Reprinted from

TECTONOPHYSICS

INTERNATIONAL JOURNAL OF GEOTECTONICS AND THE GEOLOGY AND PHYSICS OF THE INTERIOR OF THE EARTH

Tectonophysics 284 (1998) 203–219

Geochemistry and tectonic significance of basalts in the Poya Terrane, New Caledonia

Jean-Philippe Eissen [a,*], Anthony J. Crawford [b], Joseph Cotten [c], Sébastien Meffre [b], Hervé Bellon [c], Mireille Delaune [d]

[a] *ORSTOM UR/GP 22, Centre ORSTOM de Brest, B.P. 70, 29280 Plouzané Cedex, France*
[b] *Department of Geology, University of Tasmania, GPO Box 252C, Hobart, Tas 7001, Australia*
[c] *Université de Bretagne Occidentale, Sciences de la Terre, UMR 6538, 6 avenue Le Gorgeu, BP 809, 29285 Brest Cedex, France*
[d] *ORSTOM UR/GP 22, Centre ORSTOM de Bondy, 32, avenue Henri Varagnat, 93143 Bondy Cedex, France*

Received 30 October 1996; accepted 16 June 1997

TECTONOPHYSICS

Scope of the journal

Tectonophysics is an international medium for the publication of original studies and comprehensive reviews in the field of geotectonics and the geology and physics of the earth's crust and interior. The editors will endeavour to maintain a high scientific level and it is hoped that with its international coverage the journal will contribute to the sound development of this field.

(Text continued on inside back cover)

⊗ The paper used in this publication meets the requirements of ANSI/NISO Z39.48-1992 (Permanence of Paper).

PRINTED IN THE NETHERLANDS

ELSEVIER

Tectonophysics 284 (1998) 203–219

TECTONOPHYSICS

Geochemistry and tectonic significance of basalts in the Poya Terrane, New Caledonia

Jean-Philippe Eissen [a,*], Anthony J. Crawford [b], Joseph Cotten [c], Sébastien Meffre [b], Hervé Bellon [c], Mireille Delaune [d]

[a] *ORSTOM UR/GP 22, Centre ORSTOM de Brest, B.P. 70, 29280 Plouzané Cedex, France*
[b] *Department of Geology, University of Tasmania, GPO Box 252C, Hobart, Tas 7001, Australia*
[c] *Université de Bretagne Occidentale, Sciences de la Terre, UMR 6538, 6 avenue Le Gorgeu, BP 809, 29285 Brest Cedex, France*
[d] *ORSTOM UR/GP 22, Centre ORSTOM de Bondy, 32, avenue Henri Varagnat, 93143 Bondy Cedex, France*

Received 30 October 1996; accepted 16 June 1997

Abstract

The Norfolk–New Caledonia Ridge represents a continental slice which drifted away from Australia during the Late Cretaceous breakup of the eastern Gondwana margin. The presence of widespread basaltic rocks beneath the main ophiolite nappe of New Caledonia has been long known but the origin and the age of the Poya Terrane basalts (PTB herein) remained controversial. Recent palaeontologically determined ages date the PTB as Late Cretaceous (Campanian). New geochemical data show that two main discrete groups constitute the PTB: a MORB-like tholeiitic suite, and a more alkaline intra-plate basaltic suite distinguished mainly on immobile HFSE and REE elements. Furthermore, low ϵ_{Nd} and high Th/Nb relative to MORB, and weak negative Nb anomalies, reflect limited assimilation of continental crust by these otherwise MORB-like tholeiites. Inter-PTB sedimentary rocks all have a pelagic or hemi-pelagic origin; detrital material originated from the nearby Norfolk–New Caledonia ridge basement. The PTB form a parautochthonous sheet below the main harzburgitic nappe constituting the New Caledonian ophiolite. They are genetically unrelated to the ophiolite, and are interpreted to be 70–85-Ma-old rift tholeiites formed during of the easternmost continental part of Mesozoic Gondwana, and opening the East New Caledonia Basin. The Norfolk–New Caledonia Ridge formed the western passive margin of this new oceanic basin, but the rifted-off eastern block is less easily identified. It may form part of the basement of the Western Belt of the New Hebrides island arc (Vanuatu). The cessation of rifting of the eastern Australian margin around 56 Ma was followed by an eastward-directed subduction which produced boninitic melts and its associated refractory harzburgitic mantle, in the forearc of the primitive Loyalty–d'Entrecasteaux arc. Following the major Pacific plate motion reorganization around 42 Ma, collision of the Norfolk–New Caledonia Ridge with the forearc region of the intra-oceanic Loyalty–d'Entrecasteaux arc around 40 Ma led first to westward thrusting of the PTB as a slice picked up from the upper crustal section of the colliding Norfolk Ridge. Subsequent collisional tectonism led to detachment of the main New Caledonian harzburgitic nappe from its forearc location in the Loyalty arc, and westward emplacement of this nappe over the PTB nearby allochthon. The presence of parautochthonous sheets of basalts unrelated to immediately overlying forearc-derived, boninite-bearing harzburgitic ophiolites is briefly discussed in the light of two other examples in arc–continent collision settings. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: SW Pacific; New Caledonia; Cretaceous; Eocene; allochthonous terrane; geodynamic significance; MORB; backarc basalts; intra-plate basalts; boninites; ophiolites; geochemistry

* Corresponding author. E-mail: eissen@orstom.fr

0040-1951/98/$19.00
PII S0040-1951(97)00183-2

1. Introduction

New Caledonia is a microcontinental island which drifted away from Australia during the Late Cretaceous breakup of the eastern Gondwana margin and opening of the Tasman Sea and New Caledonia Basin (Paris, 1981; Kroenke, 1984; Mignot, 1984; Rigolot, 1989; Cluzel et al., 1994). It is constituted by rocks which record at least two arc–continent collisions, the first in the early Mesozoic, the more recent in the mid-Eocene (Cluzel et al., 1994; Aitchison et al., 1995a; Meffre et al., 1996). The latter collision resulted in SSW-directed emplacement of a massive harzburgite-dominated nappe probably at least 6 km thick (Fig. 1) (Avias, 1967; Guillon, 1975; Prinzhoffer et al., 1980). Although this sheet appears to be broadly continuous with crust of the adjacent South Loyalty Basin to the east of New Caledonia

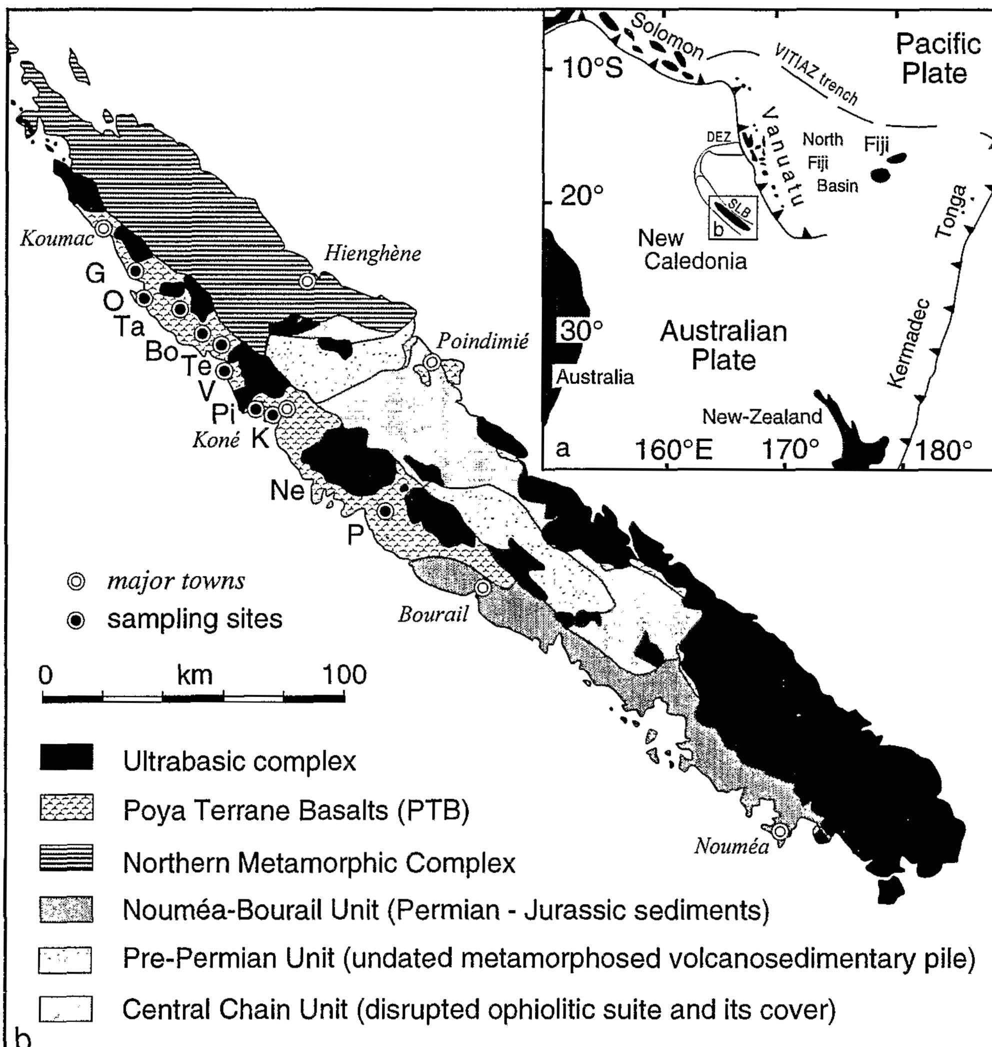


Fig. 1. (a) Location of New Caledonia in the SW Pacific. *DEZ* = d'Etrecasteaux Zone; *SLB* = South Loyalty Basin. (b) Simplified geological map of New Caledonia showing the location of the Poya Terrane basalts along the western coast between Bourail and Koumac. *Ne* = Népoui. Sample sites: *G* = Gomen; O =Ouaco; *Ta* = Taom; *Bo* = Boyen; *V* = Voh; *Te* = Temala; *Pi* = Pinjen peninsula; *K* = Kone; *P* = Poya (including samples from a 150-m-deep drilling done by the BRGM on the Honfleur sulphide deposit).

(Collot et al., 1987), there are no known occurrences of volcanics associated with the nappe on New Caledonia, and magmatic rocks are restricted to limited occurrences of cumulates and occasional dolerite dykes (Prinzhoffer et al., 1980; Dupuy et al., 1981).

The presence of widespread basaltic rocks beneath the New Caledonia ophiolite nappe has been long known and well documented (Routhier, 1953; Lillie and Brothers, 1970; Guillon, 1972; Guillon and Gonord, 1972; Rodgers, 1975; Parrot and Dugas, 1980; Paris, 1981; Kroenke, 1984; Maurizot et al., 1985; Black, 1993; Cluzel et al., 1994; Aitchison et al., 1995a,b). Marine geophysical data indicate that this basaltic formation, as well as the main harzburgite nappe, extend 300 km northwestward in the basement of the northern lagoon of New Caledonia (Collot et al., 1988). Guillon (1972) first recognized that these basaltic rocks form an extensive nappe, outcropping over much of the west coast of New Caledonia, where these rocks have been called the 'Formation des Basaltes de la Côte Ouest' (West Coast Basalts Formation). More recent studies (Cluzel et al., 1994; Meffre, 1995; Aitchison et al., 1995a) have confirmed that the West Coast Basalt Formation represents the western part of a 20–500-m-thick nappe, which extends over much of the island as a slice beneath the main harzburgite nappe. Basalts of similar petro-geochemical characteristics outcrop also locally along the east coast of New Caledonia as a thin slice beneath the harzburgites (Cluzel et al., 1994, 1995; Meffre, 1995). This basaltic nappe has been termed the Poya Terrane (Cluzel et al., 1994; Aitchison et al., 1995a). Ongoing controversy surrounds the affinities, origin and tectonic significance of the Poya Terrane basalts (PTB herein).

Here, we provide new petrological, geochemical and sedimentological data which address this problem. We note that the implications of these data have more than local significance, as extensive sheets of metabasaltic rocks, almost certainly parts of large nappes, occur beneath several other large harzburgite-dominated, boninite-bearing ophiolite sheets in the southwest Pacific region, for example the Emo-Kokoda metamorphics beneath the Papuan ophiolite (Davies and Jaques, 1984; Worthing and Crawford, 1996), and the Crimson Creek Formation and correlative basalts beneath the Cambrian boninite–harzburgite ophiolites in Tasmania at the base of the Lachlan Foldbelt in eastern Australia (Crawford and Berry, 1992).

2. Poya Terrane

The Poya Terrane was emplaced as a relatively thin thrust sheet along with but beneath the main harzburgite sheet of the New Caledonia ophiolite, between 38 and 46 Ma (Cluzel et al., 1994, 1995; Aitchison et al., 1995a; Meffre, 1995). The direction and sense of its emplacement was determined by careful examination of the geological contacts, a kinematic analysis of the normal faults, the polarity of the metamorphism which affects the PTB, which increases northward along the east coast (Cluzel et al., 1994, 1995; Meffre, 1995) and its strong link with the emplacement of the main harzburgite sheet from the north-northeast (Guillon, 1975; Prinzhoffer et al., 1980; Collot et al., 1987).

Poya Terrane sequences are dominated by low-grade metamorphosed, often tectonized, pillowed basalts, with associated hyaloclastites, fine-grained tuffaceous sediment and calcareous sediments known as the 'Koné facies' (Carroué, 1972), radiolarian cherts and more locally massive basalts, gabbros and dolerites. Occasional sheeted basaltic flows and serpentinites have also been observed.

The age of the Poya Terrane has been a controversial issue, with arguments being presented in the literature for Eocene–Paleocene and/or Cretaceous ages (Routhier, 1953; Espirat, 1963; Coudray and Gonord, 1967; Carroué, 1972; Guillon, 1972; Cluzel et al., 1994; Aitchison et al., 1995a; Meffre, 1995). Palaeontological ages range between 88 and 45 Ma (Coudray and Gonord, 1967; Carroué, 1972). However, most cherts clearly interbedded with the basalts have yielded Radiolaria indicating a Campanian (73–83 Ma) age (two new ages from Meffre, 1995 and ten from Aitchison et al., 1995b). Several fossiliferous Senonien intercalations (66–88 Ma) in the Koné facies were also described by Espirat (1963) and Carroué (1972), and Paris (1981) associated a Turonian to Santonian (83–90 Ma) *Inoceramus* macrofauna with the same facies.

Most palaeontologically determined Eocene ages for sequences containing basalts come from the area south of Bourail. Aitchison et al. (1995a) and Meffre (1995) have argued that these basalts are probably olistoliths (up to almost 1 km long in places) reworked in Upper Eocene detrital sediments and breccias during their emplacement over the New Caledonia core.

Published K–Ar ages for PTB are 38.5 ± 1.5 Ma, 42 ± 2 Ma, 51 ± 7 Ma and 59 ± 6 Ma (Guillon and Gonord, 1972). We have obtained 9 new K–Ar age determinations for low-grade metamorphosed PTB and these range from 39.7 ± 2.1 Ma to 61.6 ± 2.8 Ma (Table 2). These new K–Ar age determinations were performed at the University of Brest by H. Bellon and J.C. Philippet following a procedure described by Bellon and Rangin (1991). Three groups can be recognized: (1) between 39.7 and 43.8 Ma; (2) between 47 and 49 Ma; and (3) with a single isotopic age of 61.6 Ma. The latter age represents the average of two dates determined on separate granulometric fractions of the same sample leached by acetic acid to eliminate the alteration phases (an age of 56.0 Ma was obtained on the same sample without the leaching procedure). All these K–Ar ages are anomalously low compared to the palaeontological ages of the few sedimentary rocks closely associated with the volcanic rocks, presumably reflecting varying extents of resetting, in part probably related to emplacement and subsequent metamorphism beneath the over-riding harzburgite nappe.

The geodynamic significance of the PTB gave rise to various interpretations. The first of these (e.g. Avias, 1967; Challis and Guillon, 1971; Cameron, 1989) argues that the PTB are the volcanic carapace of the main New Caledonia ophiolite. The second (Espirat, 1966, 1971; Guillon, 1972; Guillon and Gonord, 1972; Avias and Coudray, 1975; Gonord, 1977; Aitchison et al., 1995a; Meffre et al., 1996) proposes that PTB represent allochthonous crust of a Late Cretaceous backarc basin. Black (1993) referred to the PTB as 'N-MORB basalts with some arc affinities'. The autochthonous or subautochthonous origin proposed by other authors (Routhier, 1953; Paris, 1981; Kroenke, 1984; Maurizot et al., 1985) is now known to be wrong. Therefore, the allochthonous models will be evaluated following presentations of our new geochemical data.

3. Associated sediments

Relatively few sedimentary rock types have been identified in close association with the PTB, most being inter-pillow sediments or local thin intercalations of pelagic or hemi-pelagic origin (Paris, 1981; Cameron, 1989; Meffre, 1995). They include (Table 1): (1) brown and dark red siliceous rocks (cherts, jaspers) occasionally containing Radiolaria, which, although generally poorly preserved, have yielded Campanian (73–83 Ma) age determinations (Meffre, 1995; Aitchison et al., 1995b); (2) white or pink micritic limestone, containing some Globigerina and rarely some Radiolaria; (3) altered hyaloclastite with green jasper fragments; (4) clast-supported breccias with dominant volcanic fragments (autobrecciated pillow lavas during of shortly after their formation or ocean floor fault screes) and siliceous or calcareous cement (calcarenite); (5) detrital rocks with clay–siliceous cement (distal turbidite type or greywacke); and (6) tuffaceous mudstone and siltstone.

The non-volcanic detrital fraction of the coarser-grained breccias appears to be derived from Palaeozoic formations of the New Caledonia basement. Despite the different types defined, no clear variations are observed within the whole formation or between the different petro-geochemical groups defined below.

4. Petrography

Our new petrographic and geochemical data (Tables 2 and 3) show that two discrete magmatic groups constitute our PTB: a MORB-like tholeiitic suite, and a more alkaline intra-plate basaltic suite. The very poor outcrop has prevented determination of mutual contact relationships between these groups.

The Poya Terrane MORB-like basalts range from subophitic-textured, almost aphyric massive flows and microgabbro plugs and dykes, through intergranular- and intersertal-textured basalts with 2–10 modal% of plagioclase and augite phenocrysts, to occasional olivine + plagioclase-phyric or plagioclase + augite-phyric pillow basalts with largely devitrified glassy rims. Except in a few unaltered glassy pillow rims (Table 4) in which fresh olivine is preserved

Table 1
Summary of the lithology and origin of the studied samples of the Poya Terrane collected along the New Caledonia west coast between Bourail and Koumac

Sample number	Lithology	Location
Bo-5	Inter-pillow greywacke	Seashore near Pouaco
Bo-7	Inter-pillow greywacke	Seashore near Pouaco
Bo-9	Inter-pillow limestone	Seashore near Pouaco
Bo-13	Gabbro	Boyen river
Bo-16	Dolerite	Boyen river
Bo-30	Gabbro	Boyen river
Bo-33	Sediment brecchia	Boyen river
Bo-34	Dolerite	Boyen river
Bo-35	Gabbro	Boyen river
Bo-40	Gabbro	Boyen river
G-1	Basaltic pillow	Gomen Point
G-2	Inter-pillow jasp with laminites	Gomen Point
G-4	Basaltic pillow	Gomen Point
G-5	Basaltic pillow	Gomen Point
K-1	Basaltic pillow	Foué Point Quarry
K-3	Pink siliceous limestone	Foué Point Quarry
K-4	Pink siliceous limestone	Foué Point Quarry
K-7	Hyaloclastite	Foué Point Quarry
K-8	Basaltic pillow	Foué Point Quarry
K-9	Pink micritic limestone with glass fragments	Foué Point Quarry
K-10	Pink micritic limestone	Foué Point Quarry
K-11	Pink micritic limestone	Foué Point Quarry
K-13	Pink siliceous siltite	Foué Point Quarry
K-19	Dolerite	Seashore south of Foué
K-21	Dolerite	Seashore south of Foué
K-22	Bio-micritic limestone	Seashore south of Foué
K-23	Inter-pillow micritic limestone	Seashore south of Foué
K-24	Greywacke	Seashore south of Foué
K-25	Greywacke	Seashore south of Foué
O-2	Basaltic pillow	Quarry bet. RT 1 – coast
O-6	Basaltic pillow	Quarry bet. RT 1 – coast
O-7	Basaltic pillow	Quarry bet. RT 1 – coast
O-10	Inter-pillow calcarenite	Quarry bet. RT 1 – coast
O-11	Inter-pillow calcarenite	Quarry bet. RT 1 – coast
O-14 [a]	Basaltic glass fragment	Along the RT1
P-1	Basaltic pillow	RT1 near Poya
P-3	Green/grey jasp lense in basalt	RT1 near Arangus
P-5	Basaltic pillow	RT1 near Arangus
P-7	Yellow siliceous sediment	Honfleur Quarry
P-8	Red jasp	Honfleur Quarry
P-10	Basaltic pillow	Honfleur Quarry
Pi-1	Inter-pillow quartzite	Pinjen peninsula
Pi-3	Greywacke brecchia	Pinjen peninsula
Pi-5	Inter-pillow pink bio-micrite	Pinjen peninsula
Pi-6	Inter-pillow calcarenite	Pinjen peninsula
Pi-8	Inter-pillow red jasp	Pinjen peninsula
Pi-9	Olivine phyric altered alkali basalt	Pinjen peninsula
Pi-11	Jasp	Pinjen peninsula
PT1-1	Basaltic pillow	Honfleur Quarry drill core
PT1-3	Basaltic pillow	Honfleur Quarry drill core
PT1-6	Basaltic pillow	Honfleur Quarry drill core
PT1-7	Basaltic pillow	Honfleur Quarry drill core
PT1-9	Basaltic pillow	Honfleur Quarry drill core
PT1-12	Basaltic pillow	Honfleur Quarry drill core
PT1-13	Basaltic pillow	Honfleur Quarry drill core
PT1-17	Basaltic pillow	Honfleur Quarry drill core
Ta-2	Siltite with laminites	Val Mango
Ta-3	Red jasp with basalt	Val Mango
Te-1	Siliceous limestone	Along RT1 near Temala
Te-2	CK sediment of geologic map	Val Mango
V-1	Altered pillowed basalt	Gatope Point
V-4	Interpillow altered basalt and limestone	Gatope Point
V-5 [a]	Glass fragment	Gatope Point
V-7	Altered pillowed basalt	Gatope Point
V-8	Red jasp	Gatope Point
V-9 [a]	Glass fragment	Gatope Point
V-11	Microgranular inter-pillow limestone	Gatope Point
V-12 [a]	Glass fragment	Gatope Point

G = Gomen; O = Ouaco; Ta = Taom; Bo = Boyen; V = Voh; Te = Temala; Pi = Pinjen peninsula; K = Kone; P = Poya; PT1 = core from the drill done by the BRGM in the Honfleur sulphide deposit near Poya. RT1 = Territorial Road number 1.
[a] Fresh glass used for microprobe analyses.

(Fo_{83-85}), sparse olivine phenocrysts are replaced by chlorite, or chlorite and calcite. Plagioclase is almost always albitized. Metamorphic assemblages are either prehnite ± pumpellyite facies or chlorite ± actinolite assemblages indicating lowest greenschist-grade burial degradation of ocean-floor type. It is noteworthy to remark that the underlying Mesozoic–Paleocene sedimentary rocks have not been affected by this metamorphic episode (Gonord, 1977; Paris, 1981; Cluzel et al., 1994; Meffre, 1995). The alkaline lavas are volumetrically much less abundant, are always notably more altered than the MORB suite, and occur in localized outcrop areas rarely larger than 2 km in diameter. They are mainly strongly vesicu-

Table 2
Bulk rock analyses of the studied volcanic samples

Sample:	Bo-13	Bo-16B*	Bo-30*	Bo-34B*	Bo-35	Bo-40	G-1	G-4*	G-4	G-5*	K-1	K-8#	K-16	K-19*	K-19	K-21	O-2	O-6
Lava type:	MORB2	MORB2	MORB2	MORB2	MORB2	MORB2	MORB1	MORB1	MORB1	MORB1	alkali	alkali	alkali	MORB2	MORB1	MORB2	MORB1	MORB3
SiO_2	50.70	49.20	50.20	49.80	49.40	49.90	49.70	48.00	50.10	48.80	49.00	47.00	45.90	48.10	49.90	49.90	49.80	50.00
TiO_2	1.27	1.25	1.21	1.26	1.23	1.10	1.41	1.57	1.63	1.58	2.09	1.83	2.02	1.36	1.39	1.25	1.41	1.62
Al_2O_3	14.10	13.70	13.70	13.67	14.10	17.00	15.20	13.70	14.50	13.80	15.70	14.50	15.10	13.90	14.60	14.40	15.20	15.50
$Fe_2O_3{}^*$	11.70	12.96	12.65	12.95	11.40	10.50	11.30	13.07	12.10	13.45	12.80	12.80	8.82	12.10	11.30	11.30	11.00	9.70
MnO	0.27	0.24	0.26	0.23	0.22	0.20	0.21	0.22	0.23	0.21	0.23	0.20	0.26	0.18	0.19	0.21	0.22	0.28
MgO	8.31	7.50	7.35	7.52	8.10	6.39	7.63	6.98	7.29	6.85	5.61	5.22	2.37	7.42	7.95	7.91	7.52	8.18
CaO	10.10	10.60	9.63	9.78	12.40	11.20	11.60	10.70	11.50	10.75	9.86	14.10	18.30	11.40	11.53	11.87	11.77	11.50
Na_2O	2.76	2.44	2.66	2.62	2.92	3.03	2.56	2.41	2.47	2.48	3.24	3.36	3.68	2.75	2.95	2.78	2.67	3.03
K_2O	0.70	0.30	0.52	0.64	0.22	0.60	0.28	0.09	0.13	0.18	1.16	0.54	2.99	0.12	0.15	0.23	0.24	0.07
P_2O5	0.13	0.14	0.13	0.13	0.08	0.08	0.12	0.16	0.14	0.16	0.34	0.33	0.53	0.13	0.11	0.10	0.13	0.13
LOI	2.52	1.83	1.27	1.40	2.98	2.39	2.87	2.62	2.33	2.26	8.20	7.06	12.03	2.79	2.58	2.06	4.06	3.35
Total	100.04	100.16	99.58	100.00	100.07	100.00	100.01	99.52	100.09	100.52	100.03	99.88	99.97	100.25	100.07	99.95	99.96	100.01
Rb	14	5.3	9.7	9.7	6.6	13.0	3.0	1.7	1.0	2.4	21	10.1	45.0	2.1	2.3	5.0	7.0	2.0
Sr	252	298	170	190	140	261	140	129	136	130	337	363	488	174	180	180	137	182
Ba	130	66	121	252	58	115	37	27	31	35	107	111	456	42	47	41	57	19
Sc	55	46.5	45	45.5	48	44	42	46	43	45	30	27	10	42.5	46	47	46	42
V	354	360	325	346	355	315	306	350	353	340	254	251	258	300	325	349	348	333
Cr	201	182	185	178	225	29	201	130	128	127	415	428	165	315	328	223	328	270
Co		50	47	49				49		50				48				
Ni	97	98	90	95	102	67	88	66	73	65	195	200	113	83	93	102	114	82
Y	27	26	26	24	25	21	27	30	30	30	24	23	22	24	25	26	27	35
Zr	60	43	36	45.5	58	42	73	83	83	86	121	108	365	46	70	62	76	96
Nb	4.8	3.95	3.7	3.95	4.4	3.4	3.3	4.1	5.1	4.15	22	19.5	61.0	3.3	3.4	5.1	3.6	2.0
Ta												0.97						
Hf												2.34						
Th												1.34						
La		4.4	3.7	4.65		3.81		4.65		4.75	13.10	10.98		3.9		4.46		3.39
Ce		11	9.5	11		9.36		12.5		13	30.70	27.19		11		11.40		10.8
Pr						1.33					4.05					1.59		1.79
Nd		9	8.5	9		6.93		11		11	18.10	16.01		10		9.01		10.7
Sm						2.46					4.87	4.29				3.19		4.17
Eu		1.00	1.15	1.10		1.01		1.25		1.35	1.80	1.40		1.10		1.09		1.49
Gd						3.27					5.12					3.96		5.48
Tb												0.65						
Dy		4.3	4.3	4.2		3.88		4.9		4.8	4.88			3.9		4.79		6.62
Er		2.8	2.9	2.7		2.33		3.4		3.2	2.47			2.6		2.95		4.27
Yb		2.53	2.58	2.35		2.03		2.80		2.80	1.72	1.48		2.13		2.78		3.95
Lu												0.20						
Ma (K/Ar)		43.7	43.8(a)	39.7				47.0(a)		48.7(a)				41.9				
Std. dev.		±2.2	±2.2	±2.1				±2.4		±2.5				±2.1				
Ti/Zr	127	174	201	166	127	157	116	113	118	110	104	102	33	177	119	121	111	101
La/Nb		1.11	1.00	1.18		1.12		1.13		1.14	0.60	0.56		1.18		0.87		1.70
Zr/Nb	13	11	10	12	13	12	22	20	16	21	6	6	6	14	21	12	21	48
Th/Nb												0.069						

Table 3
Bulk rock analyses of the studied volcanic samples (continued)

Sample:	O-7	P-1#	P-5#	P-10	Pi-9	PT1-1	PT1-3#	PT1-6	PT1-7*	PT1-7	PT1-9*	PT1-9	PT1-12	PT1-13#	PT1-17	V-1	V-7*	V-7
Lav a type:	MORB1	alkali	MORB1	alkali	alkali	MORB1	MORB1	MORB1	MORB1	MORB1	MORB1	MORB1	MORB1	MORB1	MORB1	MORB1	MORB3	MORB3
SiO_2	51.30	52.10	49.50	51.60	40.60	50.40	50.40	51.10	4920	50.70	49.00	50.40	50.70	50.80	50.10	50.30	50.50	51.10
TiO_2	1.30	1.93	1.27	2.24	2.03	1.40	1.34	1.12	1.69	1.73	1.47	1.50	1.74	1.40	1.43	1.45	0.98	0.99
Al_2O_3	16.20	16.90	15.20	17.10	13.30	13.30	14.50	14.80	13.65	14.20	14.10	14.60	13.60	14.30	14.70	15.70	15.10	15.50
$Fe_2O_3^*$	7.80	10.90	11.10	10.70	10.10	12.70	11.00	10.10	13.35	12.40	12.15	11.20	12.90	11.30	11.60	9.53	9.80	8.96
MnO	0.16	0.18	0.21	0.12	0.17	0.19	0.21	0.17	0.22	0.23	0.23	0.23	0.26	0.21	0.21	0.17	0.17	0.17
MgO	7.92	4.61	7.94	4.62	2.58	8.78	8.05	8.34	6.55	6.87	7.10	7.40	6.92	7.78	7.95	6.05	7.85	8.02
CaO	11.87	8.55	11.70	7.54	24.60	9.63	12.00	11.65	10.45	11.00	11.30	11.80	10.20	10.80	10.60	12.93	11.80	12.30
Na_2O	3.15	3.50	2.85	3.80	4.08	3.42	2.34	2.41	2.37	2.60	2.35	2.72	3.24	3.00	3.04	3.00	2.30	2.55
K_2O	0.18	1.24	0.17	1.86	1.87	0.08	0.08	0.16	0.14	0.14	0.12	0.12	0.23	0.23	0.29	0.72	0.38	0.40
P_2O5	0.14	0.12	0.08	0.51	0.68	0.12	0.11	0.09	0.17	0.16	0.15	0.12	0.16	0.13	0.14	0.12	0.10	0.08
LOI	3.78	5.14	2.74	4.22	16.30	3.57	2.58	3.52	2.23	2.06	2.21	3.01	2.42	3.38	2.88	2.93	1.47	1.28
Total	100.02	100.03	100.02	100.09	100.01	100.02	100.03	99.94	100.02	100.03	100.18	100.09	99.95	99.95	100.06	99.97	100.45	100.07
Rb	4.0	25	9	32	32	2.0	1.0	2.2	2.1	1.4	1.9	1.0	3.0	3.0	3.0	16.0	7.2	7.0
Sr	196	254	115	261	141	142	136	179	164	169	140	149	155	164	160	116	87	88
Ba	27	193	30	249	300	36	36	85	51	60	33	43	62	43	47	18	7	12
Sc	47	41	52	47	7	46	44	46	44	44	43.5	45	45	45	45	47	39.5	44
V	308	290	295	288	173	309	307	277	360	390	320	336	377	323	299	332	254	285
Cr	366	104	410	55	298	260	249	374	88	95	286	299	82	241	268	283	230	280
Co									50		46						44	
Ni	156	45	70	61	164	80	79	100	60	72	84	97	65	86	87	96	73	78
Y	31	39	31	46	25	28	25	25	31.5	32	28	30	31	27	30	33	25	26
Zr	85	140	88	181	254	75	72	69	95.5	97	81	82	98	75	81	90	48.5	50
Nb	3.6	25	3.8	36	44.5	4.1	3.7	3.8	4.75	4.9	4.05	2.5	5.3	4.7	4.9	3.8	0.85	0.5
Ta		1.76	0.60				0.42							BDL				
Hf		3.07	1.42				1.58							2.44				
Th		1.90	BDL				0.46							0.41				
La		16.80	3.64				3.98		5.75		4.55			5.81			2.2	
Ce		33.80	9.14				10.00		15		11.5			15.43			7	
Pr																		
Nd		20.00	7.59				7.99		12		10.5			12.38			7	
Sm		5.61	2.58				2.77							4.08				
Eu		1.71	0.97				0.94		1.35		1.15			1.47			0.85	
Gd																		
Tb		1.13	0.58				0.66							0.96				
Dy									5.2		4.6						4	
Er									3.7		3						2.8	
Yb		3.43	2.15				2.27		2.90		2.55			2.94			2.48	
Lu		0.51	0.31				0.34							0.44				
Ma (K/Ar)									49.0(a)		61.6(b)						48.1(a)	
Std. dev.									±2.5		±2.8						±2.4	
Ti/Zr	92	83	87	74	48	112	112	97	106	107	109	110	106	112	106	97	121	119
La/Nb		0.67	0.96				1.08		1.21		1.12			1.24			2.59	
Zr/Nb	24	6	23	5	6	18	19	18	20	20	20	33	18	16	17	24	57	100
Th/Nb		0.076					0.124							0.087				

Analysts : Phil Robinson at the University of Tasmania, Hobart, Australia (major, traces, and REE by XRF), * Joseph Cotten at University of Bretagne Occidentale, Brest, France (major, traces and REE by ICP–AES), and # Helen Waldron at Becquerel Laboratories, Menai, Australia (REE, Hf, Th, and Ta by NAA). BDL = below detection limit. MORB1 = N-MORB; MORB2 = Boyen doleritic MORB suite; MORB3 = MORB with BABB affinity; alkali = alkali suite (see text for explanations). $^{40}K/^{40}Ar$ whole-rock dates: (a) average of two dates; (b) average of two dates done on two separate granulometric fractions leached by acetic acid to eliminate alteration phases. All analyses (isotopic composition of argon by mass spectrometry using isotopic dilution and potassium by atomic absorption spectrophotometry) were performed at the University of Bretagne Occidentale by Hervé Bellon and Jean-Claude Philippet.

Table 4
Fresh glass rim analyses (averages) done using the 'Microsonde Ouest' CAMECA SX50 microprobe of Brest

Sample number:	V-5	V-7	V-9	V-12	O-14
Number of analyses:	4	6	1	2	4
SiO_2	49.97	49.98	49.61	49.58	49.78
TiO_2	1.09	1.27	1.61	1.63	1.40
Al_2O_3	15.55	15.42	14.63	14.58	15.04
FeO^*	8.86	9.15	11.08	11.01	10.02
MnO	0.15	0.16	0.15	0.17	0.16
MgO	9.331	8.97	7.74	7.77	8.45
CaO	12.55	12.15	11.82	11.75	12.07
Na_2O	2.39	2.50	2.72	2.55	2.54
K_2O	0.03	0.05	0.15	0.15	0.09
P_2O_5	0.00	0.00	0.17	0.00	0.04
Total	99.92	99.65	99.68	99.19	99.59

Analysts : Jean-Philippe Eissen and Marcel Bohn. The entire set of glass microprobe analyses is available upon request from the senior author of this paper.

lar pillow basalts with common olivine phenocrysts replaced by hematite and calcite, and occasional albitized plagioclase phenocrysts. Abundant vesicles are filled by calcite.

5. Analytical methods

The samples analysed were finely powdered in an agate mill. Major and trace elements analysed in Brest, except for Rb, were measured by ICP–AES with an ISA Jobin-Yvon® JY 70 Plus apparatus. Rb was measured by flame atomic emission using a Perkin-Elmer® 5000 spectrometer. The procedure of solution preparation was presented by Cotten et al. (1995). All the elements were determined from one solution without selective extraction. Calibrations were made using international standards (JB2, BEN, ACE, Mica-Fe) as well as specific references samples. Relative standard deviations are $\leq 2\%$ for major elements and $\leq 5\%$ for trace elements. Detection limits are Rb 0.5 ppm, Sr 0.5 ppm, Ba 2 ppm, Sc 0.2 ppm, V 3 ppm, Cr 2 ppm, Co 2 ppm, Ni 2 ppm, Y 0.5 ppm, Zr 2 ppm, Nb 1 ppm, La 0.8 ppm, Ce 2 ppm, Nd 2 ppm, Eu 0.2 ppm, Dy 0.3 ppm, Er 1 ppm and Yb 0.1 ppm. XRF major and trace elements analyses were performed at the University of Tasmania using an automated Philips® PW 1410 spectrometer. Major elements were measured with Rh tube, Sc, V, Cr, Sr, Zr, Nb and Ba using a Au tube and Ni, Rb and Y a Mo tube. Trace elements were determined using mass absorption coefficients calculated from major element analyses. Major elements were analysed using fused discs, following the method of Norrish and Hutton (1969). Loss on ignition was measured as weight percent loss of 1 g of powdered sample heated to 1000°C for 12 h, followed by 5 h at 400°C. Trace elements were analysed on 6-g pressed powder pellets coated with boric acid, using the method of Norrish and Chappel (1977). The REE data were measured using the ion separation XRF technique described by Robinson et al. (1986). INAA data were obtained at Becquerel Laboratories, Lucas Heights Research Laboratories, New South Wales (analyst Helen Waldron). Detection limits are Hf 0.5 ppm, Ta 0.2 ppm and Th 0.2 ppm.

6. Geochemistry

We have analyzed 36 basalts from outcrops along the length of the Poya Terrane between Bourail and Koumac on the west coast of New Caledonia (Fig. 1). Also available for consideration are eleven analyses of MORB-like basalts from this same area, reported by Cameron (1989). All analyzed PTB are basaltic compositions, and despite careful sample selection and analytical procedures, loss on ignition values are typically 1–4% for the MORB-like suite, and usually 5–8% for the amygdaloidal alkaline suite. Thus we consider it unlikely that the measured alkali- and K-group element abundances are pristine, and we rely mainly on immobile HFSE and REE elements for determining the affinities of these basalts.

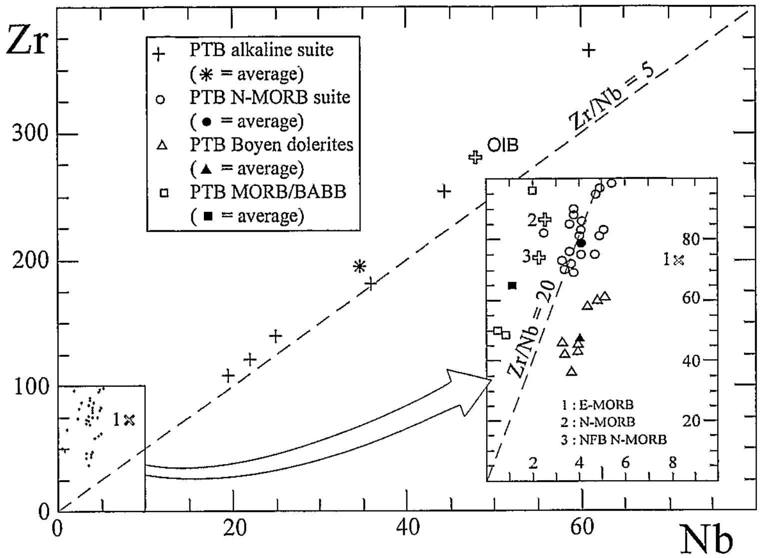


Fig. 2. Zr versus Nb of the Poya Terrane basalt compositions showing the more alkaline suite and the MORB suite (enlarged area). OIB, E-MORB and N-MORB references after Sun and McDonough, 1989; North Fiji Basin N–S segment N-MORB average after Eissen et al., 1994.

The alkaline basalts have Nb contents at least twice those of the MORB-like suite at similar stages of fractionation, and all have Zr/Nb values between 5 and 6 (Fig. 2; 'alkali' samples of Tables 2 and 3). N-MORB-normalized element variation patterns for immobile elements (Fig. 3) for this suite show significant enrichment in the more incompatible elements, and fall between those of enriched ridge-generated MORB (E-MORB) and ocean island basalt (OIB). We interpret these basalts to have derived from seamounts formed on ocean crust. They may be essentially in situ on MORB-like PTB, or they may have been scraped off their original oceanic substrate during subduction, and emplaced onto PTB MORB-like basalts during emplacement of the PTB as an allochthonous slice beneath the main harzburgitic ophiolite.

The MORB-like basaltic suite shows a limited fractionation range (36–103 ppm Zr), and has TiO_2 contents from 1.0–1.8%; ferrobasalts ($FeO^* > 14\%$) are unrecorded. The majority of these basalts have of Ti/Zr (87–137) and La/Nb (1.09 ± 0.12), values characteristic of N-MORB. However, Zr/Nb values (20 ± 4) are slightly lower than for N-MORB (32–40), due to very slightly higher Nb values of the PTB compared to N-MORB at similar stages of fractionation (Fig. 2). Some dolerites which outcrop mainly along the Boyen River or near Koné, even have slightly lower Zr/Nb values (12 ± 2), but their spidergrams are very similar to those of the main basaltic lava group (MORB 2 of Table 2). Despite this, N-MORB-normalized element variation patterns show weak negative Nb anomalies and have Th/Nb values (0.09 and 0.12 for the two samples analyzed) significantly higher than values for N-MORB (0.03–0.08: our average of 51 samples from the literature is 0.066 ± 0.015). Chondrite-normalized REE patterns show only slight LREE-enrichment, and flat HREE (Fig. 4). However, at least two basalts of the MORB-like suite show more depleted REE patterns and a slight but significant negative Nb anomaly (Fig. 3) relative to adjacent La as observed for BABB (MORB 3 of Tables 2 and 3); however, these more depleted basalts have Zr/Nb~50, values characteristic of LREE-depleted N-MORB.

Cameron (1989) reported Nd–Sr isotopic data for three PTB with a Zr/Nb of 18–22, for which initial ϵ_{Nd} values (recalculated to 80 Ma) are +3.1, +3.5 and +4.6, significantly below values for N-MORB of this age (>+8). We suggest that the trend to low ϵ_{Nd} and high Th/Nb relative to MORB, and the weak negative Nb anomalies, reflect limited assimilation

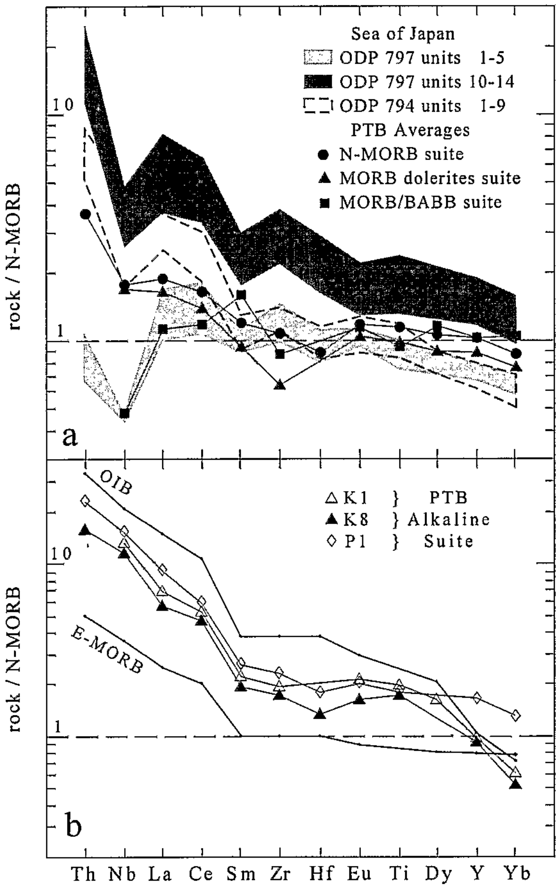


Fig. 3. Variation diagrams of N-MORB-normalized elements showing representative patterns for: (a) averages of the PTB N-MORB suite, the PTB Boyen dolerites and the PTB MORB/BABB in comparison with selected patterns from three different units of ODP Site 797 (Sea of Japan; data from Allan and Gorton, 1992 and Pouclet and Bellon, 1992); (b) three lavas for the Poya Terrane basalts alkaline suite. N-MORB, E-MORB and OIB values after Sun and McDonough (1989).

of older (Mesozoic or Palaeozoic?) continental crust during eruption of these otherwise MORB-like rift tholeiites. We note that backarc basin basalts from stable intra-oceanic backarc basins such as the southern and central parts of the North Fiji Basin and the northern Lau Basin have ϵ_{Nd} values normally >7 and Th/Nb <0.08 (Jenner et al., 1987; Volpe et al., 1988; Auzende et al., 1990). In contrast, BABB generated during rifting of older continental margin arc crust (e.g. Sea of Japan) have ϵ_{Nd} values between 3 and 7, and Th/Nb values averaging 0.120 ± 0.04 for Sea of Japan ODP Site 794 (sixteen samples) and 0.273 ± 0.06 for the lower basalts in ODP Site 797 (eight samples) (Pouclet and Bellon, 1992; Nohda et al., 1992; Cousens and Allan, 1992). Basalts in the Okinawa Trough, a backarc rift in the thinned continental margin crust of eastern China, have ϵ_{Nd} values from +2.3 to +4.7 (Chen et al., 1995), but Th/Nb values are unavailable.

7. Discussion

Our new data for the PTB indicate that they are an allochthonous slice of tholeiites produced during rifting at ~70–80 Ma along the eastern margin of the Norfolk–New Caledonia Ridge. The PTB cannot be related to the main New Caledonian harzburgitic ophiolite because of the very refractory nature of the latter (see below). The PTB are interpreted instead as an allochthonous slice below the ophiolite, picked up by the ophiolite and transported shortly southwestward along the base of the ophiolite during its emplacement in the Upper Eocene.

The major tectono-stratigraphic unit in New Caledonia is the massive harzburgitic ophiolite, for which the cumulate carapace is volumetrically insignificant and directly associated lavas remain unknown. The very refractory nature of the dominant harzburgitic tectonites (Prinzhoffer et al., 1980) indicates that equilibrium melts must have been depleted, second-stage melts, not MORB-type tholeiites such as the PTB, which would have been in equilibrium with lherzolitic residues (Falloon et al., 1989). Lavas chemically appropriate for equilibrium melts with the harzburgitic tectonites are the low-Ca boninites that crop out in several restricted areas, probably as blocks within a serpentinite melange, immediately beneath the ophiolitic harzburgites in the Nepoui area of western New Caledonia (Fig. 1b). These boninites contain Fo_{94} olivine phenocrysts and extremely refractory Cr-rich chromites ($Cr/(Cr + Al) = 0.84$ to 0.88; Cameron, 1989). We suggest that these boninites are part of the liquid complement of the ophiolite represented by the harzburgites, and that slices of the carapace of the ophiolite were over-ridden by massive harzburgite allochthons during emplacement.

Analogous to the Bonin–Mariana forearc, the New Caledonian boninites and their overlying

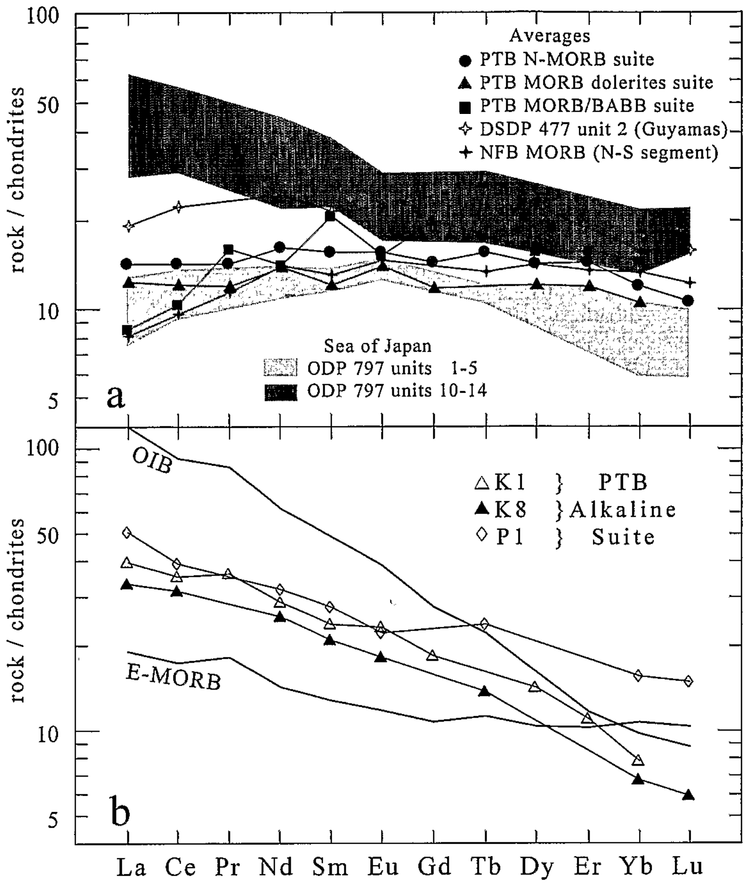


Fig. 4. Variation diagrams of chondrite-normalized rare earth elements showing representative patterns for: (a) averages of the PTB N-MORB suite, the PTB Boyen dolerites and the PTB MORB/BABB in comparison with selected patterns from the Guyamas Basin, Gulf of California (DSDP, Site 477; Saunders et al., 1982) and the Sea of Japan (ODP Site 797; Allan and Gorton, 1992; Pouclet and Bellon, 1992); (b) three lavas for the Poya Terrane basalts alkaline suite. C1 chondrite, E-MORB and OIB values after Sun and McDonough (1989).

harzburgitic residues may represent forearc basement to an oceanic island arc represented now by the basement of the Loyalty Islands, presently capped by Quaternary coral reefs (Maillet et al., 1983; Collot et al., 1987; Aitchison et al., 1995b). Strongly altered lavas of intraplate affinity (K/Ar age of 9–11 Ma) outcrop in a restricted area of the island Mare (Baudron et al., 1976; Monzier, 1993) and OIB and comendites (K/Ar age of 30–33 Ma) have been described in the submarine basement of the island Mare between water depths of 4000 and 5200 m associated with backarc basin basalts (Monzier et al., 1989; Monzier, 1993).

However, the Loyalty Islands are the emergent part of an 1100-km-long ridge that includes 12–15 seamounts; the islands are ~150 km east of the leading edge of the main harzburgitic ophiolite nappe in New Caledonia, and are spaced ~70 km apart, similar to the spacing for major volcanoes in the Mariana arc (50 km; Bloomer et al., 1989) and the southern part of the New Hebrides arc (90 km; Macfarlane et al., 1988). Where the Loyalty Ridge swings northeastward into the d'Entrecasteaux Ridge, seamounts on the latter are known to be composed of primitive island arc tholeiites (Coltorti et al., 1994; Baker et al., 1994), strongly supporting the suggestion that the Loyalty Ridge marks an intra-oceanic arc. Arc-derived volcaniclastics of Mid-Eocene age drilled in the North Loyalty Basin at DSDP Site 486 (Andrews et al., 1975) can be traced seismically to lap onto the northern Loyalty Ridge seamounts (Meffre, 1995).

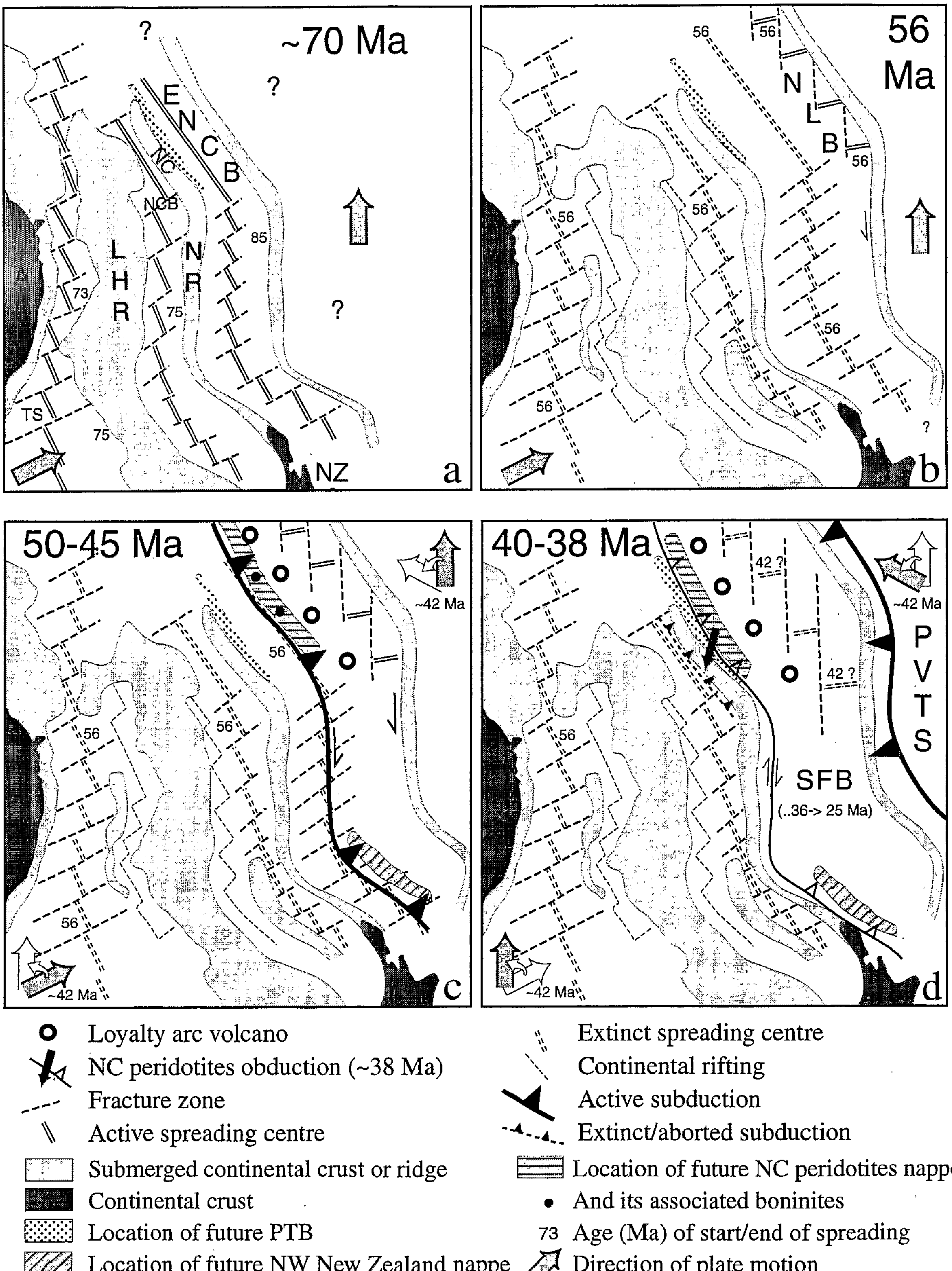
The cessation of magmatism on the arc volcano seamounts of the South d'Entrecasteaux Chain has been dated at around 38 Ma (Quinn et al., 1994; Baker et al., 1994), and in Hole 486, a marked decrease in volcaniclastic sedimentation in the Late Eocene suggests that arc magmatism may have ceased on the Loyalty arc around 38 Ma (Andrews et al., 1975). The North Loyalty Basin contains magnetic lineations, oriented N70° to N80°, which have been interpreted as anomalies 18 to 23 (42 to 55 Ma; Lapouille, 1982; Weissel et al., 1982).

We suggest that the eastern margin of the Australian section of Gondwana was fragmented by progressive, subparallel rifting episodes around 50–75 Ma, with the creation of true ocean crust and magnetic anomalies around 73 Ma in the Tasman Sea and around 75 Ma in the New Caledonia Basin. This rifting created, from west to east, the Tasman Sea, the Lord Howe Rise, the New Caledonia Basin, and the Norfolk–New Caledonia Ridge. That ribbon of continental crust represented by the basement of the Norfolk Ridge (Green, 1978) is now only exposed in the core of New Caledonia, where it is composed of a Permo–Triassic arc-related collage (Paris, 1981). The nature of the freeboard east of the Norfolk Ridge at this time is unknown, but we note that no Paleocene or late Mesozoic subduction-related volcanics are known along the SW Pacific margin, implying that the eastern margin of the pre-Eocene Australian plate was not an active subduction margin.

We have argued above that the PTB represent rift magmatism produced during the breakup stage of development of a small ocean basin. In our preferred tectonic model, the PTB represent a slice of the near-breakup western passive margin of a small ocean crust-floored basin, here called the East New Caledonia Basin, that began to form around 85 Ma (Fig. 5a). Later east-directed subduction of the ocean crust of the East New Caledonia Basin led first to the closure of the latter followed by the collision of the western passive margin of the ERast Caledonia Basin with the forearc of the Loyalty oceanic arc (see later) which emplaced the main New Caledonian ophiolite sheet from the north-northeast back onto this passive margin (Fig. 5b). If this is correct, there must be a conjugate passive margin representing the eastern side of the East New Caledonia Basin. We suggest that the remnants of this easternmost ribbon of continental crust that rifted eastward from the Norfolk–New Caledonia Ridge during opening of the East New Caledonia Basin, and later of the South Fiji Basin, is now located in the basement of the Western Belt of the New Hebrides (Vanuatu) island arc (Fig. 1), and possibly also in the basement of the Fiji platform, both of which evolved later into the Vitiaz arc. Isotopic data for Pb-Ns-Sr for Oligo-Miocene volcanics do suggest the presence of a continental source component beneath Espiritu Santo (Laporte et al., 1997). In the Western Belt of the New Hebrides arc, Oligo–Miocene arc volcanics are markedly different from the basalt-dominated intra-oceanic arc volcanics of the modern arc (Monzier et al., 1997) and include abundant medium- to high-K hornblende andesites and diorites hosting porphyry-Cu-style mineralization (Macfarlane et al., 1988).

In this model, there are two conceivable possibilities for the origin of the North Loyalty Basin. It may simply be a remnant of the youngest part of the East New Caledonia Basin, which continued to spread until at least 42 Ma following cessation of rifting in the Tasman Sea and New Caledonia Basin at ~56 Ma (Fig. 5b). But this hypothesis is in contradiction with the NE–SW orientation of the magnetic lineations (Lapouille, 1982; Weissel et al., 1982). Alternatively, the North Loyalty Basin may have been a backarc basin of the Loyalty–d'Entrecasteaux arc which evolved eventually later into the South Fiji Basin after the formation of the Vitiaz–Lau–Colville arc (proto-New Hebrides–Tonga–Kermadec

Fig. 5. Schematic geodynamic reconstruction of New Caledonia and the SW Pacific around ~70 Ma (a), near 56 Ma (b), between 50 and 45 Ma (c); and around 40–38 Ma (d). *A* = Australia; *ENCB* = East New Caledonia Basin; *LHR* = Lord Howe Rise; *NC* = New Caledonia; *NCB* = New Caledonia Basin; *NLB* = North Loyalty Basin; *NR* = Norfolk Ridge; *NZ* = New Zealand; *PVTS* = Proto Vitiaz Tonga Subduction; *SFB* = South Fiji Basin; *TS* = Tasman Sea. See text for explanations.


~70 Ma
E
N
C
B
NC
NCB
L
H
R
N
R
73
75
85
TS
NZ
a
56
Ma
N
L
B
56
b
50-45 Ma
~42 Ma
56
c
40-38 Ma
42 ?
P
V
T
S
SFB
(..36-> 25 Ma)
d
Loyalty arc volcano
NC peridotites obduction (~38 Ma)
Fracture zone
Active spreading centre
Submerged continental crust or ridge
Continental crust
Location of future PTB
Location of future NW New Zealand nappe
Extinct spreading centre
Continental rifting
Active subduction
Extinct/aborted subduction
Location of future NC peridotites nappe
And its associated boninites
73 Age (Ma) of start/end of spreading
Direction of plate motion

arc). However, this demands the existence of an early subduction and arc formation at least around 55 Ma, for which there is no evidence. DSDP drilling in the North Loyalty Basin penetrated only open ocean, pelagic sediments of Eocene age, despite the proximity to the Loyalty–d'Entrecasteaux arc volcanoes.

Following cessation of rifting in the Tasman Sea, New Caledonia Basin and Eastern New Caledonia Basin at ~56 Ma (Fig. 5b), continued extension at the eastern margin of the Australian plate was taken up by opening of the North Loyalty Basin, in which the oldest magnetic anomalies are ~56 Ma, which evolved later into the South Fiji Basin. This opening combined with the general northward displacement of the Australian plate, presumably generated regional more or less NE–SW compression, which we believed initiated subduction along the spreading ridge in the East New Caledonia Basin spreading centre (Fig. 5c). This slow subduction, NE deepening, generated boninitic lavas from the hot young lithospheric wedge of the just extinct spreading centre and explains the very refractory nature of the associated harzburgitic crust in the forearc position of the nascent Loyalty–d'Entrecasteaux arc, with the mantle now exposed in the New Caledonia ophiolite. Boninite generation requires abnormally high temperatures at relatively shallow levels in the upper mantle (Crawford et al., 1989), and subduction initiation may well have been focussed on the thermally weakened, only recently extinct, spreading centre in the East New Caledonia Basin. Continued subduction, albeit relatively short-lived, produced the primitive arc volcanoes of the Loyalty–d'Entrecasteaux arc.

The major reorganization of plate motion in the Pacific region around 42 Ma, best shown by the bends in the intraplate island chains in the Pacific Ocean such as that in the Hawaiian–Emperor chain, led to a NW-directed motion for the Pacific plate. This reorganization also affected the Australian plate motion (Duncan and McDougall, 1989; Lanyon et al., 1993). At anomaly 19 (~43 Ma), spreading in the Southern Ocean between Australia and Antarctica accelerated to about 5 times its previous velocity, and imposed a major N–S-directed motion on the Australian plate (Veevers et al., 1991).

This reorganization eventually drew the PTB-bearing rifted eastern margin of the Norfolk–New Caledonia Ridge into the trench around 38 Ma, terminating arc magmatism on the Loyalty–d'Entrecasteaux arc and emplacing the forearc-derived ophiolite on New Caledonia and initiating accompanying foredeep sedimentation (Fig. 5d).

Middle Eocene foredeep sediments and olistostromes record the collision of the Norfolk–New Caledonia Ridge continental ribbon with the forearc region of the intra-oceanic Loyalty–d'Entrecasteaux arc (Aitchison et al., 1995a). We propose that the first nearby allochthon (almost parautochthon) to be detached and emplaced southwestward in this collision is that represented by the PTB. Subsequent allochthons were derived from the forearc region of the colliding arc system, and these piggy-backed over the PTB parautochthon. The mantle section of the forearc may eventually have over-ridden its own lava-cumulate carapace. This ophiolite emplacement could have been synchronous or preceded a similar collision observed in the NW New Zealand peninsula (Brothers and Delaloye, 1982). Post-collisional extension led to exhumation of the high-grade metamorphic basement of the Norfolk–New Caledonia Ridge in northern New Caledonia (Aitchison et al., 1995a; Cluzel et al., 1995).

In summary, we believe that the Poya Terrane basalts form a proximal allochthonous sheet below the main harzburgitic nappe constituting the New Caledonian ophiolite. They are genetically unrelated to the ophiolite, and are interpreted to be 70–80-Ma-old rift tholeiites formed during opening of the East New Caledonia Basin, when an unknown continental fragment rifted eastward from the Norfolk–New Caledonia Ridge. Later closure of the East New Caledonia Basin, by an east-directed subduction, led to the collision of the western passive margin of the latter ridge with the forearc region of the intra-oceanic Loyalty–d'Entrecasteaux arc around 40 Ma. This collision forced the westward translation of the PTB as a slice picked up from the upper crustal section of the colliding Norfolk–New Caledonia Ridge. Subsequent collisional tectonism led to the detachment of the main New Caledonian harzburgitic nappe and its associated boninites from their forearc location, and their southwestward emplacement over the PTB nearby allochthon, the boninites being emplaced first below the main harzburgitic nappe.

8. Implications for other ophiolites

It is noteworthy that, in at least two other arc–continent collision settings with which we are familiar, there are parautochthonous sheets of basalts unrelated to immediately overlying forearc-derived, boninite-bearing harzburgitic ophiolites. Worthing and Crawford (1996) have documented the geochemistry of the Emo-Kokoda metabasalts from beneath the harzburgite-dominated, Eocene, boninite-bearing (Cape Vogel) Papuan ophiolite. Like the PTB, the Emo-Kokoda greenschists and amphibolites are dominated by low-K tholeiites with Zr/Nb values mainly between 8 and 16, but with two samples having typical N-MORB Zr/Nb values (>30). N-MORB-normalized element variation patterns show weak negative Nb anomalies, and the two samples analyzed for Nd isotopes have initial ϵ_{Nd} values of $+3$ to $+4$. In the extensive Early to Middle Cambrian ophiolites of the Lachlan Foldbelt of eastern Australia, latest Proterozoic rift tholeiites (Crimson Creek Formation and correlatives) underlie the boninite-bearing, harzburgite-dominated ophiolite sheet at numerous locations in Tasmania where sections are best exposed (Crawford and Berry, 1992). These basalts are compositionally identical to the PTB, despite being ~600 million years older.

We conclude that basaltic volcanics underlying major ophiolites are not necessarily genetically related to the adjacent supra-subduction zone, probably forearc-derived ophiolites. Rather, they probably represent tholeiites erupted during extension and rifting of continental crust to form a passive margin. Subsequent arc–continent collision may have emplaced forearc-derived ophiolite allochthons onto the tholeiite-bearing passive margin, and one or more parautochthonous slices of this passive margin basement may have been transported along it, attached to the base of the ophiolite nappe.

Acknowledgements

This work was supported by the UR 14 (now GP 22) of ORSTOM (Institut Français de Recherche Scientifique pour le Développement en Coopération). AJC acknowledges support from the Australian Research Council via a Senior Fellowship and Large Grant. We thank Jacques Récy for initiating and supporting this work, the BRGM of New Caledonia for providing us with samples from the Honfleur drill hole, Jean-Claude Philippet, Marcel Bohn, Phil Robinson and Helen Waldron for their help in performing careful analytical work, André Schaaf for his attempt to find Radiolaria in the sediments associated with the lavas, Jean-Louis Laurent for his help during the field work, Christian Picard and Jon Aitchison for constructive discussions about this work and Jean-Yves Collot and Richard Price for their careful and constructive reviews which greatly improved the paper.

References

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

Aitchison, J.C., Meffre, S., Cluzel, D., 1995b. Cretaceous/Tertiary Radiolarians from New Caledonia. Geol. Soc. N.Z. Misc. Publ. 81A, 1–70.

Allan, J.F., Gorton, M.P., 1992. Geochemistry of igneous rocks from Legs 127 and 128, Sea of Japan. Proc. ODP Sci Results 127/128, Part 2, pp. 905–929.

Andrews, J.E., Packham, G. et al., 1975. Initial Reports DSDP, 30. U.S. Govt. Printing Office, Washington DC.

Auzende, J.-M., Boespflug, X., Bougault, H., Dosso, L., Foucher, J.-P., Joron, J.-L., Ruellan, E., Sibuet, J.-C., 1990. From intracratonic extension to mature spreading in back arc basins: examples from the Okinawa, Lau and, North Fiji Basins. Oceanol. Acta 10, 153–163.

Avias, J.V., 1967. Overthrust structure of the main ultrabasic New Caledonia massives. Tectonophysics 4, 531–541.

Avias, J.V., Coudray, J., 1975. Sur la nature et l'origine des 'épanchements volcano-sédimentaires paléogènes' de la Nouvelle-Calédonie. C.R. Acad. Sci. Paris, Sér. D 280, 545–546.

Baker, P.E., Coltorti, M., Briqueu, L., Hasenaka, T., Condliffe, E., Crawford, A.J., 1994. Petrology and composition of the volcanic basement of Bougainville guyot, site 831. Proc. ODP Sci. Results 134, 363–373.

Baudron, J.-C., Guillon, J.-H., Récy, J., 1976. Géochronologie par le méthode K/Ar de l'île de Maré, archipel des Loyauté (Sud-Ouest Pacifique). Bull. Bur. Rech. Géol. Min. 2, 165–176.

Bellon, H., Rangin, C., 1991. Geochemistry and isotopic dating of Cenozoic volcanic arc sequences around the Celebes and Sulu seas. Proc. ODP Sci. Results 124, 321–338.

Black, P.M., 1993. Tectonism, magmatism and sedimentary basin development, Paleozoic to Paleogene, New Caledonia. Geol. Soc. Malaysia Bull. 33, 331–341.

Bloomer, S.H., Stern, R.J., Fisk, E., Geschwind, C.H., 1989. Shoshonitic volcanism in the Northern Mariana Arc, 1. Mineralogic and major and trace element characteristics. J. Geophys. Res. 94 (B4), 4469–4496.

Brothers, R.N., Delaloye, M., 1982. Obducted ophiolites of North Island, New Zealand: origin, age, emplacement and tectonic implications for Tertiary and Quaternary volcanicity. N.Z.J. Geol. Geophys. 25, 257–274.

Cameron, W.E., 1989. Contrasting boninite–tholeiite associations from New Caledonia. In: Crawford, A.J. (Ed.), Boninites. Unwin Hyman, London, pp. 314–336.

Carroué, J.P., 1972. Carte et notice explicative de la carte géologique de Nouvelle-Calédonie à l'échelle du 1/50.000: feuille de Pouembout. Bureau de Recherches Géologiques et Minières, Orléans.

Challis, G.A., Guillon, J.-H., 1971. Etude comparative à la microsonde électronique du clinopyroxène des basaltes et des périodites de Nouvelle-Calédonie. Possibilité d'une origine commune de ces roches. Bull. Bur. Rech. Géol. Min. 4 (2), 39–45.

Chen, C.-H., Lee, T., Shieh, Y.-N., Chen, C.-H., Hsu, W.-Y., 1995. Magmatism at the onset of back-arc spreading in the Okinawa Trough. J. Volcanol. Geotherm. Res. 69 (3/4), 313–322.

Cluzel, D., Aitchinson, J., Clarke, G., Meffre, S., Picard, C., 1994. Point de vue sur l'évolution tectonique et géodynamique de la Nouvelle-Calédonie. C.R. Acad. Sci. Paris, Sér. II 319, 683–690.

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

Collot, J.-Y., Malahoff, A., Récy, J., Latham, G., Missègue, F., 1987. Overthrust emplacement of the New Caledonia ophiolite. Tectonics 6, 215–232.

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

Coltorti, M., Hasenaka, T., Briqueu, L., Baker, P.E., Siena, F., 1994. Petrology and magmatic affinity of the north d'Entrecasteaux ridge, central New Hebrides trench, Site 828. Proc. ODP Sci. Results 134, 353–362.

Cotten, J., Le Dez, A., Bau, M., Caroff, M., Maury, R.C., Dulski, P., Fourcade, S., Bohn, M., Brousse, R., 1995. Origin of anomalous rare-earth element and Yttrium enrichments in subaerial exposed basalts: evidence from French Polynesia. Chem. Geol. 119, 115–138.

Coudray, J., Gonord, H., 1967. Extension de la paléosurface d'émersion intra-éocène dans les régions nord-ouest du bassin de Nouméa. C.R. Soc. Géol. Fr. 3, 105–107.

Cousens, B.L., Allan, J.F., 1992, A Pb, Sr and Nd isotopic study of basaltic rocks from the Sea of Japan, Leg 127/128. Proc. ODP Sci. Results 127/128, Part 2, pp. 805–818.

Crawford, A.J., Berry, R.F., 1992. Tectonic implications of Late Proterozoic–early Palaeozoic igneous rock associations in W Tasmania. Tectonophysics 214, 37–56.

Crawford, A.J., Falloon, T.J., Green, D.H., 1989. Classification, petrogenesis and tectonic setting of boninites. In: Crawford, A.J. (Ed.), Boninites. Unwin Hyman, London, pp. 1–49.

Davies, H.L., Jaques, A.L., 1984. Emplacement of ophiolites in Papua New Guinea. In: Gass, I.G., Lippard, S.J., Shelton, A.W. (Eds.) Ophiolites and Oceanic Lithosphere. Geol. Soc. London Spec. Publ. 13, 341–349.

Duncan, R.A., McDougall, I., 1989. Volcanic time–space relationships. In: Johnson, R.W. (Ed.), Intraplate Volcanism in Eastern Australia and New Zealand. Cambridge University Press, Cambridge, pp. 43–54.

Dupuy, C., Dostal, J., Leblanc, M., 1981. Geochemistry of an ophiolitic complex New Caledonia. Contrib. Mineral. Petrol. 76, 77–83.

Eissen, J.-P., Nohara, M., Cotten, J., Hirose, K., 1994. North Fiji Basin basalts and their magma sources, Part I. Incompatible element constraints. In: Auzende, J.M., Urabe, T. (Eds.), North Fiji Basin: STARMER French–Japanese Program. Mar. Geol. 116, 153–178.

Espirat, J.-J., 1963. Etude géologique de régions de la Nouvelle-Calédonie septentrionale (extrémité nord et versant est). Doctorat d'Etat, Thesis, Univ. de Paris, 217 pp.

Espirat, J.-J., 1966. Carte et notice explicative de la carte géologique de la Nouvelle-Calédonie à l'échelle du 1/50.000: Feuille de Koumac. Bureau de Recherches Géologiques et Minières, Orléans.

Espirat, J.-J., 1971. Carte et notice explicative de la carte géologique de la Nouvelle-Calédonie à l'échelle du 1/50.000: Feuille de Oua-Tom. Bureau de Recherches Géologiques et Minières, Orléans.

Falloon, T.J., Green, D.H., McCulloch, M.T., 1989. Petrogenesis of high-Mg and associated lavas from the north Tonga Trench. In: Crawford, A.J. (Ed.) Boninites. Unwin Hyman, London, pp. 357–395.

Gonord, H., 1977. Recherches sur la géologie de la Nouvelle-Calédonie, sa place dans l'ensemble structural du Pacifique sud-ouest. Doctorat d'Etat, Thesis, Univ. of Toulouse, 341 pp.

Green, T.H., 1978. Rare earth geochemistry of basalts from Norfolk Island, and implications for mantle inhomogeneity in the rare earth elements. Geochem. J. 12, 165–172.

Guillon, J.-H., 1972. Essai de résolution structurale d'un appareil ultramafique d'âge alpin: les massifs de Nouvelle-Calédonie. Implications concernant la structure de l'arc mélanésien. C.R. Acad. Sci. Paris, Sér. D 274, 3069–3072.

Guillon, J.-H., 1975. Les massifs péridotitiques de Nouvelle-Calédonie. Type d'appareil ultrabasique stratiforme de chaîne récente. Mém. ORSTOM 76, 120 pp.

Guillon, J.-H., Gonord, H., 1972. Premières données radiométriques concernant les basaltes de Nouvelle-Calédonie. Leurs relations avec les grands événements de l'histoire géologique de l'arc mélanésien interne au Cénozoïque. C.R. Acad. Sci. Paris, Sér. D 275, 309–312.

Jenner, G.A., Cawood, P.A., Rautenschlein, M., White, W.M., 1987. Composition of back-arc basin volcanics, Valu Fa ridge, Lau Basin: evidence for a slab-derived component in their mantle source. J. Volcanol. Geotherm. Res. 32, 209–222.

Kroenke, L.W., 1984. Cenozoic tectonic development of the southwest Pacific. United Nations Economic and Social Commission for Asia and the Pacific, Committee for Coordination of Joint Prospecting for Mineral Ressources in South Pacific Offshore Areas (CCOP/SOPAC), Tech. Bull. 6, 122 pp.

Lanyon, R., Varne, R., Crawford, A.J., 1993. Tasmanian tertiary basalts, the Balleny plume, and opening of the Tasmanan Sea (southwest Pacific). Geology 21, 555–558.

Laporte, C., Briqueu, L., Cluzel, D., Eissen, J.-P., 1997. Gradients géochimiques et isotopiques le long de l'arc des Nouvelles-Hébrides (Vanuatu, Pacifique SW). Collision de la Zone d'Entrecasteaux et hétérogénéité des sources mantelliques. C.R. Acad. Sci. Paris (submitted).

Lapouille, A., 1982. Étude des bassins marginaux fossiles du sud-ouest Pacifique: bassin Nord-d'Entrescasteaux, bassin Nord-Loyauté, bassin Sud-Fidjien. In: Équipe de Géologie-Géophysique du Centre ORSTOM de Nouméa (Ed.), Contribution à l'étude géodynamique du sud-ouest Pacifique. Trav. Doc. ORSTOM 147, 409–438.

Lillie, A.R, Brothers, R.N., 1970, The geology of New-Caledonia. N.Z.J. Geol. Geophys. 13 (1), 145–183.

Macfarlane, A., Carney, J.N., Crawford, A.J., Greene, H.G., 1988, Vanuatu — A review of the onshore geology. In: Greene, H.G., Wong, F.L. (Eds.) Geology and Offshore Resources of Pacific Island Arcs–Vanuatu Region. Circum Pacific Council for Energy and Mineral Resources, Houston, Texas, Earth Sciences Series, 8, pp. 45–91.

Maillet, P., Monzier, M., Selo, M., Storzer, D., 1983. The d'Entrecasteaux zone (southwest Pacific). A petrological and geochronological reappraisal. Mar. Geol. 53, 179–197.

Maurizot, P., Paris, J.-P., Feignier, D., 1985. Paléogéographie de part et d'autre de l'accident ouest calédonien durant la période Crétacé supérieur-Paléocène: autochtonie de la formation des basaltes de la Côte-ouest. Géol. Fr. 1, 53–60.

Meffre, S., 1995. The Development of Island Arc-Related Ophiolites and Sedimentary Sequences in New Caledonia. PhD thesis, University of Sydney, 239 pp.

Meffre, S., Aitchison, J.C., Crawford, A.J., 1996. Geochemical evolution and tectonic significance of boninites and tholeiites from the Koh ophiolite, New Caledonia. Tectonics 15, 67–83.

Mignot, A., 1984. Sismo-stratigraphie de la terminaison nord de la ride de Lord Howe. Evolution Géodynamique du Sud-Ouest Pacifique entre l'Australie et la Nouvelle-Calédonie. PhD thesis, Université de Paris VI, 205 pp.

Monzier, M., 1993. Un modèle de collision arc insulaire–ride océanique. Evolution sismo-tectonique et pétrologique des volcanites de la zone d'affrontement 'Arc des Nouvelles-Hébrides–Ride des Loyauté'. Doctorat d'Université thesis, Université Française du Pacifique, Nouméa, 322 pp.

Monzier, M., Boulin, J., Collot, J.-Y., Daniel, J., Lallemand, S., Pelletier, B., 1989. Premiers résultats des plongées Nautile da la campagne SUBPSO 1 sur la zone de collision 'ride des Loyauté arc des Nouvelles-Hébrides' (Sud-Ouest Pacifique). C.R. Acad. Sci. Paris 309, 2069–2076.

Monzier, M., Robin, C., Eissen, J.-P., Cotten, J., 1997. Geochemistry vs. seismo-tectonics along the volcanic New Hebrides Central Chain (Southwest Pacific). J. Volcanol. Geotherm. Res. 78 (1/2), 1–30.

Nohda, S., Tatsumi, Y., Yamashita, S., Fujii, T., 1992, Nd and Sr isotopic study of Leg 127 basalts: implications for the evolution of the Sea of Japan Backarc Basin. Proc. ODP Sci. Results 127/128, Part 2, pp. 899–904.

Norrish, K., Chappel, B.W., 1977. X-ray fluorescence spectrography. In: Zussman, J. (Ed.), Physical Methods in Determinative Mineralogy. Academic Press, London, pp. 161–214.

Norrish, K., Hutton, J.T., 1969. An accurate X-ray spectrographic method for the analysis of a wide range of geological samples. Geochim. Cosmochim. Acta 33, 431–455.

Paris, J.-P., 1981. Géologie de la Nouvelle Calédonie. Un essai de synthèse. Bur. Rech. Géol. Min. Orléans, Mém. 113, 279 pp.

Parrot, J.F., Dugas, F., 1980. The disrupted ophiolitic belt of the southwest Pacific: evidence of an Eocene subduction zone. Tectonophysics 66, 349–372.

Pouclet, A., Bellon, H., 1992. Geochemistry and isotopic composition of volcanic rocks from the Yamato basin: hole 794D, Sea of Japan. Proc. ODP Sci. Results 127/128, 779–789.

Prinzhoffer, A., Nicolas, A., Cassard, D., Moutte, J., Leblanc, M., Paris, J.-P., Rabinovitch, M., 1980. Structure in New Caledonia peridotites–gabbros: implications for oceanic mantle and crust. Tectonophysics 69, 85–112.

Quinn, T.M., Taylor, F.W., Halliday, A.N., 1994. Strontium-isotopic dating of neritic carbonates at Bougainville Guyot (site 831), New Hebrides island arc. Proc. ODP Sci. Results 134, 89–95.

Rigolot, P., 1989. Evolution du système ride de Nouvelle-Calédonie. Ride de Norfolk. PhD thesis, Université de Bretagne Occidentale, Brest, 319 pp.

Robinson, P., Higgins, N.C., Jenner, G.A., 1986. Determination of rare-earth elements, yttrium and scandium in rocks by an ion exchange–X-ray fluorescence technique. Chem. Geol. 55, 121–137.

Rodgers, K.A., 1975. Lower Tertiary tholeiitic basalts from southern New-Caledonia. Mineral. Mag. 40, 25–32.

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. N.S. 322 (67), 122–133.

Saunders, A.D., Fornari, D.J., Morrison, M.A., 1982. The composition and emplacement of basaltic magmas produced during the development of continental-margin basin: the Gulf of California, Mexico. J. Geol. Soc. London 139, 335–346.

Sun, S.S., McDonough, W.F., 1989. Chemical isotopic systematics of oceanic basalts. In: Saunders, A.D., Norry, M.J. (Eds.), Magmatism in the Ocean Basins. Geol. Soc. Spec. Publ. 42, 313–345.

Veevers, J.J., Powell, C., Roots, S.R., 1991. Review of seafloor spreading around Australia, 1. Synthesis of the patterns of spreading. Aust. J. Earth Sci. 38, 373–390.

Volpe, A.M., Macdougall, J.D., Hawkins, J.W., 1988. Lau basin basalts (LBB): trace element and Sr–Nd isotopic evidence for heterogeneity in back-arc basin mantle. Earth Planet. Sci. Lett. 90, 174–186.

Weissel, J.K., Watts, A.B., Lapouille, A., 1982. Evidence for Late Palaeocene to Late Eocene seafloor in the Southern New Hebrides Basin. Tectonophysics 87, 243–251.

Worthing, M.A., Crawford, A.J., 1996. The igneous geochemistry and tectonic setting of metabasites from the Emo Metamorphics, Papua New Guinea; a record of the evolution and destruction of a backarc basin. Mineral. Petrol. 58 (1/2), 79–100.

Publication information
Tectonophysics (ISSN 0040-1951). For 1998 volumes 279–293 are scheduled for publication. Subscription prices are available upon request from the publisher. Subscriptions are accepted on a prepaid basis only and are entered on a calendar year basis. Issues are sent by surface mail except to the following countries where air delivery via SAL is ensured: Argentina, Australia, Brazil, Canada, Hong Kong, India, Israel, Japan, Malaysia, Mexico, New Zealand, Pakistan, PR China, Singapore, South Africa, South Korea, Taiwan, Thailand, USA. For all other countries airmail rates are available upon request. Claims for missing issues must be made within six months of our publication (mailing) date. For orders, claims, product enquiries (no manuscript enquiries) please contact the Customer Support Department at the Regional Sales Office nearest to you:
New York, Elsevier Science, P.O. Box 945, New York, NY 10159-0945, USA. Tel: (+1) 212-633-3730, [Toll Free number for North American customers: 1-888-4ES-INFO (437-4636)], Fax: (+1) 212-633-3680, E-mail: usinfo-f@elsevier.com
Amsterdam, Elsevier Science, P.O. Box 211, 1000 AE Amsterdam, The Netherlands. Tel: (+31) 20-485-3757, Fax: (+31) 20-485-3432, E-mail: nlinfo-f@elsevier.nl
Tokyo, Elsevier Science, 9-15, Higashi-Azabu 1-chome, Minato-ku, Tokyo 106, Japan. Tel: (+81) 3-5561-5033, Fax: (+81) 3-5561-5047, E-mail: kyf04035@niftyserve.or.jp
Singapore, Elsevier Science, No. 1 Temasek Avenue, #17-01 Millenia Tower, Singapore 039192. Tel: (+65) 434-3727, Fax: (+65) 337-2230, E-mail: asiainfo@elsevier.com.sg

US mailing notice – *Tectonophysics* (ISSN 0040-1951) is published bi-weekly by Elsevier Science B.V. (Molenwerf 1, Postbus 211, 1000 AE Amsterdam). Annual subscription price in the USA US$ 3362 (US$ price valid in North, Central and South America only), including air speed delivery. Periodicals postage paid at Jamaica, NY 11431.
USA POSTMASTERS: Send address changes to *Tectonophysics*, Publications Expediting, Inc., 200 Meacham Avenue, Elmont, NY 11003.
Airfreight and mailing in the USA by Publications Expediting.

NOTE TO CONTRIBUTORS

A detailed Guide for Authors is available on request. Please pay attention to the following notes:

Language
The official language of the journal is English.

Preparation of the text
(a) The manuscript should preferably be prepared on a word processor and printed with double spacing and wide margins and include an abstract of not more than 500 words.
(b) Authors should use IUGS terminology. The use of S.I. units is also recommended.
(c) The title page should include the name(s) of the author(s), their affiliations, fax and e-mail numbers. In case of more than one author, please indicate to whom the correspondence should be addressed.

References
(a) References in the text consist of the surname of the author(s), followed by the year of publication in parentheses. All references cited in the text should be given in the reference list and vice versa.
(b) The reference list should be in alphabetical order.

Tables
Tables should be compiled on separate sheets and should be numbered according to their sequence in the text. Tables can also be sent as glossy prints to avoid errors in typesetting.

Illustrations
(a) Illustrations should be submitted in triplicate. Please note that upon submission of a manuscript *three sets* of all photographic material printed *sharply* on *glossy paper* or as *high-definition laser prints* must be provided to enable meaningful review. Photocopies and other low-quality prints will not be accepted for review.
(b) Colour figures can be accepted providing the reproduction costs are met by the author. Please consult the publisher for further information.

Page proofs
One set of page proofs will be sent to the corresponding author, to be checked for typesetting/editing. The author is not expected to make changes or corrections that constitute departures from the article in its accepted form. To avoid postal delay, authors are requested to return corrections to the desk-editor, Mr. Herman E. Engelen, by FAX (+31.20.4852459\) or e-mail (h.engelen@elsevier.nl), preferably within 3 days.

Reprints
Fifty reprints of each article published are supplied free of charge. Additional reprints can be ordered on a reprint order form, which will be sent to the corresponding author upon acceptance of the article.

Submission of manuscripts
Three copies should be submitted to: Editorial Office *Tectonophysics*, P.O. Box 1930, 1000 BX Amsterdam, The Netherlands.
Submission of an article is understood to imply that the article is original and unpublished and is not being considered for publication elsewhere.
Upon acceptance of an article by the journal, the author(s) will be asked to transfer the copyright of the article to the publisher. This transfer will ensure the widest possible dissemination of information under the U.S. Copyright Law.
The indication of a fax and e-mail number on submission of the manuscript could assist in speeding communications. The fax number for the Amsterdam office is +31-20-4852696.
Authors in Japan, please note: Upon request, Elsevier Science Japan will provide authors with a list of people who can check and improve the English of their paper (before submission). Please contact our Tokyo office: Elsevier Science Japan, 1-9-15 Higashi-Azabu, Minato-ku, Tokyo 106; Tel. (+81) 3 5561 5032; Fax (+81) 3 5561 5045.
THERE ARE NO PAGE CHARGES

Submission of electronic text
In order to publish the paper as quickly as possible after acceptance authors are encouraged to submit the final text also on a 3.5″ or 5.25″ diskette. Essential is that the name and version of the wordprocessing program, type of computer on which the text was prepared, and format of the text files are clearly indicated. Authors are requested to ensure that apart from any such small last-minute corrections, the disk version corresponds exactly to the hardcopy.
If available, electronic files of the figures should also be included on a separate floppy disk.