The emplacement of the Peridotite Nappe of New Caledonia and its bearing on the tectonics of obduction:

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Key Points:
- Compressional structures characterize the internal deformation of the Peridotite Nappe of New Caledonia
- The nappe has been emplaced in a context of crustal-scale contraction driven by oblique convergence
- Obduction involved synconvergence exhumation of HP-LT rocks in a fold nappe rising through the rear part of the orogen

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The emplacement of the Peridotite Nappe of New Caledonia and its bearing on the tectonics of obduction

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Abstract The Peridotite Nappe of New Caledonia is one of the few ophiolites worldwide that escaped collisional orogeny after obduction. Here we describe the deformation associated with serpentinization in two klippes of the nappe in northwestern New Caledonia. The klippes are flat lying and involve S/SW vergent reverse-slip shear zones which are true compressional structures in origin. Further northeast, the nappe is folded in association with the development of a steep schistosity in low-grade metasediments. This difference in structural style indicates that the Peridotite Nappe experienced compression at greater depths toward its root zone, suggesting a "push from the rear" mechanism of emplacement. This supports the view that the nappe has been emplaced through horizontal contraction sustained by plate convergence. We establish a crustal-scale cross section at the end of the obduction event, before Neogene extension. This involves a large fold nappe of high-pressure rocks bounded from below by a major thrust. Furthermore, we show that obduction in New Caledonia occurred through dextral oblique convergence. Oblique convergence probably resulted from the initial obliquity between the subduction trench and the continental ribbon that became incorporated in it. This obliquity can solve the paradox of the Peridotite Nappe seemingly being emplaced at the same time the high-pressure rocks were exhumed. Oblique convergence together with focused erosional denudation on the northeastern flank of the island led to exhumation of the metamorphic rocks in a steep fold nappe rising through the rear part of the orogen.

1. Introduction

Ophiolites commonly occur within orogenic belts as a result of the obduction of a piece of oceanic lithosphere upon a continental basement [*Coleman*, 1971; *Dewey and Bird*, 1971]. Ophiolitic nappes are often strongly deformed during subsequent collision tectonics and so are often not suitable for studying the initial obduction process. The Peridotite Nappe of New Caledonia is known as an emblematic example of an ophiolite because, as in Oman, the region has not suffered collision since the mid-Cenozoic obduction [e.g., *Cluzel et al.*, 2012a]. However, to date, there is no consensus on the mechanism that led to the emplacement of the Peridotite Nappe or on the tectonic evolution of New Caledonia at the time of obduction [*Cluzel et al.*, 1995, 2001, 2012a; *Rawling and Lister*, 1999; *Spandler et al.*, 2005; *Baldwin et al.*, 2007; *Lagabrielle et al.*, 2013]. The different models proposed so far rely essentially on data from the rock units underlying the Peridotite Nappe but not on structural data from the nappe itself. Structural analysis of the peridotites has focused on high-temperature fabrics related to intraoceanic stages of deformation [*Prinzhofer et al.*, 1980; *Nicolas*, 1989; *Titus et al.*, 2011]. Only a few studies have described lower temperature-related structures that could reflect the emplacement of the nappe or/and later tectonic events [*Guillon and Routhier*, 1971; *Guillon*, 1975; *Leguéré*, 1976; *Poutchovsky and Récy*, 1982; *Lagabrielle and Chauvet*, 2008].

Recently, the deformation associated with serpentinization and carbonation of the peridotites has been characterized in the Koniambo Massif, one of the klippes of the Peridotite Nappe in northern New Caledonia [*Quesnel et al.*, 2013, 2016a]. Here we summarize the results of this analysis and present additional observations made in other klippes. Together with constraints from the literature about the rock units beneath the Peridotite Nappe and the offshore domain, these new data yield a picture of the distribution of low-temperature deformation within the nappe that enables us to describe its mechanism of emplacement and the tectonics of obduction.

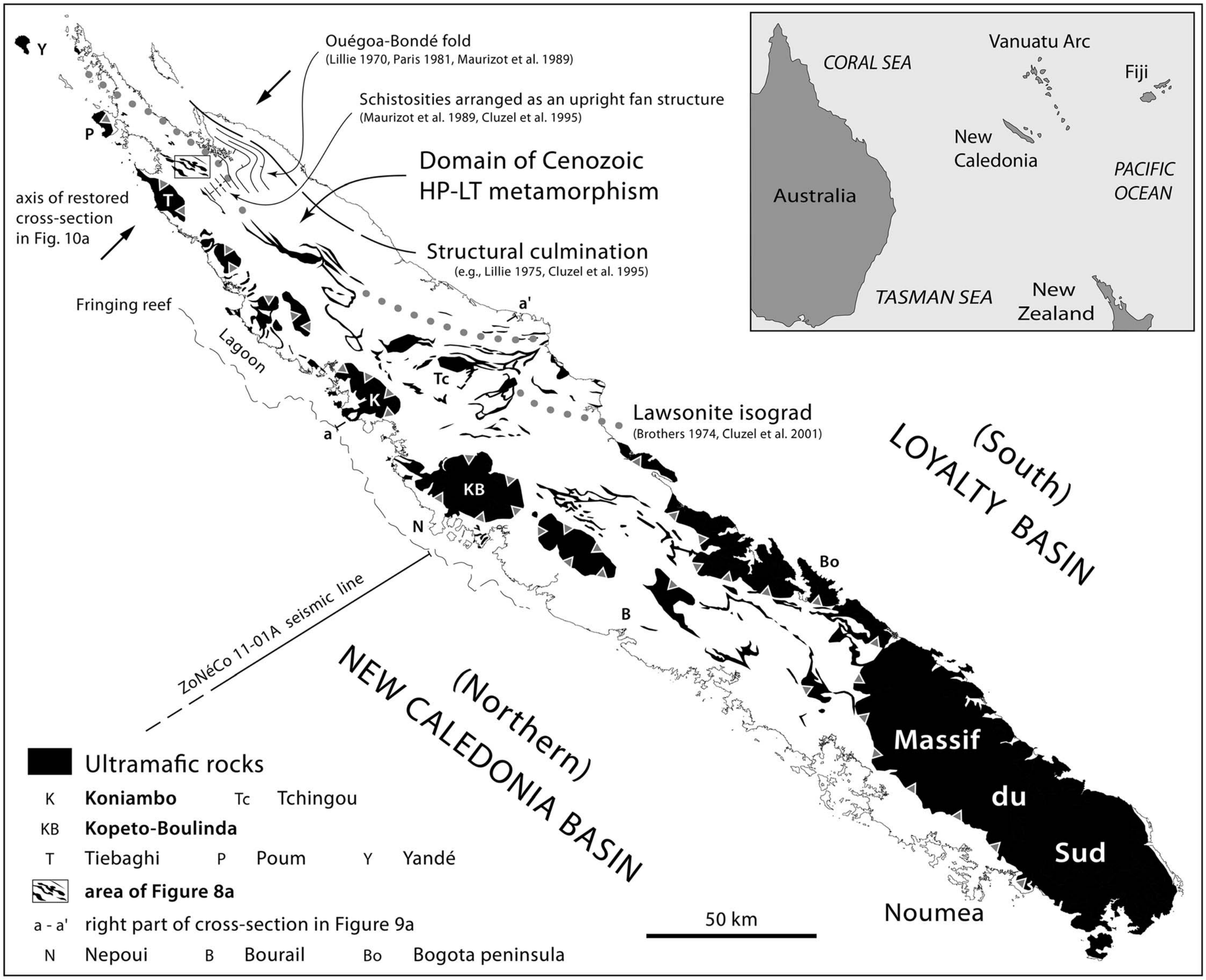

Figure 1. Simplified structural map of the Grande Terre, New Caledonia. The distribution of ultramafic rocks is slightly modified from *Maurizot and Vendé-Leclerc* [2009]. Most of these rocks are originally part of the Peridotite Nappe.

2. Geological Setting

2.1. New Caledonia

New Caledonia is located in the southwest Pacific Ocean, 1300 km east of Australia (Figure 1). On the main island, known as the "Grande Terre," the Peridotite Nappe overlies, with a subhorizontal tectonic contact [*Avias*, 1967; *Guillon*, 1975], a substratum composed of four main rock assemblages [*Paris*, 1981; *Cluzel et al*., 2001, 2012a].

The "basement," forming the central part of the island consists of Permian to Early Cretaceous volcano-sedimentary rocks with a variable pre-Coniacian metamorphic overprint. This basement forms the backbone of a ≤ 100 km wide ribbon of continental crust that extends, south of the Grande Terre, into the shallow submarine N-S trending Norfolk Ridge.

The second group of rocks consists of Late Cretaceous (Coniacian) to late Eocene sediments. The Late Cretaceous deposits unconformably overlie the basement and are interpreted as a synrift (with associated volcanic rocks) to postrift sequence. Following Paleocene pelagic sedimentation, turbidites started to accumulate in the north of the island during the late early Eocene at ~50 Ma [*Maurizot*, 2011]. This change in sedimentation is interpreted as a first record of deformation in the foreland of the convergent plate boundary that eventually led to the obduction of the Peridotite Nappe. The onset of clastic sedimentation is progressively delayed further southeast [*Cluzel et al*., 2012a; *Maurizot and Cluzel*, 2014], occurring in the late Eocene near Noumea [*Cluzel et al*., 2001].

A third rock assemblage is represented by the Poya Terrane, with dolerites, basalts, and minor bathyal sediments representing the remnants of a Late Cretaceous to earliest Eocene oceanic floor [*Cluzel et al*., 2001]. The Poya Terrane occurs as a package of steep fault-bounded sheets intercalated between the overlying Peridotite Nappe and the underlying basement and its Late Cretaceous-Eocene cover.

Finally, a fourth group of rocks is characterized by the record of a high-pressure-low-temperature (HP-LT) metamorphic overprint of Cenozoic age. These rocks are exposed in the northwestern half of the Grande Terre (Figure 1). Within this area, a northeastward increase in metamorphic grade is recognized [e.g., *Brothers*, 1974; *Vitale Brovarone and Agard*, 2013]. To the southwest, the first noticeable planes of schistosity dip at ~50° to the northeast [*Maurizot et al*., 1989]. Moving northeastward, the main schistosity progressively steepens, becoming vertical about 2.5 km before the lawsonite-in isograd, and then dips to the southwest [*Lillie*, 1970; *Maurizot et al*., 1989] (Figure 1). As a result, schistosities define an upright fan-like structure with a width of about 10 km [*Cluzel et al*., 1995, 2001; *Vitale Brovarone and Agard*, 2013]. Further northeast, despite local complications due to some fault zones, a major structural culmination is recognized adjacent to the northeastern coast [*Lillie*, 1975; *Cluzel et al*., 1995, 2012a; *Rawling and Lister*, 1999; *Vitale Brovarone and Agard*, 2013] (Figure 1). Southwest of this culmination, schistosities define a large asymmetric fold with a steeply plunging axis, the Ouégoa-Bondé fold [*Lillie*, 1970; *Paris*, 1981; *Maurizot et al*., 1989]. Its asymmetry is consistent with dextral shearing along a trend parallel to the culmination (Figure 1). Equivalent folds exist further northwest and southeast, slightly west of the lawsonite isograd [*Paris*, 1981].

Within the domain of Cenozoic metamorphism, two units are distinguished [*Cluzel et al*., 1995; *Clarke et al*., 1997]. The Pouebo Terrane, along the northern coast, is a mélange carrying blocks of mafic eclogites and minor metasediments within a matrix of talcschists. Geochemical and protolith age data indicate that the blocks in the mélange and the Poya Terrane are probably derived from the same oceanic domain [*Cluzel et al*., 2001; *Spandler et al*., 2005]. The Diahot Terrane, across which much of the northeastward increase in metamorphic grade occurs, has Late Cretaceous-Paleocene sedimentary and volcanic protoliths reminiscent of the series covering the basement [*Paris*, 1981; *Cluzel et al*., 2012a]. U-Pb ages of ~44 Ma on metamorphic rims of zircon grains have been interpreted as dating peak conditions in the Pouebo Terrane [*Spandler et al*., 2005]. Other time constraints mostly consist of ^{39}Ar-^{40}Ar ages on white micas, of ~36.5–40 Ma in the Pouebo Terrane and ~35–38 Ma in the higher-grade part of the Diahot Terrane, interpreted as dating cooling of the metamorphic rocks down to ~350–450°C [*Ghent et al*., 1994; *Baldwin et al*., 2007] Using a pressure-temperature path established by *Fitzherbert et al.* [2004]; *Baldwin et al.* [2007] concluded that the above ^{39}Ar-^{40}Ar ages date a stage of the decompression path at around 5–8 kbar. A later stage of the path is constrained by one fission track age on apatite at 34 ± 4 Ma [*Baldwin et al*., 2007].

2.2. The Peridotite Nappe

The Peridotite Nappe is mainly exposed in the "Massif du Sud," covering much of the southeastern third of the Grande Terre and in a series of klippes along the northwestern coast (Figure 1). In the Massif du Sud, the thickness of the nappe is at least 1.5 km but locally may reach 3.5 km [*Guillon*, 1975]. The nappe is mostly composed of harzburgites except in the northernmost klippes (Tiebaghi, Poum, and Yandé; see Figure 1 for location) where lherzolites are dominant [e.g., *Nicolas*, 1989]. In the harzburgites, compositional layering is represented by 1 to 100 m thick layers of dunite [e.g., *Guillon*, 1975; *Ulrich et al*., 2010]. In high-elevation areas of the Massif du Sud, the harzburgites are capped by massive dunites overlain by layered wehrlites, pyroxenites, and gabbros, representing the base of an oceanic crust [*Guillon*, 1975; *Prinzhofer et al*., 1980; *Paris*, 1981]. Earlier authors considered this crust as being formed at a mid-oceanic spreading ridge, but recent work has shown that it is mainly a fore-arc crust formed in a suprasubduction zone setting [*Marchesi et al*., 2009; *Pirard et al*., 2013]. The harzburgites represent residues produced by either a single partial melting event associated with the formation of the fore-arc crust [*Marchesi et al*., 2009] or, more probably, at least two partial melting events, the first of which likely relates to a spreading ridge [*Ulrich et al*., 2010; *Pirard et al*., 2013].

In the main part of the Peridotite Nappe, the degree of serpentinization of the peridotites is moderate but variable [*Orloff*, 1968], serpentines occurring preferentially along a network of mm to ~10 cm thick fractures and shear zones [e.g., *Leguéré*, 1976; *Lahondère et al*., 2012; *Quesnel et al*., 2016a]. In contrast, serpentinization is pervasive along the base of the nappe, forming a "sole" with an intense internal deformation [*Avias*, 1967; *Orloff*, 1968; *Guillon*, 1975; *Leguéré*, 1976; *Cluzel et al*., 2012a; *Quesnel et al*., 2013, 2016a]. The thickness of this sole is a few tens of meters in the Massif du Sud but reaches a few hundred meters in the northwestern klippes [*Guillon*, 1975; *Maurizot et al*., 2002]. Deformation along the serpentine sole is commonly interpreted as resulting from the emplacement of the nappe [e.g., *Cluzel et al*., 2012a]. Alternatively, deformation along the sole may partly result from subsequent extensional reactivation of the basal contact of the nappe [see *Lagabrielle and Chauvet*, 2008, Figure 9].

A general consensus exists that the Peridotite Nappe originated from the Loyalty Basin (Figure 1) [e.g., *Avias*, 1967; *Guillon*, 1975; *Collot et al*., 1987; *Cluzel et al*., 2012a] so that it must have been emplaced with a roughly southwest vergence. However, kinematic data are scarce [*Guillon and Routhier*, 1971; *Guillon*, 1975; *Poutchovsky and Récy*, 1982] and mostly emanate from the rock units underneath the nappe [e.g., *Tissot and Noesmoen*, 1958; *Gonord*, 1977; *Paris*, 1981; *Cluzel et al*., 2001; *Maurizot*, 2011]. *Quesnel et al.* [2013] presented field evidence for top-to-SW shearing along the serpentine sole of the Koniambo Massif but left it open as to whether this deformation relates to the emplacement of the nappe or to later extensional reactivation.

The Peridotite Nappe includes a number of felsic dykes, some with boninitic affinity, dated at ~53 Ma [*Cluzel et al*., 2006]. These dykes probably reflect a stage of high-temperature intraoceanic subduction soon after the inversion of a mid-oceanic spreading ridge [*Ulrich et al*., 2010; *Cluzel et al*., 2012a]. Right beneath the Peridotite Nappe, local slivers of metabasic rocks preserve evidence of a high-temperature amphibolite facies event dated at ~56 Ma [*Cluzel et al*., 2012b]. These slivers, interpreted as relics of a metamorphic sole, support the hypothesis of a warm intraoceanic subduction at ~53–56 Ma. As a result, the emplacement of the Peridotite Nappe onto the Norfolk Ridge microcontinent is likely younger than ~53 Ma. The emplacement of the nappe occurred after that of the underlying Poya Terrane sheeted complex, as suggested by the presence of clasts derived from the latter and the basement, but not from the peridotites, within the Eocene foreland basins [*Cluzel et al*., 2001, 2012a]. Pelagic sedimentation persisted until the mid-Eocene in the Poya Terrane [*Cluzel et al*., 2012b]. Therefore, the Peridotite Nappe was probably emplaced later than ~45 Ma. An even tighter time constraint is provided by the age of the uppermost sediments buried beneath either the Poya sheeted complex or the Peridotite Nappe itself. According to biostratigraphic constraints, the oldest possible age of these uppermost sediments is ~38 Ma at Nepoui and ~34–35 Ma near Bourail and around Noumea [*Cluzel et al*., 2001; *Maurizot and Cluzel*, 2014] (see Figure 1 for location). Close to Noumea, the Saint-Louis granodiorite, a small intrusion dated at ~27 Ma, cuts across the basal contact of the Peridotite Nappe [*Paquette and Cluzel*, 2007]. Hence, near the southern end of the Grande Terre, the nappe was emplaced at some time between ~35 and ~27 Ma.

Following its exposure to aerial conditions, the Peridotite Nappe was subjected to intense weathering under warm and wet climatic conditions, which led to the development of thick laterites. Leaching of the peridotites by meteoric waters induced a redistribution of elements, leading to nickel mineralization at the base of the weathering profile [e.g., *Orloff*, 1968; *Leguéré*, 1976; *Paris*, 1981]. World class nickel ore deposits have been exploited in New Caledonia for more than a century. Most observations and measurements reported in this work were collected on two large mining sites, in the Koniambo Massif (as detailed in *Quesnel et al.* [2016a]) and in the nearby Kopeto-Boulinda Massif (Figure 1). Magnesite veins, which frequently occur along the serpentine sole of the Peridotite Nappe, represent another by-product of the leaching of the peridotites by meteoric fluids [*Ulrich*, 2010; *Quesnel et al*., 2013, 2016b]. In the Koniambo Massif, *Quesnel et al.* [2013] showed that at least some of these veins were emplaced during shearing along the sole.

2.3. The Offshore Domain

The Grande Terre is surrounded by a ~5 to 15 km wide reef lagoon system. Beyond the fringing reef, the island is flanked by two deep basins (Figure 1).

To the northeast, the Loyalty Basin is separated from the Grande Terre by a steep submarine slope that has several northeast dipping normal faults of Neogene age [*Bitoun and Récy*, 1982; *Chardon and Chevillotte*, 2006; *Chardon et al*., 2008]. Based on geophysical data, the Loyalty Basin is floored by oceanic crust and represents the basin from which the Peridotite Nappe originated [*Bitoun and Récy*, 1982; *Collot et al*., 1987]. This crust is overlain by a thick sedimentary sequence. The lower part has geometrical relations indicating deposition soon after the emplacement of the Peridotite Nappe whereas the upper part relates to Neogene extensional tectonics [*Bitoun and Récy*, 1982; *Chardon and Chevillotte*, 2006]. On a NW-SE trending cross section along the axis of the Loyalty Basin, *Bitoun and Récy* [1982] showed that the lower sedimentary sequence is ~3.5 to 4 km thick in the part of the basin facing the Grande Terre and only ~0.5 km thick further northwest, which suggests that these sediments essentially consist of erosional products derived from the Grande Terre.

To the southwest, the New Caledonia Basin is separated from the Grande Terre by another steep submarine slope that includes southwest dipping normal faults of Neogene age [*Rigolot*, 1989; *Chardon and Chevillotte*, 2006]. Hence, the Grande Terre appears as a large horst since at least the late Miocene [e.g., *Chardon and Chevillotte*, 2006; *Lagabrielle and Chauvet*, 2008]. The northern part of the New Caledonia Basin, facing the Grande Terre, has a fairly constant water depth of ~3500 m. It is made up of a crust ~10 km thick overlain by a sedimentary sequence that defines an asymmetric basin deepening toward the island [*Dubois et al*., 1974; *Lafoy et al*., 2004, 2005; *Klingelhoefer et al*., 2007; *Collot et al*., 2008]. On seismic lines (e.g., the ZoNéCo 11-01A line; see Figure 1 for location), the sediments are horizontal, showing a progressive onlap onto a prominent northeast dipping reflector. Based on long-distance correlation of borehole data, this reflector coincides with a major unconformity formed at some time between ~45 and ~30 Ma. As discussed by *Collot et al.* [2008], the most likely interpretation of these features is that obduction on the Grande Terre triggered rapid subsidence and tilting of the foreland domain, which then became progressively filled with posttilt sediments. Since *Dubois et al.* [1974], a debate exists as to whether or not significant lithospheric convergence occurred across the boundary between the Grande Terre and the New Caledonia Basin. One hypothesis is that this boundary coincides with a subduction trench that was already active when obduction occurred on the Grande Terre [e.g., *Dubois et al*., 1974; *Rawling and Lister*, 1999]. In contrast, recent interpretations favor an activation of the boundary after the obduction event [e.g., *Cluzel et al*., 2001]. In these interpretations, the amount of convergence is either small (limited thrusting of the Grande Terre over the New Caledonia Basin [*Lafoy et al*., 2004; *Collot et al*., 2008]) or large (subduction of the easternmost $>$100 km of the New Caledonia Basin beneath the Grande Terre [*Paquette and Cluzel*, 2007; *Cluzel et al*., 2012a]). Southwest vergent thrusts and folds deform the sedimentary pile along the foot of the steep submarine slope west of the island [*Rigolot*, 1989; *Lafoy et al*., 2004], but it is unclear whether these structures reflect lithospheric convergence or only local contraction at the front of large gravitational slides [*Lafoy et al*., 2004; *Chardon and Chevillotte*, 2006]. Further southwest, underneath the mid-Cenozoic unconformity, a structure with half grabens up to ~40 km wide has been identified along some seismic lines, supporting the view that the northern part of the New Caledonia Basin is floored by thinned continental crust [*Lafoy et al*., 2004, 2005; *Paquette and Cluzel*, 2007].

3. Previous Models for the Emplacement of the Peridotite Nappe

Several authors have pointed out that the emplacement of the Peridotite Nappe and the development of HP-LT metamorphism in the northern part of the Grande Terre were broadly contemporaneous, suggesting a genetic link between the two processes [e.g., *Coleman*, 1967; *Brothers*, 1974]. However, since the publication of the white mica ^{39}Ar-^{40}Ar ages from the HP-LT domain at ~35–40 Ma, interpreted as cooling ages [*Ghent et al*., 1994; *Baldwin et al*., 2007], and the dating of the topmost sediments beneath the Peridotite Nappe at ~34–35 Ma [*Cluzel et al*., 2001], a consensus has arisen that the nappe was emplaced while the metamorphic rocks were on their way to the surface. This may be viewed as a paradox and existing scenarios of the Cenozoic evolution of New Caledonia differ in the way this apparent paradox is solved.

For *Spandler et al.* [2005], the metamorphic rocks were exhumed during a short-lived (from $<$44 to ~34 Ma) episode of plate divergence and lithospheric extension that temporarily interrupted the process of plate convergence and obduction. Considering the metamorphic domain, *Cluzel et al.* [1995] and *Rawling and Lister* [1999] have argued for the existence of "normal-sense" ductile shear zones associated with extensional tectonics. However, the same authors emphasize that these shear zones are deformed by tight upright to steep folds [see also *Maurizot et al*., 1989], so deducing their tectonic origin from their orientation may be problematic. *Cluzel et al.* [1995] and *Clarke et al.* [1997] reported that some of the shear zones are associated with the superposition of lower grade rocks (from the high-grade part of the Diahot Terrane) onto much higher-grade rocks (from the Pouebo eclogitic mélange), providing stronger evidence for significant normal-sense displacements. According to *Clarke et al.* [1997], the related shearing event occurred at pressures greater than ~13 kbar, equivalent to depths greater than ~45 km. Normal-sense shearing at such depths suggests a process of exhumation taking place along the subducting slab and does not clearly support the hypothesis of a brief episode of whole lithosphere extension. Steep normal faults are also present in the high-grade part of the metamorphic domain [*Cluzel et al*., 1995; *Rawling and Lister*, 1999], but these could be late structures postdating the emplacement of the Peridotite Nappe. For instance, they may be related to the Neogene event(s) that shaped the Grande Terre as a horst [*Chardon and Chevillotte*, 2006; *Lagabrielle and Chauvet*, 2008].

For *Baldwin et al.* [2007], exhumation of the metamorphic rocks and emplacement of the Peridotite Nappe were synchronous but occurred at different sites along the strike of the plate boundary. Current remnants of the nappe west of the metamorphic domain would have been carried there by a major postobduction wrench event resulting in at least 150 km of dextral displacement along the strike of the island, in agreement with an early proposal of *Brothers* [1974]. However, the nature of the main fault proposed to have accommodated this displacement, the so-called "West Caledonian Fault," is highly controversial. For *Paris* [1981] and *Maurizot et al.* [1985a], it is essentially a pre-Cenozoic structure that has been later reactivated as a steep thrust zone [see also *Guillon*, 1975] and then as a SW dipping normal fault. For other authors, the West Caledonian Fault is just a Neogene SW dipping normal fault of limited [*Cluzel et al*., 2001] or greater [*Lagabrielle and Chauvet*, 2008] importance. In any case, a major postobduction wrench displacement along this fault seems ruled out.

A third scenario, recently put forward by *Lagabrielle et al.* [2013], considers that much of the emplacement of the Peridotite Nappe has occurred by gravitational sliding along a SW dipping slope produced by crustal-scale upward arching/doming of the underlying thrust stack. This model, also suggested by *Guillon and Routhier* [1971] and *Cluzel et al.* [1995], has the advantage that it readily solves the above paradox if the apex of the arch, from where the nappe slided away, coincides today with the higher-grade part of the metamorphic domain. In line with this hypothesis, the highest-grade rocks occur in the same area where the main structural culmination of the metamorphic domain is located, close to the northern coast [e.g., *Cluzel et al*., 1995] (Figure 1). Gravitational sliding down a very gentle slope may have been facilitated by the presence of the serpentine sole at the base of the nappe, acting as a weak décollement [*Lagabrielle et al*., 2013]. This model, however, cannot be applicable to the whole of the Grande Terre. To the southeast, ignoring the effect of secondary normal faults, the basal contact of the Peridotite Nappe is horizontal around much of the Massif du Sud and west of it until around Bourail [e.g., *Gonord*, 1977; *Lagabrielle and Chauvet*, 2008] while along the northeastern coast the peridotites plunge abruptly toward the Loyalty Basin [*Guillon*, 1975; *Paris*, 1981]. Therefore, this region seems to lack a structural culmination from which the nappe could have slipped down. Despite this restriction, gravitational sliding could account for the geological situation in at least the northwestern half of the island.

Finally, although they also pointed out the synchronism between the emplacement of the Peridotite Nappe and the exhumation of the HP-LT rocks, *Cluzel et al.* [2001] developed a scenario that does not clearly address this issue [see also *Cluzel et al.*, 2012a]. Hence, of the different tectonic models proposed so far, the one involving an emplacement of the Peridotite Nappe by gravitational sliding [*Lagabrielle et al*., 2013] seems the most simple and appropriate. Alternative models implicitly assume that the nappe has been emplaced through horizontal contraction sustained by plate convergence [e.g., *Guillon*, 1975; *Cluzel et al*., 2001, 2012a; *Spandler et al*., 2005]. Thus, the various models proposed to date involve different mechanisms of emplacement for the Peridotite Nappe, and it is the aim of this paper to assess which mechanism is the most likely. This, in turn, may provide constraints on how obduction occurred in New Caledonia.

4. The Deformation in the Northwestern Klippes of the Peridotite Nappe

4.1. The Koniambo Massif

In the Koniambo Massif, the Peridotite Nappe is exposed from its base, near sea level, up to ~800 m elevation (Figures 2a and 2b). Map relations [*Carroué*, 1972; *Maurizot et al*., 2002] show that the basal contact is subhorizontal around much of the massif. The Koniambo Massif consists of harzburgites with interlayers of dunite

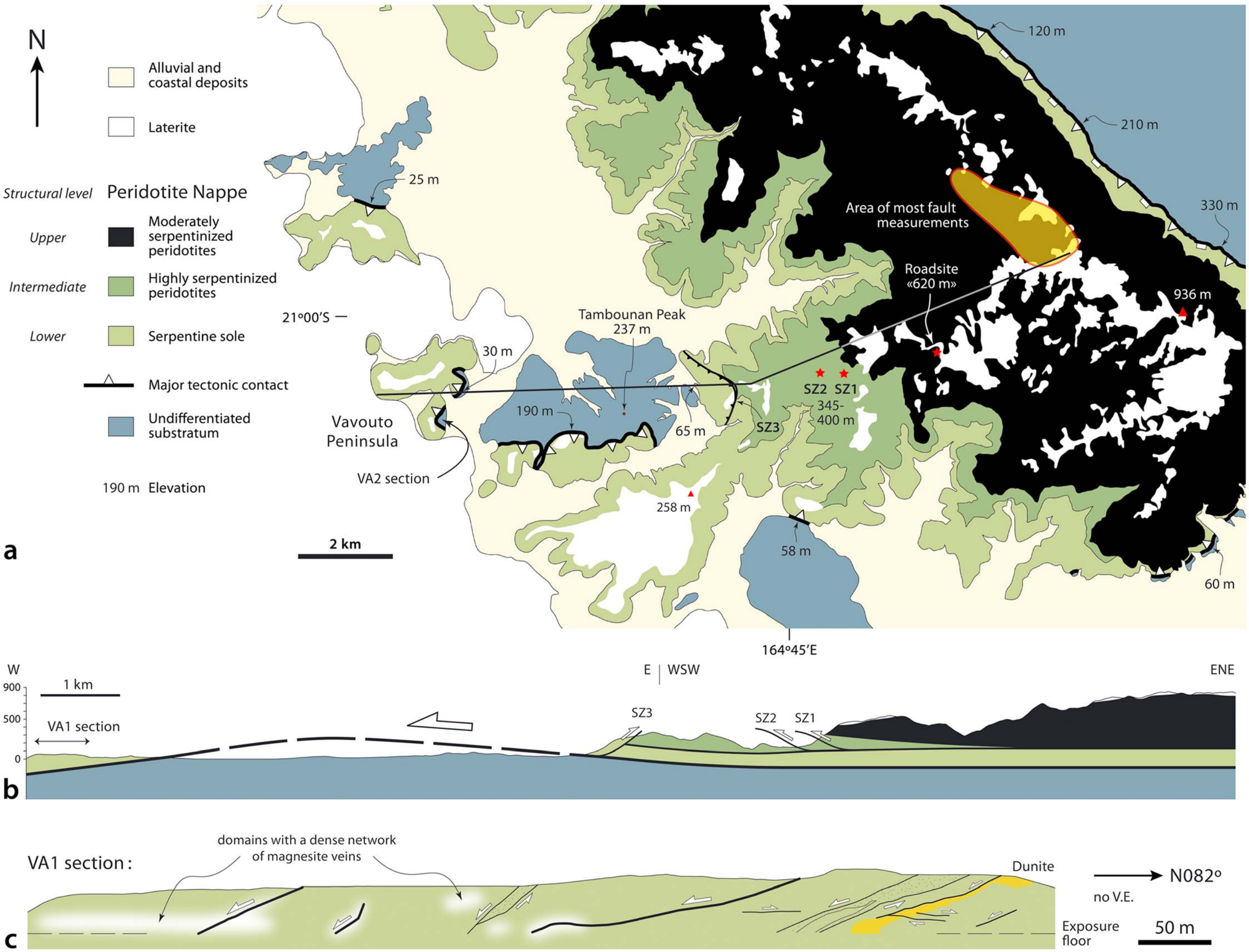

Figure 2. (a) Geological map of the central and southern parts of the Koniambo Massif, adapted from *Carroué* [1972] and *Maurizot et al.* [2002]. (b) General cross section of the Koniambo Massif, located in Figure 2a. (c) Report of the main fault zones along the VA1 section in the Vavouto peninsula. Figures 2b and 2c are adapted from *Quesnel et al.* [2016a].

that define a compositional layering with a fairly regular ENE-WSW strike and a ~50° southward dip [*Maurizot et al*., 2002]. With regard to the degree of serpentinization, *Maurizot et al.* [2002] distinguished three main rock types, namely, (i) moderately serpentinized peridotites in which the primary compositional layering is preserved, (ii) highly serpentinized peridotites, and (iii) massive serpentinites. The latter form the serpentine sole of the nappe about 200 m thick. The highly serpentinized peridotites overlie the sole and form a distinct layer which, according to *Maurizot et al.* [2002], is ~200 m thick on the western flank of the massif but thins out further east (Figures 2a and 2b). The moderately serpentinized peridotites occupy the higher part of the massif.

An analysis of deformations associated with distinct serpentine polymorphs and magnesite has been presented by *Quesnel et al.* [2016a], and here we summarize the results of this work. The mineralogical content of veins, fracture infillings, and cleavage domains has been determined through a multitechnique approach including Raman spectroscopy. Although rarely quoted in the literature on New Caledonia, polygonal serpentine was found to be widespread, a massive and matte aspect and a pale green color being its distinctive macroscopic characteristics. We identified three structural levels, which correlate well with the rock horizons defined by *Maurizot et al.* [2002] (Figures 2a and 3).

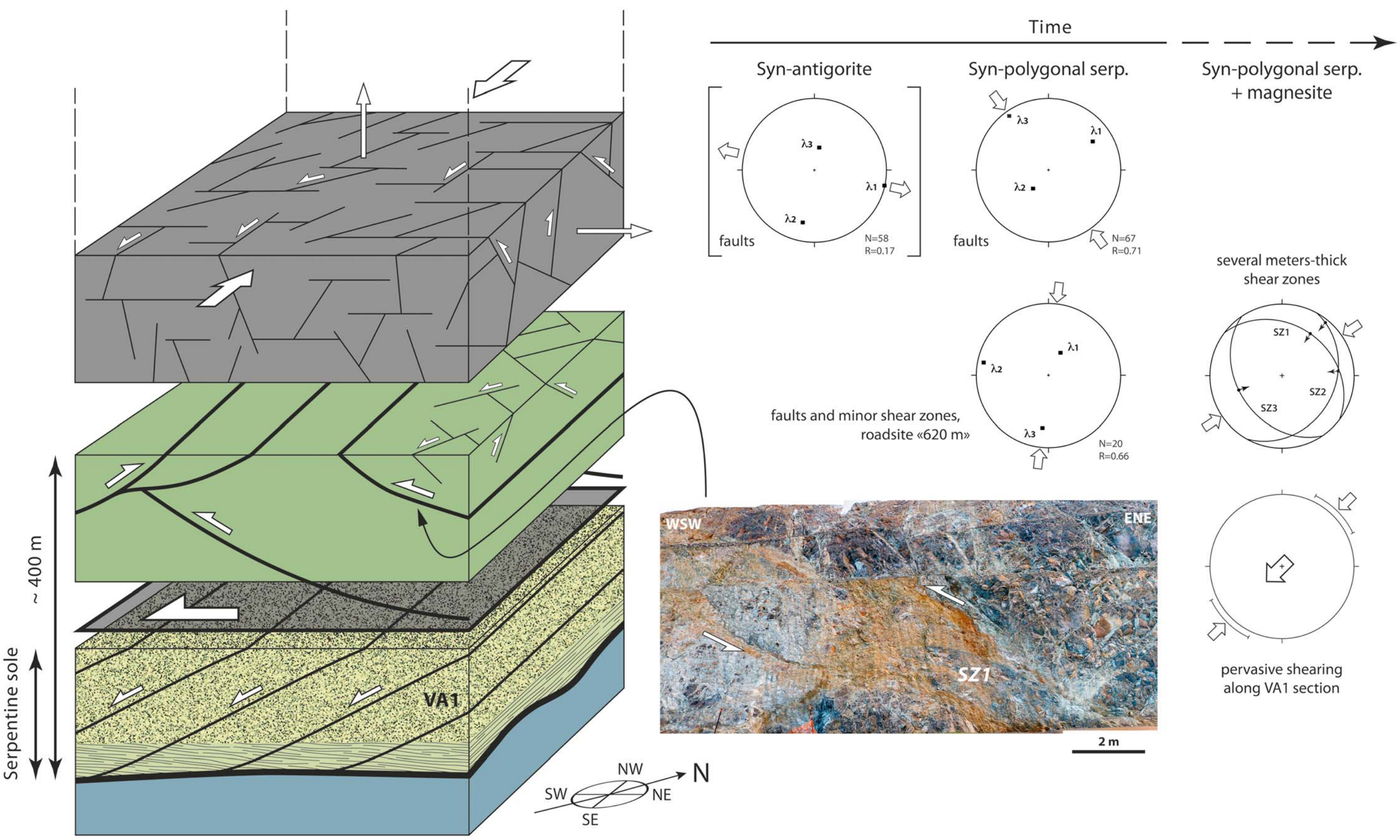

Figure 3. Summary of the results of structural analysis in the Koniambo Massif, adapted from *Quesnel et al.* [2016a]. (left) Block diagram depicting the style of deformation in the three structural levels identified in the massif. For the upper structural level, the drawing shows the deformation associated with polygonal serpentine. (right) Synthesis of the results of strain inversion as a function of the structural level (vertically) and as a function of the main minerals associated with deformation, which enable a sequence of events to be identified (horizontally). Strain inversion of fault slip data has been carried out with the FaultKin software of *Allmendinger et al.* [2012]. The parameter R relates to the shape of the strain ellipsoid ($R = (\varepsilon_2 - \varepsilon_3)/(\varepsilon_1 - \varepsilon_3)$ hence R equates 0 for pure constriction, 0.5 for plane strain, and 1.0 for pure flattening).

The peridotites of the upper structural level are crosscut by a dense network of fractures filled with one or several types of serpentine. Antigorite and polygonal serpentine commonly form stepped slickenfibers along fault planes. Fault slip analysis returned two strikingly different strain ellipsoids (Figure 3). Antigorite-bearing faults yield a highly constrictional ellipsoid with λ_1, the axis of maximum stretching, lying horizontally along a WNW-ESE trend. Polygonal serpentine-bearing faults yield an ellipsoid in the flattening field with λ_3, the axis of maximum shortening, lying subhorizontally along a NW-SE trend. Microstructural observations indicate that polygonal serpentine postdates antigorite [see also *Ulrich*, 2010].

The serpentine sole of the Koniambo Massif is well exposed in the Vavouto peninsula (Figure 2a). Breccias dominate while foliated mylonitic serpentinites form a distinct basal layer at least 20 m thick (Figure 3). The sole has experienced pervasive noncoaxial deformation with a top-to-SW sense of shear. Polygonal serpentine and magnesite are synkinematic phases with respect to this deformation. Along the 700 m long VA1 section (Figure 2c), shallow-dipping shear zones are distributed with a ~100 m lengthscale. Their mean obliquity with respect to the basal contact of the nappe is ~22°.

The main part of the intermediate structural level is similar to exposures of the upper structural level, with a dense network of serpentine-bearing fractures, but this rock mass is crosscut by reverse-slip shear zones several meters in thickness (Figures 2b and 3). Top-to-SW shear zones are synthetic to pervasive shearing along the serpentine sole and also involve polygonal serpentine and magnesite as synkinematic mineral phases. Therefore, although this contact could not be observed in the field, we suggest that the shear zones root along the roof of the serpentine sole, with the whole sole acting as a décollement (Figure 4, relationship

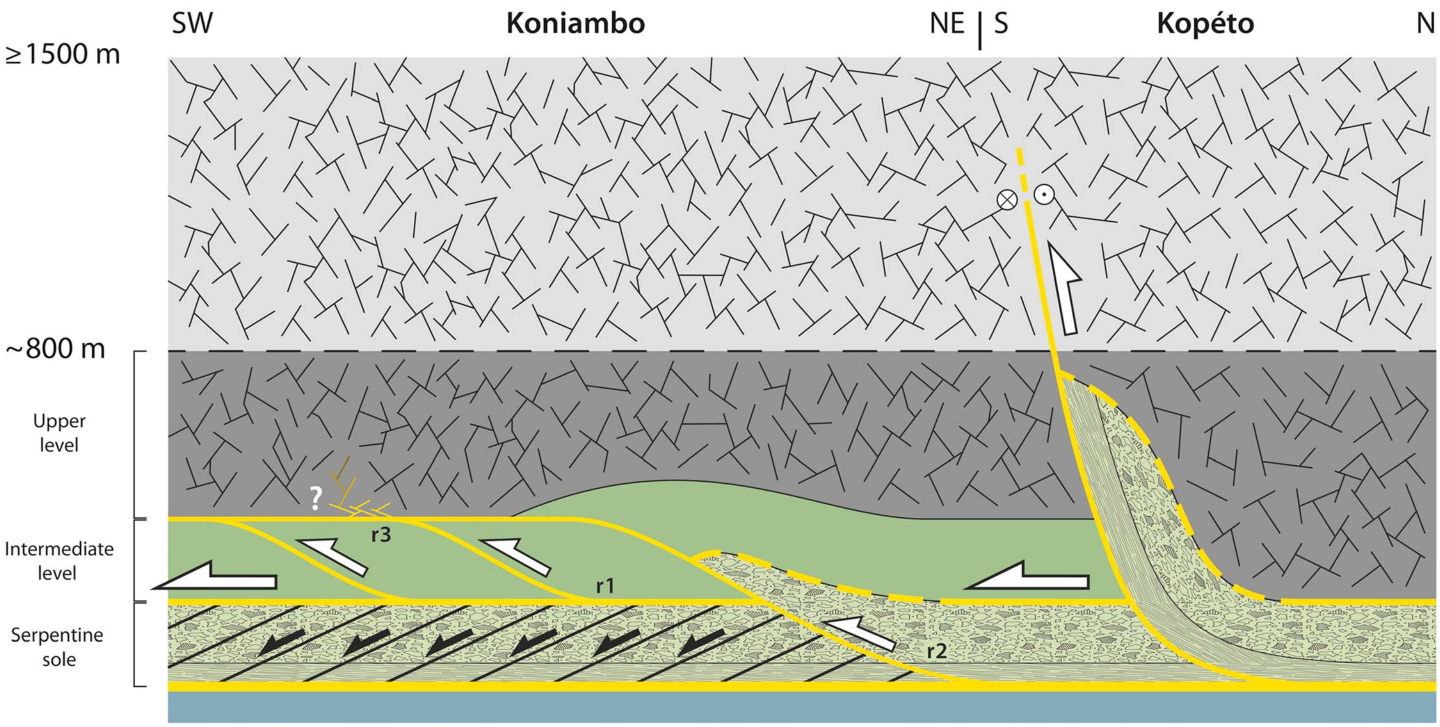

Figure 4. Schematic cross section depicting the vertical distribution of deformation associated with serpentinization in the Koniambo Massif (left; from *Quesnel et al.* [2016a]) and the Kopéto-Boulinda Massif (right; this work). r1 to r3 are geometric relationships discussed in the text. The thickness and the topography of the nappe are poorly constrained and are likely to have changed during deformation.

"r1"). In Figures 2b and 4, the roof of the sole is schematically shown as a distinct fault, but it most likely corresponds to a zone across which the intensity of brecciation progressively diminishes. In addition, some shear zones may root at deeper level (Figure 4, relationship "r2"). The NE-SW horizontal spacing between two consecutive top-to-SW shear zones, SZ1 and SZ2, is ~450 m (Figures 2a and 2b). This is slightly less than the thickness of the upper structural level in the Koniambo Massif and much less than the thickness of the Peridotite Nappe in the Massif du Sud (≥1.5 km). This narrow spacing suggests that at least some of the shear zones do not cross the nappe up to the surface but remain confined to the intermediate structural level. Although rock exposures are abundant in the open pits on the top of the Koniambo Massif, such shear zones could not be observed in the upper structural level. Based on this indirect evidence, we suggest that the shear zones connect to another flat-lying décollement located along the roof of the intermediate structural level (Figure 4, relationship "r3"). As for the roof of the sole, this décollement might not correspond to a distinct fault but to a zone across which the displacement along the shear zones is absorbed through diffuse faulting.

Another prominent fault zone, SZ3, is exposed in the intermediate structural level (Figures 2a, 2b and 3). It dips southwestward and involves a ~30 m thick lens of fine-grained sediments [*Maurizot et al.*, 2002]. These sediments resemble the volcano sedimentary series that immediately underlie the Peridotite Nappe [e.g., *Cluzel et al.*, 2001]. Hence, the fault zone likely roots slightly beneath the nappe. Alternatively, it may root along the basal contact of the nappe since this contact commonly displays sheets of serpentinite mixed with the volcano sedimentary rocks [e.g., *Maurizot et al.*, 1985b]. Shear sense criteria indicate a reverse-slip displacement along SZ3, consistent with the incorporation of rocks from beneath the nappe into the fault zone and with the probable offset of the roof of the serpentine sole across it (Figures 2a and 2b). This top-to-ENE fault can be viewed as a conjugate shear with respect to the top-to-SW SZ1 and SZ2 shear zones (Figure 3).

The upper structural level provides a record of a temporal change from WNW-ESE horizontal stretching, during antigorite crystallization, to NW-SE horizontal shortening, during polygonal serpentine crystallization. The origin of the other variations in orientation of the principal strain axes is more difficult to assess because they involve the same serpentine polymorph (polygonal serpentine) and occur across distinct levels of the nappe (Figure 3). The change from NW-SE shortening in the upper structural level to NE-SW shearing in

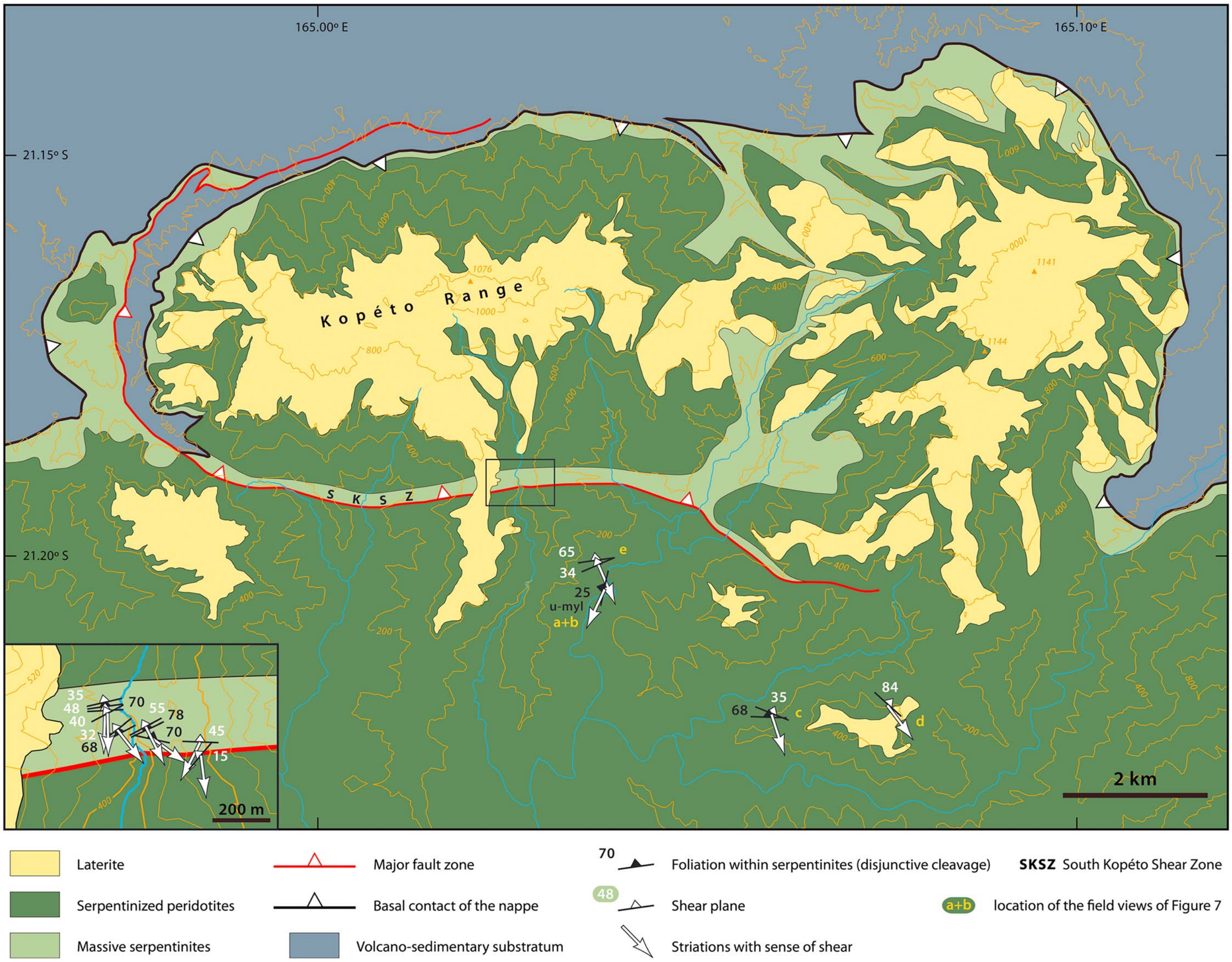

Figure 5. Geological map of the northern part of the Kopéto-Boulinda Massif, adapted from *Maurizot* [2007]. Structural data according to this work.

the serpentine sole could reflect a spatial rather than a temporal evolution, i.e., vertical strain partitioning at a specific evolutionary stage of the nappe. The ~ N-S direction of shortening recorded at an intermediate elevation, on roadsite "620 m" (Figures 2a and 3), may support this view. Despite this, it can be argued that the observed changes in shortening direction are more likely to reflect a temporal evolution [*Quesnel et al.*, 2016a]. The main argument is that it seems difficult to conceive a tectonic setting in which the nappe would undergo horizontal shortening at right angle to its direction of displacement (assuming that the latter is given by the direction of shear along the basal décollement). The observed sequence of minerals associated with deformation, from antigorite to polygonal serpentine ± magnesite, is consistent with progressive rock cooling [*Ulrich*, 2010], which may reflect a change of the geothermal gradient and/or the progressive reduction in thickness of the nappe.

4.2. The Kopéto-Boulinda Massif

The geology of the Kopéto-Boulinda Massif is broadly similar to that of the Koniambo Massif. The basal contact of the Peridotite Nappe is subhorizontal as well and underlined by a serpentine sole that thickens southwestward [*Carroué and Espirat*, 1967; *Carroué*, 1972; *Maurizot*, 2007]. In the northern part of the massif, the most remarkable feature is a ~250 m thick sheet of serpentinite running along the southern flank of the

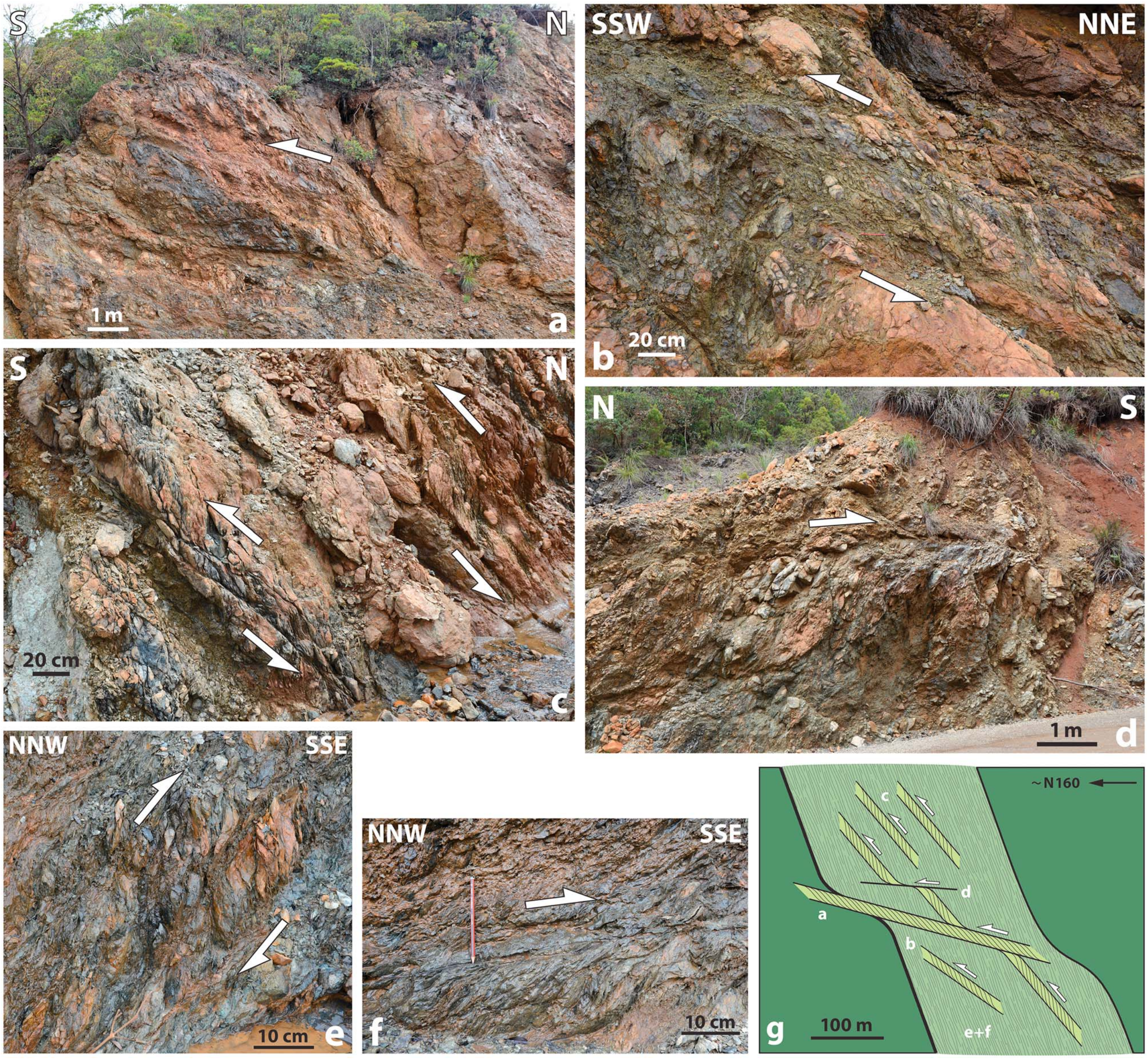

Figure 6. (a–f) Field views inside the South Kopéto Shear Zone (from the area shown as inset in Figure 5). (g) Sketch depicting the orientation and relations between secondary shear zones within the South Kopéto Shear Zone.

Kopéto Range (Figure 5). *Guillon* [1975] interpreted this structure as a major south dipping normal fault. In contrast, *Maurizot et al.* [1985b] reported the sheet as dipping to the north at an angle around 45°. To the northeast, the sheet seems to root into the serpentine sole, while to the west, map relations suggest that the southern margin of the sheet is a fault rooted farther north, slightly beneath the basal contact of the Peridotite Nappe [*Maurizot et al.*, 1985b; *Maurizot*, 2007] (Figure 5). On the southwestern flank of the Kopéto Range, the serpentine sole stands at elevations around 200 m. Further east, the serpentinite sheet climbs among the peridotites up to the main lateritic cover of the massif, at ~500 m elevation.

Within the serpentinite sheet, rocks show a pronounced planar fabric underlined by a disjunctive anastomosing cleavage (Figure 6). In the area of higher elevations, where good exposures are provided by the access road to the Kopéto mining site, this foliation dips about 70° to the north (Figure 5, insert). Map contours suggest that the serpentinite sheet as a whole is steeply dipping (Figures 5 and 6g). The sheet includes a great number of shear planes with a mean ENE-WSW strike and variable northward dips. They bear striations with a mean NNW-SSE trend (Figure 5, insert). On a 10 cm to ~5 m scale, sigmoidal cleavage domains occur in between parallel shear planes, defining local shear zones that consistently indicate a top-to-S/SE sense of shear (Figure 6). Most shear planes have dips between ~35° and ~55° (Figures 5, 6b, 6c, and 6e), but some have dips as low as ~10° (Figures 6d and 6f). A large shallow-dipping shear zone marks the southern margin of the serpentinite sheet along the mine access road (Figure 6a). The bulk picture (Figure 6g) is consistent with the serpentinite sheet representing a major shear zone and the local shear zones representing associated C′-type shear bands [cf. *Berthé et al*., 1979; see also, e.g., *Passchier and Trouw*, 1996]. Hereafter, the serpentinite sheet will be referred to as the South Kopéto Shear Zone (SKSZ). Some of the smaller shallow dipping shear zones could have been formed lately during the development of the SKSZ (Figure 6g, case "a").

Further south, smaller-size structures equivalent to the SKSZ are found (Figure 7). Associated striations have the same orientation as in the SKSZ (Figure 5). Figure 7a illustrates the case of reverse-slip shear planes rooted into a flat-lying shear zone along which ultramylonitic serpentinites with fish-shaped clasts of tremolite document a top-to-SSW sense of shear (Figure 7b). Other sites display shear zones a few meters (Figure 7e) to a few tens of meters thick (Figure 7c). These shear zones have intermediate to steep northward dips and consistent top-to-SSE kinematics (Figures 5, 7c, 7d, and 7e).

Some of the shear zones contain one or several dismembered felsic veins (e.g., the white layer offset by an oblique shear band at the core of the shear zone in Figure 7e). The vein(s) and the host shear zone are commonly subparallel. In at least some cases, this parallelism does not result from the transposition of the vein due to deformation; rather it reflects the fact that the shear zone was formed parallel to the vein. This indicates that the distribution of the shear zones may have been influenced by the presence of a network of felsic veins. The veins are intimately associated with tremolite $\pm$ chlorite mineralizations [*Lahondère et al*., 2012]. In zones of lesser strain, tremolite locally occurs as sheaves of large crystals with no preferred orientation; in zones of higher strain, tremolite occurs as clasts (Figure 7b). Together with the dismembered aspect of the felsic veins, this indicates that much of the activity of the shear zones, if not all of it, postdates the emplacement of the veins and associated alteration. No analytical work has been carried out to determine the nature of the serpentine polymorph(s) involved in the shear zones. Nevertheless, judging from the pale green color of cleavage domains within some of the shear zones (Figures 6b, 7b, and 7e), and by analogy with the situation in the Koniambo Massif [*Quesnel et al*., 2016a], we hypothesize that polygonal serpentine is again the dominant synkinematic mineral phase.

5. Additional Constraints From the Central Part of Northern New Caledonia

In addition to the Massif du Sud and the northwestern klippes, many exposures of ultramafic rocks are found along the axis of the Grande Terre (Figure 1). The smaller exposures are described as discontinuous sheets of serpentinite spread along fault zones [e.g., *Gonord*, 1977; *Paris*, 1981] while the larger bodies include moderately serpentinized peridotites. There has been much debate about the significance and initial structural position of these rocks [e.g., *Brothers*, 1974; *Gonord*, 1977; *Paris*, 1981; *Maurizot et al*., 1985b], but there is broad agreement that the larger bodies represent remnants of the Peridotite Nappe. A clear example is provided by the Tchingou Massif (Figure 1) which overlies pre-Coniacian basement rocks through a subhorizontal contact [e.g., *Guillon*, 1975; *Maurizot et al*., 1985b].

In map view, most ultramafic rocks close to the axis of the island appear as narrow strips with a NW-SE to W-E strike. This is the case in the area around the Ougne summit (Figure 8a), near the northwestern tip of the Grande Terre (Figure 1). There, the ultramafic rocks and closely associated mafic rocks have been interpreted either as fragments of an ophiolite that would have initially underlain the Late Cretaceous-Eocene sedimentary series of the same area [*Brothers*, 1974; *Maurizot et al*., 1989] or as remnants of the Peridotite Nappe and underlying Poya Terrane thrust sheets [*Cluzel et al*., 1995; *Maurizot*, 2011]. The map of Figure 8a is mainly based on *Maurizot et al.* [1989] and satellite images. A composite cross section has been derived from this map (Figure 8b). The ultramafic rocks, which consist of partly serpentinized peridotites overlying a serpentine sole, form the core of a series of synclines. This strongly supports the view that the ultramafic rocks do not originate from beneath the sedimentary cover but represent remnants of the overlying Peridotite Nappe. The fold wavelength is approximately 750 m, in contrast with the nearly flat attitude, at the same scale, of the basal contact of the Peridotite Nappe in the northwestern klippes (Figures 1, 2a, 2b, and 5).

The folds occur in a domain where the Late Cretaceous-Eocene sediments are pervasively schistosed and underwent metamorphism at temperatures around 270°C [*Vitale Brovarone and Agard*, 2013]. Schistosity

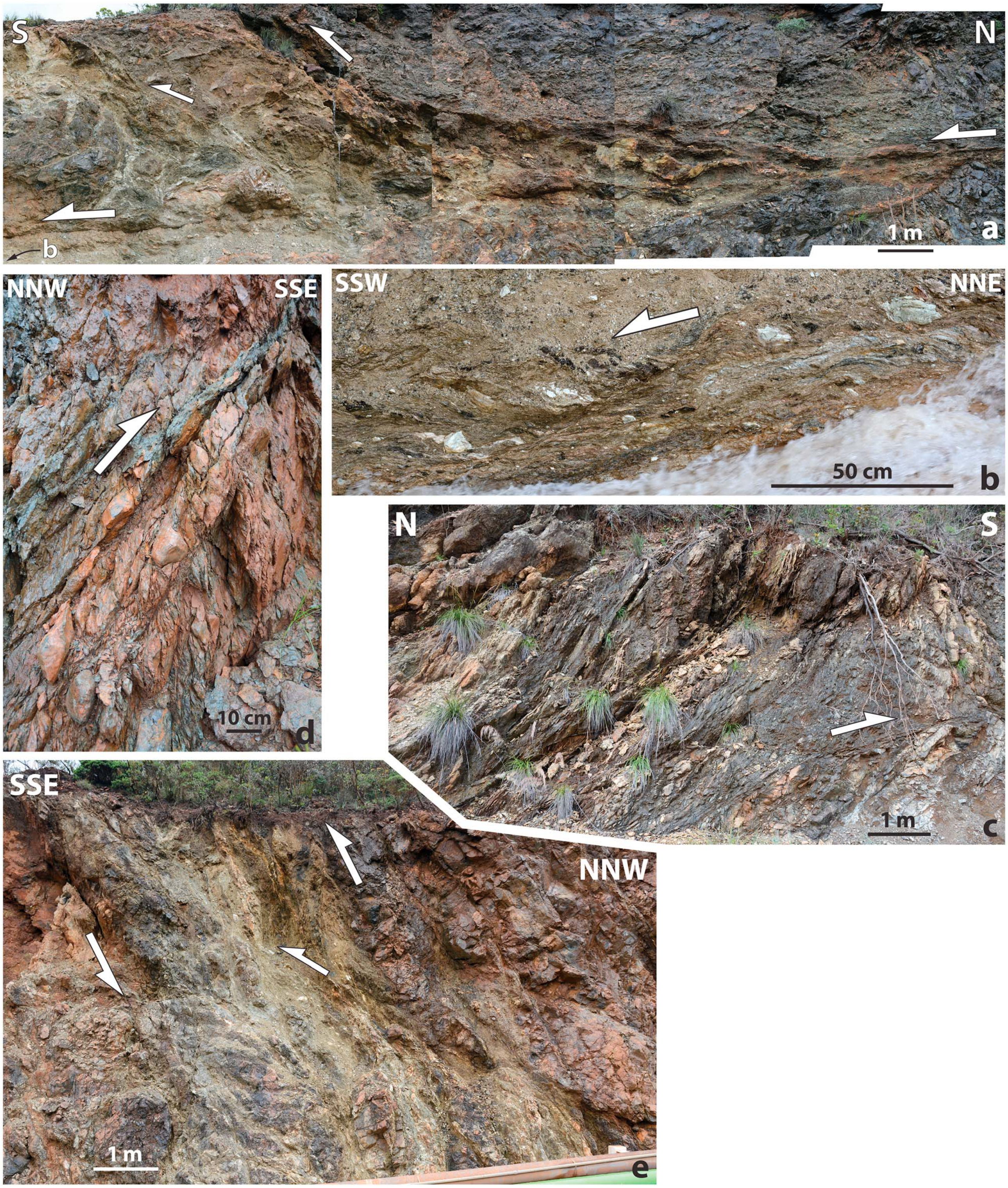

Figure 7. Field views of subsidiary shear zones in the footwall of the South Kopéto Shear Zone (location in Figure 5).

planes dip steeply northeastward as part of the fan-like structure reported in Figure 1 and section 2.1. This schistosity is parallel to the axial plane of tight overturned folds (Figure 8c). The large synclines are also asymmetric with northeast dipping axial surfaces, and additionally, a northeast dipping thrust cuts across the structure (Figure 8b). Thus, top-to-SW shearing is recorded in this area, in agreement with descriptions of

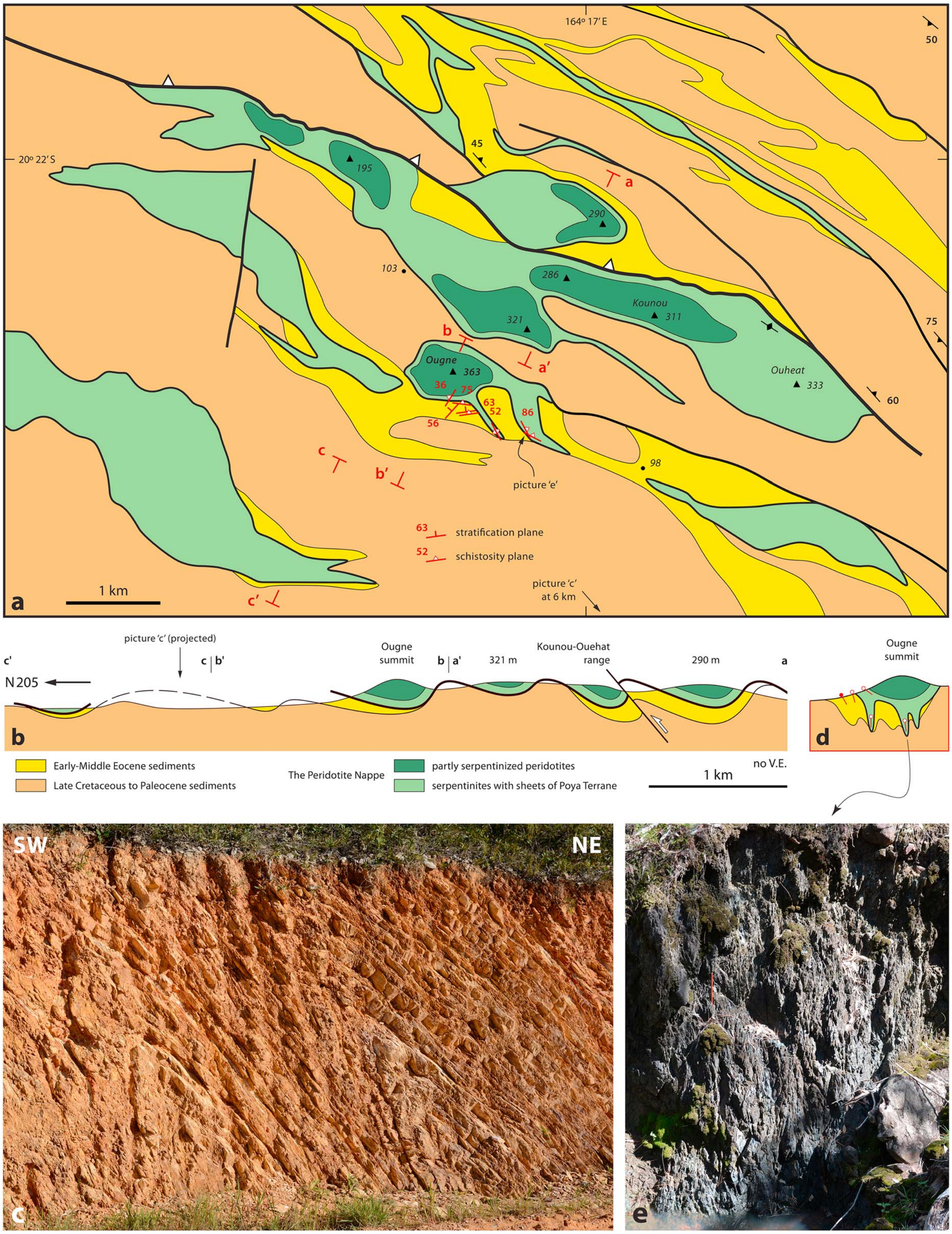

Figure 8. (a) Geological map of the Ougne summit area (location in Figure 1) based on *Maurizot et al.* [1989], the updated version of Maurizot et al.'s map available at http://explorateur-carto.georep.nc (which uses the stratigraphic scheme of Cenozoic sediments revised by *Maurizot* [2011]), satellite images, and field observations carried out on the southern flank of the Ougne summit. (b) Composite cross section located in Figure 8a, deduced from the same data set except the field observations. (c) Field view of tight overturned folds in schistose metasediments. (d) Modified cross section of the Ougne summit taking into account the field observations reported in Figure 8a. The same type of geometry likely exists all along cross section (Figure 8b) but is not drawn because field data are not available. (e) Subvertical schistosity in a serpentinite sheet within the metasediments.

the wider region given by *Cluzel et al.* [1995] and *Maurizot* [2011]. Field observations on the southern flank of the Ougne summit further document that, away from the contact with the overlying peridotites, the serpentine sole of the Peridotite Nappe is steeply schistosed (Figure 8e) and interdigitated with the underlying metasediments (Figure 8a). Figure 8d shows a modified cross section of the Ougne summit according to these observations. The geometry of the klippe is strikingly similar to that proposed by *Maurizot et al.* [1985b] for the Tchingou Massif. This geometry implies the existence of a contrast in strength between the peridotites and the serpentinites, the latter being approximately as weak as the underlying metasediments. This seems to contradict the conclusion we previously drew from the Koniambo Massif, that the peridotites overlying the serpentine sole are enough affected by serpentinization to be nearly as weak as pure serpentinite [*Quesnel et al*., 2016a]. The degree of serpentinization in the peridotites of the Ougne summit area is not known; therefore, the contradiction is perhaps only apparent. Regardless, not only has the serpentine sole undergone ~ NE-SW shortening, the overlying folded and faulted peridotites have as well. Therefore, at least the lower levels of the Peridotite Nappe were involved in compressional deformation. Because of the large competence contrast between the peridotites and the underlying rocks implied by the geometry in Figure 8d, the thickness of the folded layer is likely to be less than the fold wavelength [e.g., *Ramsay and Hubert*, 1987]. Hence, the folded layer is probably less than ~750 m thick, and this may represent what was left of the Peridotite Nappe when folding occurred.

6. Implications for the Mechanism of Emplacement of the Nappe

6.1. The Record of Compressional Deformation in the Northwestern Klippes

Figure 4 shows schematically how major shear zones are distributed in the Koniambo Massif [*Quesnel et al*., 2016a] and in the northern part of the Kopéto-Boulinda Massif according to the observations reported in section 4.2.

The serpentine sole represents a zone of strong tangential shear at the base of the Peridotite Nappe. As stated in section 2.2, this deformation may reflect the emplacement of the nappe [e.g., *Cluzel et al*., 2012a] and/or a later episode of extensional reactivation [*Lagabrielle and Chauvet*, 2008]. The top-to-SW sense of shear observed in the Koniambo Massif is consistent with both interpretations: in the first case because there is a consensus that the nappe originates from the Loyalty Basin and in the second case because it may be assumed that the basal contact of the nappe was reactivated as a southwest dipping detachment. The presence of localized normal-sense shear zones such as those visible along the VA1 section (Figure 2c) might be viewed as supporting the hypothesis of an extensional setting for at least part of the deformation recorded by the sole. However, if these shears represent normal fault zones related to a late extensional event, their upward extension into the rock mass above the sole should occasionally be visible, taking into account the short spacing (~100 m) between the shear zones. This is not the case from our experience; therefore, the normal-sense shear zones seem to be confined to the serpentine sole [see also *Lahondère et al*., 2012, Figure 115]. As a result, the shear zones of Figure 2c are better interpreted as subsidiary C′-type shear bands developed within a ~200 m thick zone of tangential shear (Figures 3 and 4). Their mean obliquity of ~22° with respect to the basal contact of the nappe is consistent with this interpretation [e.g., *Passchier and Trouw*, 1996].

According to our observations, all the shear zones found above the serpentine sole are reverse-slip shears in the present state. It may be asked whether this represents their original attitude or whether they were once significantly tilted. For instance, in the hypothesis where the Peridotite Nappe has been emplaced as a large gravitational slide (see section 3), the slide is supposed to have occurred on a southwest dipping slope; therefore, the present subhorizontal attitude of the basal contact of the nappe should be restored into a southwestward dip in the initial state. Provided that the shear zones developed during sliding, they should be back tilted as well, perhaps up to the point that their original attitude was that of normal-sense shear zones. This hypothesis is tested below.

In the case of the Koniambo Massif, the presently northeast dipping shear zones (SZ1 and SZ2; Figures 2b and 3) keep a reverse sense of slip unless back tilting amounts to more than ~25°, far more than the topographic slope of ~3° proposed in the gravitational slide hypothesis [*Lagabrielle et al*., 2013]. For the presently southwest dipping shear zone (SZ3), back tilting would only strengthen its reverse slip nature. The sediments pinched in this shear zone also attest for its origin as a thrust. As a consequence, the fact that SZ3 crosscuts and offsets the serpentine sole further weakens the hypothesis that part of the internal deformation of the sole may result from a younger extensional event.

In the case of the Kopéto-Boulinda Massif, the SKSZ has a northward dip of about 70° at a structural height ~300 m above the serpentine sole (Figures 5 and 6g). It is possible that the shear zone steepens even more upward, in a section of the nappe now eroded (Figure 4). Back tilting the whole nappe would make the SKSZ less steep but would maintain its reverse-slip kinematics. This is also the case for the subsidiary steep shear zones located further south (Figures 7c–7e). In addition, the inclusion within lower levels of the nappe of a sheet of volcano sedimentary rocks belonging to the substratum, as suggested by map contours west of the Kopéto Range (Figure 5), supports the view that the southern margin of the SKSZ is a thrust fault in origin. This fault roots northward [see also *Maurizot et al*., 1985b] while top-to-south shearing is recorded across the SKSZ (Figure 6). Therefore, the two structures probably relate to the same tectonic event.

In summary, the reverse-slip shear zones of the Koniambo and Kopéto-Boulinda klippes are true compressional structures in origin. In the Koniambo Massif, these shear zones accommodate NE-SW shortening, consistent with the top-to-SW sense of shear recorded by the serpentine sole (Figures 3 and 4). In the Kopéto-Boulinda Massif, the SKSZ strikes ~ W-E and accommodates top-to-SSE shearing, which implies a small component of dextral displacement. The steepest cleavage domains within the SKSZ further include a set of west plunging striations implying a more oblique-slip displacement. This, together with the very steep attitude of the shear zone, suggests that it has been formed as an oblique thrust with a dextral wrench component (Figure 4). Some authors already pointed out the influence of dextral transcurrent tectonics in the early Cenozoic evolution of the Grande Terre [*Gonord et al*., 1973; *Gonord*, 1977; *Paris*, 1981; *Cluzel et al*., 2001; *Titus et al*., 2011].

Top-to-SSE shearing along the SKSZ is fairly consistent with the deformation recorded by polygonal serpentine-bearing faults in the upper structural level of the Koniambo Massif (Figure 3). The "strike-slip" regime seen in Figure 3, with both λ_1 and λ_3 having low plunges, is dominated by NNE-SSW striking reverse-sinistral faults [*Quesnel et al*., 2016a]. These faults may represent conjugate shears with respect to the SKSZ. The flattening-type strain ellipsoid returned by the fault slip analysis implies stretching along the steep λ_2 axis, which is consistent with the hypothesis of a transpressional setting [e.g., *Fossen*, 2010]. These features suggest that deformation progressively evolved from a transpressional setting along a ~ W-E structural trend (recorded along the SKSZ and in the upper structural level of the Koniambo Massif) to pure NE-SW compression (recorded in the serpentine sole and the intermediate structural level of the Koniambo Massif and possibly as local shear zones in the Kopéto-Boulinda Massif; cf. Figures 5, 7a, and 7b).

The observation of compressional structures in the Koniambo and Kopéto-Boulinda klippes contrasts with the opinion of *Lagabrielle et al.* [2013] that no such structure exists in the Peridotite Nappe. *Lagabrielle et al.* [2013] used the apparent lack of compressional structures as a key argument for an emplacement of the nappe through gravitational sliding. Conversely, the presence of compressional structures is consistent with the alternative hypothesis that the nappe has been emplaced through horizontal contraction sustained by plate convergence. Nevertheless, natural examples of gravitational slides (e.g., along a salt or shale décollement down the slope of a passive continental margin) and analogue models of the process also show the development of compressional structures in the frontal part of the nappe [e.g., *Demercian et al*., 1993; *Morley and Guerin*, 1996; *Fort et al*., 2004; *Loncke et al*., 2006; *Mourgues et al*., 2009; *de Vera et al*., 2010; *Brun and Fort*, 2011]. In the next section, we examine whether compressional deformation in the Koniambo and Kopéto-Boulinda klippes could reflect the latter case.

6.2. Compression at the Front of a Large Gravitational Slide?

Natural and analogue examples of gravitational slides display compressional structures around the toe of the topographic slope. Compression tends to propagate upslope during continued sliding [*Fort et al*., 2004; *Brun and Fort*, 2011] but always remains confined to the lower half of the slope [e.g., *Morley and Guerin*, 1996; *de Vera et al*., 2010]. Therefore, a key question is whether the rocks of the Koniambo and Kopéto-Boulinda klippes were located near the toe of a regional southwest dipping slope by the time the nappe was emplaced.

As stated in section 2.3, the Grande Terre is flanked by the New Caledonia Basin, which has a water depth of ~3500 m and a sedimentary sequence resting horizontally against a northeast dipping unconformity of mid-

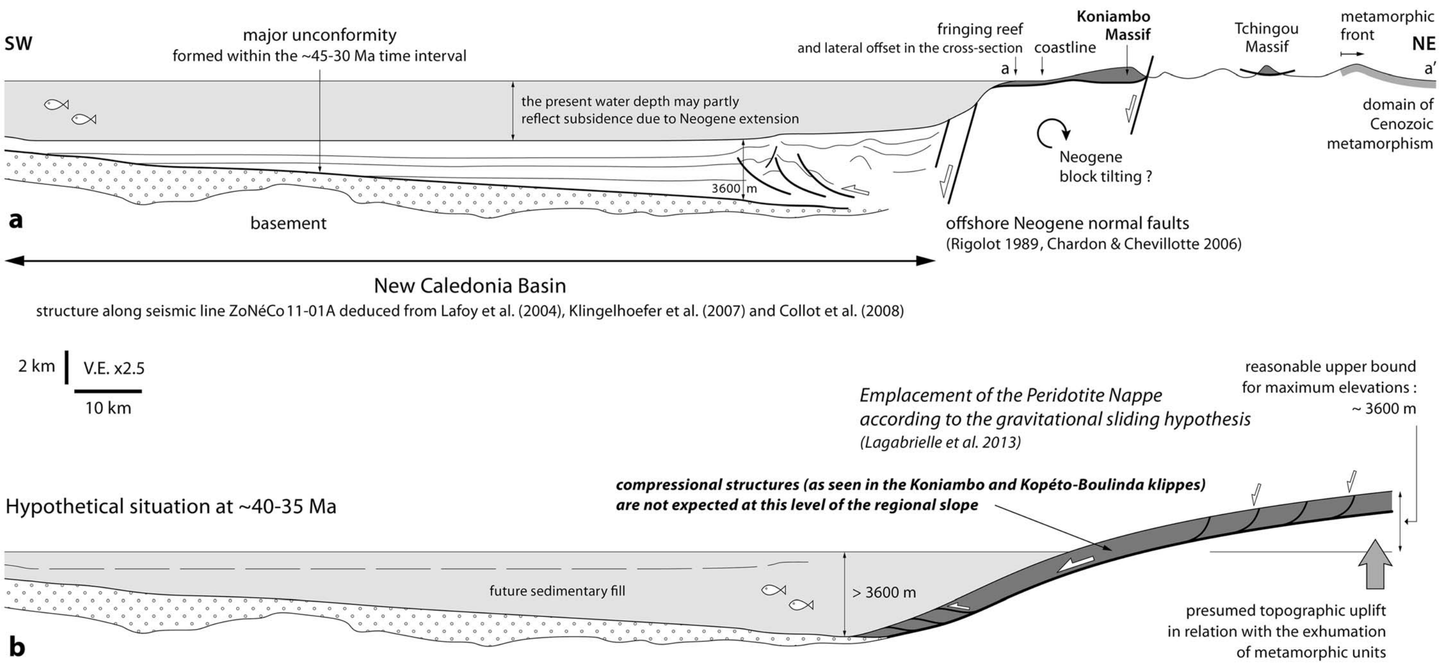

Figure 9. (a) Cross section showing the relations between the Grande Terre and the New Caledonia Basin (location in Figure 1). (b) The same cross section at ~40–35 Ma, build for testing the hypothesis that the Peridotite Nappe was emplaced as a large gravitational slide.

Cenozoic age. This geometry, well visible along the ZoNéCo11-01A seismic line (Figures 1 and 9a), is interpreted as resulting from a two-stage evolution [*Collot et al.*, 2008]: (i) the obduction event on the Grande Terre triggered almost instantaneous tilting of the foreland domain and (ii) the trough became progressively filled with posttilt sediments. Hence, at the time Peridotite Nappe was emplaced, a trough existed immediately to the southwest. Its depth can be estimated as follows. Along the ZoNéCo11-01A seismic line, the eastern end of the posttilt sedimentary wedge is ~3600 m thick (Figure 9a). Further east, closer to the Grande Terre, the pile is thicker, but this may partly result from folding and thrusting, as visible along the seismic line [*Lafoy et al.*, 2004]. On one hand, subsidence due to the sediment load may have increased the deepening of the eastern part of the basin. On the other hand, compaction of the sedimentary pile certainly reduced its thickness. In addition, the top of the pile is at a depth of 3500 m at present. The current water column may partly relate to subsidence due to Neogene extension, but this tectonic event of moderate intensity probably had a limited impact. Judging from the horizontal attitude of the posttilt deposits, posttilting deepening of the basin, if any, seems to have been spatially homogeneous. As a result, by the time the Peridotite Nappe was emplaced, the trough southwest of it was most probably at least 3600 m deep (Figure 9b). There is no tight constraint on elevations at that time on the Grande Terre. In some young orogens occurring as elongated islands, present elevations can reach values as high as ~3600 m, as in New Zealand or Taiwan. In the case of the Grande Terre, the orogen is narrower and was capped by a thick sheet of dense ultramafic rocks; therefore, 3600 m is a reasonable upper bound for the maximum elevations ever reached in this orogen. As a consequence, the rocks of the northwestern klippes were initially located in the upper part of the regional slope (Figure 9b). As discussed above, compressional structures are not expected at this level of the slope in the hypothesis of a gravitational slide. Hence, the structures seen in the Koniambo and Kopéto-Boulinda klippes seem to rule out gravitational sliding as the mechanism of emplacement of the Peridotite Nappe.

The reasoning above assumes that the southwest dipping slope joining the Grande Terre orogenic domain to the New Caledonia Basin was fairly regular (Figure 9b). However, at present, a flat domain exists at an intermediate level of the slope, corresponding to the reef lagoon system that surrounds the island. This morphology partly results from the building of the fringing reef since the late Neogene. The reef must have developed at very shallow water depths and without a strongly eroding aerial slope nearby; hence, the flat domain existed prior to the late Neogene. The lagoon is presently 5 to 10 km wide in the area of the Koniambo and Kopéto-Boulinda klippes (Figure 1), but the flat domain may have extended further northeast as suggested by the low elevation and subhorizontal attitude of the basal contact of the nappe around the klippes. Despite the regional slope toward the New Caledonia Basin, this flat domain could have played the role of an intermediate slope toe against which a gravitational slide might have experienced compressional deformation.

In Figure 9a, it is suggested that the flat domain actually results from block tilting between two southwest dipping normal fault zones associated with Neogene extension. One fault zone is the set of normal faults reported from the steep submarine slope immediately southwest of the reef [*Rigolot*, 1998; *Chardon and Chevillotte*, 2006]; the other coincides with the West Caledonian Fault (see section 3). According to *Gonord* [1977], the West Caledonian Fault bounds the Koniambo Massif as a network of steep NW-SE-trending faults, which is consistent with the rectilinear aspect of lithological contours and the present landscape morphology in this area. In Figure 2a, the probable existence of this fault zone is shown with a box ornament added to the basal contact of the nappe. The contact stands at higher elevations there than it does elsewhere around the massif, which may result from drag folding due to normal-sense displacement along the fault zone. Hence, Neogene block tilting could perhaps account for the secondary development of a flat segment in an initially continuous regional slope (Figure 9).

However, this interpretation is merely a possibility, and we cannot exclude that the flat domain already existed when the Peridotite Nappe was emplaced. For instance, if the hypothesis of a large thrust carrying the Grande Terre over the New Caledonia Basin at the end of the obduction event is correct (see section 2.3), then the region of the northwestern klippes likely coincided with a flat domain above this thrust. As mentioned above, this domain could have played the role of a local slope toe against which the Peridotite Nappe might have undergone compression in the context of a large gravitational slide. Therefore, in order to reach a firm conclusion, the structural record in klippes of the Peridotite Nappe located away from the flat domain must be considered.

6.3. Spatial Variations in Structural Style Associated With Compression, Implications

In the area around the Ougne summit, the Peridotite Nappe has undergone compressional deformation (Figure 8). This area is located about 10 km at the rear of the northwestern klippes, significantly closer to the main structural culmination of the HP-LT metamorphic domain (Figure 1). In the gravitational slide hypothesis, sliding is supposed to start from this culmination. The Ougne summit area lies fairly close to this axis, and as discussed in section 6.2, compression should not be observed in such a shallow part of the southwest dipping regional slope (Figure 9b). In contrast, compression within any part of the nappe is consistent with its emplacement through crustal-scale horizontal contraction. The northwestern klippes are flat lying, overlying at high angle the steep fault complex of the Poya Terrane [*Cluzel et al.*, 2001]. In the Ougne summit area, the Peridotite Nappe is folded in association with the development of a steep pervasive schistosity in low-grade metasediments. This difference in structural style implies that the Peridotite Nappe experienced compression at greater depth conditions toward the northeast. This feature, unexpected if the nappe had been emplaced by gravitational sliding, is consistent with an emplacement through a "push from the rear" mechanism [e.g., *Merle*, 1986]. A push from the rear mechanism implies a context of bulk horizontal contraction and plate convergence. It also implies the existence of a major thrust at the rear of the nappe, the precise location of which is discussed in the next section.

7. Obduction Tectonics in New Caledonia

7.1. Pre-Neogene Crustal-Scale Restoration

Based on our results and on data from the literature, Figure 10a shows a crustal-scale cross section of northernmost New Caledonia (see Figure 1 for location) tentatively restored in a pre-Neogene setting, i.e., before the evolution of the Grande Terre as a large horst [e.g., *Chardon and Chevillotte*, 2006]. The key elements of this cross section are as follows.

The Peridotite Nappe originates from the Loyalty Basin [e.g., *Collot et al.*, 1987], however, in the tectonic stage shown in the restoration (at ~34 Ma), the spatial continuity of the nappe is already lost due to the surge of the metamorphic domain. To the southwest, the nappe is partly eroded and represented by a large klippe. At its front, the nappe is about 1 km thick, flat lying, and includes SW-vergent thrusts deduced (and projected) from

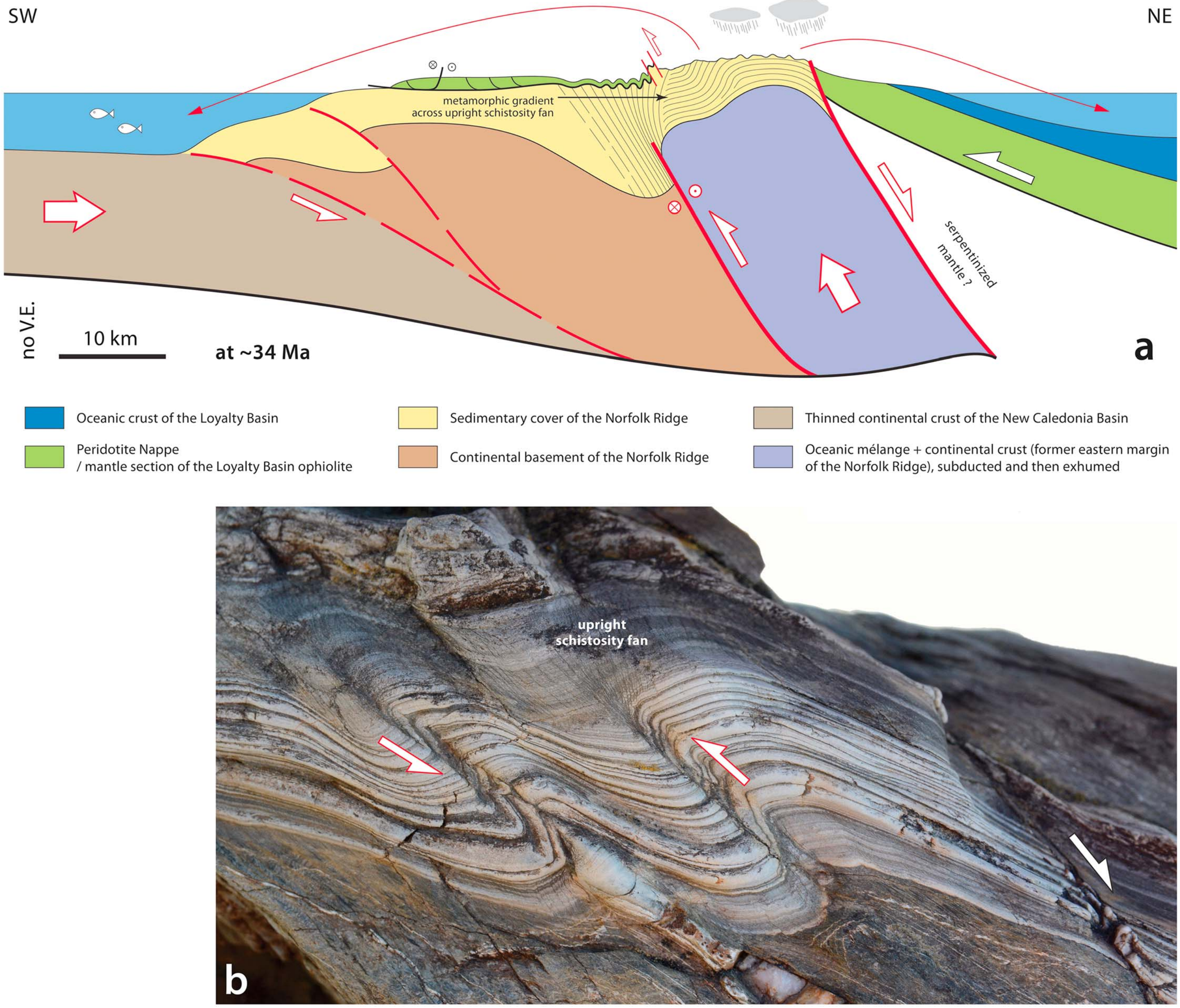

Figure 10. (a) Crustal-scale cross section of northernmost New Caledonia (location in Figure 1) restored in a pre-Neogene setting. For the sake of simplicity, the section omits the Poya Terrane, a thin package of highly faulted oceanic rocks between the Peridotite Nappe and the sedimentary cover of the Norfolk Ridge (for details regarding the Poya Terrane, see *Cluzel et al.* [2001]). See the text for a description of the section. (b) Field view illustrating the deformation of metasediments in the footwall of the Lizard ophiolite, southwestern England (Porthleven section; see, e.g., *Leveridge and Shail* [2011]). This ~30 cm wide outcrop represents a plausible analogue of the crustal-scale structure of New Caledonia after obduction.

the Koniambo/Kopéto-Boulinda area (Figure 4). Further northeast, the nappe is about 500 m thick, folded, and faulted, as deduced from the Ougne summit area (Figure 8).

The Ougne summit area is also part of the domain where schistosities in the underlying metasediments define a ~10 km wide upright fan (Figure 1). We interpret this fan as the upward extension, within the soft sedimentary cover of the Norfolk Ridge, of a major thrust carrying the HP-LT rocks onto the continental basement of the ridge. The fan shape reflects the progressive transition from northeast dipping schistosities resulting from thrusting to southwest dipping schistosities concordant with the southwestern limb of a large fold nappe of exhumed HP-LT rocks. A ~30 cm scale analogue of this geometry is visible in the picture of

Figure 10b, taken in metasediments from the footwall of the Lizard ophiolite, southwestern England [e.g., *Leveridge and Shail*, 2011]. Figure 10a thus provides a simple explanation for the presence of the upward schistosity fan. It differs from the interpretation of *Rawling and Lister* [1999] who assumed that the southwest dipping schistosities are associated with a relatively young normal-sense shear zone crosscutting the thrust-related northeast dipping schistosities. The thrust zone flanking the fold nappe likely accounts for part of the emplacement of the Peridotite Nappe having occurred through a push from the rear mechanism.

Further northeast, we propose that the fold nappe was flanked by a major northeast dipping normal-sense fault zone. Normal faulting along the northeastern coast of the Grande Terre is documented for Neogene times [*Bitoun and Récy*, 1982; *Chardon and Chevillotte*, 2006; *Chardon et al.*, 2008], but these minor faults can barely account for the huge vertical offset implied by the occurrence of the HP-LT rocks in close contact with the Loyalty Basin peridotites which underlie the eastern lagoon according to gravity data [e.g., *Collot et al.*, 1987; *Cluzel et al.*, 2012a]. We suppose that, on its eastern side, the fold nappe of HP-LT rocks was exhumed in the footwall of a northeast dipping normal fault zone and that this normal fault developed synchronously with the thrust zone associated with the schistosity fan (Figure 10a). This interpretation is reminiscent of the model proposed by *Chemenda et al.* [1996] for Oman, which also predicts the existence of an upright fan of schistosities at the front of a fold nappe of HP-LT rocks [see also *Cluzel et al.*, 2012a, Figure 9].

To the southwest, we accept the common view that the Norfolk Ridge is thrust over the thinned continental crust of the New Caledonia Basin [e.g., *Cluzel et al.*, 2001; *Lafoy et al.*, 2004; *Collot et al.*, 2008]. The related thrusts are shown as dashed lines in Figure 10a to emphasize that there is no direct evidence for their existence to date (see section 2.3). We leave it open whether convergence along the western margin of the Grande Terre ever involved the subduction of an oceanic lithosphere [*Paquette and Cluzel*, 2007; *Cluzel et al.*, 2012a]. If so, this ocean would already be subducted at the stage shown in Figure 10a, but we do not mean that this was necessarily the case as early as ~34 Ma. Due to its position right above the presumed major thrust system, the frontal part of the Peridotite Nappe may have undergone renewed tangential shear on this occasion. In line with this hypothesis, top-to-SW shearing along the serpentine sole of the Koniambo Massif involves synkinematic magnesite veins [*Quesnel et al.*, 2013, 2016a] formed at temperatures of only ~30°C [*Quesnel et al.*, 2016b], which suggests that the thickness of the Peridotite Nappe had already been much reduced when this deformation occurred.

7.2. The Record of Oblique Convergence and its Geodynamic Setting

Several features indicate that obduction in New Caledonia occurred through oblique convergence with a dextral wrench component.

First, as discussed in section 6.1, deformation associated with serpentinization in the Koniambo and Kopéto-Boulinda klippes is consistent with a progressive evolution from a transpressional setting involving dextral shearing along a ~ W-E structural trend to pure NE-SW compression. Further northwest, starting from the western margin of the Tiebaghi Massif, the klippes of the Peridotite Nappe include a prominent zone of dextral shear involving southwest dipping mylonitic lherzolites [*Nicolas*, 1989; *Leblanc*, 1995]. For *Nicolas* [1989], this shear zone represents a transform fault inherited from the preobduction oceanic accretion period. However, as discussed by *Titus et al.* [2011], the trend of the shear zone is difficult to reconcile with this hypothesis. *Titus et al.* [2011] suggested that the shear zone represents an old structure (the paleospreading ridge?) reactivated as a wrench fault after obduction. However, as it involves high-temperature mylonites, the shear zone is unlikely to postdate obduction. Instead, it may date from the early stages of obduction. In the Poum Massif, the southwest dipping foliation of the mylonitic lherzolites bears a mineral lineation with a mean ~ N-S trend [*Nicolas*, 1989; *Leblanc*, 1995]. Hence, dextral shearing is associated with a component of reverse shear, consistent with a transpressional setting. In Figure 10a, we tentatively show this shear zone rooting into the basal contact of the Peridotite Nappe by analogy with the situation in the Kopéto-Boulinda Massif (Figures 4 and 5).

Second, dextral shearing along a trend parallel to the Grande Terre is also recorded in the rock units underlying the Peridotite Nappe. Several kilometer long dextral faults are reported from the region west of the Massif du Sud [*Gonord et al.*, 1973; *Gonord*, 1977]. Further northwest, in the vicinity of the lawsonite isograd, lithological contours suggest the presence of large asymmetric folds consistent with dextral wrenching [*Paris*, 1981]. East of the isograd, the Ouégoa-Bondé fold supports this interpretation (Figure 1). At the front of the

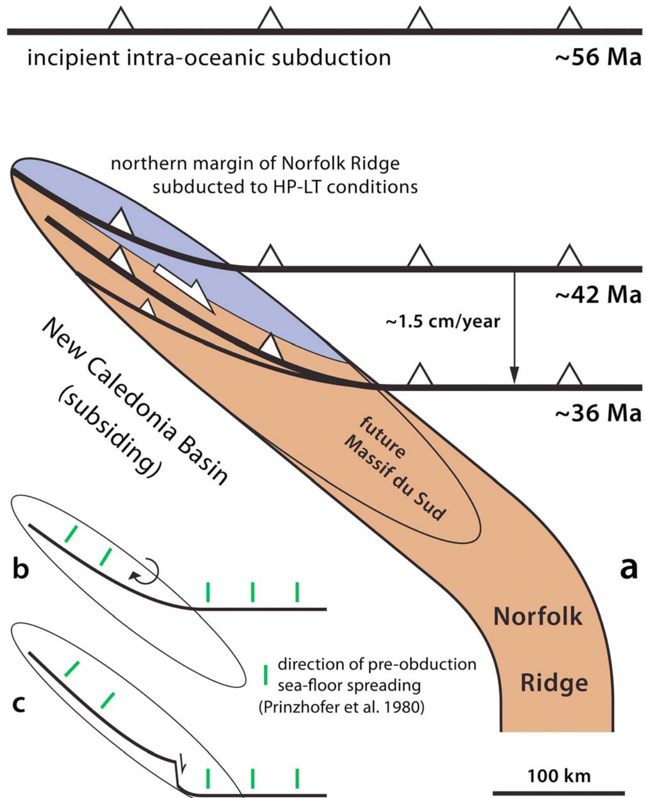

Figure 11. (a) Description, in map view, of the geodynamic setting that led to obduction of the Peridotite Nappe under dextral oblique convergence. (b and c) Sketches aiming at discussing the relations between clockwise rotation of the Peridotite Nappe, as expected from the scenario in Figure 11a, and the orientation of preobduction structures. See the text for explanation.

upward schistosity fan, schistosity planes dip northeastward at angles around 50–55° [*Maurizot et al*., 1989; *Cluzel et al*., 1995] (Figure 8c). This suggests that the thrust presumed to underlie the fan is relatively steep and, thus, includes a strike-slip component (Figure 10a).

Third, oblique convergence is consistent with several additional features of the geology of the Grande Terre. As pointed out by *Paris* [1981] and *Cluzel et al.* [2001], the emplacement of the Peridotite Nappe was probably diachronous along the strike of the island, occurring earlier in the north. The best evidence for diachronism is the fact that the onset of clastic sedimentation in the foreland basins occurred progressively later southeastward [*Cluzel et al*., 2012a; *Maurizot and Cluzel*, 2014]. In addition, only the northwestern half of the island includes a domain of Cenozoic HP-LT rocks (Figure 1). These two features are best explained by assuming that the axis of the Norfolk Ridge and the zone of intraoceanic subduction that eventually led to the obduction of the Peridotite Nappe were not parallel, as in most geodynamic models of the region [e.g., *Crawford et al*., 2003; *Titus et al*., 2011], but significantly oblique [*Cluzel et al*., 2001]. Figure 11a shows a possible configuration for this obliquity. The W-E strike of the trench is deduced from (i) the fact that subduction probably initiated through the inversion of a mid-oceanic ridge [*Crawford et al*., 2003; *Ulrich et al*., 2010; *Cluzel et al*., 2012a, 2012b] and (ii) the various structural elements of the Peridotite Nappe documenting a ~ N-S direction of spreading at this ridge [*Prinzhofer et al*., 1980], although *Titus et al.* [2011] have questioned the validity of this inference. The Peridotite Nappe is now considered as essentially a fore-arc ophiolite that recorded widespread partial melting during early intraoceanic subduction [*Marchesi et al*., 2009; *Ulrich et al*., 2010; *Pirard et al*., 2013]. As a result, it may be asked whether the structural elements measured by *Prinzhofer et al.* [1980] relate to the initial mid-oceanic ridge or to later fore-arc spreading. However, the strike of the trench would also be ~ W-E in the latter case because fore-arc spreading is expected to occur at high angle to the trench [e.g., *Stern et al*., 2012]. The geodynamic setting in Figure 11a implies that the northern tip of the Norfolk Ridge met the trench first. The progressive entrance of more southerly parts of the continental ridge at the trench is consistent with the sedimentary record in foreland basins and may have had two effects. It probably made the subduction of this low-density material more difficult so that only the northern margin of the ridge could be buried to HP-LT conditions. In addition, it may have forced the trench to drape against the ridge so that the convergent front rotated clockwise and started to accommodate a dextral wrench component (Figure 11a), in line with the observations reported above. As shown in Figure 11b, not only the trench but also the rocks in its hangingwall are expected to have rotated clockwise. Therefore, the question arises whether it makes sense to use the orientation of preobduction structures [*Prinzhofer et al*., 1980] to infer the initial strike of the trench. *Prinzhofer et al.* [1980] deduced a ~ N-S direction of spreading from data gathered in the Massif du Sud. In contrast, their measurements of high-temperature mineral lineations in the northwestern klippes have a mean NE-SW trend [see also *Nicolas*, 1989], consistent with the rotation predicted in Figure 11b. In Figure 11c, we propose that the rocks of the Massif du Sud experienced no rotation because this part of the Peridotite Nappe has been emplaced along a ~ N-S dextral tear fault. Following *Titus et al.* [2011], such a fault may exist slightly off the western margin of the Massif du Sud, representing a reactivation of the preobduction transform fault zone identified in the Bogota peninsula [*Nicolas*, 1989] (see Figure 1 for location). Further east, within the Massif du Sud, *Guillon and Routhier* [1971] identified an important ~ N-S dextral fault associated with serpentinites, the Kouakoué fault zone, which could be subsidiary to the main tear fault.

Cluzel et al. [2001, 2012a] have already proposed a sketch resembling that of Figure 11a. The main differences are the strike of the trench before obduction, supposed to be ~ NW-SE, and the initial trend of the Norfolk Ridge at the latitude of the Grande Terre, taken as ~ N-S, which coincides with the present orientation of the ridge south of the Grande Terre. To the north, the ridge would have rotated anticlockwise as a result of its arrival at the trench, becoming parallel to the trench. Hence, the current bend, in map view, of the Norfolk Ridge would be a consequence of the obduction process [*Cluzel et al*., 2001] whereas we assume in Figure 11a that this bend existed before. The difference between the two models is only minor as both predict a southward propagation of deformation along the Grande Terre and oblique convergence with a dextral wrench component during obduction (in Cluzel et al.'s model, dextral shearing is a necessary consequence of the anticlockwise rotation of the ridge). The advantage of our model is that it better integrates the data of *Prinzhofer et al.* [1980]. Moreover, according to some paleomagnetic data [*Ali and Aitchison*, 2002], the basement of the Grande Terre underwent no significant rotation during the obduction. This is consistent with our model in which only the trench and its hangingwall (i.e., the Peridotite Nappe) rotate (Figures 11a and 11b).

7.3. Synconvergence Exhumation of the HP-LT Rocks

The scenario of Figure 11a, characterized by a diachronous emplacement of the Peridotite Nappe along the strike of the Grande Terre, may provide a simple explanation for the apparent paradox of the nappe having been emplaced at the same time the HP-LT rocks were on their way to the surface (see section 3). In the north, the nappe could have been emplaced at ~42–40 Ma, accompanied by the burial of the northern margin of the Norfolk Ridge. At ~36 Ma, the nappe had not yet reached the south of the Grande Terre (Figure 11a), but its northern part, emplaced earlier, could have already been affected by the uplift of the HP-LT fold nappe, which was almost completed at ~34 Ma (Figure 10a). This scenario is compatible with all available time constraints (see section 2) except the white mica ^{39}Ar-^{40}Ar ages from the HP-LT domain at ~35–40 Ma, provided that they represent cooling ages reflecting late stages of exhumation [*Ghent et al*., 1994; *Baldwin et al*., 2007]. The latter view is questionable because most white mica ^{39}Ar-^{40}Ar ages were obtained on rocks with well preserved HP-LT assemblages, such as blueschist facies metabasites. Therefore, these ages may essentially reflect the conditions of blueschist facies metamorphism, at pressures higher than 9 kbar [e.g., *Fitzherbert et al*., 2005], corresponding to depths greater than 30 km. Only the youngest ^{39}Ar-^{40}Ar ages, at ~35–37 Ma, might record the exhumation to shallower depths.

According to our interpretation, the exhumation of the HP-LT rocks occurred during ongoing convergence and crustal-scale contraction (Figure 10a). In addition to exhumation processes that may have taken place along the subduction "channel" [e.g., *Agard et al*., 2009; *Agard and Vitale Brovarone*, 2013; *Guillot et al*., 2015], two factors could have assisted unroofing. One factor is the obliquity of convergence (see section 7.2) since oblique convergence is suspected to be more favorable to exhumation than pure convergence [e.g., *Mann and Gordon*, 1996; *Boutelier and Chemenda*, 2008]. The second factor is the possibility that high erosion rates prevailed in the area above the exhuming fold nappe. Figure 10a suggests that erosion was much more efficient in this area than on the southwestern flank of the island where klippes of the Peridotite Nappe are preserved. This asymmetry in the distribution of erosion fits with the current distribution of rainfall, in the range of 1600 to 3700 mm/yr along the northeastern coast versus 800–1300 mm/yr along the southwestern coast [*Maitrepierre*, 2012]. The strongly asymmetrical distribution of rainfall across the Grande Terre is a consequence of the dominant winds coming from the east-southeast, a feature that may have already existed ~35 Ma ago. Focused erosion on the northeastern flank of the island may have helped to produce a fold nappe rising through the rear part of the orogen [e.g., *Chemenda et al*., 1996; *Willett*, 1999]. The basins on both sides of the Grande Terre have a thick sedimentary infill broadly contemporaneous with obduction (see section 2.3); hence, a large part of this infill may consist of rocks eroded from above the fold nappe. This is especially likely in the case of the Loyalty Basin where pre-Neogene postobduction deposits are

~3.5 to 4 km thick in the part of the basin facing the Grande Terre; this thickness decreasing to ~0.5 km further northwest [*Bitoun and Récy*, 1982]. Summing up, both oblique convergence and focused erosional denudation may have helped to exhume the HP-LT rocks in the form of a steep fold nappe (Figure 10a).

8. Conclusions

This study provides a better understanding of the relationships between the Peridotite Nappe and its substratum along a cross section through the northern part of the Grande Terre. As illustrated by the Koniambo and Kopéto-Boulinda massifs, the northwestern klippes are essentially flatlying but involve reverse-slip shear zones which are true compressional structures in origin. Further northeast, closer to the structural culmination of the HP-LT metamorphic domain, the Peridotite Nappe is folded in association with the development of a steep schistosity in low-grade metasediments. This difference in structural style indicates that the Peridotite Nappe experienced compression at greater depth conditions toward the northeast, i.e., toward its root zone, suggesting a push from the rear mechanism of emplacement. Irrespective, these features are inconsistent with an emplacement of the nappe as a gravitational slide. Instead, they imply that the Peridotite Nappe has been emplaced through horizontal contraction sustained by plate convergence. Combining this evidence with additional features such as the existence of a large upward fan of schistosities in the area where the nappe is the most deformed, a crustal-scale cross section has been built for the period preceding Neogene normal faulting. It involves a fold nappe of HP-LT rocks bounded from below by a major thrust and from above by a large normal-sense shear zone, much alike in the interpretation of *Chemenda et al.* [1996] for Oman.

Additional considerations suggest that obduction in New Caledonia occurred through oblique convergence with a dextral component. Oblique convergence is expected as a result of the initial obliquity between the ~ W-E striking subduction trench and the NW-SE trending continental ribbon of the Norfolk Ridge. *Cluzel et al.* [2001, 2012a], who suggested a slightly different configuration, pointed out that a significant obliquity between the trench and the continental ribbon is the easiest way to account for the diachronous record of compression along the strike of the Grande Terre. We have shown that this diachronism may also solve the paradox of the Peridotite Nappe being emplaced seemingly at the same time the HP-LT rocks were on their way to the surface. Oblique convergence together with focused erosional denudation on the northeastern flank of the Grande Terre probably helped to exhume the HP-LT rocks in the form of a steep fold nappe rising through the rear part of the orogen.

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