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- New deepwater fold-and-thrust belt discovered off New Caledonia's western margin
- Origin of the deepwater fold-and-thrust belt is related to postobduction isostasic rebound
- Triggering of the deepwater fold-and-thrust belt is controlled by oversteepening of the margin

Supporting Information:
- Supporting Information S1

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Deepwater Fold-and-Thrust Belt Along New Caledonia's Western Margin: Relation to Post-obduction Vertical Motions

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Abstract Classically, deepwater fold-and-thrust belts are classified in two main types, depending if they result from near- or far-field stresses and the understanding of their driving and triggering mechanism is poorly known. We present a geophysical data set off the western margin of New Caledonia (SW Pacific) that reveals deformed structures of a deepwater fold-and-thrust belt that we interpret as a near-field gravity-driven system, which is not located at a rifted passive margin. The main factor triggering deformation is inferred to be oversteepening of the margin slope by postobduction isostatic rebound. Onshore erosion of abnormally dense obducted material, combined with sediment loading in the adjacent basin, has induced vertical motions that have caused oversteepening of the margin. Detailed morphobathymetric, seismic stratigraphic, and structural analysis reveals that the fold-and-thrust belt extends 200 km along the margin, and 50 km into the New Caledonia Trough. Deformation is rooted at depths greater than 5 km beneath the seafloor, affects an area of 3,500 km^2, and involves a sediment volume of approximately 13,000 km^3. This deformed belt is organized into an imbricate fan system of faults, and one out-of-sequence thrust fault affects the seabed. The thrust faults are deeply rooted in the basin along a low-angle floor thrust and connected to New Caledonia Island along a major detachment. This study not only provides a better knowledge of the New Caledonia margin but also provides new insight into the mechanisms that trigger deepwater fold-and-thrust belts.

1. Introduction

Over the past few decades, significant advances have been made in understanding deepwater fold-and-thrust belts (DWFTBs), and a wide variety of contexts and driving mechanisms have been described (Hamilton & De Vera, 2009; King & Morley, 2017; Krueger & Gilbert, 2009; Morley et al., 2011; Rowan et al., 2004). DWFTBs are commonly classified into two main types, depending on whether they result from near- or far-field stresses, or a combination of the two. In the first case, deformation is driven by gravitational processes, confined to the sedimentary section and typically occurs on passive margins characterized by low-angle slopes into deep water, high sedimentation rates, and a thick sedimentary cover. In the second case, deformation is the result of regional-scale crustal shortening and occurs on active margins and continental convergence zones. Despite the increasing number of studies, many aspects of the causative mechanisms, structural style, and kinematics are still debated and poorly known, especially the triggering mechanisms for failure.

We have mapped a DWFTB on the western margin of New Caledonia, where onshore geology is characterized by nappes of sediment, basalt, and peridotite that were obducted during the Eocene (Paris, 1981). Postobduction tectonics are inferred to be primarily related to the restoration of isostasic equilibrium (Lagabrielle et al., 2005; Moretti & Turcotte, 1985).

Due to the long history of New Caledonia as an active margin, far-field stress is one possible explanation for the DWFTB of the western margin (Cluzel et al., 2005). In this paper, we propose that the evolution of New Caledonia's western margin slope is related to the postobduction evolution of New Caledonia and suggest that the principal trigger of the DWFTB is gravitational slope instability.

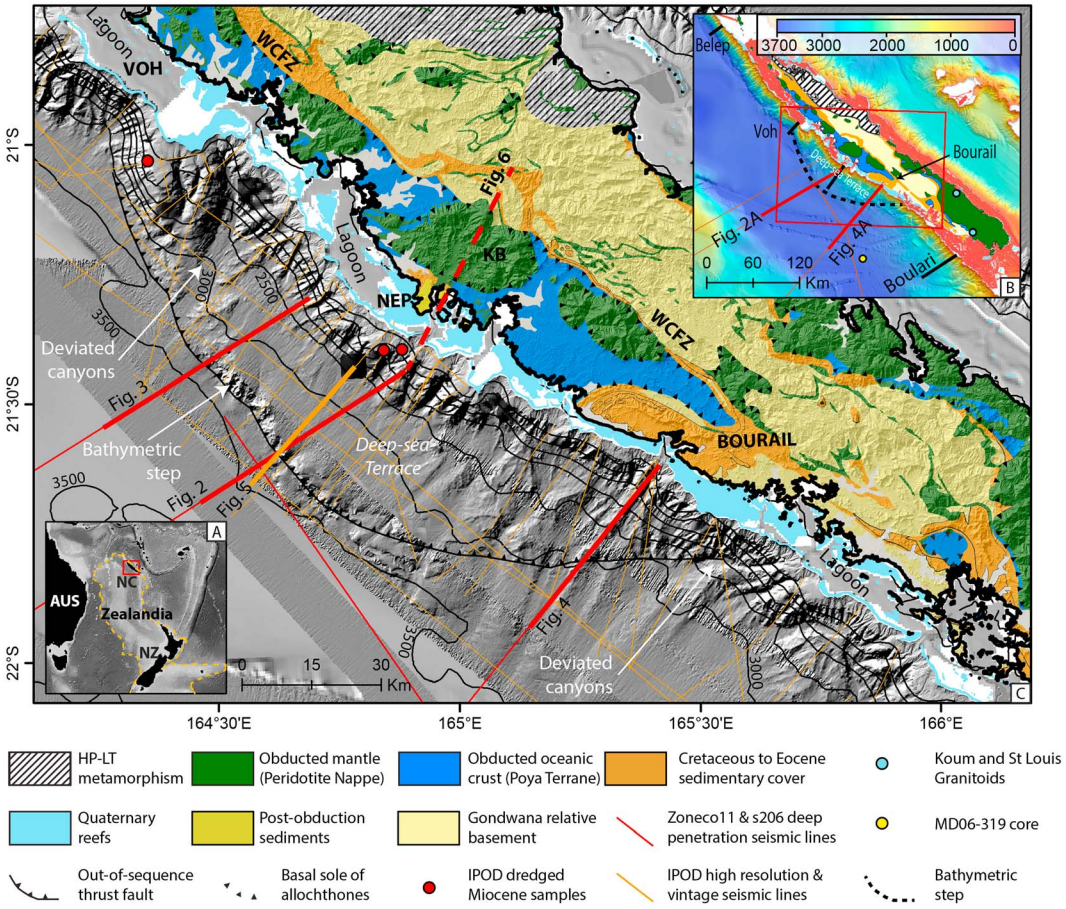


Figure 1. Location map of the Népoui DWFTB extending 200 km along the margin and 50 km into the basin. (a) Regional bathymetric map showing Australia, New Zealand, New Caledonia and limits of the Zealandia continent. (b) Bathymetric and geological map of New Caledonia. Black lines indicate position of bathymetric profiles of Figure 2. Dashed black line is the main bathymetric step at the front of the DWFTB that delineates the seaward extent of an arcuate deep-sea terrace. Light blue circles indicate position of Koum (northern) and Saint Louis (southern) Miocene granodiorites. (c) Bathymetric and geological map of New Caledonia and its west coast, where the DWFTB is found. Position of thrust faults and depocenters is based on interpretation of seismic profiles and morphobathymetric data. NEP: Nepoui, KB: Kopeto Boulinda, WCFZ: West Caledonian Fault Zone.

We use seismic reflection and multibeam bathymetric data to describe the DWFTB. We analyze the post-obduction evolution of New Caledonia and discuss a possible connection to an upslope extensional domain. The data used are a combination of deep-penetration multichannel seismic data acquired in 2004 during the Zonéco-11 voyage on board R/V *L'Atalante* (Lafoy et al., 2004), from the S206 voyage on board R/V *Southern Surveyor* in 1998 (Lafoy et al., 1998), a set of high-resolution seismic data and dredges acquired during the IPOD (Investigating Post Obduction Deposits) voyage onboard R/V *L'Alis* in 2012 (Collot et al., 2013), a compilation of existing (Juffroy, 2009) and newly acquired (Williams et al., 2016) multibeam bathymetric data and other reprocessed legacy seismic reflection lines from the Zonéco-3 voyage (Missegue et al., 1996), and the Gulfrex exploration survey (see location map on Figure 1 and Table S1 in the supporting information for seismic acquisition parameters). For the purpose of this study, seismic line z1101 was prestack depth migrated using preserved-amplitude Ray Born diffraction tomography (Jin et al., 1992; Thierry et al., 1999). This method, through careful migration velocity analysis, provides reliable migrated images and enables quantitative estimation of velocities and associated errors (Al-Yahya, 1987). This line images the New Caledonia Trough (NCT) down to its basement at 6 km beneath seafloor. All seismic sections used in this study are available in the Tasman Frontier database (Sutherland et al., 2012).

2. Geological Setting

The Grande Terre Island of New Caledonia is 450 km long and 80 km wide and located at the northern end of the mostly submerged Zealandia continent (Mortimer et al., 2017). It is bounded to the west by the NCT, a 3,700 m deep basin, and to the east by the South Loyalty Basin, which is 2,200 m deep. During the Late Paleozoic to Early Cretaceous, Zealandia was located at the eastern active margin of the Gondwana supercontinent and New Caledonia was in a forearc position (Cluzel & Meffre, 2002). During the Late Cretaceous, widespread rifting affected the region and subsequent seafloor spreading occurred in the Tasman Sea from Late Cretaceous to late Paleocene time and Zealandia became isolated from Australia (Collot et al., 2009, 2011, 2012; Gaina et al., 1998).

Late Paleocene to early Eocene subduction resumption along the eastern margin of the Zealandia continent marked the onset of a major contractional event that profoundly affected the geology of New Caledonia and Zealandia throughout the Eocene (Aitchison et al., 1995; Hackney et al., 2012; Maurizot & Cluzel, 2014; Rouillard et al., 2017; Sutherland et al., 2017). During this period, Paleocene to late Eocene syntectonic turbidites (i.e., "flysch") were deposited and can be observed today on the west coast of Grande Terre. Contemporaneously, exhumation of high-pressure low-temperature (HP/LT) metamorphic rocks affected the northeastern part of Grande Terre (Baldwin et al., 2007), and obduction of mafic and ultramafic sheets from the Loyalty Basin onto New Caledonia occurred during latest Eocene time (Aitchison et al., 1995; Collot et al., 1987; Lagabrielle et al., 2012). During the obduction event, the NCT reacted as a flexural basin by tilting eastward and an 8–9 km deep asymmetrical trough was created northwest of the margin of New Caledonia (Collot et al., 2008; Moretti & Turcotte, 1985). Onshore, synobduction deposits crop out at Népoui and are composed of deepwater turbidites (Cluzel, 1998; Coudray, 1976).

Postobduction extensional tectonics is thought to have occurred from Oligocene to mid-Miocene along major listric normal faults that bound klippes of the ultramafic nappe (Chardon & Chevillotte, 2006; Lagabrielle et al., 2005). Tectonic thinning associated with tropical weathering and erosion resulted in an intense dismantling of the ultramafic sheets that fed neighboring basins and led to a 6 km thick sedimentary fill in the NCT (Collot et al., 2008). Antithetic effects of unroofing the ridge of dense material and loading the adjacent basin resulted in subsidence of the basin and the uplift of the ridge (Moretti & Turcotte, 1985). These vertical motions, which we relate to postobduction isostasic readjustments, are thought to be still active south of New Caledonia (Le Roy et al., 2008). In the NCT basin, the thick postobduction sedimentary unit is composed of tabular uniform turbidites, with little deformation. However, locally, compressional structures within this unit crop out on the seafloor and were first identified at the base of the slope of the New Caledonia western margin by Rigolot and Pelletier (1988) from single-channel seismic reflection data. These authors interpreted the structures as having been active after obduction in the late Eocene and until the Pliocene and to have resulted from large-scale motions along the western margin of New Caledonia. Until now, no such postobduction large-scale motions have been described elsewhere.

3. Morphology and Structure of the Margin

Late Eocene flexure of the NCT was related to the obduction event in New Caledonia, based on mapping of a tilted seismic reflector (Collot et al., 2008) (see reflector "RN" on Figure 2). On the eastern side of the profile, located in front of Népoui, a deformed structure is noteworthy and corresponds to folded sediments identified on shallow-penetration seismic reflection data by Rigolot and Pelletier (1988). Analysis of the depth-migrated seismic line z1101, combined with field observations, allows us to define three main domains between onshore and the deep basin (Figure 1): (i) a 30 km wide onshore zone extending from the obducted allochthons to the shelf edge; (ii) a narrow 7–8 km wide, steep slope domain extending from the reef barrier down to the base of the slope at 3700 m water depth; and (iii) a wider downslope deep-sea terrace from the base of the slope to 50 km into the basin.

The onshore domain is characterized by the presence of (i) the 10 km wide and 50 km long Kopeto-Boulinda obducted ophiolite massif, which overlies obducted basalts of the Poya Terrane (Eissen et al., 1998), Gondwana-related sedimentary basement, synobduction turbidites and Cretaceous rifted blocks and (ii) latest Eocene and Miocene sedimentary outcrops that are only found in the Népoui area between the shore and obducted massifs and respectively record the final stages of Eocene obduction and Miocene postobduction extensional tectonics (Coudray, 1976; Maurizot et al., 2016; Paris et al., 1979). Elements constituting the

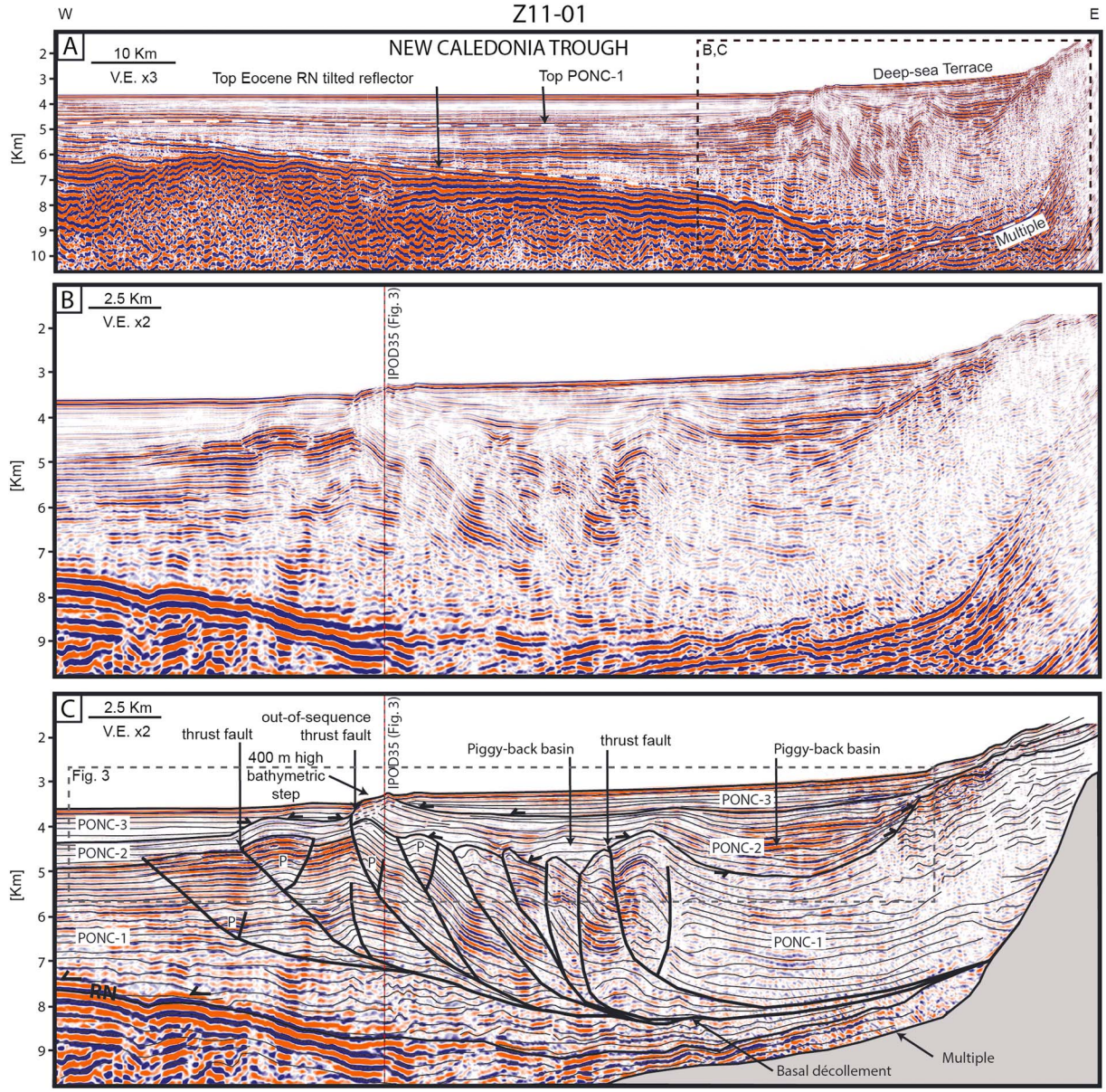


Figure 2. Depth-migrated multichannel seismic profile z1101 in the central part the DWFTB. See location in Figure 1. (a) Overview of New Caledonia flexural basin. (b) Seismic data. (c) Line drawing revealing seismic stratigaphy of DWFTB. PONC-1: pre-DWFTB deformation unit. PONC-2: syn-DWFTB deformation. PONC-3: syn-DWFTB to post-DWFTB deformation. P: Pop-up structures. Out-of-sequence thrust fault is mapped in Figure 1.

synobduction to postobduction marine sediments are essentially erosional products of the ophiolites mixed with bioclastic-biogenic limestones. The postobduction sediments reveal a general 10° dip toward the southwest and lie unconformably on deformed and folded synobduction Eocene turbidites. Postobduction normal faults were identified in this region and interpreted by Lagabrielle and Chauvet (2008) to be related to brittle extensional deformation.

The second domain is restricted to a narrow zone characterized by steep slopes that locally reach 10–15°. The steep slopes prevent good seismic imaging of the subseafloor and could be related to seaward dipping normal faults. Numerous head scarps are visible on the shallower part of the margin (0–1000 m) and postobduction conglomerates with ultramafic rounded clasts in a Miocene marine mudstone matrix (Morgans, 2014) were dredged during the IPOD voyage from ~1000 m water depth (Collot et al., 2013) (see Figure 1c for location).

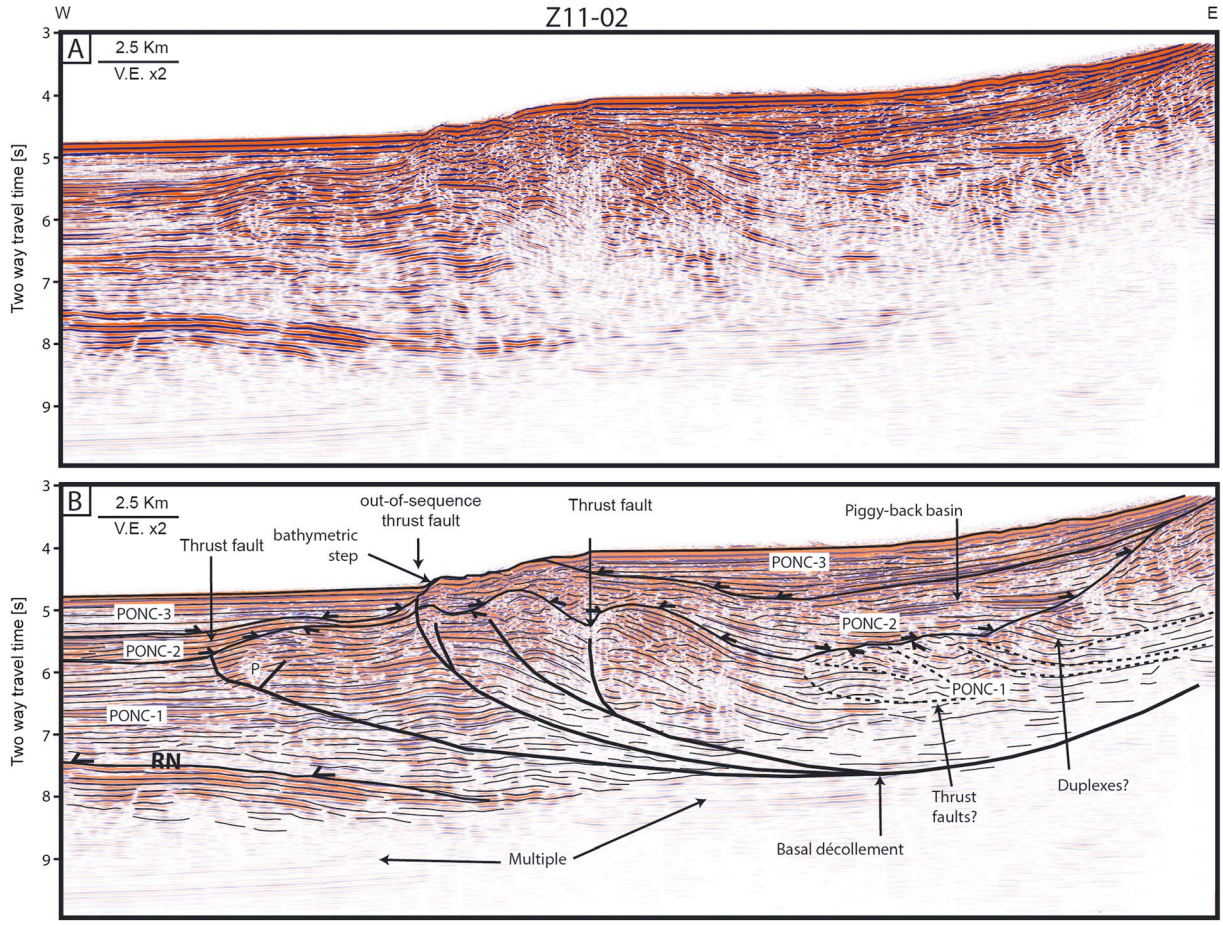


Figure 3. Time-migrated multichannel seismic profile z1102 at the northern extremity of the DWFTB. See location in Figure 1. (a) Seismic data; (b) line drawing revealing seismic stratigraphy of DWFTB. PONC seismic units. PONC-1: pre-DWFTB deformation unit, PONC-2: syn-DWFTB deformation, and PONC-3: syn to post-DWFTB deformation. P: Pop-up structures. Out-of-sequence thrust fault is mapped on Figure 1.

Downslope, at about 3300 m water depth, a 400 m high bathymetric step overhangs the NCT. In map view, this morphologic step (Figure 1) delineates the seaward extent of an arcuate deep-sea terrace. The deep structure responsible for the morphologic step is mapped on the basis of three deep penetration seismic sections: one in the central part (Figure 2) and two at the northern and southern extremities (Figures 3 and 4) of the arcuate deep-sea terrace.

All three lines show the presence of a fold-and-thrust belt composed of several landward dipping thrust faults responsible for the faulting and folding of a 4 km thick sedimentary section (Seismic Unit 1, which we name Post-Obduction-New-Caledonia-1, PONC-1). Overlapping faults are organized in an imbricate fan system (McClay, 1991; Morley, 1988) that is deeply rooted in the basin along a concave upward sole décollement about 5 km beneath seafloor (Figures 2 and 3) and forms the base of the DWFTB (Morley et al., 2011). The basal décollement together with the overlying deformed 4 km thick sedimentary unit warps up toward the margin with a steep 10° dip (Figures 2–4).

The central part of the DWFTB is composed of nine main faults of 5–10 km scale that affect strata >40 km into the basin (Figures 2). Several back thrusts are observed, leading to the formation of pop-up structures, especially in the head (basinward) of the fan system (Figures 2 and 3). On the edges (Figures 3 and 4), the DWFTB is shorter (<10 km), composed of fewer (three to five) and shorter faults (1–5 km). The edges of the DWFTB also reveal upslope a 1.5 s two-way travel time thick duplex system within the deformed strata (PONC-1) that is visible in Figure 3 and tentatively identified on Figure 4 and extends over 10 to 15 km in the hinterland. This duplex structure develops between two basinward dipping décollements.

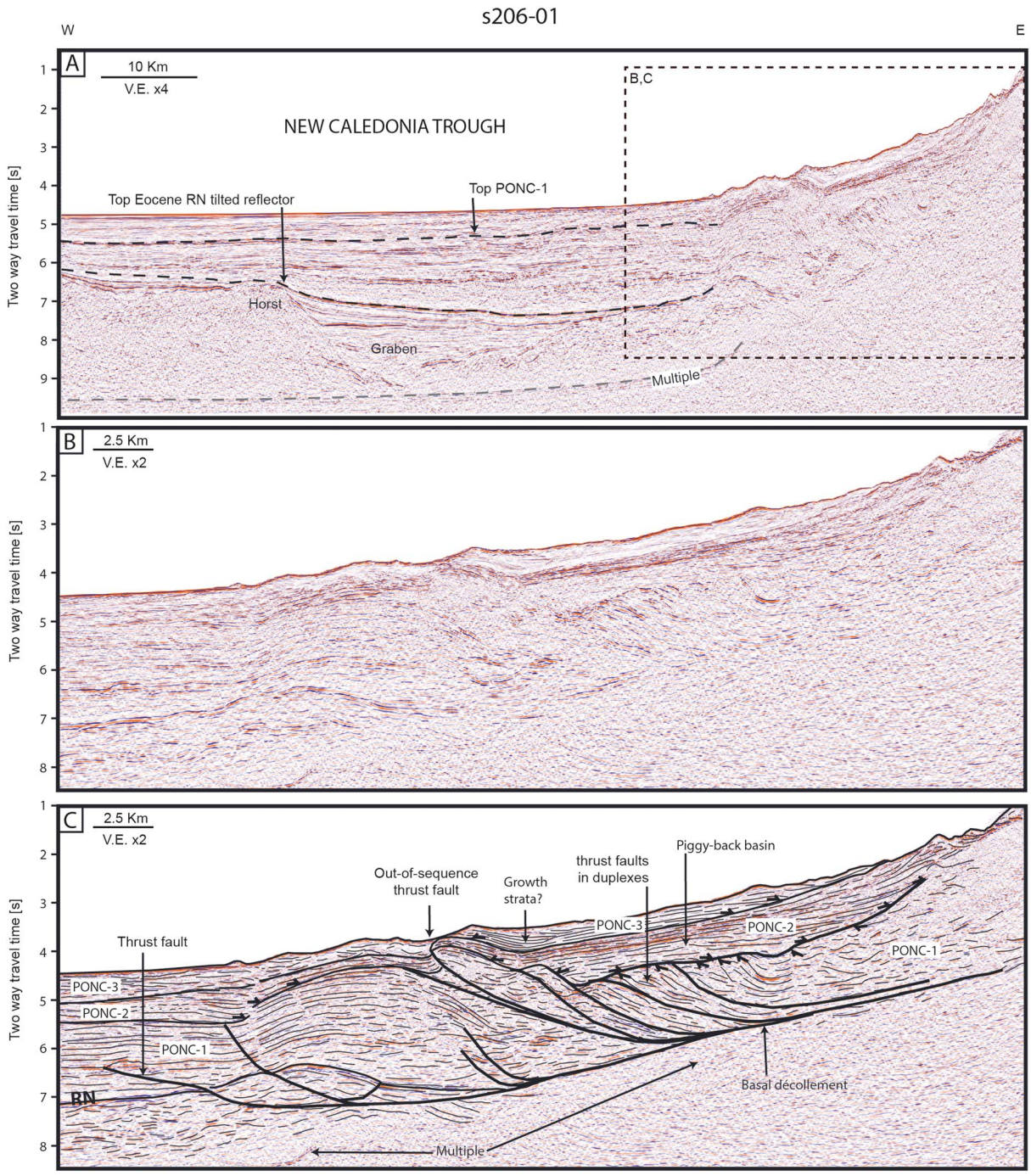


Figure 4. Time-migrated multichannel seismic profile s206-01 at the southern extremity of the DWFTB. See location in Figure 1. (a) Overview of New Caledonia flexural basin and underlying horst and graben. (b) Seismic data. (c) Line drawing revealing seismic stratigraphy of DWFTB. PONC seismic units. PONC-1: pre-DWFTB deformation unit. PONC-2: syn-DWFTB deformation. PONC-3: syn-DWFTB to post-DWFTB deformation. Out-of-sequence thrust fault is mapped in Figure 1.

The structural development of the DWFTB led to formation of piggyback basins for 200 km in the margin-parallel direction and 40 km across, between the major thrust and the foot of the margin slope (Figure 2b).

Within the imbricated fan system, an out-of-sequence thrust (OOST) is observed in a position close to the frontal portion of the DWFTB. This main thrust, in contrast to the other thrust faults, is not sealed by the overlying seismic unit (PONC-2 in Figures 2–5) but deforms, uplifts, and offsets it. Growth strata in PONC-2 are

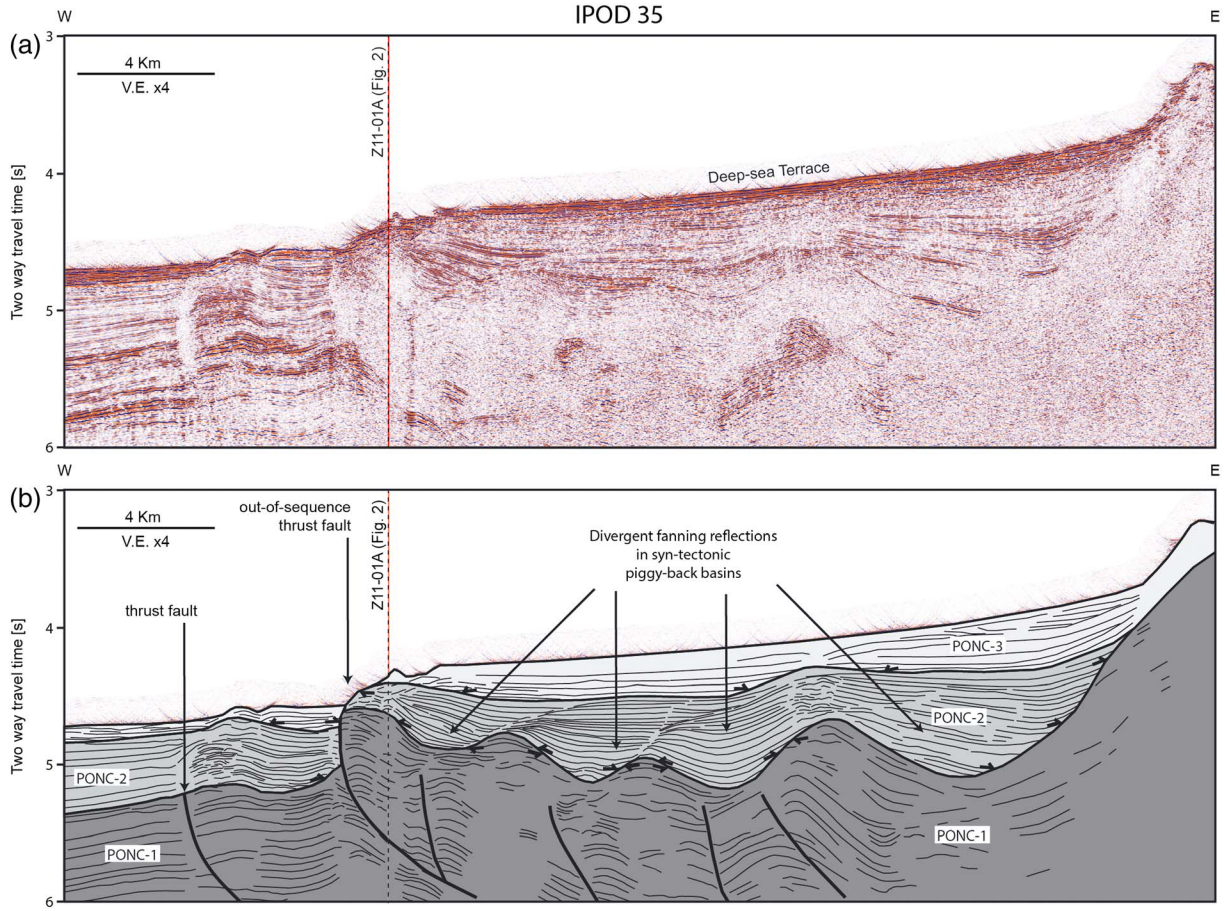


Figure 5. High-resolution IPOD-35 seismic profile across the DWFTB. See location in Figure 1. (a) Seismic data. (b) Line drawing revealing detailed seismic stratigraphy. PONC seismic units. PONC-1: pre-DWFTB deformation unit. PONC-2: syn-DWFTB deformation. PONC-3: syn-DWFTB to post-DWFTB deformation.

observed on the back of the OOST (see paragraph 4), constituting piggyback basins, but are not observed in the frontal part of the thrust. The activity of this thrust is responsible for the morphological step observed in bathymetry.

The bathymetric step is laterally continuous, has a seaward convex shape, and joins the margin toe around Voh to the north and Bourail to the south (Figure 1). In these two localities, the submarine canyons obliquely incise the margin, converging toward the area of maximum width of the DWFTB, rather than being perpendicular to the margin as seen elsewhere (Figure 1). This suggests that the Voh and Bourail canyon paths were controlled by structures of the DWFTB. The DWFTB also follows this bathymetric step and is hence less developed at its extremities close to the continental slope in Voh and Bourail. This is corroborated by seismic data that reveal the DWFTB is less developed at its extremities. The slope of the margin segment located between these two localities is around 9°, which is significantly less steep than the northern part of the margin, which is characterized by slopes ranging between 15° and 25° (e.g., respectively, in Belep and Voh; see supporting information Data Set S1) and can be locally $>30°$.

To the south of the DWFTB, local slope instabilities occur that involve superficial sediments, but there are no associated compressional structures observed in the NCT. Conversely, seismic data reveal a horst and graben structure of the margin and gentler slopes, which ranges between 5° and 10°, see profile 3 shown by Rigolot and Pelletier (1988). Several mass transport deposits are observed in the seismic data and a debris flow lobe with kilometer-scale blocks is visible on bathymetry that suggests recent gravity-induced instabilities.

4. Seismic Stratigraphy

More than 2,500 km of 2-D seismic profiles were interpreted (Figure 1). Using the principles of seismic stratigraphy (Mitchum et al., 1977) and analysis of seismic reflection character and unconformities, we define three postobduction seismic units.

Seismic Unit 1, which we name Post-Obduction-New-Caledonia-1 (PONC-1) onlaps the RN-tilted reflector (Figure 2). In the study area, close to the margin, this unit is bounded at its top by an onlap surface (Figures 2 and 5) and is affected by thrust faults beneath the slope and is almost undeformed farther basinward (Figures 2–4). PONC-1 is highly folded beneath the deep-sea terrace, and in some places toplaps exist at the top of the unit (Figures 2 and 5). Its internal facies is tabular, parallel, and has variable to high-amplitude reflections toward the top of the unit (Figure 2). It reaches 4 km in thickness and has an overall wedge-shaped geometry due to the tilt of the RN reflector (Figure 2a). PONC-1 is thus interpreted to have been deposited during a period of relative tectonic quiescence that was followed by compressive deformation. Landward (Figure 2b) of the thrust faults and piggyback basins, reflectors of PONC-1 are progressively tilted seawards to a dip of 10°.

Seismic Unit 2 PONC-2 onlaps the flanks of PONC-1 folds, which are steep in some places, and is bounded at its top by another onlap surface (Figures 2 and 5). PONC-2 is characterized by divergent fanning reflections (Figures 2 and 5), particularly in piggyback basins. It exhibits lateral thickness variations and pinches out close to the top of folds. Its thickness is between 0.5 km in the NCT and 1.5 km in the center of piggyback basins (Figure 2). PONC-2 is interpreted as syntectonic and records the deepening of piggyback basins created by folding and fault growth within the PONC-1 unit. PONC-2 is likely to be composed of proximal gravity flow deposits sourced from the shelf and possibly from growing anticlines, alternating with hemipelagic background deposits. Stratal relationships indicate a progressive upward attenuation of deformation within piggyback basins (Figure 5), except for the major out-of-sequence thrust that deforms the seafloor and uplifts and offsets PONC-2 at the front of the deep-sea terrace. Reflector geometries do not constrain the relative timing of thrusts (i.e., if imbrication was in-sequence and break-forward, or out-of-sequence and break-back).

Seismic Unit 3 (PONC-3) onlaps and locally downlaps onto PONC-2 in piggyback basins and onlaps onto PONC-2 in the basin (Figures 2–5). The upper boundary of PONC-3 is the seafloor and its base is the top of PONC-2. PONC-3 is composed of subparallel very high to medium amplitude reflections that dip slightly westward along the slope and above piggyback basins and are subhorizontal in the basin. PONC-3 is slightly thicker in the NCT (0.8 km thick) than in piggyback basins (0.6 km thick). PONC-3 is posttectonic, as it seals PONC-1 and PONC-2 deformation. However, PONC-3 is locally deformed by the out-of-sequence thrust fault and has growth strata adjacent to it (Figure 4), and it fills the piggyback basins and spills into the NCT.

5. Discussion

5.1. Age of the DWFTB

In terms of relative age, the postobduction units (PONC-1, PONC-2, and PONC-3) that fill the flexural basin above the RN reflector are interpreted to be Oligocene to present day (Collot et al., 2008). Onshore, the only coeval postobduction marine rocks crop out in the Népoui area and consist of early Miocene shallow-water to outer shelf carbonate systems mixed with coarse detrital products that are primarily derived from erosion of the ophiolite (Coudray, 1976; Maurizot et al., 2016) and Quaternary reefs (Cabioch et al., 2009). Gravity core MD06-3019 was recovered during voyage Zonéco-12 (Foucher & Scientific Party, 2006) at 3520 m water depth in the center of the NCT (see location on Figure 1b), probably in the distal part of a submarine canyon or the deep-sea fan (Foan, 2015). The core is 36.25 m long and corresponds to alternating hemipelagic oozes and deepwater turbidites of mixed carbonate siliciclastic composition, and the base is dated at 1.26 Ma (Foan, 2015). Sedimentation rates of turbidite layers are between 80 and 10 m/Ma (Foan, 2015). These rates are to be taken cautiously since the core only samples a very superficial part of the sedimentary column of NCT and is probably located in a zone where sediments are not uniformly accumulated but transferred into the deeper part of the basin.

Considering the maximum depth (~ 5.5 km) and the late Eocene age (circa 34 Ma) of the RN reflector inferred by Collot et al. (2008) (Figure 2), the average sedimentation rate since the late Eocene in the NCT can be estimated at 160 m/Ma. According to the maximum depth of the top of PONC-1 (1.5 km below seafloor) and

assuming that average sedimentation rates were constant from late Eocene to present day (160 m/Ma), we suggest that the DWFTB deformation started during late Miocene times (circa 9 Ma). The average thickness of PONC-2 also suggests that the main phase of deformation lasted at least 6 Myr and locally more along the active out-of-sequence thrust fault that affects the seabed. No clear evidence of syntectonic growth strata exist within PONC-3, except in the vicinity of the out-of-sequence thrust, but this is classically the case in superficial sediments in piggyback basins of accretionary prisms (Zoetemeijer et al., 1993). In the case of a total lack of tectonic activity, it is very likely that sediments of PONC-3 would have smoothed the relief created by the thrust, at least in some places. This is not what is observed. Instead, erosion is locally observed suggesting a very local uplift. We suggest that the out-of-sequence thrust was active throughout PONC-2 and that its tectonic activity likely decreased during PONC-3 to be residual at present day. This relatively long duration of deformation, combined with the fact that the DWFTB has clear internal seismic reflection structure (not a debris-flow avalanche or mass transport deposit), suggests a progressive and noncatastrophic event.

5.2. What Caused the Deepwater Fold-and-Thrust Belt?

The morphologic and seismic data we present can be interpreted in several ways to explain the origin of the DWFTB. One possible origin, following the interpretation of Cluzel et al. (2005), is that the DWFTB is the accretionary prism of a postobduction subduction of the NCT beneath New Caledonia. For various reasons presented below, we believe that a gravity driven process is a more likely explanation for the DWFTB.

5.2.1. Evolution of the Western Margin of New Caledonia

Depth-migrated profile z1101 (Figure 2) reveals that reflectors within unit PONC-1 and more particularly the basal décollement of the DWFTB and the RN reflector are progressively warped upward toward the western margin of New Caledonia. The increase in dip reaches 10 ± 2° along the margin, revealing that the inner part of the DWFTB rises toward the margin of New Caledonia, rather than being deeply rooted along a paleosubduction interface.

A significant time gap of about 25 Ma (computed from the thickness of PONC-1 and estimated sedimentation rates; see previous paragraph) exists between flexure of the basin, marked by the RN-tilted reflector on which PONC-1 homogeneously onlaps, and the onset of deformation associated with the DWFTB, which is marked by the top of PONC-1. This time gap suggests that the origin of the DWFTB is related to an event disconnected from flexure of the basin and that the event may not have occurred during the shortening period that affected New Caledonia during the Eocene. Moreover, this is confirmed by the fact that if the DWFTB deformation was continuous in space and time with the New Caledonia obduction event, which terminated during latest Eocene, its age would be late Eocene to early Oligocene. This hypothesis would imply that the 2 km thicknesses of PONC 2 and 3 was deposited over a period of circa 34 Ma, implying sedimentation rates of 55 m/Ma in the NCT, which is comparable to deep-sea pelagic sedimentation rates of 40 m/Ma (Hüneke & Henrich, 2011). However, high relief, tropical weathering, and high erosion rates characterize New Caledonia. Higher sedimentation rates may be expected in this context. For example, 250–300 m/Ma was measured in the Alpine foreland basin in Annot sandstones according to Guillocheau et al. (2014). We suggest that the origin of the DWFTB is likely to have been disconnected in time from the NCT basin flexure that occurred during Eocene obduction in New Caledonia.

No evidence of Oligocene to present-day compressive tectonics exists onshore New Caledonia, but extensional tectonics are described both from onshore and offshore observations (Chardon et al., 2008; Chardon & Chevillotte, 2006;Lagabrielle et al., 2005 ; Lagabrielle & Chauvet, 2008). In Saint Louis and Koum (see location in Figure 1), two Miocene granodiorites have been interpreted as arc related volcanism (Cluzel et al., 2005) or as postorogenic collapse plutons (Lagabrielle & Chauvet, 2008). Because of the 200 km distance between these plutons and the area where the DWFTB if observed (see Figure 1), it is unlikely that these granites are related to subduction involving the DWFTB.

The 10° seaward dip of PONC-1 along the western margin of New Caledonia is concordant with the general 10° dip toward the southwest of nearby postobduction sediments that crop out on the coast near Népoui (Coudray, 1976; Maurizot et al., 2016) (Figure 6), and of dipping planation surfaces on allochthonous ophiolitic massifs (Chardon & Chevillotte, 2006; Chevillotte et al., 2006). Onshore, these dips are interpreted to be the result of postobduction epeirogenic uplift motions (Chardon & Chevillotte, 2006; Chevillotte et al., 2006). Based on the altitude of the allochthonous sole and the geometry of the planation surfaces, the central

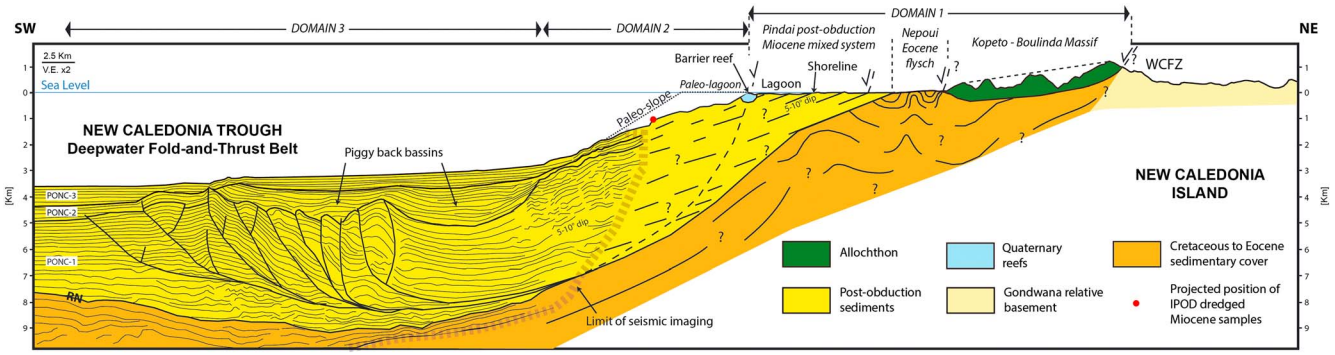


Figure 6. Schematic interpretative geological cross section from the New Caledonia trough to the center of New Caledonia Island. Location of profile is indicated on Figure 1. Geometries of the onshore domain (1) are deduced from the geological map. Geometries of the offshore domain (3) are defined from seismic data (see thick dashed line for limit of seismic imaging). Geometries along the slope (domain 2) are interpolated between domains 1 and 3. For the sake of clarity, the Poya Terrane is included in "allochthon."

part of New Caledonia is interpreted to be the place that underwent maximum postobduction uplift in New Caledonia (Chardon & Chevillotte, 2006; Sevin et al., 2014). We suggest that the dip of reflectors within PONC-1 along the margin is a consequence of postobduction vertical motions.

During latest Eocene time, as the mantle sheet of the South Loyalty Basin was being obducted onto Norfolk Ridge, the NCT subsided under the effect of shortening and loading (Collot et al., 2008) (Figure 7, Step A). This unstable situation with abnormal dense material on the ridge led isostasy to restore equilibrium by removal of the mantle sheet either by tectonic process, erosion, or leaching (Lagabrielle et al., 2005; Lagabrielle & Chauvet, 2008). This process has been recognized as leading to important and particularly localized vertical motions (Martinez et al., 2001). Moreover, the juxtaposition of erosion and deposition of such dense eroded material on land and in the nearby basin led to an inversion of vertical motions over a short distance, with uplift on land and subsidence in the basin that resulted in progressive steepening of the margin (Moretti & Turcotte, 1985); see Figure 7, Step B. Tilting of the margin is illustrated as a short-wavelength flexure in Figure 7, but a normal fault is an alternative interpretation. A late Miocene slab-breakoff beneath the eastern margin of New Caledonia has also been suggested as being responsible for a short-lived east to west tilting of Grande Terre (Cluzel et al., 2005; Sevin et al., 2014). This tilting could have partly contributed to slope steepening of the western margin of NC, but this model, notably the amplitude, lateral extent, and wavelength of deformation, remains poorly documented.

5.2.2. Causal Link Between Postobduction Isostasic Rebound and DWFTB

Isostasic rebound following obduction of ultramafics on Norfolk Ridge led the margin slopes to become oversteepened. Latest Eocene turbidites that were deposited in deep marine conditions (>2,000 m depth) crop out in Népoui and Bourail and are unconformably overlain in Nepoui by early Miocene shallow-water carbonates. These are strong indicators of at least 2 km of post-Eocene vertical uplift over a period of <10 Ma, suggesting minimum vertical uplift rates of 200 m/Ma.

North of the Népoui–Bourail area, the margin slopes dip 15–25° (Figure S1), which is steep in comparison with slope dips measured on continental slopes of transform margins around the world, which have typical median values of 5° (Mercier de Lépinay et al., 2016). South of the Népoui-Bourail area, slopes dip ~10°, but in that area the NCT shows no signs of flexure (Collot et al., 2008) and the allochthonous ophiolitic massif is still present, which suggests that it has been less intensively exhumed and eroded. We suggest that the northern part of the margin (slopes of 15–25°) may be similar to initial conditions that existed before the DWFTB formed and that the gravity-driven DWFTB lowered the slope to its present value of 9°. Variations in the width of the lagoon (see Figure 1) are compatible with this hypothesis: the lagoon is narrow where the margin is affected by the DWFTB (<5 km wide or nearly absent near Bourail), and wider elsewhere (between 15 and 20 km wide farther north and south; Figure 1b). This width difference suggests that a paleolagoon (see Figure 2) was drowned as the extensional domain of the DWFTB subsided to its present-day position.

Development of the DWFTB happened in that particular area because of three factors: (i) this may be where the steepest slope was situated; (ii) this is where the maximum uplift of Grande Terre is recorded (Chardon &

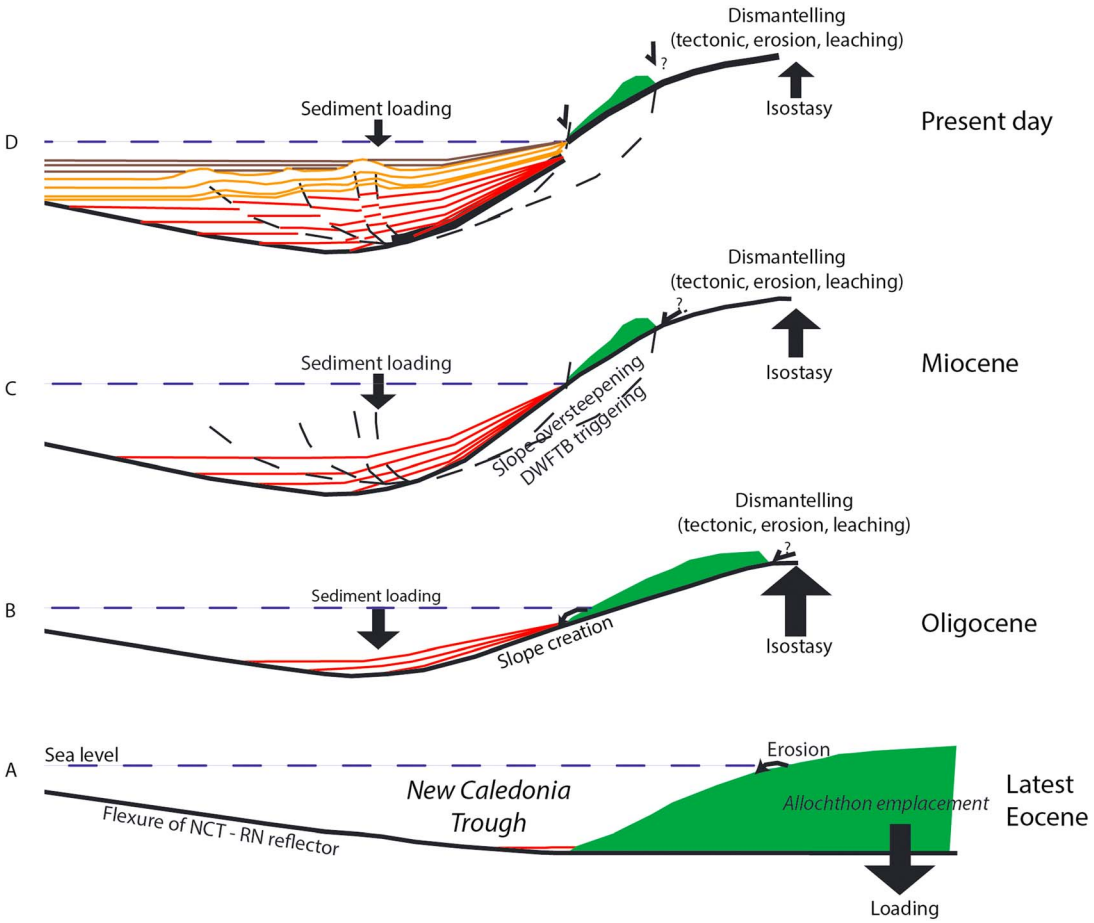


Figure 7. Evolution scheme of the western margin of the NCT (not to scale). Step A: obduction of a mantle sheet onto the Norfolk Ridge and flexure of the NCT. Step B: Isostasy restores equilibrium by dismantling the allochthons, which leads to uplift of the ridge and local subsidence of the basin. Step C: Oversteepening of the margin triggers a gravitational instability and formation of the deep-water fold-and-thrust belt. Several hypotheses exist on the location of the uphill extensional domain. Note the change in wavelength of the initial flexing and later tilting of the margin. Tilting of the margin during steps B, C, and D is illustrated as a flexure but could be a normal fault.

Chevillotte, 2006; Sevin et al., 2014); and (iii) the basal décollement of the DWFTB reaches its deepest point at the top of a graben visible on seismic line s206-01 (Figure 4), suggesting the presence, as observed onshore, of Cretaceous coaly sediments and associated fluids that may be favorable for the development of a décollement layer.

Together these observations lead us to concludes (i) that the origin of the DWFTB is not related to subduction, but rather to a gravity-driven process; (ii) that the margin was over-steepened by differential uplift of New Caledonia's Grande Terre and subsidence of the NCT, associated with postobduction vertical tectonics; and (iii) that the age of the DWFTB is coeval with the oversteepening of the margin. For these reasons, we suggest that oversteepening of the margin likely created the conditions of gravitational instability and triggered formation of the DWFTB (Figure 7, Steps C and D).

5.3. Extensional Domain

The upslope extensional domain of this gravity-driven DWFTB is not marked onshore by a major visible tectonic feature, and several hypotheses on its expression and location exist. It could be connected to a single or several normal faults that are (i) embedded along the present-day slope of the western margin of New Caledonia, (ii) in the onshore Miocene platform located between the shore and the obducted massifs, (iii) along the southwestern flank of the allochthon, and/or (iv) along the northeastern flank of the allochthon.

Uncertainties in location of the upslope extensional domain are due to several factors. On the platform, normal faults are locally observed (Coudray, 1976; Lagabrielle et al., 2005), but the strong competition between reefal carbonate growth and coeval very high energy deposits from terrigenous sources induces high lateral facies variability that makes it difficult to establish the range, extent, and importance of faults.

Because of its very linear character, the southwestern limit of the Kopeto Boulinda ultramafic massif is a good candidate for being fault bounded, but the quality of outcrops does not allow us to definitively test this hypothesis.

To the east of the Kopeto Boulinda Massif lies the West Caledonia Fault (Figure 1), a regional linear geological (cartographic) feature and major structural break that marks the boundary between allochthons and Mesozoic basement (Baldwin et al., 2007; Lillie & Brothers, 1970). However, the nature of this contact remains debated. It has been interpreted as a major strike-slip boundary (Brothers & Blake, 1973; Paris, 1981; Rawling & Lister, 1999; Routhier, 1953), or as the shift from ridge-normal extension to a transtensional regime during the Cenozoic (Chardon & Chevillotte, 2006; Lagabrielle & Chauvet, 2008). Conversely, Cluzel et al., (2001) argued that the West Caledonian Fault does not exist. In the study area, although the massif seems to locally crosscut the potential fault, this fault could be the remnant of a southwest dipping normal fault system of which the peridotite footwall may be completely eroded, leaving basement outcropping and the hanging wall as the Kopeto-Boulinda Massif.

Poor seismic imaging along the steep slopes of the NCT margins prevents identifying directly the continuity and relationship of the basal décollement of the DWFTB with the slope itself. That said, the singular flat horizontal geometry of postobduction strata in the NCT suggests that no vertical movements were involved in the NCT at the time of isostasic uplift of New Caledonia. These facts indicate that the NCT and New Caledonia did not react as a single rigid block but rather that the differential motion must have been controlled by a structural break (decoupling) between the two. We suggest that this structural limit is a normal fault that could be responsible for the slope steepening, and that this fault spatially corresponds to the upslope extensional domain of the DWFTB.

5.4. Driving and Triggering Mechanisms of Deepwater Fold-and-Thrust Belts

5.4.1. Driving Mechanism and Tectonic Setting

Data reviewed by Morley et al. (2011) show that DWFTBs can be classified based on their driving mechanism, detachment type, and tectonic setting. In this classification, far-field stress systems are exclusively accretionary prisms in active margin settings and most near-field stress systems are confined to passive margins. The only two known exceptions where near-field DWFTBs are found in nonpassive margin settings are (i) the Cyprus and Nile Delta DWFTBs in the Mediterranean Sea and (ii) the Sandakan Delta in Indonesia. In the first case the collisional setting of the Mediterranean and climate forcing are interpreted to have produced the Messinian evaporates (Cita, 2013; Fauquette et al., 2006) which acted as a detachment zone to these DWFTBs. In the second case, the Sandakan Delta developed when tectonic uplift of Borneo triggered sedimentation and forced progradation of the delta in the Celebes Sea (Balaguru & Hall, 2009). In both cases, these DWFTBs did not form in typical passive margins and the controlling factors are, respectively, the presence of a particularly favorable detachment zone and the unusually thick sedimentary pile. The New Caledonia Trough DWFTB is a new example of a near-field stress system that is not confined to rift-related subsidence of a passive margin or to upslope overaccumulation of sediments.

5.4.2. Driving Mechanism and Detachment

Near-field stress DWFTB systems form either as the result of gravity sliding or gravity spreading, or as a combination of the two (Peel, 2014). Gravity sliding requires a slope (e.g., margin tilting) (Duval et al., 1992; Hudec & Jackson, 2004; Mahanjane & Franke, 2014), whereas gravity spreading occurs when unstable rocks collapse under their own weight, which does not necessarily require a preexisting slope (e.g., new slope creation by high sedimentation rates) (Krueger & Gilbert, 2009).

Because of the steep basinward slope of the margin and the basal detachment of the NCT DWFTB, we suggest that the DWFTB was generated by a gravity-sliding mechanism.

In most gravity-sliding DWFTBs, the main cause of instability is the strongly reduced basal traction caused by an extremely weak layer at the base of the wedge (Poblet & Lisle, 2011). This can occur in the case of high sedimentation rates and/or if an efficient décollement layer preexists (Morley et al., 2011). Salt or shale

layers are the two known detachment types for DWFTBs, and both types exhibit diapirs, and mud volcanoes are common in the case of shale detachments (Morley et al., 2011). In the case of the NCT DWFTB, no diapirs or no mud volcanoes are seen in the basin or onshore. This suggests that no major detachment layer exists, but because of the lack of well data in the basin and the presence of a graben beneath the toe of the DWFTB (Figure 3), the role of an efficient decollement layer or very high sedimentation rates cannot be completely excluded as a being a codriving mechanisms.

5.4.3. Triggering Mechanisms

Our analysis reveals interesting observations in terms of triggering mechanisms. First, we show that postobduction uplift was substantial (>2000 m) along a short lateral distance of <15 km, and this created steep slopes (>15°). In comparison, the Angola margin has a salt detachment layer and postrift uplift of the Kwanza Basin DWFTB is of the order of 1000 m spread out over 150 km, which has resulted in failure produced by slopes of only approximately 1° (Hudec & Jackson, 2004). Second, we infer that postobduction sliding was coeval with oversteepening of the margin and that the sliding occurred where the margin was the steepest (i.e., where uplift is thought to be the maximum onshore (Chardon & Chevillotte, 2006; Sevin et al., 2014)). Together these observations suggest that oversteepening triggered instability. We cannot rule out that the trigger was combined with other factors such as high sedimentation rates and/or seismicity related to postobduction isostatic rebound (e.g., postglacial seismicity in Fennoscandia, (Fjeldskaar et al., 2000)), but the high values of oversteepening strongly suggest that it was the triggering mechanism. Known contemporaneous sedimentary records of the Miocene mixed carbonate siliciclastics series of Népoui (Maurizot et al., 2016) do not reveal particularly high sedimentation rates but indicate sediments were deposited in a shelf environment close to the coast. Moreover, they are Miocene in age and obduction is thought to have finished during latest Eocene (Cluzel, 1998). Oligocene is a major hiatus onshore New Caledonia, which probably reflects a major erosional phase that could be associated to high sedimentation rates in the basin. Regarding paleoseismology, no indications of paleoearthquakes are reported.

6. Conclusions

We present evidence for a causal link between postobduction vertical motion of New Caledonia, which was controlled by isostatic processes, and formation of a deep-water fold-and-thrust belt (DWFTB) in the NCT. The combination of unloading the island, which was capped by dense and unstable obducted mantle material, and loading the adjacent NCT resulted in relative vertical motions that oversteepened the margin and created a bathymetric step more than 3 km high. Very high prefailure slopes of 15° to 35° are inferred from observations of the northern part of the margin, where there are no folds or faults, and we conclude that the high slopes caused by tiliting led to margin collapse along a 200 km long section between Bourail and Voh during the Miocene over a time period of at least 5 Myr. One fault in this fold and thrust system continues to show minor activity to the present day. Folding and thrusting lowered the margin slope to present-day values of 5–10°. The DWFTB deformed sediments over a 50 km width into the basin and is rooted along a décollement layer reaching 5 km depth below seafloor.

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