Available online at www.sciencedirect.com

SCIENCE DIRECT

Tectonophysics 403 (2005) 1–28

TECTONOPHYSICS

www.elsevier.com/locate/tecto

Post-Eocene extensional tectonics in Southern New Caledonia (SW Pacific): Insights from onshore fault analysis and offshore seismic data

Yves Lagabrielle[a,*], Pierre Maurizot[b], Yves Lafoy[c], Guy Cabioch[d], Bernard Pelletier[e], Marc Régnier[f], Isabelle Wabete[g], Stéphane Calmant[h]

[a] *UMR 5573, Laboratoire Dynamique de la Lithosphère, CC 60, I S T E EM-UM2, Place Eugène Bataillon, 34095 Montpellier Cedex 5, France*
[b] *Bureau de Recherche Géologique et Minière, SME, BP465, 98845 Nouméa Cedex, New Caledonia*
[c] *Service des Mines et de l'Energie, BP465, 98845 Nouméa Cedex, New Caledonia*
[d] *IRD (Institut de Recherche pour le Développement), UR055 Paléotropique, B.P. A5, 98848 Nouméa Cedex, New Caledonia*
[e] *IRD (Institut de Recherche pour le Développement), UR082/UMR Géosciences Azur B.P. A5, 98848 Nouméa Cedex, New Caledonia*
[f] *IRD, UR082/UMR Géosciences Azur, 250 rue Albert Einstein, Sophia Antipolis, 06560 Valbonne, France*
[g] *IRD, UR082/UMR Géosciences Azur, B.P. A5, 98848 Nouméa Cedex, New Caledonia*
[h] *IRD, UR065/UMR LEGOS Observatoire Midi Pyrénées, 31400 Toulouse Cedex, France*

Received 29 October 2003; accepted 22 February 2005
Available online 23 May 2005

Abstract

Ductile to brittle extensional deformation following thrusting of the peridotites nappe during the Upper Eocene has been shown to play a major role in the Tertiary tectonic evolution of the northern part of the main island of New Caledonia and its eastern and western margins. In this study, we provide new tectonic data from southern New Caledonia that allow to better constrain the tectonic evolution of the southern part of the main island. We present a kinematic analysis of faults and striations obtained mainly from exposures of sedimentary rocks in the region of Nouméa with complements from measurements made farther north at Népoui within post-obduction Middle-Miocene deposits. We also present additional results of an interpretation of seismic lines from the lagoon south of the Nouméa Peninsula which provide constraints on the current tectonic regime of southern New Caledonia. Extensional faults in the Nouméa region have been studied within terranes of various ages including pre- and syn-obduction deposits and ophiolites. Hence, we demonstrate that important extensional events have affected the southern part of the New Caledonia block after the obduction of the peridotite nappe. The direction of maximum extension is variable at the scale of the region. Both high angle and low angle normal faults are present and block rotation is observed at some localities. This suggests that detachments accommodating significant displacements are cutting through the sedimentary pile. The average final strain pattern of the region can be regarded as the results of a multidirectional flattening, a hypothesis consistent with vertical uplift associated with regional extension. These results are in good agreement with conclusions of earlier workers showing late extensional evolution of the ophiolites along

* Corresponding author. Tel.: +33 4 67 14 35 85; fax: +33 4 67 14 36 42.
E-mail address: Yves.Lagabrielle@dstu.univ-montp2.fr (Y. Lagabrielle).

doi:10.1016/j.tecto.2005.02.014

the chain and generalized extension in northern New Caledonia. The extensional faulting event in southern New Caledonia started after the obduction of the ophiolite, probably during the Oligocene. Extension was still active after the Middle Miocene, as shown by normal faulting in the Népoui conglomerates. Quaternary neotectonic features are observed in the lagoon and correspond to groups of short segments of vertical faults having orientation of N90, N40–50, N0–10 and minor N140, delineating subsiding areas. These faults are reactivated features with orientations corresponding to trends of coastlines and other main morphological features of the island. This study enhances the strong influence of normal-faulting neotectonics and recent tectonics on the current landscape evolution of southern New Caledonia. We infer that these tectonic processes played an important role during the weathering of the peridotites and subsequent development of the lateritic Ni-bearing layers as they increase the penetration of ground waters within the actively expending peridotite basement.

Keywords: Normal faulting; Post-nappe tectonics; Nouméa basin; Seismic lines

1. Introduction, purpose of study

The New Caledonia archipelago (SW Pacific) consists of a main island (the Grande Terre) and subordinate islands including the Belep Islands, the Isle of Pines, and the Loyalty Islands located along the N130 trending Loyalty ridge (Fig. 1). The Grande Terre is 400 km long and 50–60 km wide. It represents the emerged portion of the N130 trending New Caledonia ridge that connects to the south to the Norfolk Ridge (Fig. 1). The Grande Terre is characterized by two major geological features: (1) it exposes a very large ophiolitic nappe, emplaced during the Upper Eocene, mainly harzburgitic in composition and lacking a sheeted dike complex and extrusive mafic rocks (Avias, 1967; Prinzhofer, 1981), (2) it displays one of the largest barrier-reefs in the world which encloses the island along some 1,000 km of coastline, isolating a lagoon locally 20 km wide (Fig. 1). The ophiolites have been extensively weathered under subaerial conditions following obduction, leading to the development of thick Ni-rich lateritic layers capped by ferricrust, and thus forming one of the largest reservoir of Nickel in the world (e.g. Trescases, 1973, and extensive references in Paris, 1981). Ferricrust and lateritic–saprolitic horizons form tilted palaeosurfaces and stepping plateaus, suggesting recent differential vertical motion of separate tectonic blocks.

Timing and tectonic–metamorphic consequences of ophiolite obduction have been constrained recently by investigations in the northern Grande-Terre of New Caledonia (Aitchison et al., 1995, 1998; Cluzel et al., 1995, 2001; Clarke et al., 1997). Ductile to brittle extensional deformation following the main compressional event has been shown to play an important role in the morphotectonic evolution of this region during Cenozoic times (Rawling and Lister, 2002). By contrast, almost no data relative to the tectonic evolution following ophiolite emplacement are available from the southern part of the Grande Terre. In this paper, we present the first compilation of fault data obtained from microtectonic investigations in the region of Nouméa (southern Grande Terre of New Caledonia) and from the analysis of seismic lines in the lagoon south of Nouméa. These data help better constrain the recent tectonic regime of this region and allow us to propose new elements that must be taken into account in any new model of post-obduction tectonic evolution of southern New Caledonia from Oligocene to the Present.

2. Dating the obduction in New Caledonia: stratigraphic and tectonic overview

The New Caledonia ophiolites represent the western edge of the lithospheric mantle forming the current basement of the Loyalty oceanic basin (sections Fig. 1) (Collot et al., 1987, 1988; Cluzel et al., 2001). Ophiolites are well exposed in the southern part of the island, where they locally form 100% of the surface (Massif du Sud, Figs. 1 and 2). They also form a series of klippes, aligned in the N135 direction along the western half of the island (Fig. 1) (Guillon

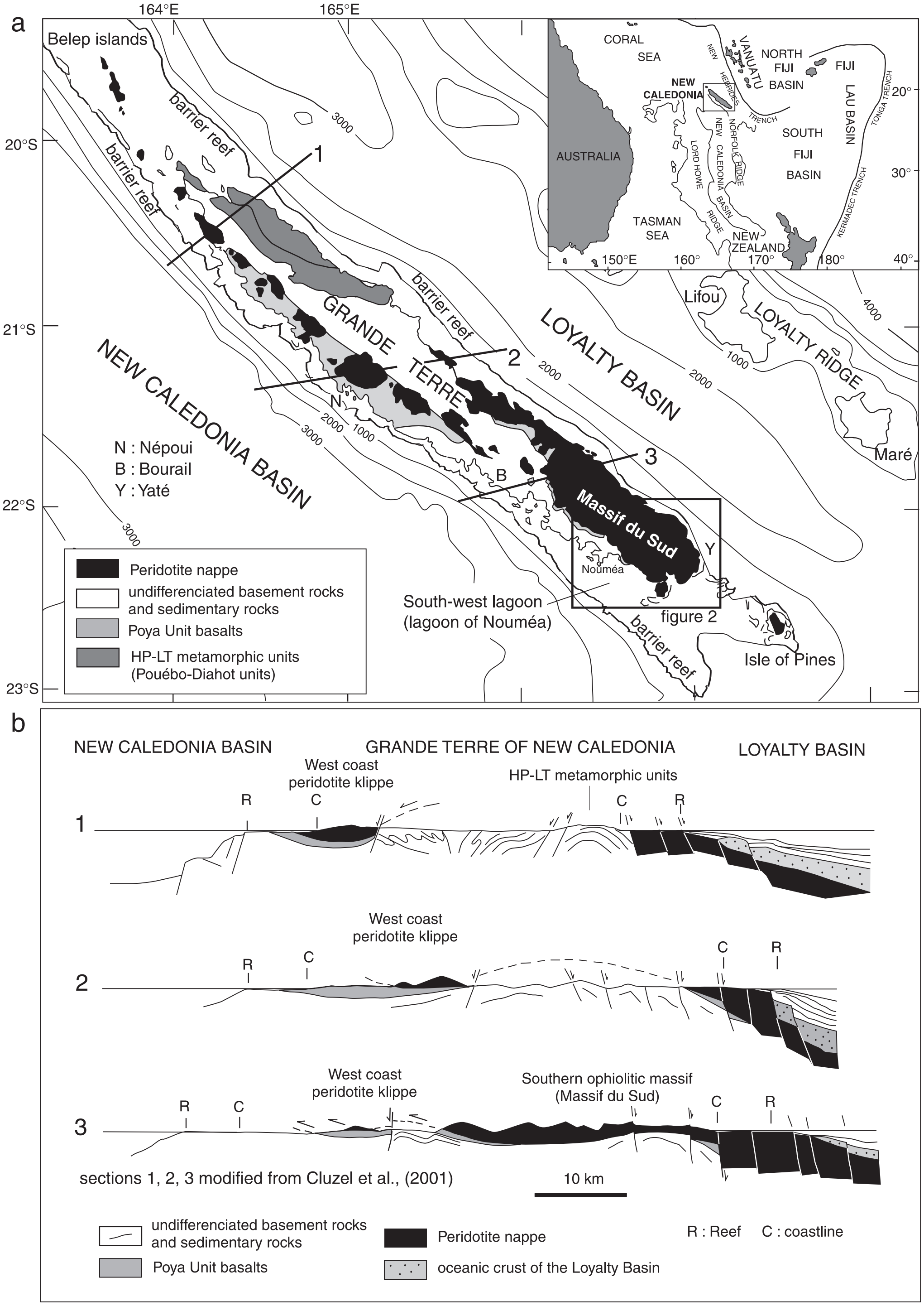

Fig. 1. a. Simplified geological map of New Caledonia showing the location of the main structural units discussed in text. b. Synthetical cross-sections 1, 2, 3, located in upper figure redrawn after Cluzel et al. (2001).

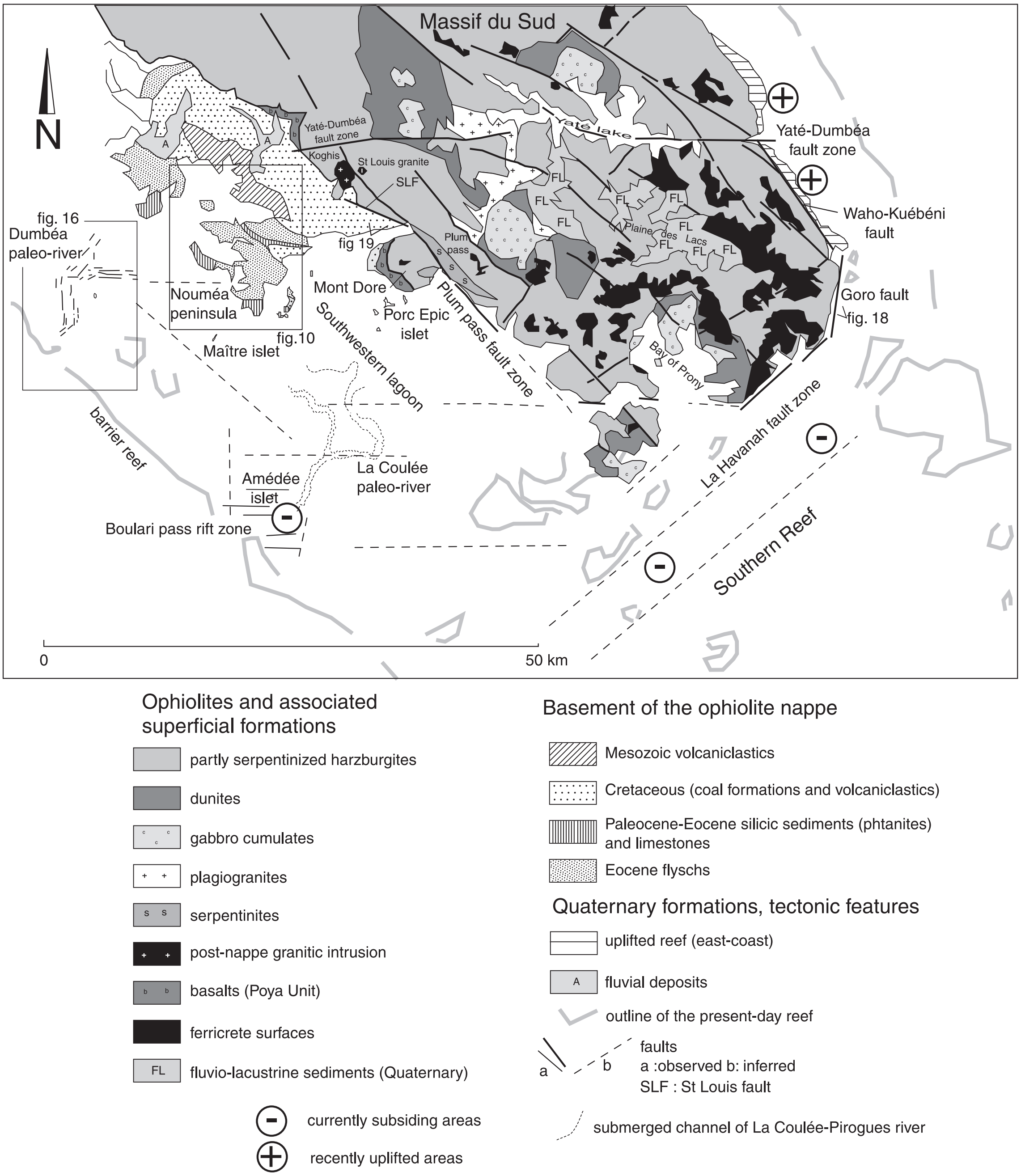

Fig. 2. Simplified geological map of southern New Caledonia. Location of areas of Figs. 10, 16, 18 and 19 is shown.

and Routhier, 1971). The ophiolitic sheet was emplaced during the Upper Eocene over units of continental affinity (Paris, 1981; Auzende et al., 2000), forming the New Caledonia block of Cluzel et al. (2001). This composite block consists of arc-derived terranes of Pre-Cretaceous age resulting from the complex evolution of the eastern Gondwana active margin. These terranes are unconformably overlain by sediments of Upper Cenomanian to Upper Eocene age. A tectonic unit of oceanic basalts of Upper Cretaceous to Eocene age, with back-arc or fore-arc affinities (Routhier, 1953; Paris, 1981; Eissen et al., 1998), named the Poya nappe following Cluzel et al. (1995, 1997, 2001), systematically underlies the ophiolite nappe. This unit is well exposed along the western coast of New Caledonia (Figs. 1 and 2) where it tectonically overlies the sedimentary rocks of Upper–Middle Eocene age (Paris, 1981).

The post-Cretaceous terranes of New Caledonia form two superposed sequences separated by an unconformity. The lower sequence includes sandstones, coaly siltstones and volcanic rocks of Upper Cretaceous age underlying discontinuous pelagic limestones, and hemipelagic cherts of Paleocene to Middle Eocene age (the Phtanites Formation). The upper sequence is a composite flysch formation of Upper Bartonian to Upper Priabonian age, the Nouméa–Bourail flysch, that was deposited after a short period of deformation and erosion over the former sequence (Routhier, 1953; Tissot and Noesmoen, 1958; Gonord, 1977; Paris, 1981). The Nouméa–Bourail flysch can be divided into four members, (a) basal neritic limestones (Uitoé member), (b) a "lower flysch" member of marls and calcareous sandy marls, (c) an "upper flysch" member composed of fine-grained calcareous turbidites interbedded with mafic breccias derived form the Poya nappe, coarsening upward into the (d) "wildflysch" member that progressively incorporates blocks and olistoliths of siliceous shales, limestones, basalts of the Poya nappe and flysch. It is topped by an olistostrome, well developed in the Nouméa Peninsula, representing the record of the Upper Eocene tectonic paroxism (37–35 Ma). These detrital sequences yielded microfauna ranging in age from Bartonian to Priabonian (Cluzel et al., 2001). In the region of Népoui (Fig. 1), a lateral equivalent of the Nouméa–Bourail flysch, the olistostrome-bearing Népoui flysch (Paris et al., 1979) that locally contains detrital serpentinites and minor peridotites (Coudray, 1976; Paris, 1981; Cluzel, 1998). The Népoui flysch lies stratigraphically over both the basalts of the Poya nappe and brecciated peridotites, and has been considered recently as originating from a piggy-back basin transported with the Poya nappe (Cluzel et al., 2001).

Predominantly mafic, high pressure–low temperature metamorphic rocks are exposed in northern New Caledonia where they form the Pouébo and Diahot units (Fig. 1) (Yokoyama et al., 1986; Black et al., 1993; Clarke et al., 1997, Aitchison et al., 1995; Cluzel et al., 2001). These units underwent a prograde evolution under eclogitic and blueschist facies conditions (20 kbar, 650 °C and 10 kbar, 400 °C, respectively) during the progressive underthrusting of the New Caledonia block beneath the Loyalty Basin oceanic lithosphere during the Eocene. They form an elongated foliation anticlinorium, a geometry similar to that of metamorphic core complexes. The foliation antiform is thought to result from rapid exhumation of the deepest eclogitic terranes or from contractional tectonics during renewed compression (Cluzel et al., 2001; Rawling and Lister, 2002). Radiometric dating of prograde and retrograde metamorphic assemblages from the Pouébo and Diahot units range from 40 Ma to 34 Ma (Aitchison et al., 1995; Baldwin et al., 1999), indicating that unroofing and exhumation of these metamorphic terranes occurred rapidly in the same time interval, as basalts of the Poya nappe together with the peridotites of the ophiolitic nappe were emplaced over the Upper Eocene flysch sequences in more external domains. Thus, there might be a relation between exhumation of deep crust in northern Grande Terre and overthrusting of the ophiolite sheet in southern New Caledonia.

New Caledonia is characterized by the lack of marine sediments of Oligocene age (Paris, 1981). Polymict fluvial conglomerates interlayered with shallow water marine limestones of Lower–Middle Miocene age are exposed in the region of Népoui (Fig. 1) (see references in Paris, 1981). They rest in erosional contact over the Népoui flysch. Weathered peridotites and fragments of ferricrust are found as important components of the conglomerates. This indicates that during the Lower Miocene and probably during the Upper Oligocene, subaerial weathering of the peridotites was active and led to the formation of thick alteration profiles and ferricrust.

As revealed by local thrusting and folding of the Upper Eocene flysch formations, crustal shortening occurred during, and slightly after, the ophiolite emplacement in southern and central Grande Terre.

The basal contact of the ophiolitic nappe is folded and locally cut by strike-slip faults, thus confirming post-nappe-emplacement compressive and transcurrent tectonics (Guillon and Routhier, 1971; Gonord, 1977). Acidic intrusions cutting through both the Cretaceous autochtonous sediments and the allochtonous peridotites at St. Louis, close to Nouméa (St. Louis granite in Fig. 2) yielded radiometric ages ranging from 32 to 24 Ma (K/Ar, Guillon, 1975). This confirms that obduction processes were completed at the end of the Oligocene. Compressional deformation ceased after the deposition of the Lower–Middle Miocene Népoui conglomerates which lack compressive folds and reverse faulting (Gonord, 1977; Paris, 1981).

3. Fault kinematics in the region of Nouméa with additional data from the region of Népoui: first evidence of post-obduction extensional tectonics

We measured stratification planes and sets of conjugate striated fault planes in various rock-types of the Nouméa region (14 measurement stations corresponding to 220 faults and associated striations), in the sheared serpentinites of the Plum Pass fault zone (1 station), and in the Miocene Népoui conglomerates (2 stations). Some stations in the region of Nouméa are located on islets within the lagoon (islets Uéré, Ngéa, Porc-Epic) (Figs. 2 and 10).

3.1. Data from the sedimentary formations in the Nouméa region

The region of Nouméa exposes sedimentary rocks of Mesozoic and Cenozoic age including (Fig. 2): (1) basal Liassic volcanoclastic, flysch-like deposits, representing here the basement of the New Caledonia Block, (2) Cretaceous sandstones associated with coal layers and volcanic rocks, (3) Paleocene–lower Eocene well-bedded limestones and cherts of the Phtanites Formation and (4) the Nouméa–Bourail flysch of Upper Eocene age. Good exposures are found along the coast as well as along numerous road cuts within and out of the town of Nouméa. The best preserved slickensides are found within the calcareous Nouméa flysch, but siliceous rocks (Liassic flysch, Cretaceous sandstones and Eocene–Paleocene phtanites) also display numerous exposures of fault surfaces. Outcrops of calcareous rocks always provide very good kinematic indicators such as calcite growth fibers and cristallization steps. Additional kinematic criteria of fault displacements such as drag folds, bedding offsets, and secondary Riedel faults are abundant in the well-bedded Eocene flysch and in the Phtanites Formation.

Compressional folds and reverse faults are frequently observed in Liassic, Cretaceous and Paleocene–Lower Eocene strata. They are less frequent in the flysch formation, but are locally well exposed as along the recent road cut near the toll gate of the VDE road (location at station 12 of Fig. 10), where a large knee fold with a N105 oriented axis and a south 20° plunge is present. This fold has an attitude consistent with thrusting direction of the ophiolite nappe from the NNE, as postulated by previous authors (Cluzel et al., 1997). Cretaceous sandstones close to the Mont Dore also display folding and associated schistosity related to the compressional phases. Here, fold hinges are oriented around N140 with plunges of 40° to the south. Well developed schistosity is oriented N150 SW 70, an orientation also consistent with compression in relation with thrusting of the ophiolites toward the SW. These compressional features are cross-cut by late, high angle normal faults with N130 strike. Other type of folds, devoid of associated schistosity, are present in the Phtanites Formation. They could have a synsedimentary origin.

In Liassic strata such as those exposed along the new road cuts north of the toll station of the RT1 road (main road from Noumea to the airport), the imprint of successive tectonic phases results in a complex pattern where compressional, strike-slip and extensional faults are observed within a series of continuous outcrops more than 100 m long each. For this reason, despite clear evidence of the presence of major extensional faults here, we did not use fault data collected in the Liassic formations to characterize the recent deformation regime.

Normal faults are observed in almost all exposures of the Nouméa Peninsula region. The most spectacular ones develop within the upper levels of the flysch sequence, such as some meters beneath the Cathédrale of Nouméa (Fig. 3). They locally

Fig. 3. Photograph of the Cathédrale normal fault cutting through beds of the Upper Eocene flysch (see location in Fig. 10).

form sets of conjugate planar faults or groups of listric faults. Conjugate normal faults are also frequently observed in the Phtanites Formation (Figs. 4 and 5). The strike of most of the measured fault planes ranges between N70 and N150, with only few faults having a N20 to N60 strike (Fig. 6a). Strike-slip faults characterized by pitch of striations lower than 20° have been observed in some places where they generally seem to represent late deformational features. They have N130–140 and N40–80 preferred orientations. Strike-slip faulting may be locally predominant such as at islet Porc Epic within the Phtanites Formation. Dips of normal fault planes generally range between 40° and 90°, with a maximum value between 40° and 60° (Fig. 6b). However, shallow dipping normal faults are present locally as examplified by the faults exposed along the VDE road (Fig. 7). Low angle faults are locally associated with high angle conjugate faults, suggesting late rotation of a former symmetrical conjugate system as in exposures at Rocher à la Voile (Fig. 8). Rotation of blocks during deformation is demonstra-

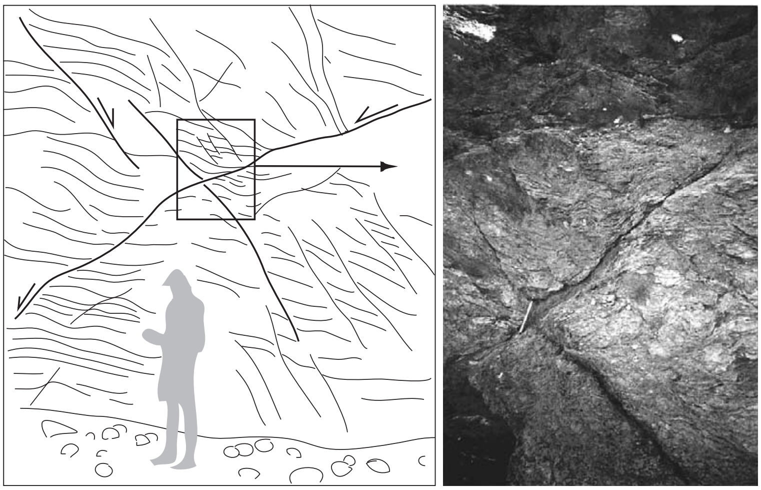

Fig. 4. Conjugate normal faults in the Phtanites Formation at Uéré islet (see location in Fig. 10).

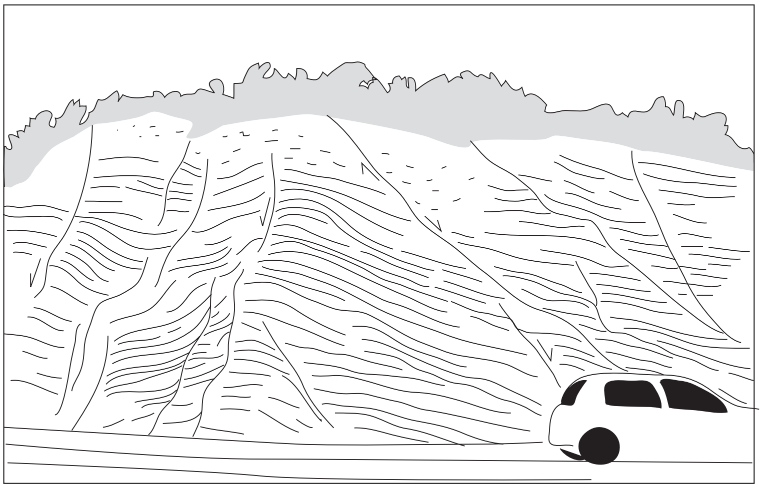

Fig. 5. Drawing of conjugate normal faults in the Phtanites Formation at la Côte Blanche (see location in Fig. 10).

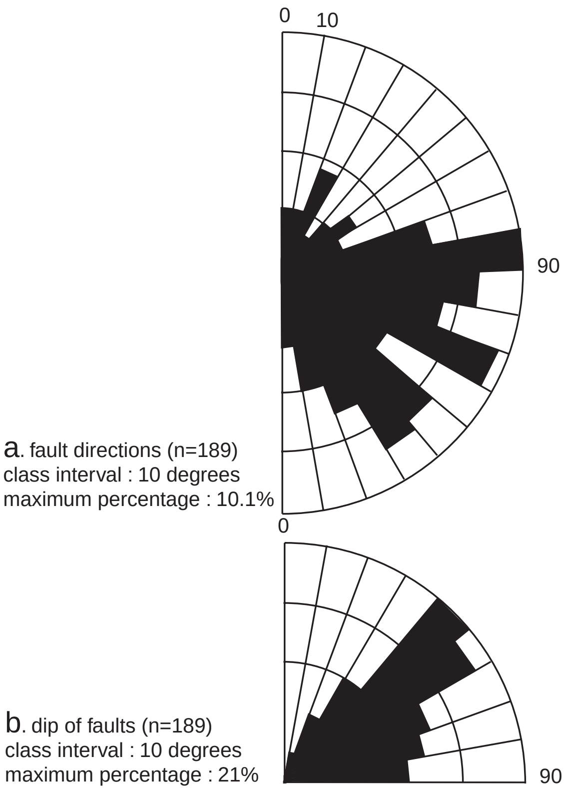

Fig. 6. Rose diagrams from fault and striation measurements in sedimentary formations of the region of Nouméa. (a) Strikes of faults, (b) dips of faults.

ted by the tilting of sedimentary beds. Such rotation may be considered as the consequence of displacement along a décollement surface located not far below, in upper crustal level (lower sketch, Fig. 8). Décollement surfaces are found as highly deformed levels of the Phtanites Formation, often few meters thick, characterized by horizontal schistosity in relation with intense shearing. Best exposures are observed at the base of the southern flank of Ouen Toro hill (orientation of lineation is N20, fault surfaces strike between N90 and N120, slightly dipping to the south, with C/S like shear structures and phacoids), and along the road cuts at the base of the Mont Dore klippe. Although they certainly represent a deformed zone that accumulated a great amount of displacement, we did not focus on such deformed levels because they do not allow to characterize the latest tectonic event with confidence. Indeed, shearing may have resulted from compressional deformation during the Upper Eocene phase (nappe emplacement), as well as from extensional deformation during post-obduction evolution. We may suspect finally that former basal thrust contacts have been used as décollements during further extensional evolution. This has been suggested earlier from similar observations in the Nouméa peninsula by Fromager et al. (1967).

We determined the shortening and stretching quadrants and the corresponding directions of principal strain axes from fault and striations

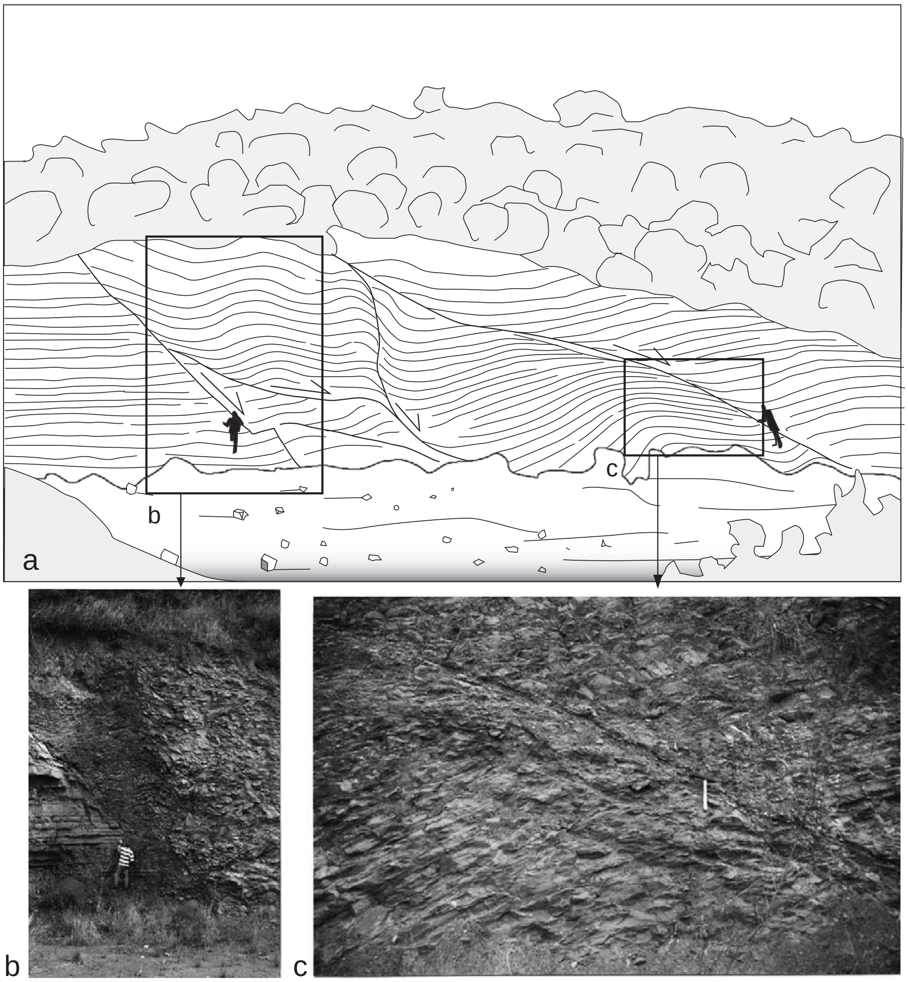

Fig. 7. Line drawing (a) and detailed photographs (b, c) of high- and low-angle normal faults cutting trough beds of the Nouméa flysch exposed along the VDE road-cut north of Nouméa (see location in Fig. 10).

analysis for the 14 localities in the region of Nouméa, using the geometrical method of the right dihedra (Angelier and Mechler, 1977) and a computer program written by one of us (MR). Additional processing has been made using the program "FaultKinWin" (Allmendinger, 2001). Results of kinematics analysis are presented as 14 stereonets in Fig. 9. Each stereonet shows the computed regions of shortening and extension. Results are reported on the map of the Nouméa Peninsula in Fig. 10 as simplified lower hemisphere stereonets showing the direction of maximum horizontal extension and the compressional quadrant. In almost all localities where late normal faults have been observed and measured, the final strain pattern is dominated by vertical compression and horizontal stretching. The axes of compression, contained within the black areas in stereonets of Fig. 10 are generally close to the vertical. The axes of horizontal stretching do not show coherent trends, indicating that the direction of maximum extension is variable at the scale of the region.

3.2. Data from the ophiolite nappe

Kinematic data related to the recent brittle deformation of the ophiolites are very scarce, and no comprehensive study allowing an overview of the

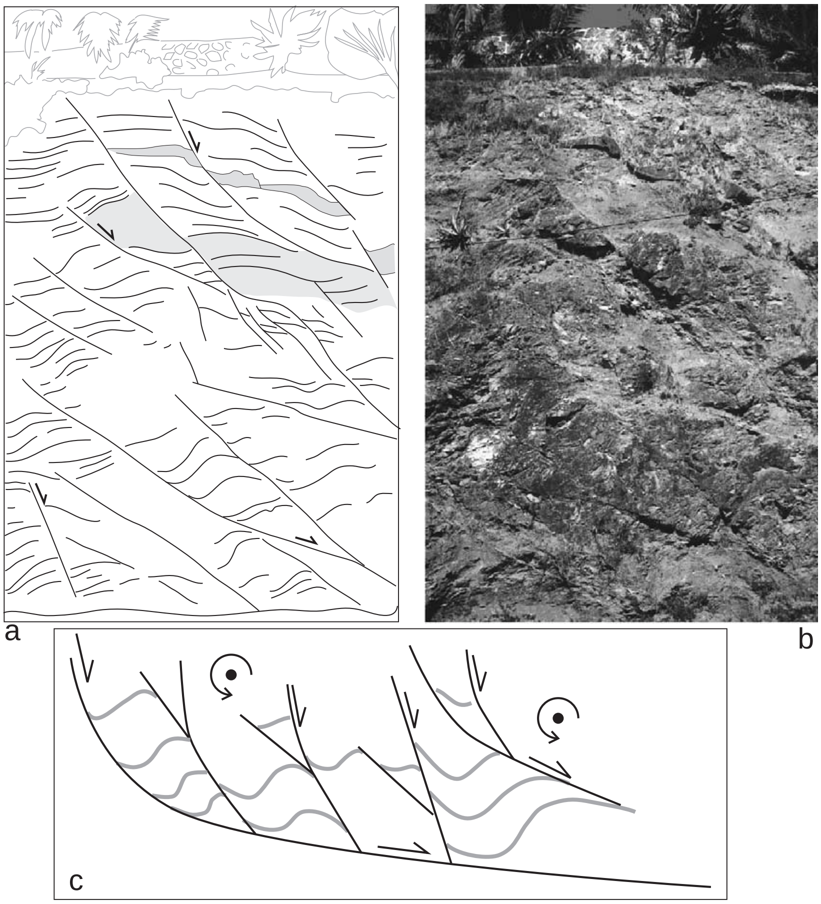

Fig. 8. a, b. Photographs and line drawing of a set of rotated conjugate normal faults in the Nouméa flysch exposed along the road-cut at Rocher à la Voile (see location in Fig. 10). c. Cartoon depicting the hypothesis of block rotation involving displacement along a deeper low-angle detachment.

post-emplacement tectonic fabric of the entire ophiolite nappe is available. The brittle tectonic fabric of the peridotite nappe and the impact of faulting on the distribution of the nickel-bearing saprolites have been studied by Leguéré (1976) in restricted regions along the ophiolite belt, mostly within serpentinites. This preliminary study shows that the last deformational event that affected the peridotites was an extensional phase of probable Miocene age, characterized by normal faulting, following a post-obduction phase of Oligocene age characterized by strike-slip deformation. Spectacular extensional listric faults have been reported from different localities within the ophiolites, such as in the Surprise Mine (Népoui region). Axes of late horizontal extension obtained by Leguéré (1976) are reported in Fig. 11. Recent work by Vigier (2001) and Cluzel (pers. comm.) in central New Caledonia are consistent with these results. Authors show that the Ni-rich garnierite mineralization from ophiolite bodies developed within vertical veins opening in response to horizontal extension. These data tend to demonstrate that the ophiolite nappe has been subjected to extensional deformation leading to normal faulting in a similar way as the autochthonous terranes in the region of Nouméa.

In order to obtain additional data from the peridotite nappe in the Nouméa region, we measured faults and striae within the Plum pass fault zone. Striations belong to two main groups: a group of mostly horizontal striations indicating strike-slip displacements and a group of high-dip striations. Despite extremely abundant slickensides, only very

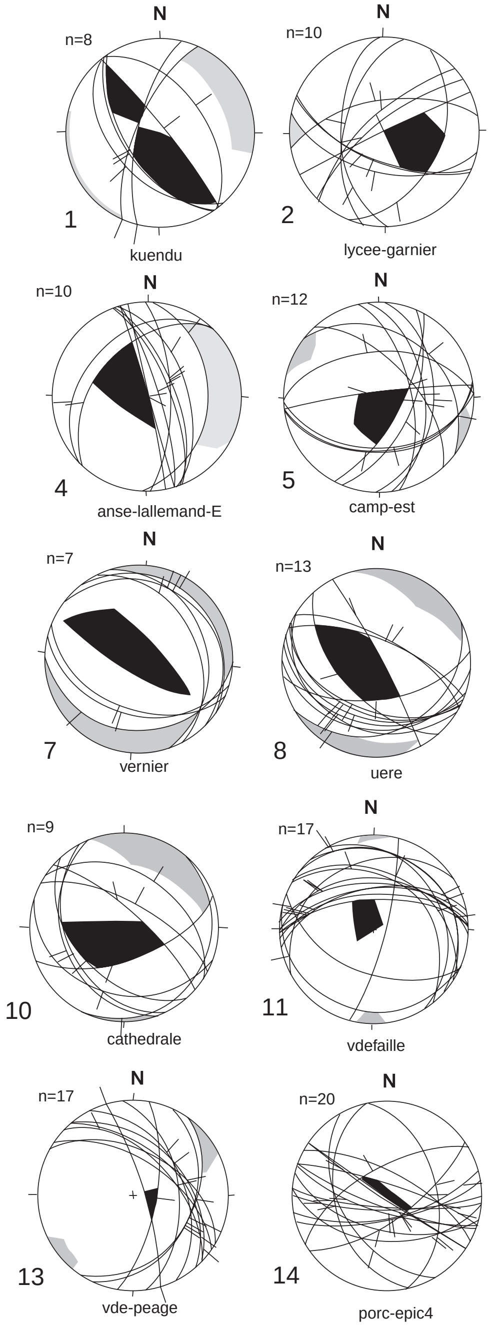

Fig. 9. Stereograms of fault and striation measurements for 14 sites in the region of Nouméa (see location in Fig. 10) (lower hemisphere).

few exposures provide confident displacement criteria. Stereodiagrams of Fig. 11 show that the average strain pattern is of extensional type with the direction of main stretching axis trending NE–SW, consistent with results obtained in the Noumea region.

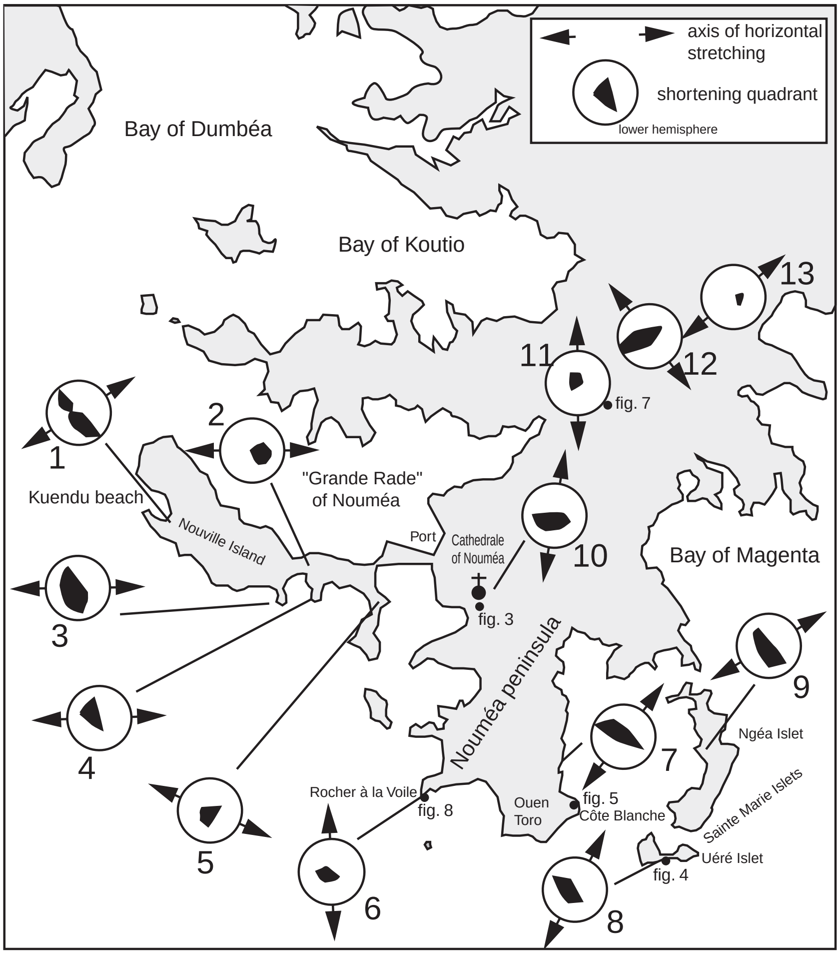

Fig. 10. Map of the region of Nouméa showing the location of the microtectonic measurement sites. For each site, the state of final strain is indicated by arrows (direction of horizontal stretching) and a black quadrant (direction of vertical shortening) (lower hemisphere).

3.3. Dating and duration of the extensional phase: preliminary constraints from the Népoui region

Evidence of normal faulting affecting both the ophiolite sheet and the Cretaceous–Upper Eocene sedimentary beds of the Nouméa Peninsula confirms that extensional deformation occurred after the main obduction phase. However, there are no direct constraints allowing precise dating of the extensional events in the Nouméa region. Additional age constraints can be obtained in the Népoui Peninsula, the only place along the coast of New Caledonia where Miocene deposits are present (Fig. 1). Exposures along the road to the Népoui Peninsula exhibit normal faults cutting through the Népoui conglomerate beds. Faulting was accompanied by block tilting as shown in Fig. 12. Stereonets from two different closed localities (Népoui 1 and 2) are reported in Fig. 11. Measurements at station Népoui 1 are made on slickensides of the main fault zone shown in Fig. 12, composed of a set of roughly parallel minor faults. Measurements at station Népoui 2 are made close to the contact between the conglomerates and the underlying Népoui flysch. Both diagrams show horizontal stretching. Axes of maximum extension do not have similar orientations, because station Népoui 1 focuses on a single fault zone. These features demonstrate that extensional deformation was initiated here after the deposition of the Lower–Middle Miocene Népoui

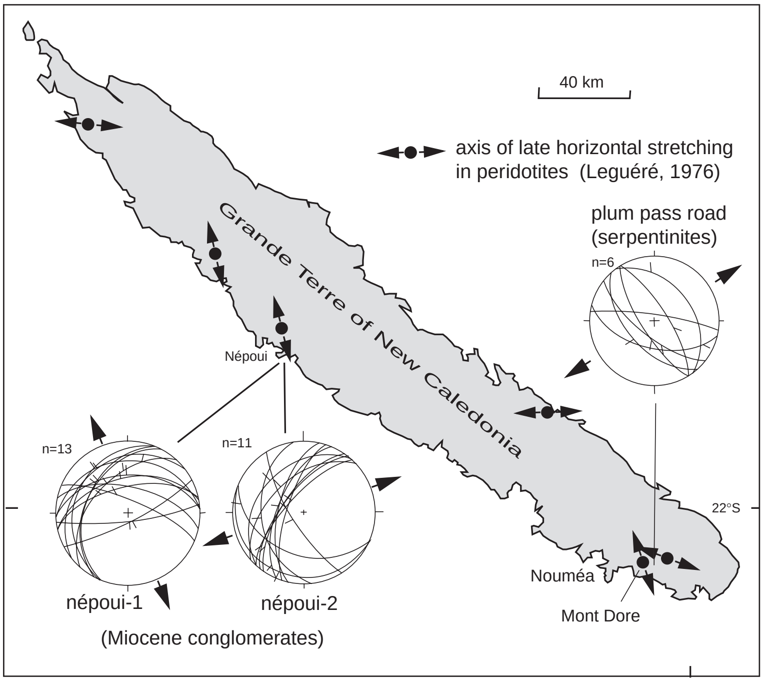

Fig. 11. A compilation of available microtectonic data at the scale of New Caledonia obtained from a former study in the peridotites by Leguéré (1976) and from this study (stereograms of Népoui and Plum pass road).

conglomerates. This is a lower age limit for the initiation of the extensional events in this region. Extension might have started before in some other places. In any case it may have lasted after the Middle Miocene.

3.4. Causes of extensional deformation: preliminary hypothesis

Various hypotheses accounting for the dispersion of the axis of horizontal stretching evidenced above can be proposed. Before all, it must be said that we lack further data allowing to clearly detect possible superimposed deformations. Extension might have occurred during successive independent phases with various orientations of their main stress axis, leading to the present-day deformational pattern. Additional age constraints are needed in order to better characterize the timing of these extensional events.

Whatever the case, the average final strain pattern of the region can be regarded as the result of multidirectional flattening. In the case of New Caledonia, regional extension should be driven by vertical uplift, a process consistent with isostatic response due to crustal thickening and ophiolite obduction. Similar deformation occurred in the Semail ophiolites of Oman and within their tectonic basement, immediatly after the obduction (Goffé et al., 1988; Michard et al., 1994; Gray and Robert, 2000). Vertical uplift and subsequent extension have been active in the northern part of the Grande Terre, and led to exhumation of deep crustal levels and to a considerable amount of vertical displacement (40–60 km) as reported in Section 2. From the results presented here, we may suggest that isostatic response to obduction also caused late normal faulting in southern New Caledonia, from Népoui to the Nouméa region. Evidence for the existence of underthrusted low density rocks at depth has been given by Régnier (1988), from the analysis of teleseismic P-waves recorded at Nouméa. The author shows that a north-dipping abnormal low velocity zone is present at approximately 60 km depth below southern New Caledonia. This anomaly is interpreted as the result of underthrusted sediments or oceanic

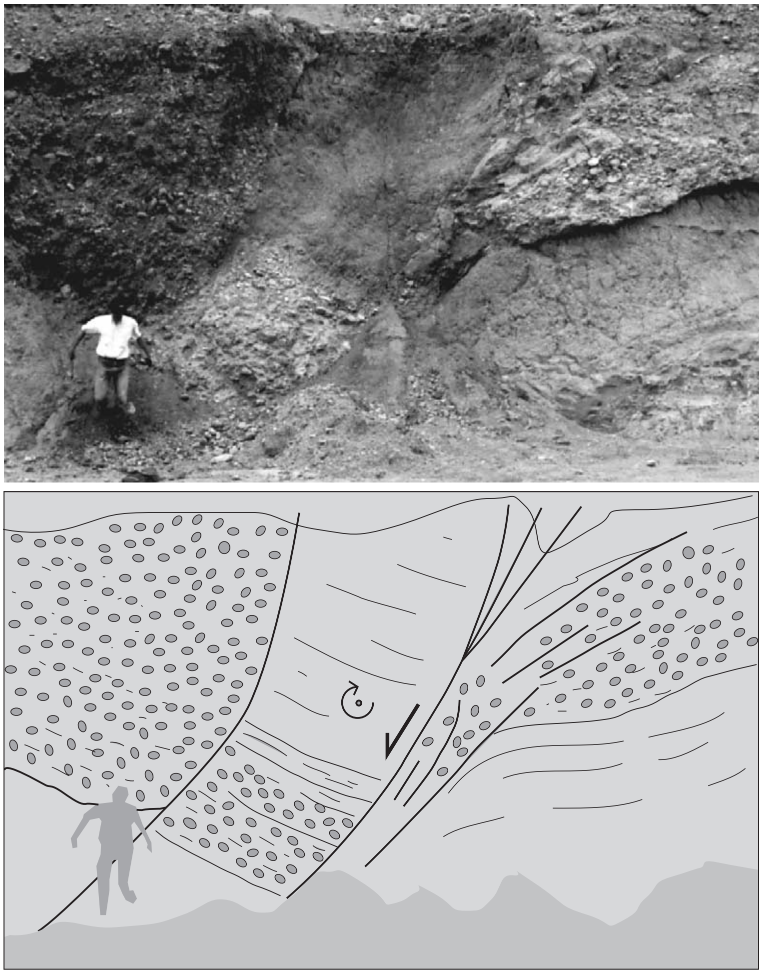

Fig. 12. Photograph and interpretative line drawing of a group of normal faults cutting through the Miocene conglomerates at Népoui. See corresponding stereograms in Fig. 11.

crust within the mantle resulting from the Upper Eocene compression.

4. Analysis of seismic reflection profiles in the SW Lagoon

The microtectonic results presented above reveal that post Middle–Miocene horizontal extension played an important role in the tectonic evolution of southern New Caledonia. Therefore, we may wonder if recent tectonic features, or even active features, related to extension can be observed in the surveyed region. The best place for an investigation of such possible recent and active faulting is the southwestern lagoon of New Caledonia which displays the most recent comprehensive sedimentary record in the region.

We have interpreted seismic lines shot during the ZoNéCo 7 cruise (11–25 June, 1999 aboard R/V Dawa) (Lafoy et al., 2000) offshore the Nouméa Peninsula, in order to investigate recent structures that could be compared to the tectonic features evidenced from the fault analysis reported above. The SW Nouméa lagoon has an average depth of 20–30 m. It was invaded by the sea for the last time during the beginning of the current interglacial period, around 6 ka ago. The morphobathymetry of the study area is dominated by two NW–SE trending ridges, the Signal–Snark–Amédée ridge to the west, and the Sèche Croissant–Maître ridge, to the east (Fig. 13). These two reefal ridges are cross cut north and south by submarine canyons. Those canyons respectively correspond to the Dumbéa channel, ending at the Dumbéa pass that shows a sigmoïd morphology with N–S and SW–NE trending segments, and to the northern arm of the Boulari pass that deepens southwestward with a N–S trend. Rivers were flowing within these valleys during the last glacial maximum.

The ZoNéCo 7 cruise acquired about 900 km of swath-bathymetric and shallow seismic reflection data, with Differential Global Positioning System (Lafoy et al., 2000). The cruise surveyed 220 km^2 of the outer lagoon, within an area that extends, from north to south, from the Dumbéa to the Boulari passes, and from west to east, from the Abore Reef to the eastern edge of the Sèche Croissant–Maître ridge. This set of data provides better understanding of the recent tectonic and sedimentary evolution of the southwestern lagoon located between the two passes, as briefly reported in Lafoy et al. (2000). The seismic record generally exhibits three to four well defined reflectors (Fig. 14). The upper reflectors can be interpreted as the result of interglacial stage and/or subsequent emersion surfaces between two interglacial periods. In response to glacio-eustatic pulsations, the duration of these interglacial events is around 100 ka (1 ka = 1000 years). Reflector 1 therefore corresponds to the high sea level, isotopic stage 5 (125 ka) and to the subsequent emersion phase extending from this last interglacial to the Holocene (10 ka). This emersion surface is observed at – 11 m and – 12 m in the Ténia and Amédée boreholes, respectively, that have been drilled previously through the main barrier

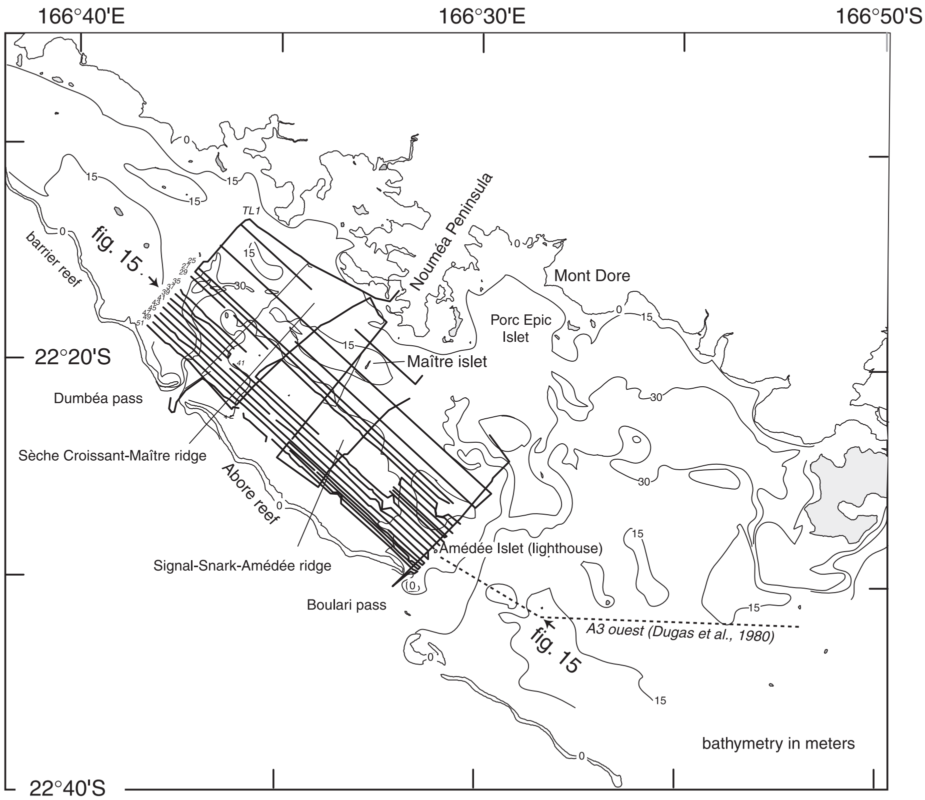

Fig. 13. Bathymetry of the Nouméa lagoon based on a compilation by P. Douillet (personal communication) and location of the seismic lines shot during the ZoNéCo 7 cruise (Lafoy et al., 2000) and line A3ouest (Dugas et al., 1980) (numbers of lines in italic; black arrows indicate the location of seismic section shown in Fig. 15).

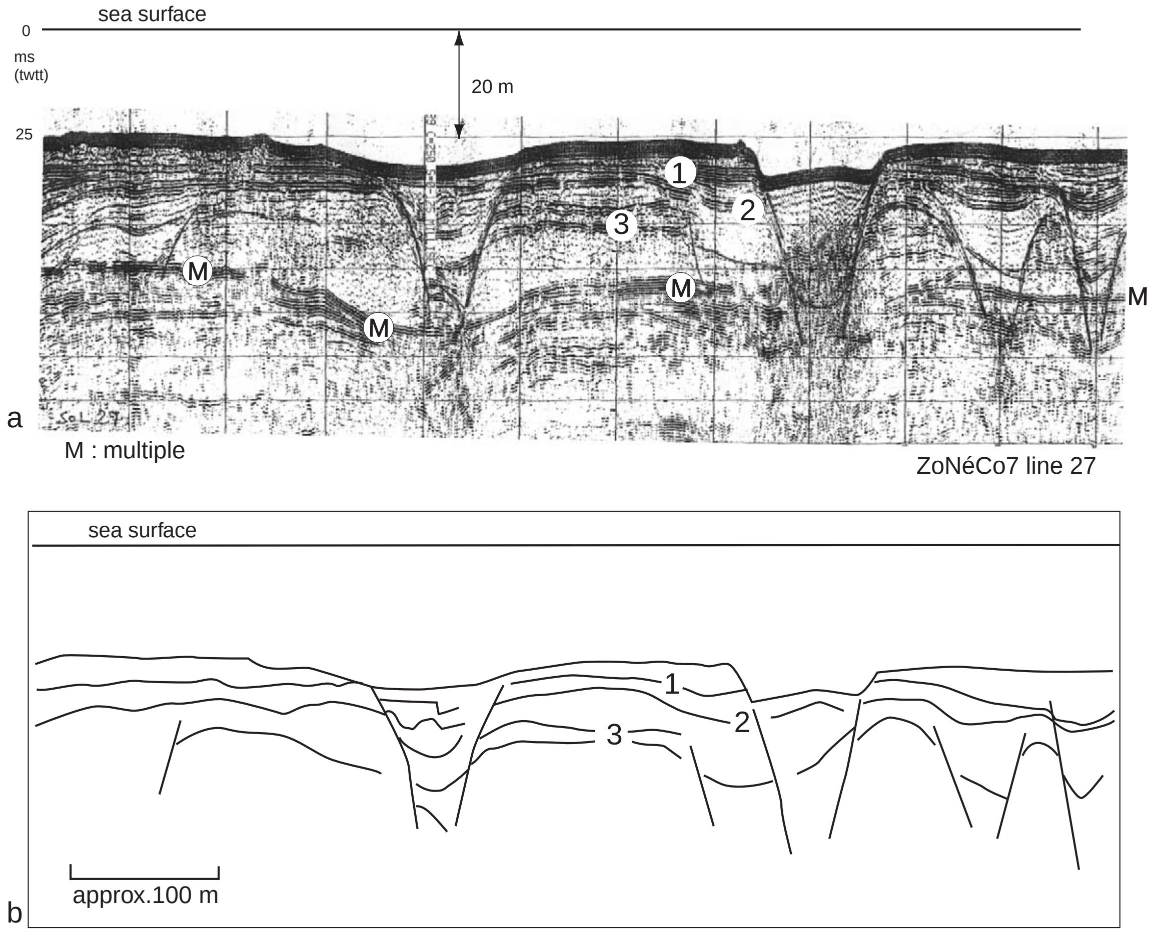

Fig. 14. An example of seismic line (a) and corresponding line drawing (b) acquired during the ZoNéCo 7 cruise (Lafoy et al., 2000). Interpretation of seismic reflectors 1, 2, 3 is given in text.

reef (Cabioch et al., 1996). In the same way, the reflector 2 can be attributed to the high sea level of isotopic stage 7 (220 ka) and/or to the subsequent emersion between 22 ka and 125 ka, as dated in the boreholes drilled at Amédée islet. Reflector 3 therefore could correspond to older high sea level-subsequent emersion surface between the interglacial periods of 220 and 330 ka or more probably, to the unconformity between the basement (including sedimentary rocks, basalts of the Poya nappe or peridotites) and the modern lagoon sedimentary infill (Coudray, 1976, 1977; Lafoy et al., 2000).

Fig. 15 shows a line drawing of the most complete seismic section available in the lagoon. It is a composite section including profiles of the cruise ZoNéCo 7 and an older line shot across the Boulari pass canyon (Dugas et al., 1980). This profile is parallel to the main trend of the Sèche Croissant–Maître ridge and shows a 20 km long portion, characterized by parallel, horizontal reflectors (reflectors 1 to 3), devoid of any sedimentary or tectonic disturbances. However, at both western and eastern ends of the section, the regions of the Dumbéa canyon and Boulari pass show evidence of paleofluvial incisions, and apparent faulting and block tilting in relation with possible recent deformation.

We focused our interpretation on the series of seismic profiles that cross-cut the Dumbéa river paleochannel (Fig. 16). Line drawings of these profiles are presented in Fig. 17. Reflectors 1 to 3 have been

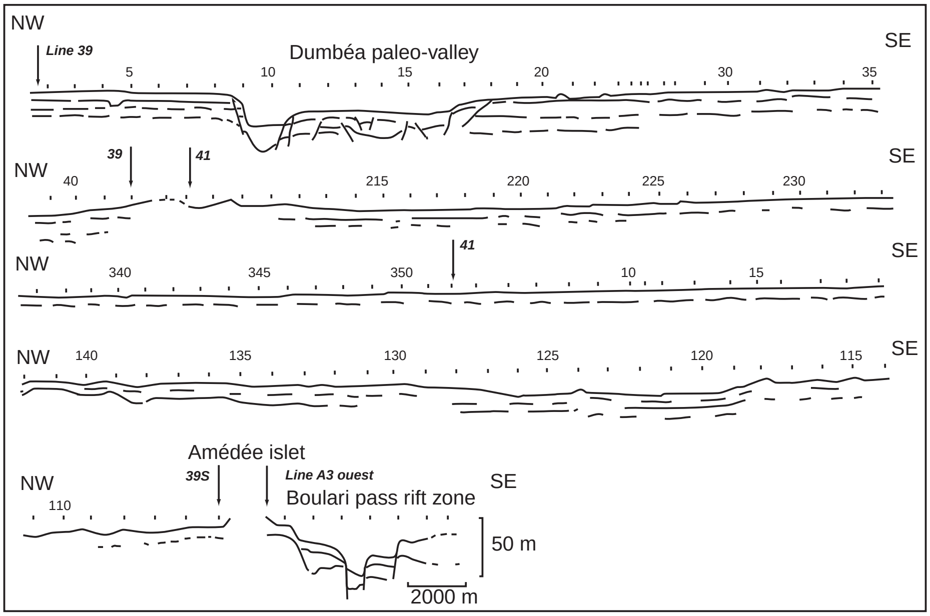

Fig. 15. Line drawing of the most complete seismic section available in the Nouméa lagoon. This section includes profiles of the cruise ZoNéCo 7 (39 and 41) and an older line shot across the Boulari pass canyon (Dugas et al., 1980). It shows a 20 km long portion, characterized by parallel, horizontal reflectors devoid of any sedimentary or tectonic disturbances. At both western and eastern end of the section, the regions of the Dumbéa canyon and Boulari pass show evidence of paleofluvial incisions, and faulting and block tilting in relation with active deformation.

represented. All profiles exhibit similar features including river incisions, channel infill and vertical offset of reflectors strongly suggesting tectonic control on the development of fluvial features by high-dip to vertical faults located within a narrow deformed area. Morphological features such as canyon flanks are associated with faults, as inferred from offsets of main reflectors. These faults locally cross-cut basement rocks. Close to the present-day canyons, buried canyons are also observed. The limit of fossil and current canyons can be easily correlated from one profile to the other and correspond to rectilinear scarps imaged by swath bathymetry (Lafoy et al., 2000), suggesting that they are controlled by faults (Fig. 16). They form groups of segments with N90, N40, N0–10 and minor N140 orientation, delineating the subsiding area of the Dumbéa fault zone. The Dumbéa pass itself, also corresponds to structural inherited features, with a strong tectonic control. The flanking normal faults control the migrations of the paleochannel and the building-up of the associated sedimentary levees. Along some profiles, the main channel appears to be relatively wide and corresponds to the juxtaposition of narrower channels that evolve toward a larger depressed area after tectonic collapse of a central horst. There are no recent seismic lines across the Boulari canyon, but according to the available profile that shows faulted blocks forming successive steps toward the pass axis (Dugas et al., 1980, Fig. 15), we may infer that a similar active deformed zone is controlling the bathymetry of the pass (named here the Boulari pass rift zone). However, by contrast to the Dumbéa fault zone, the Boulari rift zone is trending E–W, with fault having a N90 overall orientation.

As the region has undergone multiple tectonic events, it is highly fractured. Therefore, all the quaternary faults observed here are probably reactivated faults. They develop within restricted deforming zones bounding undeformed blocks, 30 km–40 km wide. These zones are clearly oblique to the main N140 trend of the island. Therefore, there is no apparent link between the geometry of the extensional system described in the sedimentary basin of Nouméa with dominant N140 direction, and the active system in the lagoon. However, the fault pattern controlling the paleorivers in the SW lagoon includes directions also typical of lineaments observed in southern New Caledonia (N90, N40, N0–10) as shown in Fig. 2. The

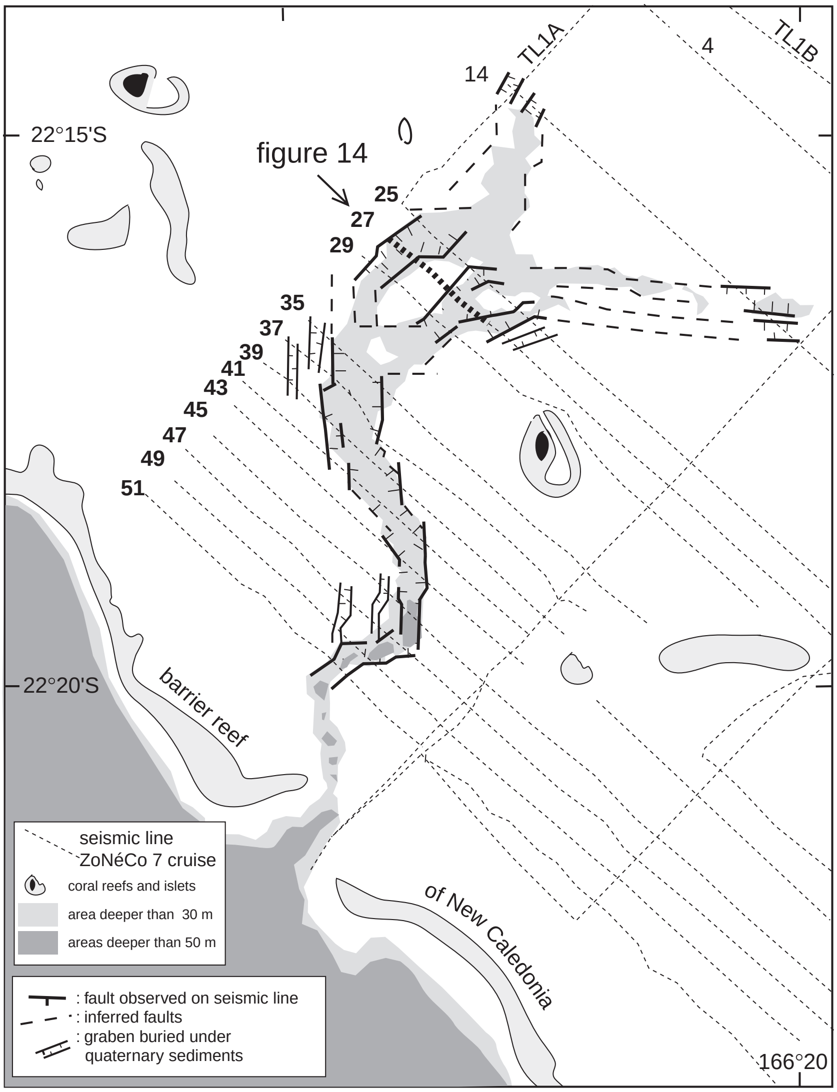

Fig. 16. Location map and structural interpretation of the western region investigated during the ZoNéCo 7 cruise (Lafoy et al., 2000) over the submerged paleo-valley of the Dumbéa river in the Nouméa lagoon. Detailed interpretation of seismic lines is given in Fig. 17.

size of blocks delineated by these recent faults is also similar to that of tectonic blocks in the Massif du Sud.

5. Discussion: comparison with previous results emphasizing the neotectonic evolution of New Caledonia

This study relates the occurrence of normal faults and associated minor strike-slip faults within terranes of various ages including pre-, syn- and post-obduction deposits and ophiolites in the region of Nouméa. These new data are consistent with former results from different sources showing that the Grande Terre has undergone, and is still undergoing, a post-obduction evolution characterized by block faulting and differential vertical motion of its western and eastern margins. These results are summarized and discussed in the following three sub-sections.

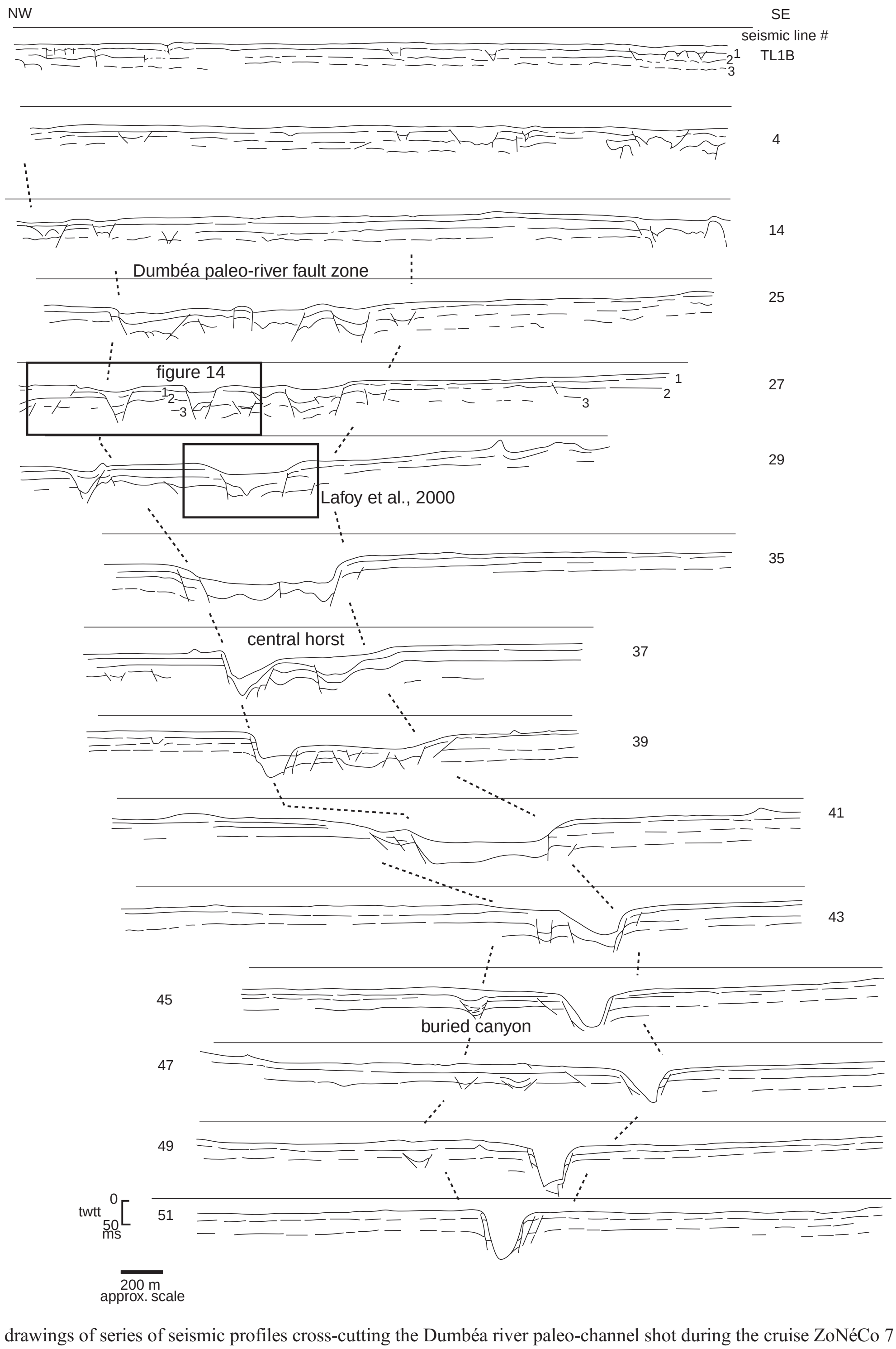

Fig. 17. Line drawings of series of seismic profiles cross-cutting the Dumbéa river paleo-channel shot during the cruise ZoNéCo 7 (Lafoy et al., 2000) (see location of lines in map Fig. 16). Reflectors 1 to 3 have been represented (see text for further details).

5.1. Tectonic lineaments in the region of Nouméa and present-day seismicity

Studies of continental surfaces and observations of submerged coastal reliefs brought evidence that New Caledonia is composed of independent blocks that underwent recent differential motions and tilting. Lineaments trending N130–140, that is, parallel to the axis of the Grande Terre, have always been recognized as major tectonic elements along which differential displacements or progressive flexures have occurred (Guillon and Routhier, 1971; Gonord, 1977; Dugas and Debenay, 1978; Paris, 1981). Successive stages in the morphogenetic evolution of New Caledonia including periods of peneplanation, uplift and fluvial incisions have been evidenced by numerous authors, but age constraints for the successive events still remain unavailable (Davis, 1925; Avias, 1967; Routhier, 1953; Trescases, 1973; Latham, 1974, 1986; Coudray, 1976; Gonord, 1977). A first phase of tectonic disruption following peneplanation probably occurred during the Lower and Middle Miocene as shown by the presence of ferricrust debris in the Népoui conglomerates. In the central chain of Grande Terre, the former peneplain is highly dissected and only small remnants of ferricrust are preserved. By contrast, very large regions of undisrupted ferricrust surfaces are well preserved in the southern part of Grande Terre (Fig. 2).

Tectonic lineaments of the southern part of New Caledonia trend N140, N90, N50 and N0–10, as reported in Fig. 2. Some of them correspond to major fault zones limiting tectonic blocks as demonstrated by basement offset. The major lineaments are the Yaté–Dumbéa fault zone, the Plum pass fault zone and the Havanah fault zone. Suspended valleys and triangular facets indicating recent vertical displacement along high angle faults are observed along the southern shoreline of New Caledonia, as exemplified by the N10 trending scarp of the Goro fault exposing peridotites. The fault scarp also cuts a comprehensive weathering profile including the ferricrust upper layer, still preserved on top of reliefs (Fig. 18). This confirms that important tectonic disruption occurred after a first phase of peneplanation with development of thick weathering profiles. Although these scarps seem to be very recent and close to active fault zones such as La Havanah fault zone (see below), no accurate dating of faulting can be proposed at present.

As noticed by previous workers (e.g. Guillon and Routhier, 1971; Gonord, 1977; Paris, 1981), the western tectonic boundary of the ophiolites in southern New Caledonia is rectilinear with a N140 overall trend and cannot correspond to a simple erosional front of the peridotite nappe, at least from mapping

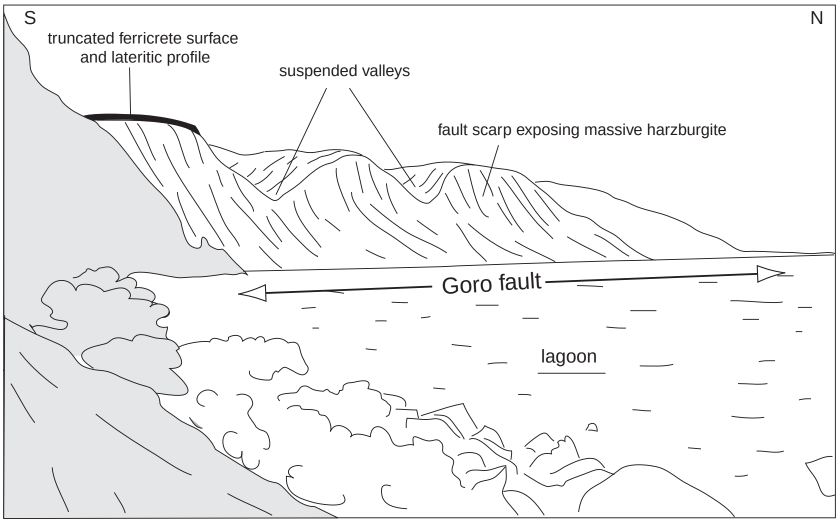

Fig. 18. A drawing of the panorama of the Goro fault scarp from the south showing suspended valleys and truncated lateritic profiles on top of reliefs, indicating recent age of the fault.

considerations. This feature has been interpreted as a flexure-fault by Guillon and Routhier (1971), but since this work, no additional geological data have been published concerning this major boundary. Based on preliminary field investigations, we noticed that near St. Louis, the contact between the ophiolites and the sedimentary basement (Fig. 2) clearly corresponds to a major scarp, 600 m high. It trends N115, and shows a succession of triangular facets (Fig. 19) which can be interpreted as the morphological expression of the presence of a major fault, dipping to the west (SLF, St. Louis fault in Fig. 2). This interpretation is consistent with the hypothesis that the frontal part of the ophiolite nappe has been subjected to a tectonic rejuvation implying normal faulting. The Plum pass fault zone is also a major fault zone trending N140–160, almost vertical, and cutting through intensively serpentinized peridotites separating the Mont Dore peridotite klippe from the main ophiolite nappe. This fault zone is a few hundred meters thick and is well exposed along the main road from Nouméa to the Plum pass. It displays evidence

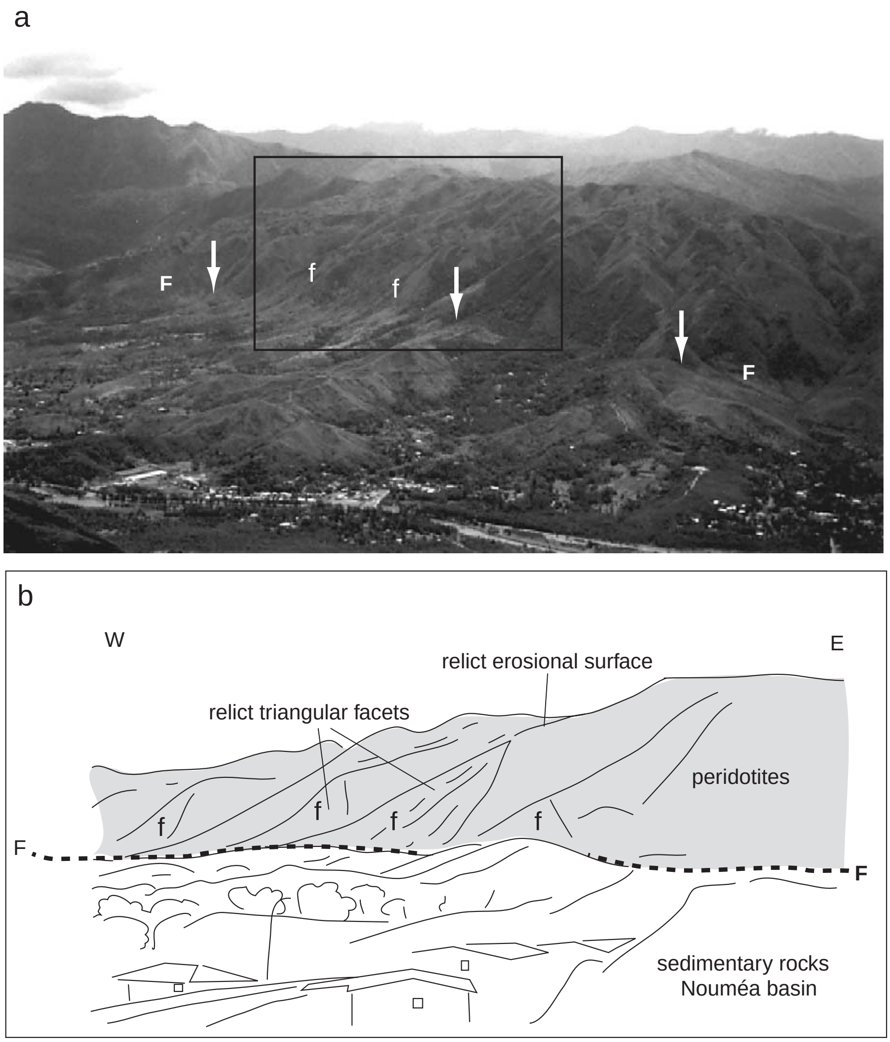

Fig. 19. a. View of the Saint Louis fault (white arrows) from the summit of Mont Dore (photograph by J.F. Sauvage). b. Drawing of the area shown in the frame of upper photograph taken from the road of Nouméa to Mont Dore town. F: fault separating the ophiolites from the Mesozoic sediments, f: relict triangular facets.

of strike slip and normal displacements as shown in Section 3.2. Its southern continuation marks the western limit of the ophiolites, from the Mont Dore to the Ouen Island (Fig. 2). The main west facing scarps of the Mont Dore and Koghi massifs, corresponding to the geological boundary between the ophiolites and the sedimentary formations, also exhibit rectilinear outlines. They are characterized by the presence of thick breccia formations composed of fragments of serpentinized and weathered peridotites, locally including hydrothermal silica veins exhibiting faulted surfaces and striations, named the Koghi breccias. As observed along the western face of the Mont Dore, the breccia layers are roughly parallel to the scarp (dips to the west with angles of 30° to 50°) and are affected by place by intense faulting and shearing. The breccias are locally more than 100 m thick and in some places, they display the characters of cataclastic breccias (Lagabrielle and Chauvet, in preparation). They could be the product of fragmentation during either (a) major gravity instabilities involving entire slopes of the peridotite massifs, as frequently observed within the ophiolitic unit itself or (b) shearing due to normal faulting and later exhumation along a major detachment fault during a post-obduction extensional phase, an hypothesis suggested by earlier studies (Leguéré, 1976), and which has been considered in a conceptual structural model in Fig. 21a.

Some of the tectonic lineaments described in southern New Caledonia are active tectonic features. Indeed, even if considered as an area undergoing low-rate deformation, the New Caledonia territory experiences a significant seismic activity, both on land and offshore (Régnier et al., 1999). Almost all of the reported activity located on the New Caledonia/Norfolk Ridge falls in the small magnitudes range (<5). Small earthquakes recorded by local network are shown on the seismicity map in Fig. 20 (Régnier et al., 1999). The earthquake distributions show N140–160° trending alignments of epicenters mainly within the peridotite nappe down to a region very close to the city of Nouméa. In all seismic zones, shallow depths of events (<5 km) were found. To the south, a permanent cluster is located in the straight between the Grande Terre and the Isle of Pines, within the western lagoon. This swarm is coincident with the ISC epicenters of the only two medium size earth-

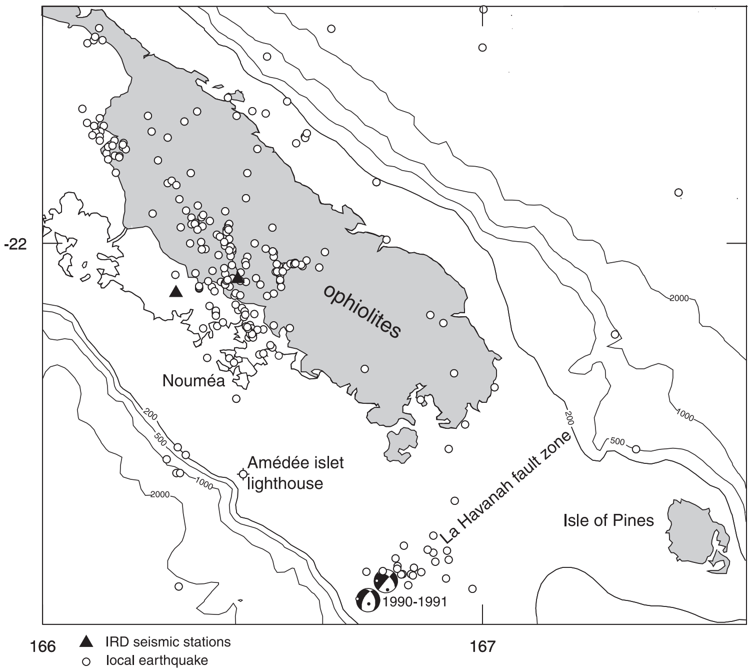

Fig. 20. Seismicity map of southern New Caledonia (Régnier et al., 1999). Note the two medium size events and the cluster of minor events delineating the southern part of the Havanah fault zone.

quakes (Mb 5.1 and 5.6, 1990 and 1991 along the reef barrier offshore Nouméa) located within the New Caledonia ridge over the last 30 years. The consistency of these two independent data sets confirms the presence of an active seismic zone in the southern part of Grande Terre, named the Havanah fault zone (Figs. 2 and 20). The two large earthquakes have CMT solutions from Harvard with T axis in the east–west direction. In both mechanisms one nodal plane is oriented N45° through the southern straight, normal to the Grande Terre axis, in agreement with the N45° trending shape of the seismic cluster. Moreover this seismic zone is located to the southwest of the N45° trending La Havanah lineament (Fig. 2) that bounds the southern coast of the Grande Terre, suggesting that both events occurred on the same fault zone running through the entire width of the New Caledonia ridge. This fault zone corresponds to an actively subsiding corridor, separating the Grande Terre from the uplifted Isle of Pines where uplift rates of 0.1 to 0.2 mm/year have been calculated for the last glacial period (Dubois et al., 1974).

5.2. Offshore data

Offshore seismic studies have confirmed that the tectonic evolution of both the eastern and western margins of the Grande-Terre of New Caledonia is controlled by normal faulting following the major phase of ophiolite obduction (Dugas and Debenay, 1978; Bitoun and Récy, 1982; Rigolot and Pelletier, 1988; Collot et al., 1988; Van de Beuque, 1999). Seismic lines perpendicular to the western margin of New Caledonia show that the deep continental slope consists of a sedimentary accretionary wedge, a possible remnant of the upper Eocene convergence (Rigolot and Pelletier, 1988). Authors state that compression may have lasted during the Oligocene. The sedimentary wedge is cut by more recent normal faults marking the main bathymetric steps of the upper margin. Seismic lines at the northeastern border of New Caledonia, in the Loyalty Basin, have shown that the dominant features of the recent margin evolution are normal faults paralleling the mean direction of the island (Bitoun and Récy, 1982). To the south, the western edge of the Loyalty Basin consists of three steps separated by faults (Dugas and Debenay, 1978). Dredging results south of the Isle of Pines have revealed that Miocene shallow water marine deposits are now lying at depth between 400 m and 850 m (Daniel et al., 1976). This implies that the margins of New Caledonia have been down-dropped at least 400 m since more than 10 Ma, leading to subsidence rates of the order of 0.04 mm/year. From seismic investigations, flat regions now lying at 300–400 m depth offshore southern New Caledonia, are regarded as down-dropped former ferricrust-covered peneplains (Pontoise et al., 1982; Rigolot, 1988).

5.3. Quaternary coral reef data

Sampling of uplifted reefs and drilling throughout fringing reefs and within the barrier reef itself have shown that the Grande Terre of New Caledonia is composed of independent blocks having differential vertical motions, defining areas undergoing uplift or subsidence (Fig. 2) (Launay and Récy, 1970; Coudray, 1976; Fontes et al., 1977; Cabioch, 1988; Cabioch et al., 1995, 1999). In the Yaté region, the last interglacial reef is uplifted up to 10 m along some 30 km of coastline, which yields a mean uplift rate close to 0.05 mm/year. The uplifted reef is associated with the Waho–Kuébéni fault (Fig. 2) that accumulated few hundred meters of vertical displacement within the peridotite basement. Moreover, the barrier reef offshore Yaté is submerged down to 15 to 20 m water-depth and is subdivided into several reef banks suggesting differential tectonic collapse. Elsewhere in the southern part of the island, the 125 ka reef unit lies under the postglacial reef or is submerged offshore. In the Nouméa area, the postglacial (Holocene)–last interglacial (125 ka) unconformity is found at −3 m. This indicates a subsidence rate of 0.07 mm/year. Coring on the barrier reef at Amedée islet, 20 km westward of Nouméa (Fig. 2), brought evidence for successive reef stages of Pleistocene age, particularly well documented in core Amédée 4. The substrate of the reef is predominantly composed of basalts of the Poya nappe and was reached at 126.50 m depth. Here, the Pleistocene 125-ka-old reef is found from 14 to 37 m depth, leading to subsidence rates of 0.14 mm/year (Cabioch et al., 1999). In the northwestern and northeastern parts of the island, the 125 ka reef unit is found directly over metamorphic basement or mesozoic sedimentary rocks, indicating more recent subsidence of these coasts. These drilling results collectively reveal increasing subsidence seaward (Lecolle and Cabioch, 1988). Therefore, the Quaternary evolution is consistent with the general slow subsidence of the New Caledonia margins since at least the Miocene.

6. Conclusion: extensional post-Eocene tectonic evolution of Southern New Caledonia

This preliminary geological study shows for the first time that extensional deformation events have affected the southern part of New Caledonia during the Neogene and the Quaternary. But for now, little can be said concerning the timing and the duration of these events and we are well aware that important work is now needed in order to better constrain the geometry and kinematics of this extensional evolution. However, our results as well as former data suggest that two separate phases must be distinguished within the post-obduction evolution of southern New Caledonia.

The first extensional phase is characterized by the development of both high- and low-angle normal faults, well exposed in the region of Nouméa and affecting the entire post-obduction tectonic pile. Since most of the observed low and high-angle faults are not active at the surface but developed at depth (as also demonstrated by abundant cristallization from relatively deep fluids circulating within the faults), a certain amount of uplift and erosion necessarily occurred in the region of Nouméa after this first phase. Normal faulting of the Népoui conglomerates demonstrates that extension was active after the Lower–Middle Miocene, but it may have started before this period. The very first extensional events in southern New Caledonia might have been contemporaneous with the very final stages of exhumation of high pressure units in northern New Caledonia as discussed above. Therefore, according to the available data, we may only conclude that early extensional deformation occurred during a large span time including the Oligocene and the Miocene, possibly as separate events. Most of the faults belonging to this first phase strike N90 to N150, with a dominant cluster around N140, corresponding to the direction of the axis of the island. In particular, we may assume that the N140 trending fault boundary separating the ophiolite sheet (including the Poya nappe) from the autochthonous sedimentary sequences of the Nouméa region was initiated during this early event. Such an extensional event might have been contemporaneous with the last phase of extension evidenced in northern New Caledonia and characterized by a generation of regional-scale high-angle normal faults followed by relatively youthful block-faulting and uplifting of the regional peneplain (Rawling and Lister, 2002).

At this stage of knowledge, only speculative mechanical models can be proposed for this first extensional phase. Early extension in the Nouméa region is related to a major phase of regional uplift accompanied by displacement that occurred along high-angle and low-angle normal faults. In the structural model of Fig. 21a and b, we infer that the boundaries of the southern ophiolitic massif, including the basalts of the Poya nappe at its base, corresponds to a major low-angle extensional detachment cut by subsequent, later high-angle normal faults. According to this interpretation, the main detachment surface is exposed along the western faces of the ophiolitic mountains and extensional allochthons are found as the basement of the western barrier reef, where basalts of the Poya nappe have been drilled (Amédée islet). As a consequence, the thick peridotite breccia formation (Koghi breccias) lying over the western slopes of the ophiolites from the Koghi to the Mont Dore should represent fault breccias still preserved along the exhumed detachment surface. Subsequent evolution of the extensional system likely led to uplift and partial exhumation of the sedimentary formations of the Nouméa basin and of the former deepest extensional fault zone, with development of numerous high-angle, late normal faults. In Fig. 21c, we propose an alternative interpretation in which the morphological front of the ophiolites is an eroded scarp of a main high-angle normal fault. According to this interpretation, there should be no large low-angle detachment exposed in southern New Caledonia.

Studies of mountain building processes have shown that in many cases, extension and exhumation of deep crustal levels may very well occur during continuing plate convergence (Platt, 1986, 1993; Chemenda et al., 1995). Normal faulting is generally observed in the upper part of an accretionary wedge thickened by underplatting. In the case of New

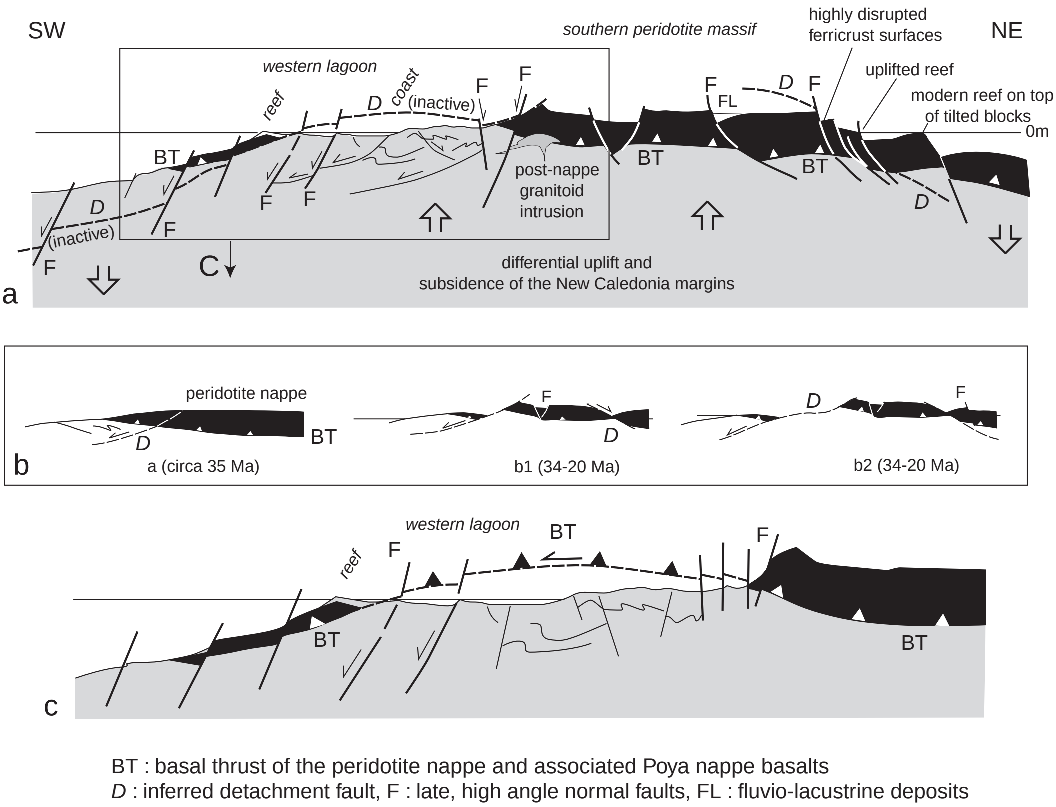

Fig. 21. Schematic cross-sections of southern New Caledonia illustrating two conceptual structural models. (a) A geometry based on a model emphasizing the presence of major post-nappe detachment faults cutting trough the ophiolites and their basement, cut by later high-angle normal faults. (b) Cartoons depicting the tectonic evolution leading to the geometry shown in a. (c) Alternative interpretation based on the absence of low angle detachments and the occurrence of high-angle normal faults. In this case, the morphological front of the ophiolite nappe is an erosive boundary and does not correspond to a major extensional detachment surface.

Caledonia, there is no indication allowing precise dating of the end of the convergence that led to ophiolite obduction and HP/LT metamorphism during the Eocene. Few lines of evidence may suggest that convergence continued at least during the Oligocene. Underthrusted low density rocks present at approximately 60 km depth below southern New Caledonia (Régnier, 1988) might have been emplaced during such a late convergence episode (Cluzel et al., 2001). But there is no control on the exact age of such short-lived subduction. Reverse faults affecting post-Eocene sediments are observed on seismic lines perpendicular to the western slope of the Grande Terre (Rigolot and Pelletier, 1988). These faults are cross cut by more recent normal faults paralleling the direction of the Grande Terre. Some authors also consider that the late Oligocene granodioritic plutons which intrude the Peridotite nappe (St. Louis and Koum–Borindi granitoids) are related to the short-lived episode of subduction of the Australia plate below the Norfolk Ridge (Cluzel et al., 2001). Whatever the case, there is no evidence that such convergence continued after the Upper Oligocene. Finally in the absence of additional tectonic and dating results obtained from southern New Caledonia, it is not possible to assess that the post-nappe-emplacement extension occurred during a last stage of convergence on top of an active accretionary wedge, or during a period of regional post-orogenic collapse after complete cessation of convergence.

The second tectonic phase corresponds to the recent and present-day evolution (Upper Pliocene–Quaternary). Here again, dating constraints remain poor, and further work is needed in order to collect more abundant chronological data. Quaternary neotectonic features observed in the lagoon are short segments of vertical faults trending N90, N40, N0–10 and delineating restricted subsiding areas with N–S and E–W orientation (Dumbéa fault zone, and Boulari pass rift zone, respectively). These faults develop within narrow deforming zones bounding undeformed blocks, 30 km–40 km wide. This fault pattern, characterized by highly localized deformation, displays similar orientations to that of the limits of tectonic block in the southern part of the Massif du Sud (N90, N40–50, N0–10 and minor N140). The orientation of these faults is also consistent with the orientation of the nodal planes of two large earthquakes and with the trend of the epicenter cluster of La Havanah fault zone (Régnier et al., 1999). They are also consistent with the trends of all the morphological features of southern New Caledonia as revealed by the adaptation of the hydrologic network and the pattern of the shoreline (Fig. 2). These directions may also control the boundaries between lateritic basins overlying the ophiolites such as in the "Plaine des Lacs" region (Fig. 2).

The overall setting of the 125 ka reef reveals irregular increase of subsidence of New Caledonia, northward and southwestward, a relatively more stable central zone and a slightly uplifted area in the southeast at Yaté (Cabioch et al., 1999). Therefore, the New Caledonian ridge seems to have undergone a continuous double warping during the past 125,000 years. This present-day differential block tectonics could be related to the flexure of the oceanic lithosphere currently subducting within the Vanuatu Trench at a rate of 12 cm/year in the ENE direction (Calmant et al., 2003). In addition, according to our results, it remains possible that post-obduction isostatic readjustments are still active at a low rate, also slightly increasing differential block motions.

Finally, in the New Caledonia deformed belt, as in most of the orogenic belts worldwide, extensional deformation is observed following or accompanying crustal thickening and ophiolite obduction. The Neogene evolution of southern New Caledonia therefore might resemble that of orogenic systems which underwent important crustal extension, under various regimes and conditions, such as the Aegean Sea, the Basin and Ranges Province or even the Oman region (Wernicke, 1981; Sokoutis et al., 1993; Jolivet et al., 1998; Gautier et al., 1999; Chéry, 2001). In southern New Caledonia, extension led to thinning of the ophiolite sheet and to the exhumation of the autochtonous basement represented by the sedimentary sequences of the Nouméa region. These tectonic processes played an important role during the weathering of the peridotites and the development of the lateritic Ni-bearing layers as they allowed considerable increase in the circulation of ground waters within actively opening faults and fissures, deep into the ophiolites, since about 20 My.

Acknowledgements

This work was made possible through material assistance on land and at sea by the IRD (Institut de Recherche pour le Développement) Center of Nouméa. Special thanks are due to the IRD and to the UMR GéoSciences Azur staff by Y.L. for excellent working conditions during his stay in New Caledonia. We are grateful to A. Chauvet, D. Chardon, J. Malavieille for stimulating discussion. D. Cluzel and R. Hertzer are thanked for very careful reviews and improving comments on the manuscript.

References

Aitchison, J., Clarke, G., Cluzel, D., Meffre, S., 1995. Eocene arc-continent collision in New Caledonia and implications for regional southwest Pacific tectonic evolution. Geology 23, 161–164.

Aitchison, J.C., Ireland, T.R., Clarke, G.L., Cluzel, D., Meffre, S., 1998. U/Pb SHRIMP age constraints on the tectonic evolution of New Caledonia and regional implications. Tectonophysics 299, 333–343.

Allmendinger, R.W., 2001. FaultKinWin, a Program for Analyzing Fault Slip Data For Windows™ Computers with Individual Scientific Subroutines by R.A Marrett and T. Cladouhos.

Angelier, J., Mechler, P., 1977. Sur une méthode graphique de recherche des contraintes principales également utilisable en tectonique et en séismologie: la méthode des dièdres droits. Bull. Soc. Géol. Fr. 7 (t. XIX), 1309–1318.

Auzende, J.M., van de Beuque, S., Régnier, M., Lafoy, Y., Symonds, P., 2000. Origin of the New Caledonian ophiolites based on a French–Australian seismic transect. Mar. Geol. 162 (2–4), 225–236.

Avias, J., 1967. Overthrust structure of the main ultrabasic New Caledonian massives. Tectonophysics 4 (4–6), 531–541.

Baldwin, S.L., Rawlings, T., Fitzgerald, P.G., 1999. Thermochronology of the northern high P/T terrane of New Caledonia: implications for mid-Tertiary plate boundary processes in the SW Pacific. In: Baldwyn, L., Lister, G.S. (Eds.), Penrose Conference, Mid-Cretaceaous to Recent Plate Boundary Processes in the Southwest Pacific, Abstr. Vol., p. 13.

Bitoun, G., Récy, J., 1982. Origine et évolution du bassin des Loyautés et de ses bordures après la mise en place de la série ophiolitique de Nouvelle–Calédonie; contribution à l'étude géodynamique du Sud-Ouest Pacifique. Trav. Doc. ORSTOM 147, 505–539.

Black, P.M., Maurizot, P., Ghent, E.D., Stout, M.Z., 1993. Mg–Fe carpholites from aluminous schists in the Diahot region and implications for preservation of high-pressure/low-temperature schists, northern New Caledonia. J. Metamorph. Geol. 11 (3), 455–460.

Cabioch, G. 1988. Récifs frangeants de Nouvelle–Calédonie (Pacifique sud-ouest). Structure interne et influences de l'eustatisme et de la néotectonique. Thèse Doct. Univ. Provence, Publ. Univ. Aix-Marseille I. 291 p.

Cabioch, G., Montaggioni, L.F., Faure, G., 1995. Holocene initiation and development of New Caledonian fringing reefs, South-West Pacific. Coral Reefs 14, 131–140.

Cabioch, G., Récy, J., Jouannic, C., Turpin, L., 1996. Contrôle environnemental et néotectonique de l'édification récifale en Nouvelle–Calédonie au cours du Quaternaire terminal. Bull. Soc. Géol. Fr. 167, 729–742.

Cabioch, G., Corrège, T., Turpin, L., Castellaro, C., Récy, J., 1999. Development patterns of fringing and barrier reefs in New Caledonia (south-west Pacific). Oceanol. Acta 22, 567–578.

Calmant, S., Pelletier, B., Lebellegard, P., Bevis, M., Taylor, F.W., Phillips, D.A., 2003. New insights on the tectonics along the New Hebrides subduction zone based on GPS results. J. Geophys. Res. 108 (B6), 2319–2340.

Chemenda, A., Mattauer, M., Malavieille, J., Bokun, A.N., 1995. A mechanism for syn-collisional rock exhumation and associated normal faulting—Results from physical modeling. Earth Planet. Sci. Lett. 132, 225–232.

Chéry, J., 2001. Core complex mechanism: from the Gulf of Corinth to the Snake Range. Geology 29 (5), 439–442.

Clarke, G.L., Aitchison, J.C., Cluzel, D., 1997. Eclogites and blueschists of the Pam Peninsula, NE New Caledonia: a reappraisal. J. Petrol. 38 (7), 843–876.

Cluzel, D., 1998. Le "flysch post-obduction" de Népoui, un bassin transporté? Conséquences sur l'âge et les modalités de l'obduction tertiaire en Nouvelle–Calédonie (Pacifique sud-ouest). C. R. Acad. Sci., Paris 327, 419–424.

Cluzel, D., Aitchison, J., Clarke, G., Meffre, S., et Picard, C., 1995. Dénudation tectonique du complexe à noyau métamorphique de haute pression tertiaire (Nord de la Nouvelle–Calédonie, Pacifique, France), Données cinématiques. C. R. Acad. Sci., Paris 321, 57–64.

Cluzel, D., Picard, C., Aitchison, J., Laporte, C., Meffre, S., Parat, F., 1997. La nappe de Poya (ex. formation des Basaltes) de Nouvelle Calédonie (Pacifique Sud-Ouest): un plateau océanique Campanien–Paléocène supérieur obducté à l'Eocène supérieur. C. R. Acad. Sci., Paris 324, 443–451.

Cluzel, D., Aitchison, J.C., Picard, C., 2001. Tectonic accretion and underplating of mafic terranes in the Late Eocene intraoceanic fore-arc of New Caledonia (Southwest Pacific): geodynamic implications. Tectonophysics 340, 23–59.

Collot, J.Y., Malahoff, A., Récy, J., Latham, G., Missègue, F., 1987. Overthrust emplacement of New Caledonia ophiolite: geophysical evidence. Tectonics 6 (3), 215–232.

Collot, J.Y., Rigolot, P., Missegue, F., 1988. Geologic structure of the northern New Caledonia Ridge, as inferred from magnetic and gravity anomalies. Tectonics 7 (5), 991–1013.

Coudray, J., 1976. Recherches sur le Néogene et le Quaternaire marins de la Nouvelle–Calédonie; contribution de l'étude sédimentologique à la connaissance de l'histoire géologique post-Eocène; Fond Singer-Polignac, Paris. Expédition française sur les récifs coralliens de la Nouvelle–Calédonie 8, 5–275.

Coudray, J., 1977. Recherche sur le Quaternaire marin de la Nouvelle–Calédonie. Contribution à l'étude des récifs coralliens et des éolianites associées à la reconstitution de l'histoire climatique et structurale. Bull. Ass. Fr. Et. Quat. 1 (50), 331–340.

Daniel, J., Dugas, F., Dupont, J., Jouannic, C., Launay, J., Monzier, M., 1976. La zone charnière Nouvelle Calédonie–Ride de Norfolk (SW Pacifique): Résultats de dragage et interprétations. Cah. ORSTOM Géol. Fr. 8 (1), 95–101.

Davis, W.M., 1925. Les côtes et les récifs coralliens de Nouvelle–Calédonie. Ann. Géogr., 34, pp. 191, 244–269, 332–359, 423–441, 521–558.

Dubois, J., Launay, J., Récy, J., 1974. Uplift movements in New Caledonia—Loyalty islands area and their plate tectonics interpretation. Tectonophysics 24, 133–150.

Dugas, F., Debenay, J.-P., 1978. Interférences des failles-flexures littorales et de l'érosion karstique sur les constructions coralliennes: le lagon de Nouvelle–Calédonie. C. R. Acad. Sci., Paris, série D 290, 963–966.

Dugas, F., Ville, P., Coudray, J., 1980. Etude sismique du lagon sud-ouest de la Nouvelle–Calédonie (Sud-Ouest Pacifique). Paléomorphologies successives et comportement au Quaternaire supérieur du littoral de l'île. C. R. Acad. Sci., Paris, série D 290, 963–966.

Eissen, J.P., Crawford, A.J., Cotten, J., Meffre, S., Bellon, H., Delaune, M., 1998. Geochemistry and tectonic significance of basalts in the Poya Terrane, New Caledonia. Tectonophysics 284, 203–219.

Fontes, J.C., Launay, J., Monzier, M., Récy, J., 1977. Genetic hypothesis on the ancient and recent reef complexes in New Caledonia. Intern. Symp. Geodyn. South-West Pacific, Noumea 1976. Technip, Paris, pp. 289–300.

Fromager, D., Gonord, H., Guillon, J.H., 1967. Sur l'enracinement de certaines structures dans la région sud-ouest du bassin de Nouméa, Nouvelle–Calédonie. C.R. Somm. Séances Soc. Géol. France 6, 242.

Gautier, P., Brun, J.P., Moriceau, R., Sokoutis, D., Martinod, J., Jolivet, L., 1999. Timing, kinematics and cause of Aegean extension: a scenario based on a comparison with simple analogue experiments. Tectonophysics 315, 31–72.

Goffé, B., Michard, A., Kiénast, J.R., Le Mer, O., 1988. A case of obduction-related high-pressure, low-temperature metamorphism in upper crustal nappes, Arabian continental margin, Oman. Tectonophysics 151, 363–386.

Gonord, H., 1977. Recherches sur la géologie de la Nouvelle–Calédonie: sa place dans l'ensemble structural du Pacifique Sud-Ouest. Thèse Doct. Univ. Montpellier. 341 p.

Gray, D.G., Robert, G.T., 2000. Implications of the structure of the Wadi Tayin metamorphic sole, the Ibra-Dasir block of the Samail ophiolite, and the Saih Hatat window for late stage extensional ophiolite emplacement, Oman. Mar. Geophys. Res. 21, 211–227.

Guillon, J.H., 1975. Les massifs péridotitiques de Nouvelle–Calédonie. Type d'appareils ultrabasiques stratiformes de chaîne récente. Mém. ORSTOM Fr. 76, 11–120 (50 fig 16 pl.).

Guillon, J.H., Routhier, P., 1971. Les stades d'évolution et de mise en place des massifs ultramafiques de Nouvelle–Calédonie; bulletin du Bureau de Recherches Géologiques et Minières. Section 4: Géologie Générale 2, 5–37.

Jolivet, L., Goffé, B., Bousquet, R., Oberhänsli, R., Michard, A., 1998. Detachment in high-pressure mountain belts, Tethyan examples. Earth Planet. Sci. Lett. 160, 31–47.

Lafoy, Y., Auzende, J.M., Smith, R., Labails, C., 2000. Evolution géologique post-Pléistocène moyen du domaine lagonaire Néo-Calédonien méridional. C. R. Acad. Sci., Paris 330, 265–272.

Latham, M., 1974. Nouvelle observation de la coupe de Népoui (Nouvelle Calédonie); conséquences sur la chronologie de l'étagement des niveaux cuirassés sur les massifs de roches ultrabasiques. C. R. Acad. Sci., Paris, série D 279 (13), 1055–1058.

Latham, M., 1986. Altération et pédogenèse sur roches ultrabasiques en Nouvelle–Caledonie. Coll. Etudes et Thèses ORSTOM, Paris. 331 p.

Launay, J., Récy, J., 1970. Nouvelles données sur une variation relative récente du niveau de la mer dans la région Nouvelle–Calédonie—îles Loyauté. C. R. Acad. Sci., Paris, série D 270, 2159–2161.

Lecolle, J.F., Cabioch, G., 1988. La limite Holocène–Pléistocène dans le récif frangeant Ricaudy (Nelle–Calédonie). Géochronologie, faciès et diagénèse. Implications eustatiques et néotectoniques. Mar. Geol. 81, 241–260.

Leguéré, J., 1976. Des corrélations entre la tectonique cassante et l'altération supergène des péridotites de Nouvelle–Calédonie. Thèse 3ème cycle, Montpellier.

Michard, A., Goffé, B., Saddiqi, O., Oberhänsli, R., Wendt, A.S., 1994. Late Cretaceous exhumation of the Oman blueschists and eclogites: a two-stage extensional mechanism. Terra Nova 6, 404–413.

Paris, J.P., 1981. Géologie de la Nouvelle–Calédonie. Mém. Bureau Rech. Géol. Min. 113, 1–278.

Paris, J.P., Andreieff, P., Coudray, J., 1979. Sur l'âge Eocène supérieur de la mise en place de la nappe ophiolitique de Nouvelle–Calédonie déduit d'observations nouvelles sur la série de Népoui. C. R. Acad. Sci., Paris, série D 288, 1659–1661.

Platt, J.P., 1986. Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks. Geol. Soc. Amer. Bull. 97, 1037–1053.

Platt, J.P., 1993. Exhumation of high-pressure rocks: a review of concepts and processes. Terra Nova 5, 119–133.

Pontoise, B., Collot, J.-Y., Missègue, F., Latham, G.V., 1982. Sismique réfraction dans le bassin des Loyautés; résultats et discussion; Contribution a l'étude géodynamique du Sud-Ouest Pacifique. Trav. Doc. ORSTOM 147, 541–548.

Prinzhofer, A., 1981. Structure et pétrologie d'un cortège ophiolitique: le massif du Sud (Nouvelle–Calédonie). Thèse Ing. Docteur, E.N.S.M. Paris.

Rawling, T.J., Lister, G.S., 2002. Large-scale structure of the eclogite–blueschist belt of New Caledonia. J. Struct. Geol. 24, 1239–1258.

Régnier, M., 1988. Lateral variation of upper mantle structure beneath New Caledonia determined from P-wave receiver function; evidence for a fossil subduction zone. Geophys. J. R. Astron. Soc. 95 (3), 561–577.

Régnier, M., van de Beuque, S., Baldassari, C., Tribot Laspiere, G., 1999. La sismicité du sud de la Nouvelle–Calédonie; implications structurales. C. R. Acad. Sci., Paris, Série 2 329 (2), 143–148.

Rigolot, P., 1988. Prolongement méridional des grandes structures géologiques de Nouvelle–Calédonie et découverte de monts sous-marins interprétés comme un jalon dans un nouvel alignement de hot-spot. C. R. Acad. Sci., Paris, Série 2 307 (8), 965–972.

Rigolot, P., Pelletier, B., 1988. Tectonique compressive récente le long de la marge Ouest de la Nouvelle–Calédonie; résultats de la campagne ZOE 400 du N/O Vauban (mars 1987). C. R. Acad. Sci., Paris, Série 2 307 (2), 179–184.

Routhier, P., 1953. Etude géologique du versant occidental de la Nouvelle–Calédonie entre le col de Boghen et la pointe d'Arama. Mém. Soc. Géol. Fr. 32, 1–271.

Sokoutis, D., Brun, J.P., Van den Driessche, J., Pavlides, S., 1993. A major Oligo-Miocene detachment in southern Rhodope controlling north Aegean extension. J. Geol. Soc. (Lond.) 150, 243–246.

Tissot, B., Noesmoen, A., 1958. Les bassins de Nouméa et de Bourail (Nouvelle–Calédonie). Rev. Inst. Fr. Pet. 13, 739–760.

Trescases, J.J., 1973. Weathering and geochemical behaviour of the elements of ultramafic rocks in New Caledonia. Metallogenic provinces and mineral deposits in the southwestern Pacific. Bull.—Aust., Bur. Miner. Resour., Geol. Geophys. 141, 149–161.

Van de Beuque, S., 1999. Evolution géologique du domaine péri-calédonien. Unpublished Doctorat thesis, Université de Bretagne Occidentale. 265 p.

Vigier, B., 2001. Caractère syntectonique des minéralisations nickélifères supergènes de Nouvelle–Calédonie. Unpublished DEA thesis, Université d'Orléans.

Wernicke, B., 1981. Low-angle normal faults in the Basin and Range Province: nappe tectonics in an extending orogen. Nature 291, 645–648.

Yokoyama, K., Brothers, R.N., Black, P.M., 1986. Regional eclogite facies in the high-pressure metamorphic belt of New Caledonia. In: Evans, Bernard W., Brown, Edwin H. (Eds.), Blueschists and Eclogites, Memoir, Geological Society of America, vol. 164, pp. 407–423.