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Earliest Eocene (53 Ma) convergence in the Southwest Pacific: evidence from pre-obduction dikes in the ophiolite of New Caledonia

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ABSTRACT

Uncertainty about the timing and location of the initiation of convergence in the western and south-western Pacific greatly hinders accurate plate tectonic reconstructions of subduction systems in that area. The chemistry and age of dikes intruding mantle peridotite in the ophiolite of New Caledonia infer that subduction-related magmatism began before 53 Ma. These new results infer that obduction in the south-west Pacific is unrelated to the reorientation of the Pacific plate motion that occurred *c.* 43 Ma and confirm new interpretations showing that changes in mantle flow, hotspot and plate motion may have occurred as soon as late Paleocene or early Eocene.

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Introduction

The post-Early Cretaceous history of the south-west Pacific is marked by the opening and subsequent partial closure of several marginal basins controlled by subduction and slab rollback processes (for a review, see Schellart *et al*., 2006 and references herein) (Fig. 1). Fragments of oceanic lithosphere have been locally obducted upon continental slices and many previous studies have tended to relate obduction in the south-west Pacific to the major plate reorganization that occurred in the Pacific plate *c*. 43 Ma (i.e. Auzende *et al*., 2000; Hall, 2002). However, stratigraphic evidence shows that obduction occurred diachronously, from the Late Eocene (e.g. New Caledonia; Cluzel *et al*., 2001) to the Late Oligocene or early Miocene (e.g. New Zealand; Ballance and Spörli, 1979), making it difficult to relate it to a single causative event. Alternatively, it has been suggested that prior to the establishment of the late Eocene west or south-west dipping Vitiaz-Fiji-Tonga subduction zone, an earlier east-dipping system existed in this area (Aitchison *et al*., 1995; Cluzel *et al*., 2001; Crawford *et al*., 2003). This earlier system that resorbed the bulk of a late Cretaceous to early Eocene marginal basin (the South Loyalty basin of Cluzel *et al*., 2001) collided diachronously with the Norfolk ridge, leading to the obduction of fore-arc lithosphere. Stratigraphic data constrain the timing of opening (bathyal sediments) and final closure of the marginal basins (foreland and post-obduction deposits), but no precise information on the timing of subduction reversal was available. Our new geochronological and geochemical data on the pre-obduction felsic dikes of New Caledonia provide the first chronological constraint on the inception of the Eocene to Oligocene subduction, and infer some regional tectonic implications.

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Regional geology

The ophiolitic nappe of New Caledonia consists of an undated harzburgite-dunite sheet with a maximum thickness of ~3500 m that tectonically overlies the Poya terrane, an allochthonous terrane composed of Late Cretaceous to Late Palaeocene basalt and abyssal sediments that in turn rests upon autochthonous Mesozoic–early Cenozoic sedimentary sequences. The ultramafic allochthon is rooted in the Loyalty Basin to the north-east of New Caledonia (Collot *et al*., 1987) while the Poya terrane rocks were scrapped off the down going plate (the South Loyalty basin) and accreted to the fore-arc before being obducted with the peridotites onto the Norfolk ridge (Cluzel *et al*., 2001). The Loyalty Ridge, to the north-east of New Caledonia, has been interpreted as an Eocene volcanic arc formed during the subduction of Late Cretaceous-Paleocene oceanic crust (Aitchison *et al*., 1995; Eissen *et al*, 1998; Cluzel *et al*., 2001). Although no subduction-related magmatic rocks are exposed in the Loyalty Islands to support this hypothesis, seamounts further north in the chain have been shown by ODP (Ocean Drilling Program) drilling to be composed of primitive arc tholeiites, and unconformable carbonates indicating arc subsidence at 37–38 Ma (Crawford *et al*., 2003 and references herein). Obduction occurred obliquely, starting in the Early to mid-Eocene in the north-east of New Caledonia with fore-arc bulge, accretion of the Poya terrane, subduction of sediment and ophiolitic melange that gave birth to HP-LT metamorphic terrane *c*. 45 Ma (Cluzel *et al*., 1998, 2001; Spandler *et al*., 2005). Exhumation of fore-arc mantle peridotite started around 38 Ma (Cluzel *et al*., 1998). The final phase of obduction dates from 34 Ma (uppermost Eocene pre-obduction sediments beneath the ophiolitic nappe; Cluzel, 1999), to 27 Ma (Late Oligocene nappe-stitching granitoids; Cluzel *et al*., 2005). The existence of an Eocene East-dipping subduction is thus based upon evidence that does not tightly con-

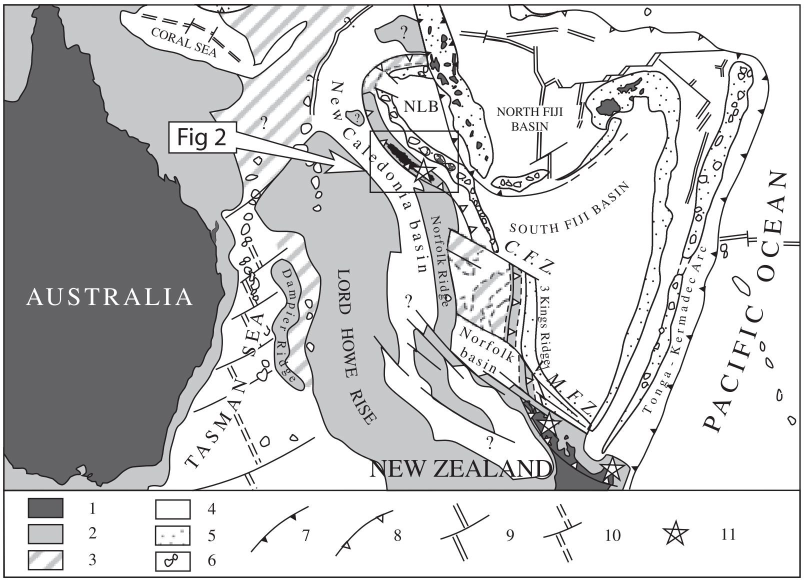

Fig. 1 Tectonic framework of the south-west Pacific. NLB: North Loyalty basin; CFZ: Cook Fracture zone; VMFZ: Vening–Meinesz Fracture Zone; 1: land; 2: continental shelf; 3: thinned/transtionnal continental crust; 4: oceanic crust; 5: volcanic-arc crust; 6: seamounts (island-arc or hot spot trail); 7: active subduction zone; 8: fossil subduction zone; 9: active spreading ridge; 10: fossil spreading ridge; 11: ophiolite location.

strain the timing of incipient convergence.

Field occurrence, petrography and geochemistry of pre-obduction dikes

The ultramafic allochthon is intruded by both mafic and felsic dikes that are never found in the autochtonous basement rocks, nor in the Poya terrane. In addition, these dikes that are well preserved in the upper levels of the allochthon, are severely disrupted at its base near the serpentinized sole and therefore predate obduction. Our work indicates that four main rock types are recognized: granitoids, boninite-like andesitic shallow intrusive rocks, high-Mg microgabbro/tonalites, and dolerite of island arc tholeiitic (IAT) affinities. A detailed petrological discussion on the geochemistry of these dikes is beyond the scope of this paper and the geochemical data presented here are only intended for establishing the supra-subduction character of this magmatic event. Major elements have been analysed by ICP-AES, trace elements and REE by ICP-MS at the Service d'Analyse des Roches et Minéraux (SARM-CRPG) of Nancy (France).

Granitoid dikes

The studied felsic dike exposures are mainly located in the Grand Massif du Sud (Fig. 2) but may also be found in most ultramafic massifs. In contrast to Oligocene post-obduction granodiorites (Cluzel *et al.*, 2005) that occur as plutons (up to 5 km across) and large dikes (20–100 m wide), the pre-obduction dikes are generally a few decimetres to 20 m thick. They are generally coarse-grained and locally show pegmatitic textures, with large quartz and plagioclase crystals, well-developed dendritic biotite, and other sub-solvus textures emphasizing the role of an abundant magmatic fluid phase. They lack chilled margins but commonly show thin reaction boundaries with talc/chlorite/serpentinite seams along contacts with the ultramafic host rocks. Some dikes may contain abundant mm-size xenoliths of serpentinized peridotite. These textures confirm that the felsic dikes were intruded when the host rocks were relatively cool and brittle and thus bear no direct relationship with ophiolite genesis. The felsic dikes have dioritic to trondhjemitic compositions characterized by: very low TiO_2 as well as other high-field strength elements (Nb, Ta, Zr and Y), and unusually high Al_2O_3 and low Fe_2O_3 compared with typical continental- or arc-type felsic volcanics and granitoids. Contents of K_2O, P_2O_5, LREE (light rare earth elements), Ba and other incompatible elements are also

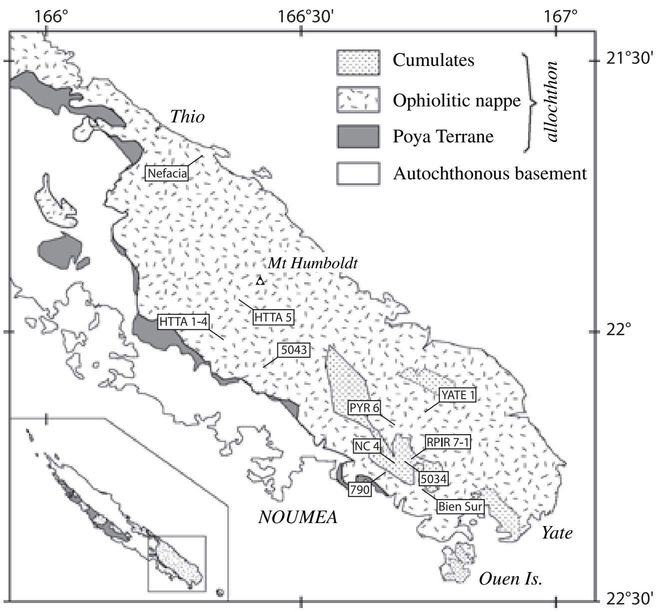

Fig. 2 Geological sketch map of the Grand Massif du Sud to show the location of the analysed/dated felsic dike samples and their dispersal throughout the ophiolitic nappe (boninite samples that are mainly found in the northern half of the island are not located on this map).

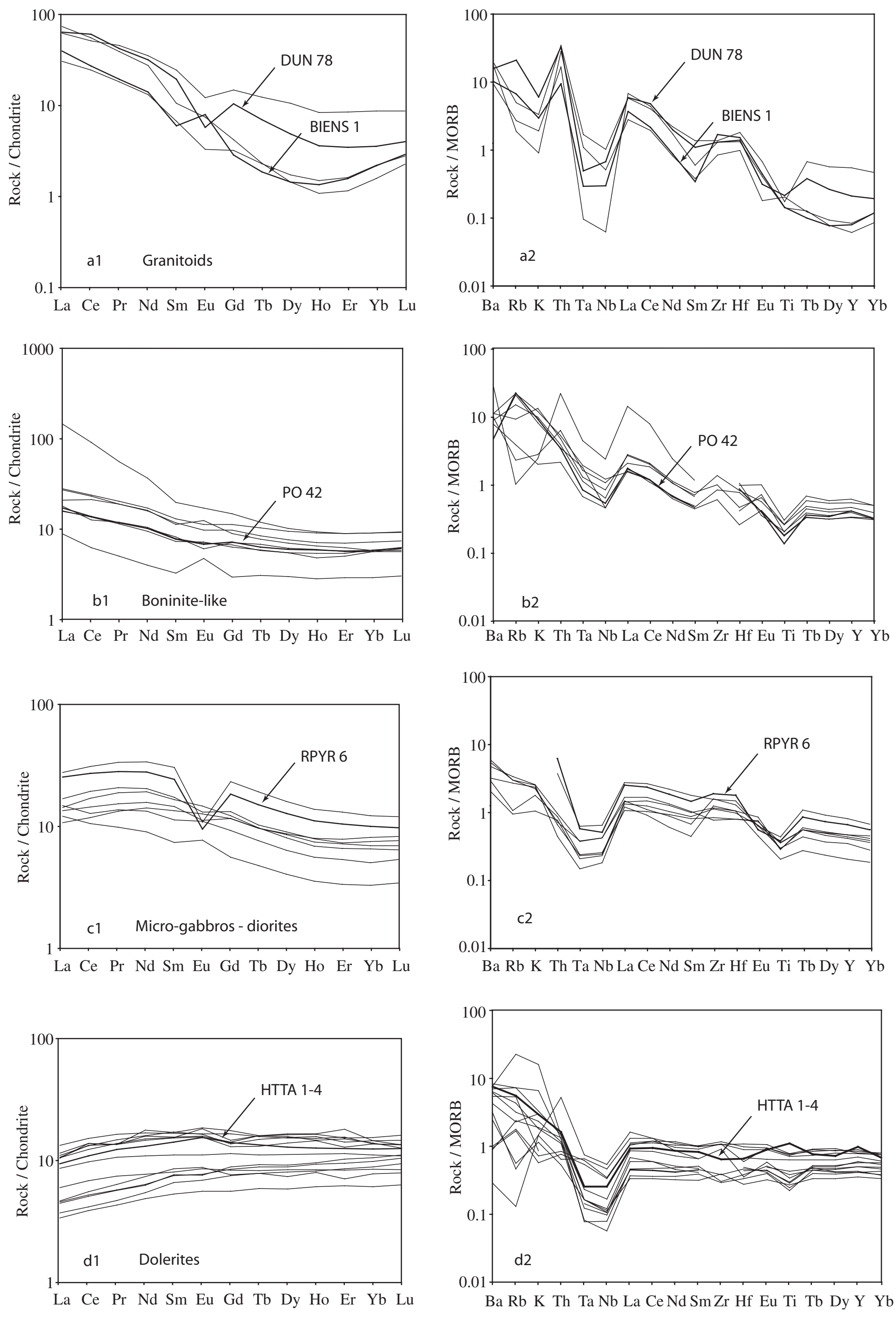

Fig. 3 Trace elements discrimination of the pre-obduction dikes. Normalization values for the chondrite C1 are from Evensen *et al.* (1978) for REE, and from Sun and McDonough (1989) for the expanded REE-trace elements spider-diagrams normalized to the average MORB. a: granitoids; b: boninite-like dikes; c: high-Mg microgabbros and diorites; d: dolerites. Bold patterns relate to analysed or dated samples (see Tables 1 and 2).

relatively low compared with typical granitoids. They display pronounced Nb–Ta negative anomalies on MORB (mid oceanic ridge basalt)-normalized imcompatible element diagrams (Fig. 3a2) that may indicate an origin from a mantle source already depleted in these elements, or alternatively by partial melting of a source with Nb–

Table 1 Major and trace elements compositions of representative pre-obduction dikes

Sample	RPIR 7–1	BIENS 1*	DUN 78*	YATE 1	HTTA 5	PO 42	PYR 6*	HTTA 1–4
Location	Prony	Bien Sur mine	Prony	Yate lake	Vulcain mine	Plaine des Gaïacs	Piroguesriver	Tontoutariver
Rock	Granitoid	Granitoid	Granitoid	Leucodiorite	Leucodiorite	Boninite	Leucogabbro	Arc-tholeiite
Type	a	a	a	a	a	b	c	d
SiO_2	77.43	74.49	71.89	66.85	64.54	57.21	44.58	49.30
TiO_2	0.183	0.19	0.279	0.267	0.226	0.16	0.5	1.30
Al_2O_3	12.96	13.38	14.86	19.14	20.73	9.03	23.58	14.00
Fe_2O_3	0.551	1.43	1.784	0.613	1.016	7.94	5.21	13.00
MnO	0.009	0.01	0.015	0.012	0.021	0.14	0.08	0.20
MgO	0.546	0.90	1.629	2.400	1.273	1.99	5.27	4.50
CaO	1.523	1.96	0.983	0.684	1.053	3.84	15.67	10.50
Na_2O	5.134	4.59	4.538	9.146	9.088	2.08	0.93	2.20
K_2O	0.285	0.44	0.89	0.136	0.499	0.62	0.03	0.20
P_2O_5	n.d.	n.d.	0.04	0.042	0.037	0.15	0.14	0.10
LOI	0.94	1.34	3.298	1.669	1.362	4.83	2.57	2.40
Total	99.56	98.73	100.20	100.96	99.85	100.00	98.52	97.70
Ba	59.36	65.51	102.8	109,00	122.2	29.41	7.755	47.80
Rb	1.564	3.822	12.11	1.08	2.851	12.42	0.337	3.827
Sr	166.2	261	137.2	124.4	423.5	120	213.8	170.4
Ta	0.013	0.04	0.067	0.149	0.229	0.11	0.074	0.033
Th	2.084	1.175	4.068	3.505	4.294	0.405	0.741	0.1913
Zr	99.19	129.5	99.7	64.18	104.9	n.d.	138.6	47.20
Nb	0.15	0.714	1.617	1.229	2.464	1.219	1.171	0.5864
Y	1.771	2.295	6.095	2.408	15.8	11.35	18.09	24
Hf	2.803	3.24	2.933	2.084	3.836	1.764	3.6	1.3286
Co	1.444	3.199	11.66	32.35	2.584	48.84	14.9	52.582
U	0.151	0.181	0.382	0.3	0.624	0.252	0.419	0.0671
Pb	2.155	2.351	4.213	3.80	2.117	2.005	0.149	0.8987
La	17.61	9.469	15.34	7.264	14.91	4.208	6.246	2.3023
Ce	34.17	16.68	37.41	15.04	31.39	8.767	17.45	6.9713
Pr	3.726	1.861	4.036	1.74	4.356	1.131	2.732	1.1824
n.d.	12.95	6.58	14.92	6.16	16.43	4.821	13.3	6.1707
Sm	1.621	0.92	2.986	1.031	3.741	1.194	3.767	2.1680
Eu	0.431	0.464	0.332	0.19	0.712	0.396	0.555	0.8917
Gd	0.869	0.583	2.137	0.655	3.054	1.468	3.771	2.8727
Tb	0.087	0.069	0.261	0.085	0.465	0.405	0.566	0.1913
Dy	0.364	0.362	1.234	0.439	2.673	1.512	3.267	3.2539
Ho	0.061	0.076	0.203	0.084	0.477	0.334	0.635	0.7158
Er	0.19	0.261	0.57	0.267	1.409	0.952	1.743	2.0824
Tm	0.033	0.047	0.085	0.045	0.216	n.d.	0.255	n.d.
Yb	0.266	0.37	0.602	0.373	1.474	0.963	1.668	2.0504
Lu	0.057	0.073	0.102	0.071	0.222	0.158	0.25	0.3170

Asterisks indicate samples taken from dated dikes; 'type' code-letters refer to Fig. 3.

Table 2 U/Pb age of the pre-obduction dykes (^{207}Pb corrected, ^{206}Pb/^{238}U weighted average)

Name	Location	Latitude	Longitude	Rock type	U–Pb age (Ma) ± 95% CI
790	Mouirange	−22.2273	166.6336	Altered granitoid	53.1 ± 1.6
Nefacia	SE Thio	−21.6503	166.3143	Unaltered granitoid	52.6 ± 0.4
BIENS 1a	Mine Bien Sur	−22.2940	166.7376	Pegmatite	53.2 ± 0.2
5043	Mt Couvelée	−22.0822	166.4444	Altered granitoid	53.0 ± 1.6
5034 zirc	Mine Dunite 78	−22.1988	166.7239	Altered granitoid	53.1 ± 1.5
5035 titan	Mine Dunite 78	−22.1988	166.7239	Altered granitoid	51.7 ± 0.4
NC4	Yate road	−22.2099	166.6774	Weathered granitoid	52.9 ± 0.9
PYR6	Pirogues river	−22.1847	166.7093	Amphibole gabbro	49.6 ± 2.8

Analyses on zircons unless otherwise stated.

Ta in the residue. They also have strong P_2O_5, Ti and Eu negative anomalies typical of granite and felsic magmas, suggesting extensive fractional crystallization. Their REE contents become progressively more depleted with increasing SiO_2 contents, suggesting an origin via either extensive hornblende-plagioclase

(± apatite) fractionation or partial melting of a garnet-bearing mafic protolith.

Fine-grained boninitic dikes

Fine-grained dikes with boninitic affinities represent another group of intrusions in the mantle section of the New Caledonian ophiolite. They generally contain clino-enstatite phenocrysts sometimes rimed by amphibole. These generally display andesitic compositions but with relatively high Mg and Cr and very low Ti and Zr contents. REE patterns are typically U shaped in the more mafic rocks and LREE enriched and concave upwards in the more felsic rocks (Fig. 3b1). REE and trace elements patterns on MORB-normalized diagrams (Fig. 3b2 display a negative slope with enrichment in LILE (large ion lithophile elements) and a strong depletion of HFSE (high field strength elements) relative to average N-MORB (normal MORB). These features are diagnostic of magmas generated via hydrous partial melting of refractory peridotite in a supra-subduction setting (Crawford *et al.*, 1989).

Microgabbro/diorite dikes

Amphibole-rich microdiorites or gabbros also occur as small dikes (up to 10 m) in the New Caledonian peridotites. These are often foliated and contain brown amphibole surrounding corroded orthopyroxene cores, Fe–Ti oxide and plagioclase. Major element compositions vary from mafic to intermediate, with very low K_20 (0.03–0.2%), generally high Al_2O_3 (12–24%), and variable MgO (3–14%) and Cr contents (12–729 ppm). They typically display hook-shaped REE patterns with enrichment in LREE and a prominent negative slope because of relative HREE depletion (Fig. 3c1). On MORB-normalized element variation diagrams, they display a slightly negative slope and prominent Nb–Ta, Hf and Ti depletions. But in contrast with the other three dike suites, they have a $(Nb_n/Ta_n) > 1$ (Fig. 3c2). The distinctive REE patterns, with LREE depletion and moderate HREE depletion, is characteristic of basalts erupted early in the rifting history of oceanic island arcs (i.e. early back-arc basin basalts; Worthing and Crawford, 1996).

Tholeiite–dolerite dikes

Dolerite dikes 1–20 m thick with chilled margins are rare but ubiquitous throughout the mantle peridotite sections in New Caledonia. They have mafic to intermediate major element compositions, and REE patterns similar to MORB although some are strongly depleted in REE (Fig. 3d1). However, on MORB-normalized multi-element diagrams (Fig. 3d2) they display a prominent enrichment in LILE (Ba to Th), and significant Nb–Ta anomalies compared with MORB, diagnostic of IAT.

The generation of felsic rocks in or beneath the residual mantle beneath fore-arc oceanic crust has not been widely documented. Similar dikes have been described from the Oman ophiolite (Amri *et al.*, 1996), where felsic dikes are associated with the margins of large gabbroic intrusion into the residual mantle section of the ophiolite. This association led Amri *et al.* (1996) to postulate that the plagiogranites formed by fractional crystallization of an off-axis intrusion emplaced into the cold and partially hydrated mantle section of the ophiolite. Although such a petrogenetic scenario may be broadly applicable in New Caledonia, a direct association with other intrusions is nowhere evident. If the plagiogranites formed via fractional crystallization from a large mafic body, this one is not currently exposed. The felsic dikes in New Caledonia have higher Al_2O_3 than those from Oman, and it is possible that they were derived from partial melting of eclogite in the down-going slab in a subduction setting. There is a close match between the major element compositions of these felsic rocks and those of experimental melts of amphibolites and eclogites (high Al, low Fe and Ti) (Beard, 1995; Koepke *et al.*, 2005) (Fig. 4), and trace ele-

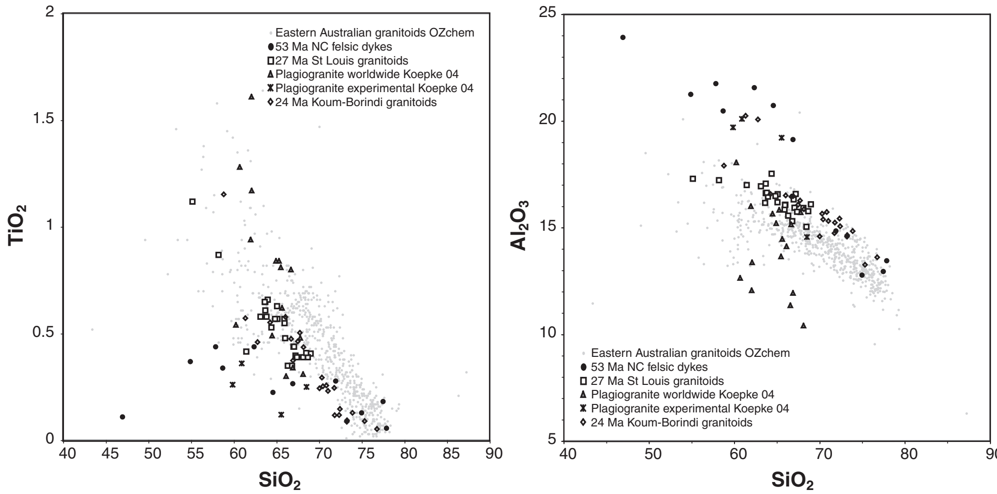

Fig. 4 Harker diagrams SiO_2 vs. TiO_2 (4a) and SiO_2 vs. Al_2O_3 (4b) to show the unusual compositions (low TiO_2, high Al_2O_3) of the 53-Ma felsic dikes (black dots) compared with eastern Australian granitoids (grey dots) Geoscience Australia OZCHEM database; Oligocene granodiorites of New Caledonia (white squares) (Cluzel *et al.*, 2005); andesites (crosses); plagiogranites (grey triangles); experimental plagiogranites (stars) (Koepke *et al.*, 2004).

ments also show impressive similarities (hook-shaped HREE which decrease with increasing partial melting; Fig. 3a1) (Arth, 1979).

The geochemical features of the dikes described above are diagnostic of a supra-subduction zone environment and suggest that the New Caledonian peridotites have undergone a complex history after the formation of the initial (Cretaceous-Paleocene ?) ocean floor. The nature of the initial crust is still not understood at present as it is only represented by scarce remnants (mafic/ultramafic cumulates, Fig. 2) that do not allow a petrogenetic model to be easily elaborated. It can only be said that it probably formed the basement into which the supra-subduction magmatism was emplaced (including the Loyalty arc). The obducted part of this mantle section probably formed the fore-arc mantle lithosphere of the Loyalty arc at the time of dike intrusion.

U–Pb zircon geochronology

Obtaining precise intrusion ages for the mafic and intermediate rocks is very difficult; however, we have been able to accurately date the felsic dikes, which contain magmatic zircon and occasionally magmatic titanite. Zircon and titanite crystals from six granitoids and one high-Mg microgabbro were dated using a Hewlett Packard HP4500 ICP-MS (Hewlett Packard, Palo Alto, CA) fitted with a Merchantek Nd-YAG laser operating at 213 nm at the University of Hobart (Tasmania). The crystals were separated using a gold pan and a magnet, mounted in epoxy blocks, and 30-μm spots on each crystal was sampled by the laser in a He atmosphere. Mass bias, machine drift and fractionation were corrected by analysing the Temora zircon standards of Black *et al.* (2003). The 1063-Ma 91500 zircons (Wiedenbeck *et al.*, 1995), and an in-house secondary standard widely used by the Australian National University (the 42.2-Ma 98521 zircons; C. Allen personal communication), were analysed in the same analytical runs as the granitoid zircons and gave results within analytical error of the recommended values. Between 12 and 24 crystals were analysed from each of the seven samples.

All dated zircons and titanites from the felsic dikes have yielded ages that are within error of each other. All of our data pooled together give a weighted average age of 52.8 ± 0.2 Ma (95% confidence MSWD 1.4) (Fig. 5). No inherited cores have been noted in the analysed zircons and preclude any contamination by continental crust-derived melts. Zircons from different samples vary widely in their contents of U and Th and other trace elements. Zircons from a pegmatitic dike have elevated U (0.5–1.6 wt%) and Hf (1.5–2 wt%) and a whole-rock analysis of this rock shows very high concentrations of incompatible elements, indicating that this was probably formed via very high degrees of fractional crystallization. Zircons

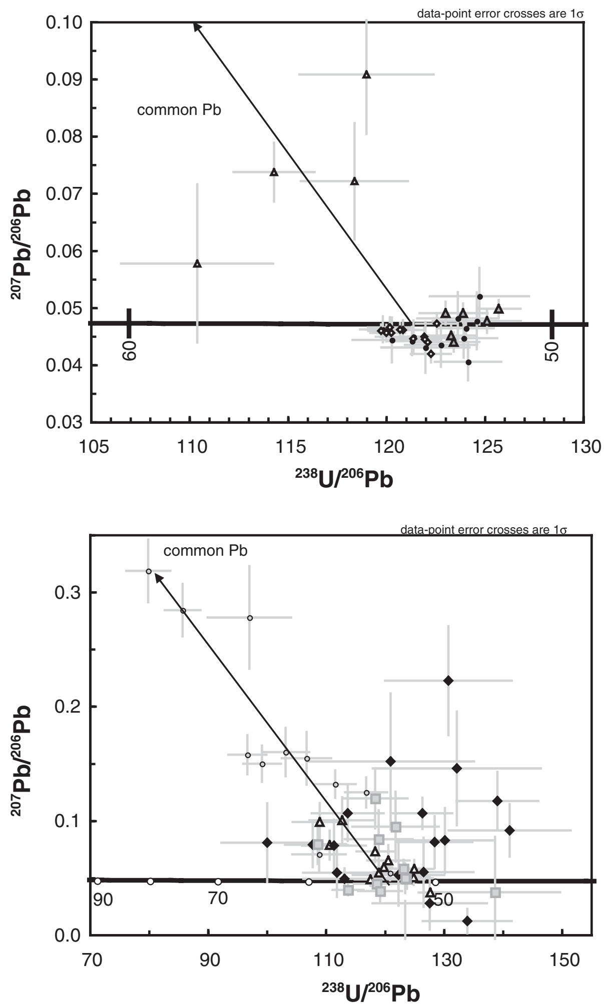

Fig. 5 (a) Reverse concordia diagram showing the samples analysed (zircons unless otherwise stated). U/Pb isotopic ratios of zircon and titanite from three samples. The majority of the data is concordant clustering 53 Ma. Four zircons have large errors and are discordant because of the very low U (4–20 ppm), low radiogenic Pb (0.6–3 ppm) and a higher proportion of common Pb. Solid line entitled 'common Pb' and 53 Ma isochron (calculated by the isoplot program of Ludwig 2003) are anchored to single-stage Pb at 53 Ma (Stacey and Kramer, 1975). Symbols as follows: black circles sample 'Nefacia'; white diamonds zircons from sample 'Bien Sur'; white triangle zircons from sample '5034'; grey triangles titanite from sample '5034'. (b) Reverse concordia diagram showing U–Pb ratios for four samples. Isochron as for (a). Black diamonds sample 'PYR6'; grey circles sample '5043'; grey squares '790'; white triangles 'NC4'. Oldest zircon is interpreted to be a statistical outlier (low U zircon with large analytical uncertainty 61 ± 12 Ma) rather than an inherited core.

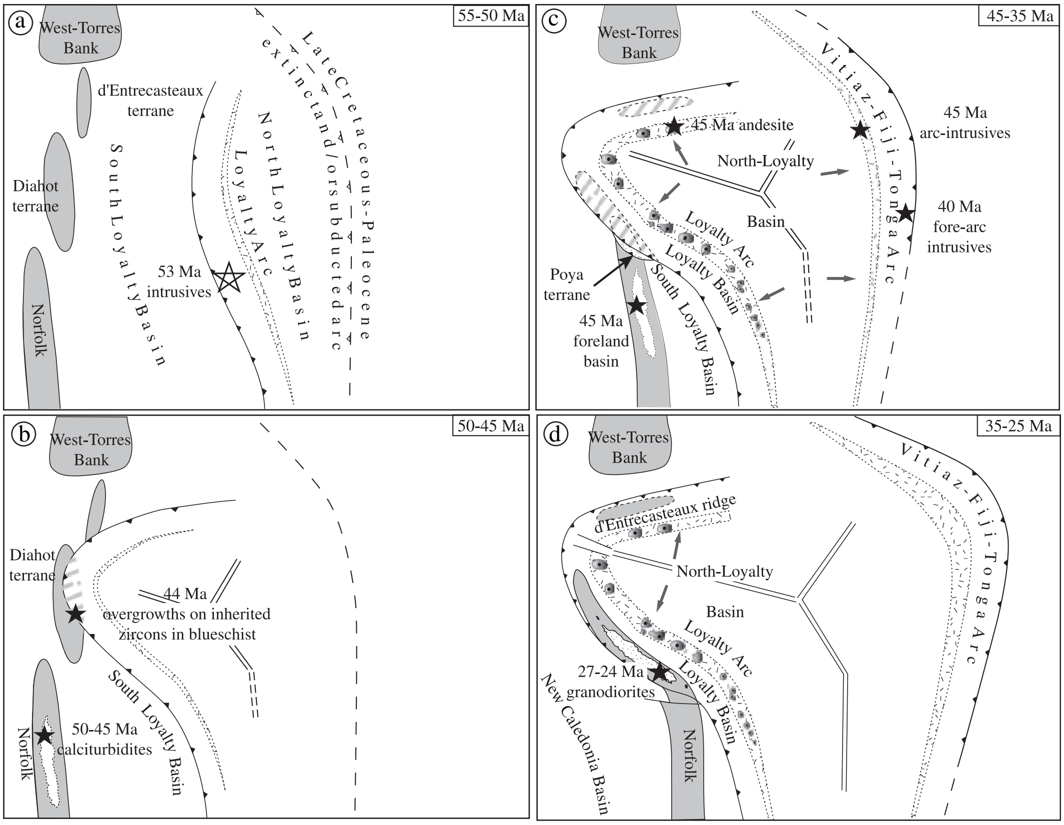

Fig. 6 A tectonic-geodynamic model for the Eocene–Oligocene subduction/obduction process in New Caledonia (modified from Cluzel *et al*., 2001). The white star in (a) indicates the postulated original location of the 53-Ma dikes studied in this paper. Smaller black stars indicate the location of major stratigraphic or radiochronologic constraints coming from previous work.

from more typical dioritic rocks with magmatic titanite have very low U contents probably because of competition for U with the abundant euhedral magmatic titanite, which in these rocks is very high in U and near concordant.

Although all rock types have not been dated so far, they all display the same pre-obduction relationship to the ultramafic rocks and may be regarded as almost contemporaneous; therefore, our new age data suggest that felsic and mafic dikes were formed by a single magmatic event at $\sim$53 Ma.

Conclusion

The felsic dikes that intrude the ultramafic allochthon of New Caledonia provide minimum ages for the lithosphere of the Loyalty basin that is thus older than 53 Myr. This magmatic event likely occurred in the fore-arc of the newly formed Loyalty arc $\sim$55 Ma during the first subduction reversal at the eastern edge of the South Loyalty basin (Fig. 6a). Magma diversity such as described above is not an uncommon feature in fore-arc areas and fit well with the evolutionary model proposed earlier by our group. This event occurred some 5 Ma than previously estimated upon stratigraphic evidence (Cluzel *et al*., 2001), and almost synchronously with the end of Tasman Sea spreading (1000 km to the west of the arc). Therefore, as there was no more 'oceanic' accretion to the west of the system, the bulk of convergence was only because of slab roll-back and arc westward migration associated with the opening of the North Loyalty back-arc basin (Fig. 6b). The subduction of thinned continental fragments (d'Entrecasteaux and Diahot terranes) and mafic mélange in the fore-arc area was responsible for HP-LT rocks development. The formation of a peel-off melange at the expenses of the down-going South Loyalty plate gave birth to the Poya terrane. The progressive blocking of the subduction also probably reactivated the older late Cretaceous subduction, and the west dipping Vitiaz-Fiji-Tonga subduction started *c*. 45 Ma (Fig. 6c). The final blocking of the subduction by the northern Norfolk ridge that resulted in ophiolite obduction, did not completely stopped the convergence between Australia and the North-Loyalty microplate, and the New Caledonia basin subducted for a while. This new subduction generated the granitoids that intruded both the ophiolite and its autochthonous basement at *c*. 27–24 Ma (Fig. 6d). The Emperor–Hawaii seamount bend 43 Ma apparently bears no relationship with these events; therefore, the Eocene–Oligocene East-dipping subduction in the south-west Pacific started in response to an event that is still to be identified.

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