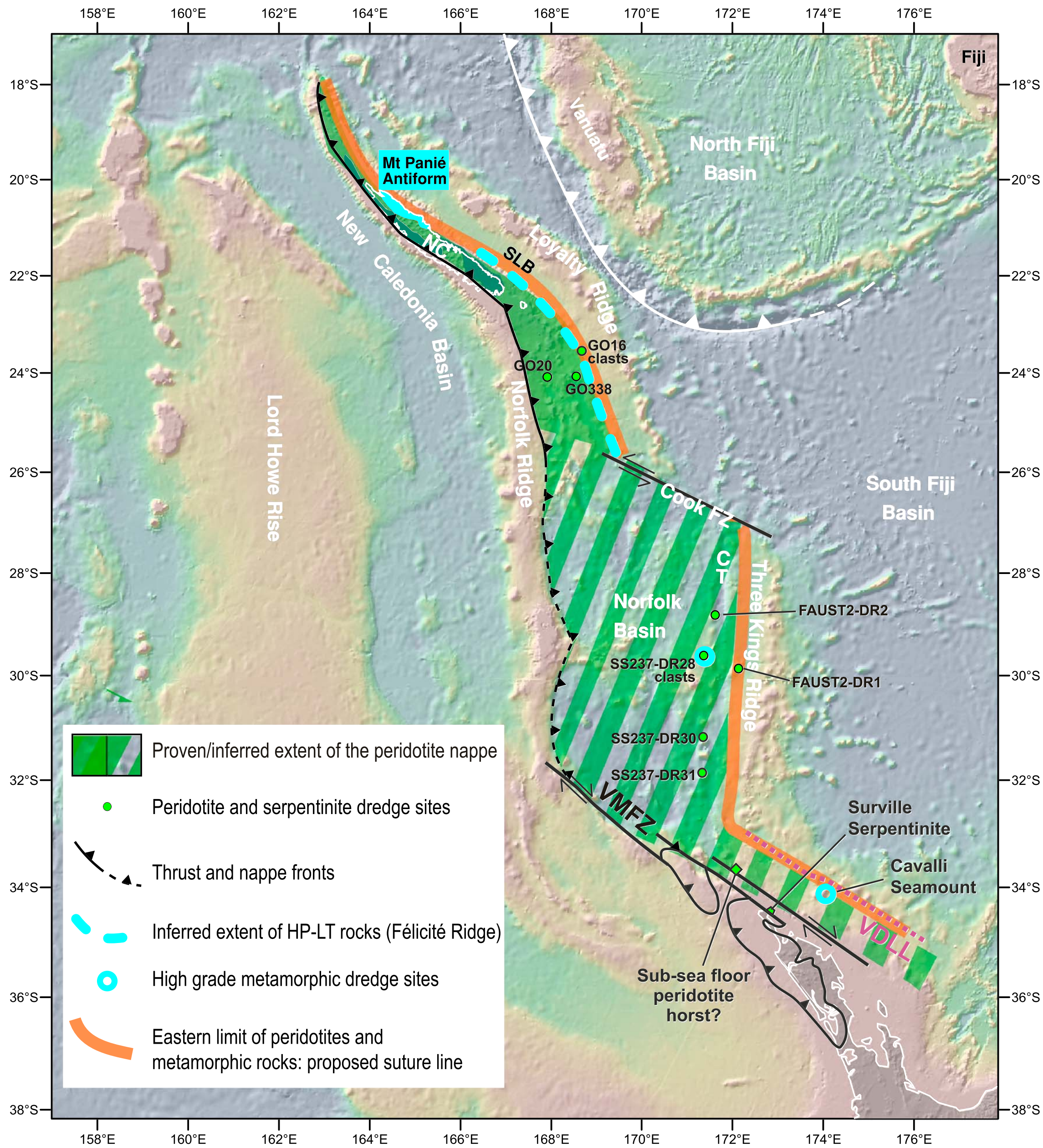

Figure 13. Known and inferred extent of obducted peridotites and high-grade metamorphic rocks along the entire northeastern Zealandia continental margin. In the Norfolk Basin the peridotite, fragmented by postobduction extension, should be found only as relict fragments and klippen. VMFZ = Vening Meinesz Fracture Zone; VDLL = van der Linden lineament (Sutherland, 1999); SLB = South Loyalty basin; CT = Cagou Trough. Possible subseafloor peridotite from Herzer et al. (2009, Figure 10). HP-LP = high-pressure-low-temperature.

Model B, where postobduction extension mostly predates the uplift of the Félicité Ridge, better integrates the kinematically preferred top-to-the-east segmentation of the Peridotite Nappe. Moreover, the position of the Peridotite Nappe between the Norfolk and Loyalty Ridges should have suppressed any postorogenic collapse of the nappe. We regard the late uplift of the Félicité Ridge, as proposed in Model B, as a more likely scenario.

5.6. Geology South of Cook Fracture Zone

Can the Peridotite Nappe and the HP-LT metamorphic antiform be traced even further south, beyond our study area, toward New Zealand? Peridotite and/or serpentinite have been dredged at four localities south of the Cook Fracture Zone, along the western side of the Three Kings Ridge: at Southern Surveyor 237 voyage, dredges 28, 30, and 31, and at FAUST-2 voyage dredge DR1 (Bernardel et al., 2003; Meffre et al., 2006; see also http://pet.gns.cri.nz; Figure 13). Late Eocene HP/LT metamorphic rocks have been dredged as clasts in a conglomerate along the western side of the Three Kings Ridge (Meffre et al., 2006), and several dredges on Cavalli Seamount near Northland, New Zealand, have yielded in situ granite and amphibolite facies metamorphic rocks (Mortimer et al., 2003, 2008) (blue circles in Figure 13). In a general sense these metamorphic dredge sites present a relatively similar structural setting to the Félicité Ridge and the Mt. Panié Antiform, corresponding to a structural high separating a northeastern oceanic basin where from the ophiolite is originally assumed to have come, from the southwestern Cenozoic Zealandia continental margin over which obduction took place. Note, however, that both the timing of obduction of ophiolitic rocks and the exhumation of the metamorphic rocks are significantly younger at Cavalli Seamount (21–23 Ma; Mortimer et al., 2003) than in New Caledonia (34 Ma, after Baldwin et al., 2007).

Collectively, the Mt. Panié Antiform, the Félicité Ridge, the Three Kings metamorphic clasts, and Cavalli Seamount broadly delineate a $>$1,500 km ophiolite suture zone (Figure 13). This might correspond with the van der Linden magnetic lineament identified by Sutherland (1999). Given the apparent continuity of this suture line from New Caledonia to New Zealand and sampling of peridotite at several sites west of the suture, we further speculate that this suture zone also indicates the likely lateral extent of the Peridotite Nappe. The Peridotite Nappe could hence have been present from 18°S to 34°S, with an eastern edge along the suture zone and a western edge along the eastern margin of the Norfolk Ridge (Figures 9 and 13). No dredged samples of peridotite have yet been reported from the Norfolk Basin, but, by analogy with the Pines and Capucine Ridges, we predict that klippes of obducted material could occur on Norfolk Basin seamounts. These would be obducted on pre-Miocene rocks and affected by the strong postobduction extension, which opened the Norfolk Basin between the Three Kings and Norfolk Ridges (Herzer et al., 2011; Mortimer et al., 1998).

6. Conclusions

We have traced the obducted Peridotite Nappe of onshore New Caledonia over a large part of the offshore region south and SSE of New Caledonia, as far south as the Cook Fracture Zone. Evidence is based mainly on characteristic seismic features resulting from the strong velocity contrast associated with the dense peridotite and less dense crustal rocks. The presence of peridotite is confirmed in rock dredge samples.

The western front of the Peridotite Nappe reached the eastern side of the Norfolk Ridge which flexured down under the nappe load. The Peridotite Nappe roots east under the South Loyalty Basin along the eastern margin of the newly named Félicité Ridge. We emphasize the geological significance of the Félicité Ridge, a subtle morphological ridge located midway between the Loyalty and Norfolk Ridges whose core probably corresponds to a continuation of the exhumed HP/LT Mt. Panié Antiform metamorphic complex seen in New Caledonia.

We observed only a few signs of compressive deformation in the study area, mostly concentrated at the leading, western, edge of the Peridotite Nappe along the Norfolk Ridge. In contrast, the Peridotite Nappe is clearly cut by normal faults associated with postobduction extension. Because the relative timing between the extension and the uplift of the Félicité Ridge is poorly constrained, we propose two alternative models of obduction to postobduction evolution. In the preferred model, uplift of the Félicité Ridge is late extension to postextension, such that most of the extension is postobduction and can be understood as resulting from eduction.

Expanding to a more regional scale, we propose that both the Peridotite Nappe and exhumed metamorphic complexes continue in parallel belts along the Three Kings Ridge as far south as New Zealand. Obducted peridotites and ophiolites, although obvious onshore, can be cryptic in the marine domain. The SW Pacific example discussed in this paper has poor to nonunique expression in bathymetric, gravity, and magnetic data sets. Instead, the area has proven to be an excellent natural laboratory to study the extent of plutonic and metamorphic rocks and obduction and eduction processes, using seismic reflection data. The study has benefitted from the special situation where the unobducted mantle lithosphere region can be observed in situ, a situation never met in ancient onshore ophiolites.

Appendix

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Seismic data supporting the analysis and conclusions of this work are available on the web page of the VESPA cruise (https://doi.org/10.17600/15001100) and in the Tasman Frontier database (https://www.gns.cri.nz/Home/Our-Science/Earth-Science/Ocean-Floor-Exploration/Oceans-Research/Tasman-Frontier). We thank the captain, crew, and science party of R/V *l'Atalante* for their work and assistance during the VESPA scientific voyage. We also thank the participants of the R/V *Alis* KANACONO biological expedition for providing rock samples. VESPA ship costs and logistics were funded by the Government of France. Our participation in the VESPA voyage and postvoyage activities was funded by the governments of New Zealand, New Caledonia, and France. The manuscript was improved by comments from Alain Chauvet, an anonymous referee, and Editor Claudio Faccenna.

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