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The zircon record of high-pressure metasedimentary rocks of New Caledonia: Implications for regional tectonics of the south-west Pacific

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ABSTRACT

We report the U-Pb age, and trace element and hafnium isotope composition of zircons recovered from clastic metasedimentary rocks that span a range of metamorphic grades (prehnite-pumpellyite to eclogite facies) across the high-pressure metamorphic belt of northern New Caledonia. We use these data to evaluate the sedimentary source and environment of formation of these rocks, as well as their respective metamorphic evolution.

Metasediments from the low-grade Koumac and blueschist-facies Diahot sequences contain zircon with age populations of 1800–1500 Ma, 700–500 Ma, 300–250 Ma and 140–80 Ma. These grains have highly variable Hf isotope compositions (εHf −36 to +12), and some have thin metamorphic rim zones dated to ~38 Ma. Zircon grains from the high-grade metamorphic section (Pouebo Eclogite Mélange) are mostly Upper Cretaceous and lowermost Eocene in age, with ~40 Ma metamorphic overgrowth zones. The Upper Cretaceous zircons from across the belt have similar isotopic compositions, whereas the lowermost Eocene zircons have relatively high εHf of +6 to +13. The zircon record of the eclogites often lacks the diverse old detrital signature that is prevalent in the blueschist-facies rocks; rather the age populations of the eclogite grade zircons reflect derivation from nearby volcanic sources.

We suggest that the bulk of Koumac and Diahot sequences represent the erosional products of the Norfolk Ridge that were transported eastwards and accumulated into the East New Caledonia Basin. Paleozoic and Precambrian zircon grains were originally sourced from Paleozoic orogenic belts of the eastern margin of Australia, and possibly from now-submerged ridges of continental character. We suggest that the Mesozoic zircon grains derived from volcanic arc activity on the eastern margin of Gondwana. Extension led to a reduced continental sediment input into the East New Caledonia Basin during the Cretaceous, which explains the limited amounts of ancient detritus in the mid-Cretaceous to Eocene sedimentary protoliths of the Pouebo Eclogite Mélange. The combined Hf isotope and age data for our zircon record point to the existence of a west-dipping subduction zone active throughout the Late Triassic to the Late Cretaceous, possibly with some short-lived periods of volcanic hiatus. In the early Eocene, a new east-dipping subduction formed following a major change in plate kinematics, producing younger metavolcanic zircons and eventually leading to the metamorphism of sedimentary units in the middle Eocene.

1. Introduction

Continuous extensional tectonics since the Cretaceous have fragmented the continental crust of eastern Gondwana and created a series of basins and ridges in the south-west Pacific. Many of these ridges (Lord Howe Rise, Fairway Ridge, Norfolk Ridge) are continental slivers that have broken away from the Australian continent, while other ridges (Loyalty Arc, Vanuatu Arc, Tonga Arc) and associated basins (New Caledonia Basin, Loyalty Basin, Fiji Basin, Lau Basin) are ancient or active volcanic arcs, back-arcs and rift basins (Fig. 1). These structures result from a complex series of subduction systems associated with a general eastward roll-back of the Pacific slab during the Cretaceous and Cenozoic (Schellart et al., 2006). Paleogeographic reconstructions of the south-west Pacific between the end of the Mesozoic and the Paleogene remain contentious due to the succession of short-lived geodynamic events that modified topological features of the eastern boundary of Gondwana. Furthermore, most of the geological terranes are now inaccessible, as they lie beneath sediments on the oceanic floor or have been entirely consumed in subduction zones. Campaigns of drilling and dredging (Mortimer, 2004; Exon et al., 2006; Higgins et al., 2011; Mortimer et al., 2015), collection of volcanic arc xenoliths (Buys et al., 2014; Tapster et al., 2014) and study of units preserved on microcontinents such as New Caledonia, New Zealand and Fiji are the only source of materials that can inform us on the geological history of the south-west Pacific.

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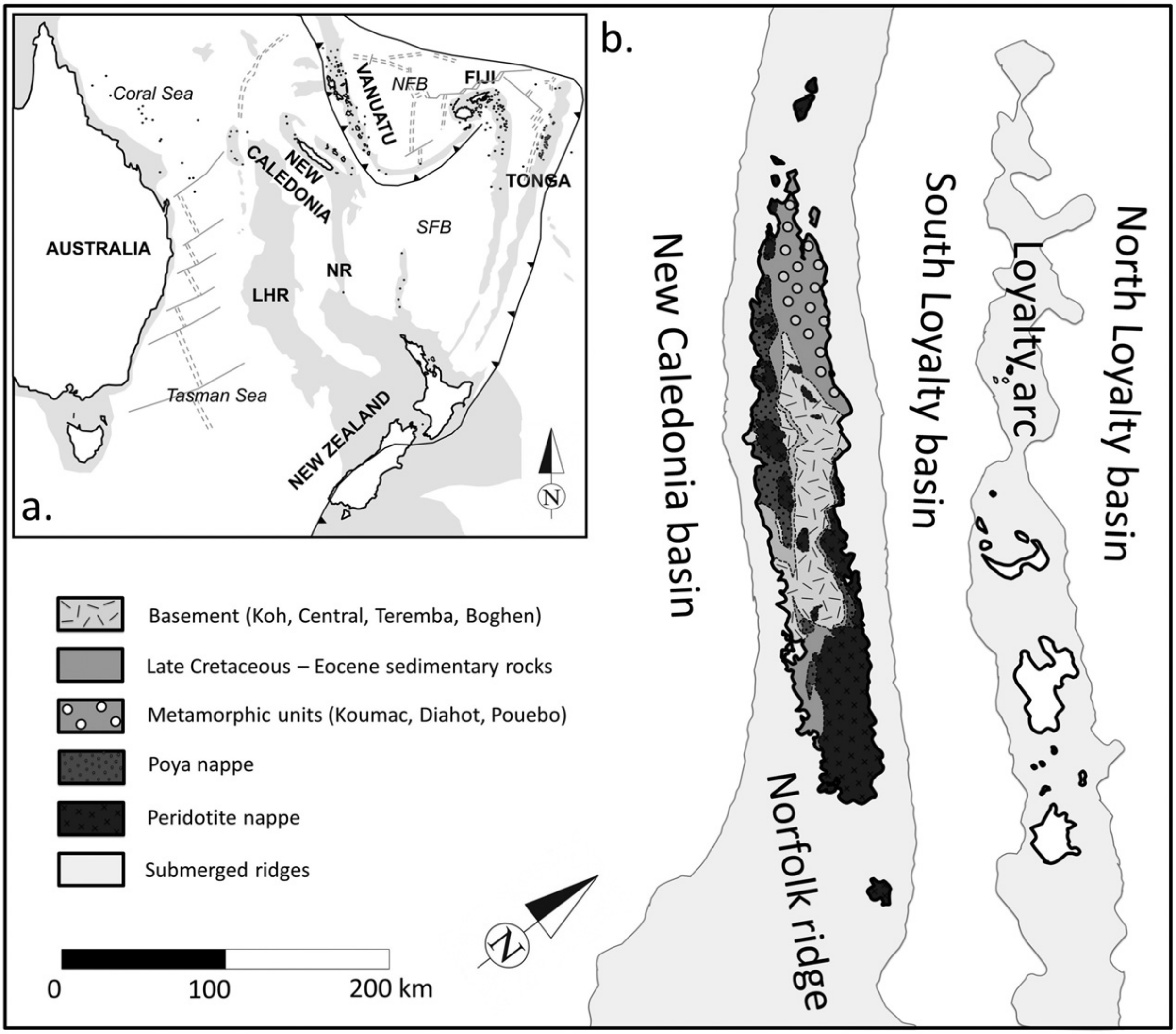

Fig. 1. a. Map of the south-west Pacific showing the main ridges and basins (LHR: Lord Howe Rise; NR: Norfolk Ridge; SFB: South Fiji Basin; NFB: North Fiji Basin). b. Bathymetric features of the New Caledonia-Loyalty region. The main terranes of the emerged part of the Norfolk Ridge are represented.

The available geological record includes igneous rock formed directly from magmatic activity related to rifting or subduction, but this record is sparse and poorly preserved. Instead, most of record is preserved in sedimentary basins that have collected erosion products of such magmatic events. In some cases, tectonic processes have led to the exhumation and surficial exposure of partially subducted sedimentary sequences, such as in northern New Caledonia.

In the south-west Pacific, the main island of the New Caledonia archipelago stands out as a rare portion of a continental ridge that is currently emerged and hence directly accessible for geological sampling. Various basement rocks on New Caledonia have provided valuable information on the distribution of basins and potential sediment sources occurring on the eastern margin of Gondwana in the Mesozoic (Adams et al., 2009; Cluzel et al., 2010). These studies have confirmed the presence of active margin tectonic settings and associated volcanism during this time. Proximal basin structures collected the volcanic detritus, together with sediments from Gondwana. In some cases, these sedimentary rocks have a subsequent metamorphic overprint formed during plate convergence and/or collisional tectonics (Cluzel et al., 2010).

In this paper, we investigate the metamorphic and detrital zircon records of metamorphosed sedimentary sequences of Northern New Caledonia that were deposited during the late Cretaceous to early Eocene. The detrital zircon records of these rocks provide information on the sources of sediment deposited in basins surrounding the northernmost Norfolk Ridge, whereas younger volcanic-derived and metamorphic zircons allow us to better identify and constrain the Cretaceous to Eocene tectonic history of the region. Although previous geochronological studies have been conducted on a range of metamorphic rocks (Spandler et al., 2005a; Baldwin et al., 2007; Cluzel et al., 2010), the relationship between protoliths of different metamorphic units remains unresolved. The highest metamorphic grade rocks provide protolith ages of 84 and 55 Ma (Spandler et al., 2005a) while rocks of lower metamorphic grade contain a wide range of Mesozoic and older zircons (Cluzel et al., 2010). To understand the relationship between these rocks, this paper investigates intermediate and felsic samples that span the range in metamorphic grade from prehnite-pumpellyite-facies, through blueschist-facies to eclogite-facies. This sample set also provides information on the effects of progressive subduction-zone metamorphism on the recrystallisation of zircon.

2. Geological outline of high-pressure rocks of New Caledonia

New Caledonia is located at the northernmost end of the Norfolk Ridge; a 2000 km long ribbon of continental crust connected to the North Island of New Zealand (Fig. 1a). The main island of New Caledonia (Grande Terre) comprises several terranes. The basement is made of Late Carboniferous to Upper Jurassic units (Teremba, Koh-Central, and

Boghen Terranes) that were accreted to the eastern margin of Gondwana during episodes of plate convergence. Proposed analogous terranes include the Gympie Terrane of southern Queensland (Aitchison et al., 1998; Spandler et al., 2005b; Adams et al., 2009), and Late Paleozoic and Mesozoic terranes of New Zealand (Aitchison et al., 1998). The sedimentary source of these basement units has been suggested to derive from Queensland (Adams et al., 2009) or Antarctica (Cluzel and Meffre, 2002). Unconformably overlying are the transgressive volcaniclastic Upper Cretaceous unit classically named Formation à Charbons (Cluzel et al., 2010) and a Late Cretaceous to Early Eocene sedimentary parautochonous unit named Montagnes Blanches Nappe (Maurizot, 2011) that formed to the west of a long-lasting west-dipping subduction zone (Schellart et al., 2006). Sections of oceanic crust that formed offshore during this time period are now preserved on the west coast as an allochtonous basaltic nappe named the Poya Terrane (Ali and Aitchison, 2002) (Fig. 1b).

Changes in geodynamic conditions in the early Cenozoic produced a north-east dipping subduction zone (Loyalty Subduction Zone) that metamorphosed parts of Formation a Charbons, Montagnes Blanches Nappe and Poya Terrane (Cluzel et al., 2001; Spandler et al., 2004; Maurizot, 2011) under high-pressure low-temperature metamorphic conditions. In the latest Eocene, the convergence of the Norfolk Ridge with the Pacific Plate led to the jamming of the Loyalty Subduction Zone, and the sequenced obduction of the Poya Terrane, followed by the Peridotite Nappe on the continental ridge (Cluzel et al., 2001; Schellart et al., 2006). The Peridotite Nappe today covers one third of New Caledonia, and is described and interpreted as a large fore-arc ultramafic nappe (Pirard et al., 2013). At the same time, the final exhumation phase of metamorphic rocks onto the Norfolk Ridge (Cluzel et al., 2001) formed the high-pressure metamorphic belt that comprises most of the northern portion of the island (Fig. 1b). Further details on the regional geological background can be found in Cluzel et al. (2012).

2.1. Metamorphic belt of Northern New Caledonia

The metamorphic rocks lying in the northern part of the island are characterised by a change in metamorphic grade from sub-greenschist facies in the west to eclogite facies to the north–east, although much of the metamorphic grade changes are due to juxtaposition of rocks of different metamorphic grade by normal faulting (Clarke et al., 1997; Rawling and Lister, 2002; Vitale Brovarone and Agard, 2013). Previously, some workers have attempted to subdivide the belt according to tectonostratigraphic terrane classification (e.g., Cluzel et al., 2001), but, as pointed out by Rawling and Lister (2002), Baldwin et al. (2007) and Spandler et al. (2008), much of these rock packages share similar lithological and geochemical associations, and underwent contemporaneous metamorphic and exhumation histories, and so are not well suited to tectonostratigraphic terrane classification (see also Vitale Brovarone and Agard, 2013). Here, our focus is on the zircon record of metasedimentary rocks across the metamorphic gradient, so detailed discussion of unit classification is beyond the scope of this paper. We therefore adopt the designation of Spandler et al. (2008) and Taetz et al. (2016), and recognise three basic geological units that comprise the belt; The highest grade Pouebo Eclogite Mélange (PEM), the Diahot Blueschists, and the Koumac Unit. These units are orientated NW-SE and each is 5 to 10 km wide with a lateral extension of 70 to 100 km long. The boundary between Koumac Unit and Diahot Blueschists has been considered as a fault boundary (Bwaluyu Fault, Potel et al., 2006) or a transition between dominantly Paleogene and Upper Cretaceous rocks (Maurizot et al., 1989) but the most common definition for the lower limit of the Diahot unit is the presence of lawsonite (Brothers, 1974; Diessel et al., 1978; Rawling and Lister, 2002; Maurizot and Collot, 2009; Cluzel et al., 2012). The division between the Diahot and PEM has been defined as the change from coherent sedimentary rocks to a heterogenous and chaotic mélange unit dominated by mafic rocks and containing sedimentary and ultramafic elements (Spandler et al., 2008).

2.1.1. Koumac Unit

The Koumac Unit comprises the western-most part of the belt and is here defined as all rocks below the lawsonite-in isograd. It is similar in many aspects to unmetamorphosed sedimentary rocks in other parts of New Caledonia such as Montagnes Blanches Nappe and Bourail (Maurizot and Collot, 2009; Maurizot, 2011). Koumac is a low-grade (prehnite-pumpellyite facies) sedimentary unit (Brothers, 1974; Black, 1977) that contains mature organic matter, vermiculite and corrensite (Potel et al., 2006) as characteristic metamorphic phases. Common lithologies found in this unit are sandstones, marls, silicified shales and pelagic micrites with black shales becoming more abundant in the east. Deposition ages are estimated to be Campanian to late Paleocene (Bodorkos, 1994; Paul, 1994), although middle Eocene ages have also been suggested for some siliceous rocks (Maurizot and Feigner, 1986). Metamorphic conditions applied to this terrane remain below 300 °C and 0.8 GPa (Potel et al., 2006).

2.1.2. Diahot Blueschists

The Diahot Blueschists is the central metamorphic group that cover rocks between the lawsonite-in and the epidote-in to omphacite-in isograds (Fig. 2). Most of the Diahot Blueschists comprise a sequence of fine-grained pelitic sediments, with black shale a common protolith, that have been recrystallised to form metamorphic lawsonite, micas, glaucophane and spessartine (Black and Brothers, 1977; Fitzherbert et al., 2003). The Diahot Blueschists are interpreted as a distal equivalent of Koumac Unit, with fine-grained sediments deposited in a deeper water environment (Cluzel et al., 2011). In addition, some intercalations of metavolcanic rocks (rhyolite, basalt) occur in some areas, particularly surrounding Cu-Zn-Pb ore deposits. At higher metamorphic grade, a distinct body of leptynite outcrops on the Bouehndep highland in the north of Pam Peninsula. This body is interpreted as a meta-rhyolitic dome genetically linked to felsic tuffs occurring in lower grade Diahot Blueschists (Maurizot et al., 1989). The deposition age for Diahot sediment is thought to be Cretaceous (Baldwin et al., 2007; Cluzel et al., 2011), but Paleocene ages have also been suggested (Maurizot et al., 1989; Cluzel et al., 1994). Metamorphic peak P-T conditions found in the Diahot Blueschists range from 300 to 570 °C and 0.8 to 1.6 GPa (Clarke et al., 1997; Fitzherbert et al., 2005) with zircon recrystallization ages at 38 $\pm$ 3 Ma (Cluzel et al., 2010).

2.1.3. Pouebo Eclogite Mélange

The Pouebo Eclogite Mélange (PEM) lies on the east coast and on the Pam Peninsula range above the omphacite-in isograd (Fig. 2). The metamorphic grade reaches upper blueschist- to eclogite-facies (up to 2.4 GPa and 550–650 °C; Clarke et al., 1997; Vitale Brovarone and Agard, 2013), although retrogressive blueschist- and greenschist-facies mineral assemblages are frequently found (e.g., Carson et al., 2000). Unlike the units to the west, the PEM is composed of mafic to felsic metaigneous rocks and serpentinite, in addition to metasedimentary rocks (Clarke et al., 1997; Carson et al., 2000; Spandler et al., 2004, 2008). These rock-types are associated as complex mélange that formed during subduction and exhumation of the oceanic crust (Rawling and Lister, 2002; Spandler et al., 2008). As a result, small-scale variations in lithology with blocks of metasediments mixed with metabasalts, serpentinites and metasomatic rocks (chlorite and talc schists, actinolitite, etc.) are frequently observed in the field. Uranium-Pb ages on core zones of zircon from micaschists of the PEM have returned Cretaceous (84 Ma) and Eocene (55 Ma) ages, whereas rims on zircon that were interpreted to have formed during peak eclogite-facies metamorphism were dated as ca. 44 Ma (Spandler et al., 2005a).

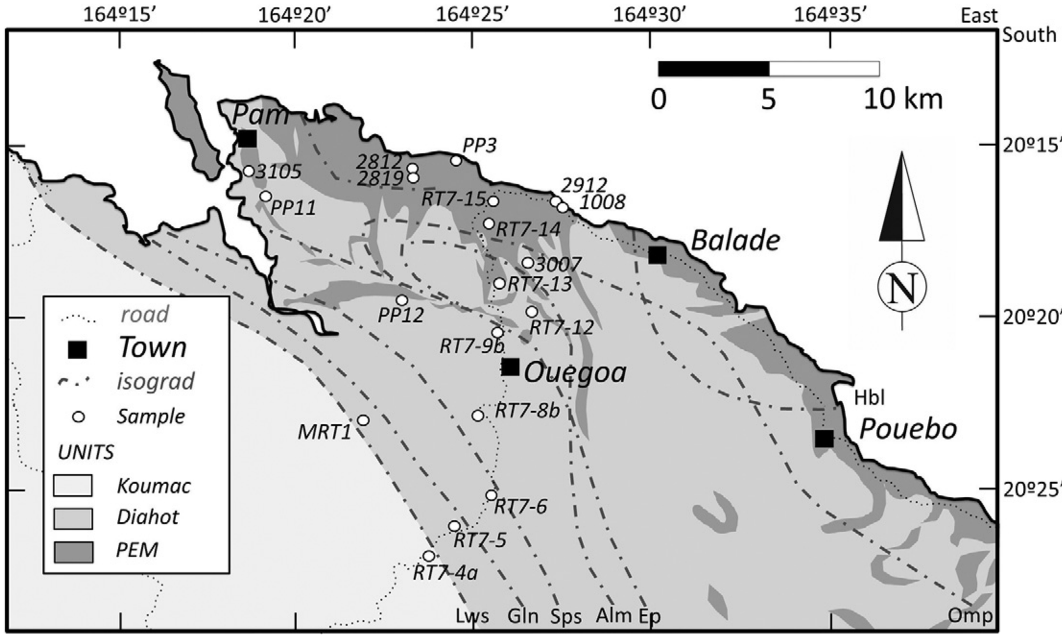

Fig. 2. Simplified geological map of the northern part of New Caledonia with the distribution of zircon-bearing samples and the metamorphic isograd of various minerals (Lws: Lawsonite-in; Gln: Glaucophane-in; Sps: Spessartine-in; Alm: Almandine-in; Ep: Epidote-in; Omp: Omphacite-in; Hbl: Hornblende-in) (adapted from Brothers, 1974; Bell and Brothers, 1985; Diessel et al., 1978; Potel et al., 2006). The upper limit of the Koumac Unit is defined by the lawsonite-in isograd. The Pouebo Eclogite Mélange (PEM) is defined as a mostly mafic metamorphic mélange while the Diahot Blueschist comprises the mostly metasedimentary units in between the Koumac Unit and PEM (Clarke et al., 1997; Maurizot and Collot, 2009).

2.2. Sample descriptions

Around 35 samples (Supplementary Table S1) from across the metamorphic belt were collected for mineral separation processing and analysis. The general sampling strategy was to collect a sequence of zircon–bearing rocks (metasedimentary or felsic-intermediate volcanic rock protolith) that range from low to high metamorphic grade. Most samples were collected along the territorial road n° 7 that transects the metamorphic belt, or along the north-eastern coastline (Fig. 2). A few samples were collected from abandoned mines (Mérétrice, Balade, Murat) and around the Pam Peninsula. Twelve of these samples (Fig. 2, Supplementary Table S1) produced a sufficient zircon yield for further study. In addition, heavy mineral separates used by Spandler et al. (2004, 2005a) were also analysed for additional U-Pb dating and Hf isotopes.

Samples from the Koumac Unit are weakly metamorphosed sediments with pelitic, psammitic and siliceous compositions. The rocks primarily consist of clay minerals and quartz, but commonly contain calcite, iron oxides, barite and accessory apatite, titanite and zircon.

Samples obtained from the Diahot Blueschists are metamorphosed clastic to volcaniclastic sediments. Metasedimentary samples from below the spessartine-in isograd retain a general fine-grained pelitic appearance and mostly contain clays, micas (muscovite), chlorite, quartz, iron oxides and accessory titanite, apatite, lawsonite and zircon. Samples collected between the spessartine-in and epidote-in isograd bear similarities with dark sedimentary shales but the increasing metamorphic gradient has resulted in considerable grainsize coarsening. Millimetric grains of Na-amphibole and phengitic muscovite are common. The mineralogy in these samples is typically quartz, phengite, paragonite, glaucophane, spessartine, lawsonite and minor calcite, epidote, graphite, iron oxides, rutile, titanite, apatite, pyrite and zircon.

In the PEM, gneisses and micaschists are the dominant metasedimentary lithologies. In most cases, primary sedimentological features have been erased by metamorphism, but in some places (e.g., Abwala Stream) primary bedding can be observed in garnet blueschist-facies rocks. The collected samples are essentially quartz-rich gneisses that are often found as decametric blocks in a mélange zone composed of mafic eclogites, retrogressed blueschists, metasomatites and serpentinites. These gneisses are interpreted to be of metasedimentary and/or metavolcanic protoliths; they contain quartz, phengite, paragonite, chlorite, glaucophane, jadeite, almandine and epidote, as well as minor/accessory titanite, rutile, apatite, allanite, pyrite and zircon. Additional samples of metarhyolite and Na-rich felsic eclogite collected from the Pam Peninsula are composed mainly of quartz, jadeite and paragonite.

3. Methods

Initial sampling involved collection of 2 to 3 kg of rock that is relatively unaltered and free of weathering. All samples were crushed and milled in hydraulic presses and a tungsten carbide disk mill with sieving at 500 μm mesh to recover >95% of the initial rock sample. The powdered material was washed and deslimed using a Wilfley table RP-4, removing most of the clay-sized fraction. Heavy minerals were separated using near saturation lithium heteropolytungstate aqueous solution at room temperature (2.88 ± 0.01 g/cm^3) and up to ~90 °C (3.25 ± 0.05 g/cm^3), or methylene iodide (3.32 ± 0.01 g/cm^3). The high temperature separation was required for efficient heavy mineral separation from the dense eclogite-facies rocks. Ferromagnetic minerals were removed using a hand magnet, followed by a paramagnetic/diamagnetic separation using Frantz isodynamic electromagnet with a range of current (0.2 to 1.5 A) set with various forward slope (5 to 45°) and tilt (5 to 20°). Zircon grains in the non-magnetic heavy mineral separate were handpicked under a binocular lens microscope. All zircon grains have been collected from zircon-poor separates, while ~100 to 150 grains have been selected in zircon-rich samples. Zircon grains were mounted in standard 25 mm polyepoxide resin, ground to expose mid-sections and polished with a final 1 μm diamond abrasive.

These mineral separation and processing procedures have been established, and are maintained, to minimize risk of cross-contamination between samples. All equipment was thoroughly cleaned before and after each processing step, with only one user operating in the laboratories at any time. A more detailed evaluation of contamination issues in our laboratory is outlined in Buys et al. (2014).

All trace element and isotopic work on zircon was conducted at the Advanced Analytical Centre of James Cook University. Grains were imaged using a JEOL JSM5410LV scanning electron microscope equipped with a Robinson cathodoluminescence detector to document internal structures with a particular emphasis given to imaging inherited core and metamorphic rim domains. Trace element concentrations and U-Pb age data were acquired using a coherent GeoLasPro 193 nm ArF Excimer laser ablation system connected to a Bruker 820-MS using a setup as described in Tucker et al. (2013). Instrument settings for analysis were 10 Hz repetition rate, a laser fluence of 6 J/cm^2 with a spot size of 32 or 44 μm for most analyses, while some thin metamorphic rim analyses were attempted with a spot size as small as 16 μm. Calibration for each spot size was made using the GJ-1 zircon as the primary bracketing standard (609 Ma, Jackson et al., 2004), while the Temora 2 zircon (416.8 Ma, Black et al., 2003) and Fish Canyon Tuff zircon (28.5 Ma, Schmitz and Bowring, 2001) were analysed as a secondary standard (Supplementary Table S2). NIST SRM 610 and NIST SRM 612 were analysed three times in each U-Pb session and every 15 analyses in trace element sessions for trace element calibration purposes. Zircon trace element data were quantified using ^{29}Si and the external standard, and the reference values of Spandler et al. (2011) for the NIST glass standards. Trace element and U-Pb age data of zircons were processed using the Glitter (Griffin et al., 2008) and Isoplot (Ludwig, 2012) software packages. All ages obtained with discordance >25% were automatically rejected.

Lutetium-Hf isotope analyses were collected using the same laser system and ablation cell, but coupled with a Thermo-Scientific Neptune multi-collector ICP-MS. The laser operating conditions were set to 4 Hz repetition rate, and a 32 to 60 μm diameter beam size with some attempts at 24 μm. Laser pits were placed adjacent to U-Pb and trace element ablation pits. The instrument setup and methodology is outlined in Kemp et al. (2009). MudTank, Temora 2 and FC1 zircon standards (Kemp et al., 2009) were analysed between analyses of 15 unknown zircons (Supplementary Table S3).

4. Results

4.1. Zircon characteristics and ages

4.1.1. Koumac Unit samples

The metamorphic rocks of northern New Caledonia present a range of zircons that have varied cathodoluminescence (CL) patterns and intensity (Supplementary Fig. 1). Significant zircon yields from samples of the Koumac Unit were only achieved from a sandy pelite just below the lawsonite isograd (RT7-4). Uranium-Pb zircon ages from RT7-4 range from Neoarchean (2540 ± 32 Ma) to Late Cretaceous (82 ± 1 Ma). Significant age populations are recorded for 600–500 Ma (22%), 250–150 Ma (18%) and between 110 and 95 Ma (19%) (Fig. 4a). Precambrian zircon grains tend to be well rounded, have a low CL intensity and lack distinct zoning. Cretaceous zircons tend to be euhedral, and almost always feature a distinct zoning with a high CL intensity. Overgrowth zones on the grains rims are not observed on any grain in these samples.

4.1.2. Diahot Blueschists samples

Many samples collected in the Diahot Blueschists had considerable zircon yields. Below the garnet-in isograd, samples are light-coloured pelites (MRT1, RT7-6) that are similar to pelites found in the Koumac Unit. Zircons from these samples are 50 to 200 μm grains that span a similar age range (2543 ± 18 to 105 ± 1 Ma) to the Koumac Unit sample (Fig. 4b). Associated with these metasedimentary rocks is volcanic-derived sample RT7-5 that contains zircon as young as 102 ± 2 Ma (Supplementary Table S4). The age population distribution is also similar to Koumac sample with a significant component of late Precambrian-Cambrian (15%) zircons, along with an abundance of 1800 and 1600 Ma grains (15%). Precambrian zircon grains in all samples tend to be well-rounded, have low CL intensity and lack strong CL zonation. Mesozoic grains tend to be euhedral, with common zoning and high CL intensity. Overgrowth zones on these grains are absent.

Samples collected above the garnet-in isograd include RT7-8b, RT7-9b, RT7-12, PP12; these are all dark-coloured metapelites with abundant glaucophane, phengite and paragonite. Zircons grains recovered from these samples are between 40 and 250 μm, and range from anhedral to euhedral with a variety of internal textures (Supplementary Fig. 1). Uranium-Pb dating of grain interiors provides ages ranging from Archean (3202 ± 28 Ma) to late Cretaceous (88 ± 1; 86 ± 1 and 75 ± 1 Ma) in 3 samples (Fig. 4c–e). There are high proportions of grains with ages of 600–500 Ma (13 to 20%) and 130–110 Ma (10 to 52%). Precambrian and Paleozoic grains are often rounded with low CL intensity, while Cretaceous zircons are often suhedral with variable CL intensity and zoning. There is a significant population of euhedral and concentric zoned zircons of age 110 and 95 Ma (7 to 22%) in two samples (Fig. 4d, e).

Sample RT7-13 is a gneiss sample from the highest-grade part of Diahot Blueschists. Zircons are large (up to 350 μm), with concentrically zoned relatively CL bright cores with well-developed rim zones (up to ~100 μm) with low CL intensity (Supplementary Fig. 1, Fig. 3b). Excluding a couple of older zircon grains of Precambrian age, these zircons range in age from ca. 50 to 60 Ma; when treated as a single population, these data return an age of 55.5 ± 1.4 Ma (MSWD = 2.4) (Fig. 5a). The spread of Eocene age zircons over 10 m.y. is likely to be related to volcano-sedimentary nature of the protolith and the duration of volcanic activity in the region producing a spread of concordant zircons.

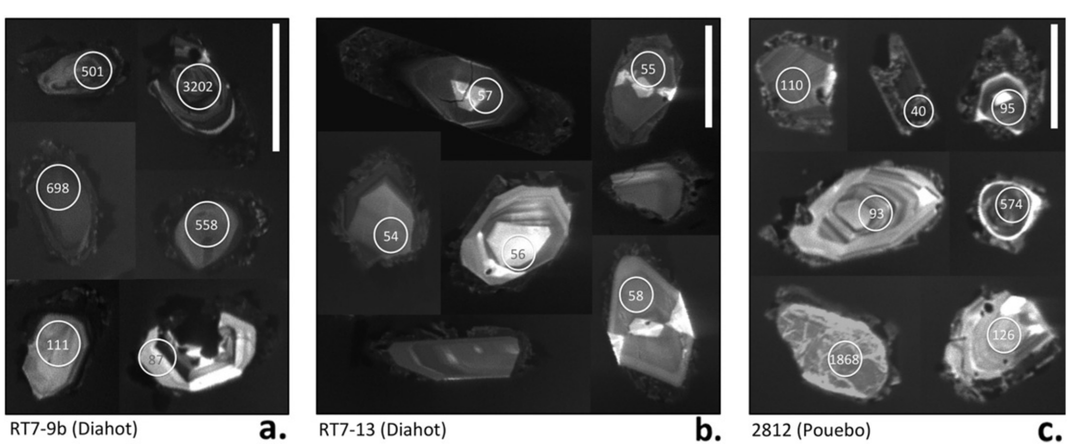

Fig. 3. Collage of cathodoluminescence images of zircons in samples RT7-9b (a), RT7-13 (b) and 2812 (c). RT7-9b and 2812 show detrital cores and RT7-13 shows igneous Eocene cores. These three samples have visible metamorphic rims at different metamorphic grade (RT7-9b: epidote-in isograd; RT7-13: below almandine-in isograd; 2812: hornblende-in isograd). Scale bar is 100 μm; circles indicate laser ablation pits for U-Pb core dating, with the determined ages (in Ma) shown.

PP11 is an eclogite-facies sample that shows a very weak foliation plane and is best described as light green leptynite. This sample contains mostly quartz, jadeite, phengite and paragonite with minor glaucophane and epidote and rare garnet. PP11 has zircons of Cretaceous age showing considerable age spread between 90 and 75 Ma (Fig. 7a).

Distinct 10 to 50 μm thick rim zones with heterogeneous low CL intensity are present on zircons from the higher-grade Diahot samples (Fig. 3a–b) to the exclusion of PP11. We could only obtain a few analyses of these zircon rims, given the spatial resolution of our analytical technique. Five reliable analyses of zircon rims in sample RT7-9b returned an age of 39.1 ± 1.0 Ma (Fig. 6a), albeit with a large MSWD of 3.7. Analyses of 4 zircon rims from sample RT7-13 returned discordant data, which could be projected back to concordia to give an age 37.2 ± 1.8 Ma (MSWD = 2.4) (Fig. 6b). The relatively large MSWD of these analyses reflect the spread of ages, which may be analytical aberrations due to accidental partial sampling of the zircon core, or may be some real age variation between zircon rims that is not quantifiable with our methods.

4.1.3. Pouebo Eclogite Mélange samples

The PEM sample 3105 contains zircon grains that range between 100 and 300 μm and are commonly euhedral with distinct oscillatory zoning and little inter-grain variation. These zircons returned a latest Cretaceous age of 66.7 ± 1.7 Ma (MSWD = 0.59) (Fig. 5b). Samples RT7-15 and 2812 have rounded and euhedral zircon grains with variable CL texture (Fig. 3c) and a spread of ages between ca. 100 and 1200 Ma (Fig. 4f). All samples show overgrowth of rims (Fig. 3c, Supplementary Fig. 1) with dating of 3 rim zones from sample 2812 giving concordant ages with a weighted average of 40.4 ± 5.2 Ma (MSWD = 3.2) (Supplementary Table S4).

PP3 is an eclogite-facies block that do not show any evident foliation and is best described as a quartz-rich jadeitite containing minor paragonite, glaucophane and garnet. Sample PP3 has exclusively

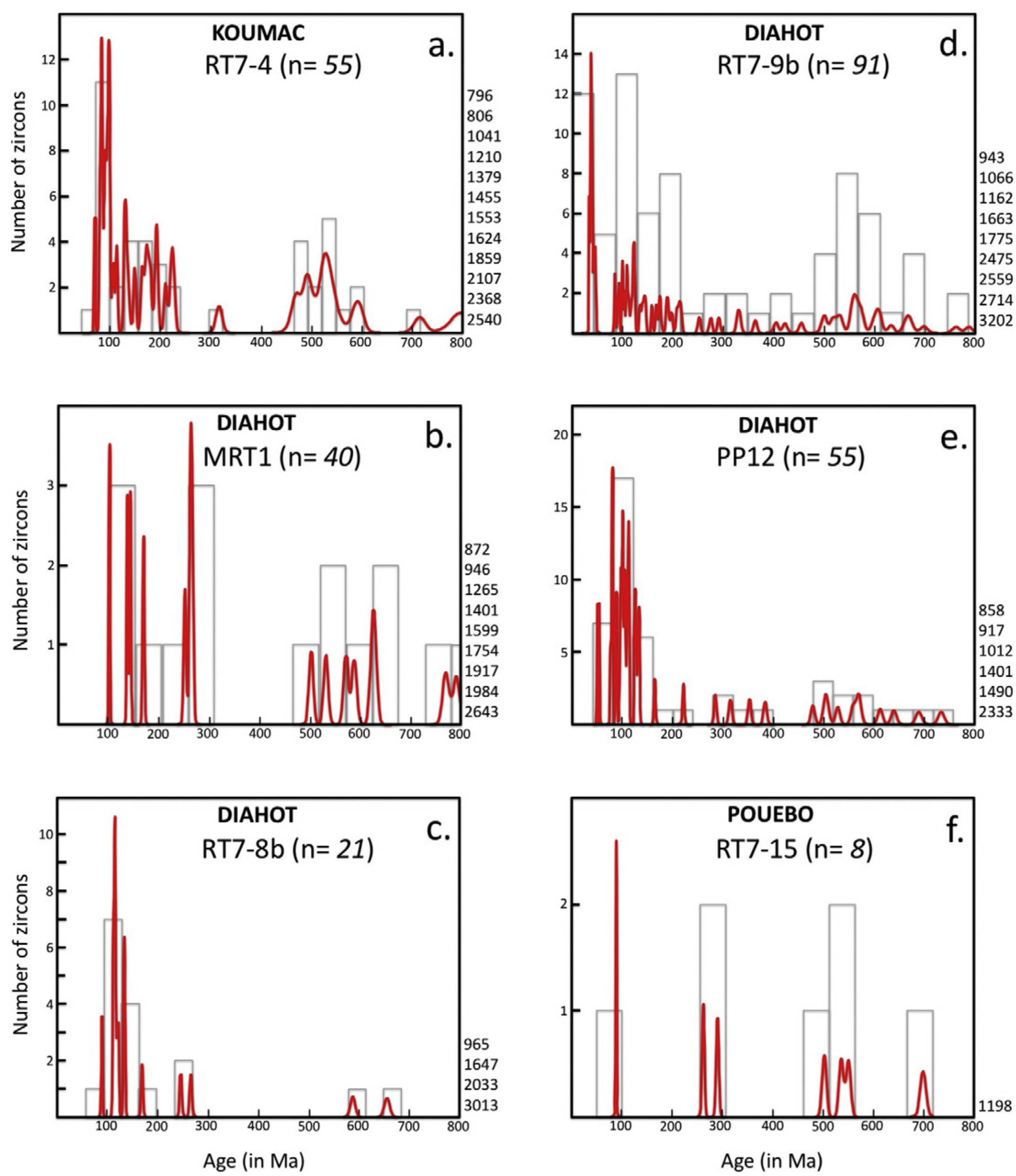

Fig. 4. Histogram distribution of zircon ages between 800 Ma and present (pre-800 Ma ages are presented as individual ages on the right margin) of detrital sedimentary samples and probability density diagram of the detrital signature. Ages are $^{238}U/^{206}Pb$ data.

rounded Proterozoic zircons with low CL intensity and ages mostly between 1500 and 2000 Ma (Fig. 7b). PP3 does not show any evidence of metamorphic rims despite the presence of high metamorphic grade mineral assemblages.

4.2. Lu-Hf isotopes

Lutetium-Hf isotope ratios have been determined for all zircon populations to monitor the evolution of εHf in the New Caledonian samples (Supplementary Table S5; Fig. 8). Proterozoic zircons have εHf between +5 and −14 based on 10 grains. The significant population in the Late Precambrian-Cambrian ranges from −36 to +9 ($\mu = -6$) for 24 zircons. Late Triassic and Jurassic grains have εHf from +0.4 to +11.6 ($\mu = +6.5$) and Early Cretaceous zircons have a range of +6.1 to +8.8 ($\mu = +7.2$). From 125 Ma to 65 Ma values remain high between +8 and +10 although a drop is noticed at 68 ± 3 Ma (+6.3). The Cretaceous metarhyolite has εHf of +9.3 ± 0.6, and ca. 55 Ma age zircons have the highest εHf values with +10.5 ± 1.7 (Fig. 8). Overgrowth rims of ages 44 Ma have +9.3 ± 2.2 while younger rims between 40.4 and 37.8 Ma in the Diahot Blueschists have a wide range of values from −21 to +8.6 that partly correlates with the Hf isotopic compositions of their respective cores (Fig. 9).

4.3. Zircon trace element compositions

Zircon populations have variable trace element concentrations (Supplementary Table S6). Late Proterozoic and Cambrian zircons show insignificant to very strong europium anomalies (Eu/Eu* = 0.71 to 0.01) and variable Th/U values (1.0 to 0.08). Precambrian and Paleozoic zircons have low HREE/MREE (Yb/Sm of 41 ± 27) (Fig. 10). Mesozoic zircons have insignificant to moderate europium anomalies (Eu/Eu* = 0.27 ± 0.12) and relatively high Th/U values (0.76 ± 0.28) (Fig. 11). Yb/Sm in these zircon grains is 114 ± 56. Cenozoic zircon cores generally have distinct negative europium anomalies (Eu/Eu* = 0.27 ± 0.08). The ca. 55 Ma Eocene zircons have a moderately high Th/U (0.62 ± 0.35) and HREE/MREE values similar or higher to Mesozoic zircons (Yb/Sm of 173 ± 52). Overgrowth rims have systematically low Th/U ratio (0.2 to 0.002) (Fig. 11) similar to previous observations (Spandler et al., 2005a); they do not have well-developed europium anomalies (Eu/Eu* = 0.6 ± 0.2) and show a relatively high HREE/MREE ratio (Fig. 10). Titanium content in zircons is not characteristic of a particular age group and ranges between 5 and 187 ppm.

5. Discussion

5.1. Interpretation of zircon characteristics

The characteristics of zircons and their age distribution in samples are indicative of the origin and process of formation of these assemblages. On the basis of zircon grain age, internal texture, morphology and geochemistry, we define 3 groups of zircon that comprise the inventory of our New Caledonian samples: 1. Detrital grains that are found in all units; 2. Late Cretaceous to Paleogene magmatic grains that are found in the PEM, and; 3. Eocene rim zones that are formed during HP metamorphism in PEM, and Diahot Blueschists above the garnet-in isograd.

5.1.1. Detrital zircons

Most metapelite samples from the Koumac Unit and Diahot Blueschists and some samples from eclogite-facies gneisses and jadeitite (RT7-15, 2812, PP3) have rounded zircons, with low CL intensity, variable zoning features, and generally a large age range that may span from the Archean to the late Cambrian to Mesozoic (Figs. 3a, c, 7, Supplementary Fig. 1; Supplementary Table S4). Significant populations are found between 1800 and 1500 Ma, between 700 and 500 Ma (particularly 600–500 Ma), 300–250 Ma, and 140 to 80 Ma (Fig. 12). Zircons from the latter population are often distinctly zoned, subhedral to euhedral with a high CL intensity. The detailed probability plot of this period shows a peak at around 110 Ma (Fig. 12b). Combined with the Cretaceous zircon distribution of Cluzel et al. (2011), this pattern indicates an increasing magmatic activity from ~140 Ma to ~110 Ma and a waning in the late Cretaceous with no additional features. In sample RT7-9b and PP12, a particularly significant detrital abundance is noticed at 88.3 ± 2.6 Ma and 85.4 ± 2.1 Ma, respectively, that end the Cretaceous magmatic activity. Sample PP12 also contain a few younger grains at 77.5 ± 1.6 Ma (PP12) (Supplementary Table S4).

The wide distribution of zircon ages from the Archean to Cretaceous indicates a continental detrital source for these sediments. The youngest age found in most of these samples is consistent with the suggestions of Maurizot et al. (1989) that these sediments were formed from eroded detritus of older formations, and were lithified between 86 and 72 Ma. Jadeitite sample PP3 containing exclusively Proterozoic zircons (Fig. 7b) could derive from a hypothetical Precambrian basement of the Norfolk Ridge, that was subducted and metasomatised into jadeitite (Harlow and Sorensen, 2005). The rounded morphology of pre-Mesozoic zircons indicates a considerable transport from their original source area (or multiple reworking events), while younger grains are mostly euhedral and subhedral, which is indicative of more local sources. Trace element concentrations in zircons do not show significant variations that would indicate a modification in the type of igneous sources through time (Belousova et al., 2002), and average calculated temperatures using Ti contents of zircons (Watson et al., 2006) are 814 ± 84 °C. Europium anomalies are variable although all Mesozoic zircons have considerable negative anomalies. Hafnium isotopes of Proterozoic zircons show relatively unradiogenic values with high variability, indicating mixing between old crustal and mantle sources. The Hf isotopes of Phanerozoic detrital zircons show an evolution from relatively unradiogenic values (εHf of −36 to +9) in the Cambrian to values of +3 to +9 for the Jurassic-Triassic, and exceeding +8 for Cretaceous detrital zircons (Fig. 8). These relatively high values indicate the limited involvement of old continental crustal rocks in the formation of these Mesozoic zircons.

5.1.2. Late Cretaceous and Paleogene magmatic grains

In the easternmost blueschists (RT7-13) and many eclogite-facies gneisses (PP11, 1007, 2812, 2819, 2912, 3007, 3105) of the PEM, zircon populations display tightly defined ages in the Late Cretaceous and Paleogene. These zircons are always euhedral with magmatic zoning, are often relatively large (150 to 250 μm), and are not mixed with other ages in a single sample. Their intrinsic properties are identical to late Cretaceous and Paleogene zircons found in detrital signatures. Such single-age populations suggest an igneous protolith source that was isolated from an eroding continental source that would deliver a diverse detrital zircon record. The oldest age group found for these rocks is 83.0 ± 4.8 Ma in a metarhyolite (PP11) (Fig. 7a), which is similar to zircon ages of 84.8 ± 0.9 and 84.9 ± 4.3 found in two Pouebo eclogites samples studied by Spandler et al. (2005a) and a metavolcanic leucocratic gneiss from the Diahot Blueschists (Cluzel et al., 2011, 83.0 ± 2.0 Ma). εHf values are high for these ca. 84 Ma zircons (above +8) but only partially overlap between samples, showing a minor variation in source. The Cretaceous-Paleocene boundary age of 66.7 ± 1.7 Ma from eclogite 3105 (Fig. 5b) is in agreement with paleontological dating of lawsonite-epidote blueschists that extend to the Paleocene (Yokoyama et al., 1986; Maurizot et al., 1989). Epidote blueschist RT7-13 contains the youngest magmatic zircons at 55.5 ± 1.4 Ma (Fig. 5a); an age consistent with the age of zircon cores from PEM samples 2912 (55.3 ± 0.8) and 3007 (55.6 ± 0.5) dated by Spandler et al. (2005a). The Late Cretaceous to Paleogene zircons have a negative europium anomaly and calculated temperatures based on Ti concentrations in zircon of 700–850 °C (Watson et al., 2006). These zircon geochemical features and bulk rock compositions are interpreted as consistent with magmatic crystallisation either with, or following, plagioclase

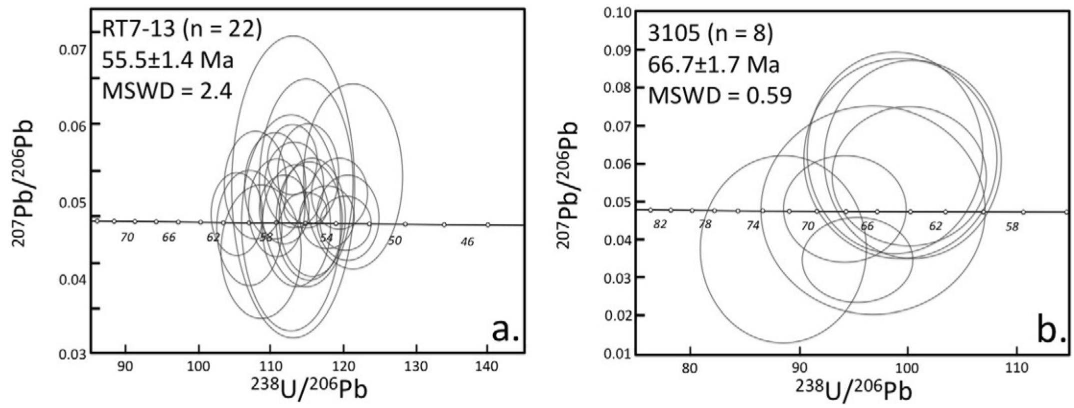

Fig. 5. Tera-Wasserburg diagram of eclogitic 'single population' samples RT7-13 and 3105 and concordant age.

fractionation (Spandler et al., 2004, 2005a). εHf values for these magmatic zircons overlaps between samples and are mostly above +9, which would indicate magma derivation from depleted mantle or juvenile crust source (Fig. 8).

5.1.3. Metamorphic rims

Zircon grains with distinct rim zones enveloping magmatic cores are observed in samples metamorphosed above the garnet-in isograd. These rims are poorly developed (<10 μm thick) at relatively low-grade metamorphic conditions (e.g. samples around Ouegoa; Fig. 2) but are a common feature around zircon cores in the blueschists and eclogitic gneisses of the PEM. In this later case, rim zones reach 30 to 50 μm thick in the blueschists and up to 100 μm in the eclogite-facies samples (Fig. 3, Supplementary Fig. 1). The occurrence of these rims, their age and characteristically low Th/U ratio (Fig. 11) is interpreted as the result of metamorphic growth during the mid to late Eocene. The ages for metamorphic rims from samples of the PEM are 44 Ma (Spandler et al., 2005a) and 40 Ma in eclogite 2812 (Supplementary Table S4). Metamorphic rims of zircon from the Diahot Blueschists are dated at 37.2 ± 1.8 (sample RT7-13), 39.1 ± 1.0 Ma (sample RT7-9b) (Fig. 6) and 38 ± 3 Ma according to Cluzel et al. (2010). These ages are in agreement with phengite Ar-Ar measurements of 37.1 ± 1.2 Ma (Baldwin et al., 2007) and recent Rb-Sr dating of eclogitic veins of 38.2 ± 0.3 Ma (Taetz et al., 2016). These ages are significantly younger than the timing of peak eclogite-facies metamorphism determined by Spandler et al. (2005a). The younger Ar-Ar and Rb-Sr ages are suggested to record the exhumation and cooling history of the eclogite unit, as peak metamorphism in the Pouebo eclogite (ca. 600 °C) is 100 to 200 °C above the estimated closure temperature of Ar and Sr in phengite (Baldwin et al., 2007; de Meyer et al., 2014). These ages therefore constrain the timing of cooling and decompression to 450–350 °C and ~0.5–0.8 GPa (Baldwin et al., 2007). Nonetheless, the ca. 6 m.y. difference in U-Pb zircon dating between eclogites and blueschists indicate that there were multiple stages of zircon growth under high pressure conditions. Modelling (Gerya et al., 2002) and empirical evidence (Rubatto et al., 2011; Kabir and Takasu, 2010; Beltrando et al., 2007) for multiple subduction-exhumation cycles provide support for such tectonic processes, but additional detailed petrographic and geochemical studies are required to validate this hypothesis for this case.

We suspect that the absence of a record of the older (ca. 44 Ma) metamorphic event in the Diahot zircons may be due to a lack of sufficient fluid flux to (re)crystalize zircon at this early stage, or that the Diahot Blueschists had a delayed metamorphic history compared to the Pouebo eclogites where multiple metamorphic cycles may have occurred at depth, as has been recorded in the Sanbagawa HP-LT belt (Kabir and Takasu, 2010). Based on the data available, the exhumation rate for the Diahot samples is calculated to be ~5 mm/yr following zircon rim growth.

The Hf isotope composition of the metamorphic rims from samples below the epidote-in isograd (RT7-9b, PP12) are, for the most part, similar to the isotopic signature of the enclosed zircon core, despite the fact that individual zircon grains have quite diverse isotopic compositions (Fig. 9). This indicates that isotopic homogenization was limited to the grain scale (Fig. 9). By contrast, in the eclogite-facies rocks, the metamorphic rims consistently have highly radiogenic and restricted εHf values (+6.5 ± 2.1 to +11.1 ± 0.5), even where detrital zircon cores have very different isotopic signatures (Fig. 9). These data indicate that Hf isotope equilibration during metamorphism extends to the hand specimen scale at least in the high grade rocks, as has also been observed in other metamorphic settings (Zeh et al., 2010). The presence of

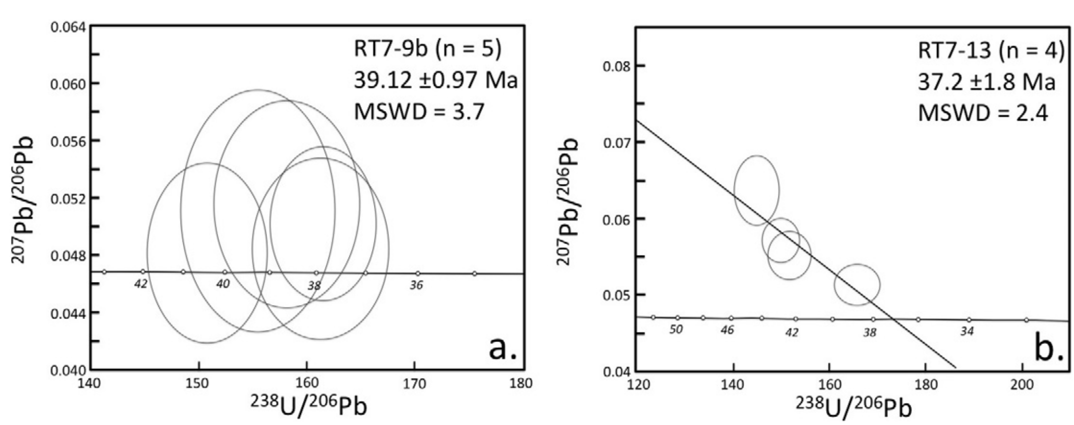

Fig. 6. Tera-Wasserburg diagram of metamorphic rim ages in sample RT7-9b and RT7-13. Average concordia age values are obtained only for analyses with relative errors of <10%.

rare, newly-formed metamorphic zircons or particularly extensive rims around cores is also indicative of high fluid/rock ratio in eclogite-facies rocks (Rubatto and Hermann, 2007) that would homogenise the isotopic signature. The lack of zircon rims in metarhyolite (PP11) and jadeitite (PP3) may be related to a different bulk composition preventing the efficient remobilisation of zircon forming components.

5.2. Origin of detrital zircons

The abundance pattern of detrital zircon ages of most low grade samples and some high grade metamorphic rocks (RT7-15, 2812) can be interpreted as the erosion product of the terranes forming the main New Caledonia range. Three volcano-sedimentary terranes comprise the basement of New Caledonia (Fig. 1b). The Koh-Central terrane is an Early Permian to Early Cretaceous unit (Adams et al., 2009) that contains an ophiolite (Koh) and associated with abundant fine-grained volcano-sedimentary rocks (Central) of black shales, graywackes, siltstones and chert. The Teremba Terrane is an alternation of volcanic (andesite to rhyolite) and sedimentary (graywacke) rocks of Late Permian to Middle Jurassic age. The Boghen Terrane is a metamorphosed slice of oceanic crust and ocean island basalts tectonically interleaved with volcaniclastic and sedimentary rocks that are up to Cretaceous in age (Maurizot and Collot, 2009). Unconformably overlying these basement rocks are a sequence of Cretaceous shallow water sediments known as Formation à Charbons. The Central Terrane (along with Formation à Charbons) is a possible source for Cretaceous zircons, and the Boghen terrane may also contribute Jurassic zircons to these rocks (Adams et al., 2009). In addition, the Central and Boghen terranes also carry a prominent Cambrian and Precambrian detrital zircon signature that is clearly visible in most metamorphic samples. The Teremba Terrane (Adams et al., 2009) seems to have a lesser importance in the sedimentary contribution to the metamorphic terranes due to the relative paucity in Triassic zircons but overall, no clear distinction can be made between local basement sources.

The morphology, abundance and age of Proterozoic zircons (Fig. 12) is consistent with derivation (directly or indirectly) from Australian Proterozoic terranes such as the Mount Isa Inlier (1890–1500 Ma; Griffin et al., 2006), Georgetown Province (1674–1544 Ma; Murgulov et al., 2007) and Yambo Province (1643–1575 Ma; Blewett and Black, 1998) of North Queensland, or possibly the Willyama supergroup (1730–1640 Ma; Willis et al., 1983) of southern Australia. Older grains (late Archean and Paleoproterozoic) are found in sedimentary basins of the Mount Isa inlier (Griffin et al., 2006) and in early Mesozoic sediments of the Norfolk Ridge (Adams et al., 2009) and cannot be associated with a specific source. Hafnium isotopes are mostly within the range of εHf values for the Georgetown inlier (−7 to +6, Murgulov et al., 2007) and Mount Isa inlier (−4 to +6, Griffin et al., 2006; −11 to +1, Bierlein et al., 2011).

The rounded morphology of the late Precambrian and Cambrian zircons (500–700 Ma) has also been reported for zircon populations of this age from Mesozoic sedimentary rocks of eastern Australia (Sircombe, 1999; Tucker et al., 2013) and New Caledonia (Adams et al., 2009). We concur with Adams et al. (2009) who proposed that these morphological features result from multiple recycling events involving secondary basins on the eastern margin of Gondwana, which subsequently were sources for sedimentary rocks of New Caledonia. The likely original source of the 500–700 Ma zircon population are terranes such as the Neoproterozoic Antarctic orogen (Sircombe, 1999, Fergusson et al., 2007), or the metamorphosed sedimentary rocks of the Anakie inlier, Charters Towers Province and Mt. Windsor volcanics (Fergusson et al., 2007). This detrital signature is common from Gondwana provinces (Veevers, 2004) and locally would be associated with the main magmatic phase of the Ross-Delamerian orogeny (540–480 Ma) could explain the latest and most abundant part of this signature while the older portion of the detrital signature from 550 to 700 Ma could be associated with the Thomson orogeny and represent an early build-up stage of the Tasmanides of eastern Australia (Henderson, 1986). The high production rate of magma in the early Cambrian (~530 Ma) has been possibly related to the presence of a juvenile arc in the Pacific outboard of the Ross-Delamerian orogeny (Fergusson et al., 2007). However, such an oceanic magmatic system is likely to produce zircons with relatively radiogenic Hf isotope compositions as it would tap a more depleted mantle and therefore is inconsistent with Hf values (+3 to −10) obtained in the New Caledonian detrital zircons of this age (Fig. 8). Rather, the low values obtained for New Caledonia zircons would indicate contributions from an unradiogenic crust or the enriched lithospheric mantle associated with the eastern margin of Gondwana.

Zircons with ages corresponding to magmatism of the Lachlan Fold Belt (545–365 Ma; Foster and Gray, 2000) are poorly represented in New Caledonia (Fig. 12). This feature has also been recognised in sedimentary deposit on the eastern Australian coast such as Hummock Hill Island (Sircombe, 1999). A similar absence of middle Paleozoic zircons in the detrital record show that the Hodgkinson Province (450–320 Ma), Kennedy Province (330–270 Ma) and older parts of the New England Orogen (NEO) have not contributed significant volumes of materials to form the sedimentary rocks now accreted in the northern part of the Norfolk Ridge. Most basement rocks in New Caledonia also do not carry any significant zircon populations from this period, and can be explained by the presence of a sediment trap inshore of New Caledonia (Adams et al., 2009). Metasedimentary protoliths in New Caledonia lacking middle Paleozoic grains are likely a result of Norfolk Ridge basement erosion, which itself may have lacked rocks of this age. Other studies on Diahot metasediments have provided detrital signatures with poor representation of pre-Cretaceous zircons (Cluzel et al., 2011), indicating that secondary sedimentary basins and Norfolk Ridge basement terranes are not the main source of sediment for the protoliths of the HP metamorphic belt. Instead, alternative intra-oceanic sources, such as a volcanic arc, need to be considered.

A significant zircon population aged 290 to 240 Ma in Diahot metasediments (Fig. 12) is characteristic of the main phase of the Hunter-Bowen Orogeny in the NEO (Korsch et al., 2009) and more specifically the Gympie Terrane. In New Caledonia, primary sources of this age remain rare, with only igneous zircons in plagiogranite from the Koh Terrane returning similar ages (295 and 290 Ma) (Aitchison et al., 1998). Petrographic and geochemical relationships have provided evidence of a genetic link between Gympie, Brook Street and Teremba Terranes (Spandler et al., 2005b) and Permo-Triassic zircons in metasediments could originate from these rocks although zircon patterns observed in Teremba Terrane are not identical to the metasediments. The Queensland Plateau and the northern part of Lord Howe Rise can also play a potential role for this material. Ages obtained from the Queensland Plateau are between 285 and 240 Ma (Mortimer et al., 2008) and metamorphosed granite in the Dampier Ridge provided an age of 270–250 Ma (McDougall et al., 1994), more adequately covering the range of zircons found in Diahot metasediments. In addition, continental fragments resting below the Vanuatu arc are also thought to originate from NEO sources (Buys et al., 2014) providing evidence that late Paleozoic to early Mesozoic continental crust is scattered as basements to ridges and arcs in the south-west Pacific.

The euhedral and subhedral igneous zircons in Diahot metasediments suggest that magmatic activity occurred since the early Mesozoic on the north-eastern margin of Australia (Fig. 9). The zircon record from the late Triassic and Jurassic indicates that an unknown magmatic event is present in the south-west Pacific and could be related to a subduction system that ended around ~150 Ma, as recorded in the Boghen terrane (Cluzel et al., 2010). Zircons extracted from granitic pebbles in sandstone collected from the Lord Howe Rise returned ages between 230 and 180 Ma suggesting that some part of the igneous activity might be located on the Lord Howe Rise and Fairway Ridge (Mortimer et al., 2015).

In the mid Cretaceous, volcanic input becomes important in New Caledonia (Fig. 12b), starting at 135 Ma (from high-pressure metapelite samples, but as also recorded in the Boghen, Central, and formation à Charbons terranes; Aitchison et al., 1998; Adams et al., 2009; Cluzel et al., 2010, 2011). The abundances of these Lower to Middle Cretaceous zircons and their euhedral morphology suggest volcanic activity was occurring relatively near to the Norfolk Ridge. Middle Cretaceous calc-alkaline igneous rocks are found in the Whitsundays Volcanic Province (WVP), New Zealand, Lord Howe Rise, Solomon Island and the Noumea Basin (Bryan et al., 1997; Tulloch et al., 2009; Nicholson et al., 2011; Higgins et al., 2011, Tapster et al., 2014). The main magmatic activity of the WVP of Central Queensland coast likely occurred between 120 and 105 Ma (Bryan et al., 1997) but detrital studies in the Eromanga Basin (central eastern Australia) suggest a more extensive period (150 to 92 Ma) of arc-related volcanic activity in the region (Tucker et al., 2016) compatible with our detrital record (Fig. 12b). However, the absence of Carboniferous NEO material that should have been transported along with the WVP material (Adams et al., 2009; Cluzel et al., 2010) in Diahot metasediment contrast with other sedimentary basins (Tucker et al., 2013, 2016). It suggests that the WVP limited the amount of sediment from inland Australia in the late Mesozoic. Alternatively, it has been suggested that the WVP is a larger unit extending from Papua New Guinea to Antarctica (Norvick et al., 2008) with signs of Mesozoic magmatic activity recorded in New Zealand and southern Lord Howe Rise (McDougall and van der Lingen, 1974; Tulloch et al., 2009; Mortimer et al., 2015) but also as felsic volcanic rocks in the northern Lord Howe Rise (97 Ma, Higgins et al., 2011), Solomon Islands (96 Ma, Tapster et al., 2014) and in lava flows on the Norfolk Ridge itself (103 Ma, Nicholson et al., 2011). Such sources, further from the NEO, could explain the presence of zircons not associated with late Paleozoic grains.

5.3. Evolution of the Loyalty Basin during the Cretaceous and Cenozoic

In the late Mesozoic, the west-dipping subduction zone lying east of Gondwana migrated outboard of Australia to establish a series of marginal basins and ridges. Although some of these basins have now disappeared due to subduction (Crawford et al., 2003), most of these features now define the crustal structure of south-west Pacific region. During the late Mesozoic, sedimentary basin development east of the Norfolk Ridge was associated with the formation of a back-arc system that will become the East New Caledonia Basin (ENCB; Eissen et al., 1998; Figs. 13, 14). Remnants of this large basin are found in the South Loyalty Basin and the fore-arc of the Tonga subduction zone (Falloon et al., 2014) where zircons of 102.4 ± 4.5 Ma have been reported (Meffre et al., 2012). On the Norfolk Ridge, overthrust basalts such as the Poya Terrane, the high-pressure metamorphic units and the New Caledonian ophiolite, are also segments of the ENCB (Eissen et al., 1998). Although the Poya Terrane is mostly Late Cretaceous in age, the thrust-sheet has preserved a series of magmatic events that can be tentatively correlated with the zircon and geochemical record (Spandler et al., 2004, 2005a). In the main ophiolite, crustal gabbros have been dated at 131 ± 16 Ma (Prinzhofer, 1987) when the peridotite massif was part of an oceanic lithosphere (Titus et al., 2011). Subsequent magmatic activity such as amphibole-bearing mafic rocks, are dated between 100 and 77 Ma (Prinzhofer, 1981; Paris, 1981, Soret et al., 2016) and related to subduction activity (Pirard et al., 2013; Soret et al., 2016). The highly radiogenic εHf values (+7 to +11) of the Cretaceous zircons from the metamorphic rocks would indicate that the source of subduction-related magmatism involved recycling of very little old crustal material. This situation is most easily met if the geodynamic system was characterised by west-dipping subduction of the Phoenix Plate, as this plate is unlikely to carry any significant component of continental detritus that could be recycled through the subduction zone (Fig. 13).

We suggest that this west-dipping subduction system was in place since the Jurassic, with increasingly active subduction-related magmatism in the Cretaceous, culminating at ca. 110 Ma based on zircon abundances (Fig. 12b). This progressive evolution coincides with the proposed close proximity of the Phoenix-Pacific Ridge and ultimately, the fragmentation of the oceanic plate around 115 Ma (Seton et al., 2012) that could have modified arc magmatic activity and distribution. The decreasing activity after this period has been related to the attempted subduction of the Hikurangi Plateau between 105 and 100 Ma (Davy et al., 2008) or 86–80 Ma (Worthington et al., 2006). Docking of the Hikurangi Plateau is proposed to have led to cessation of seafloor spreading in the area (i.e. Osbourn trough) (Seton et al., 2012), which would have limited the rate of subduction and associated magmatism. After a short hiatus recorded in the zircon record between 95 and 89 Ma, renewed subduction produced magmatism directly on the Norfolk Ridge, which is now represented by volcanic rocks in the Noumea Basin (89 to 71 Ma; Tissot and Noesmoen, 1958: Nicholson et al., 2011; Cluzel et al., 2012), and in the Diahot Blueschists (metarhyolite sample P11; 83 ± 5 Ma; Fig. 7a).

There is a clear geochemical correlation between Poya basalts and the mafic protolith of the PEM (Spandler et al., 2004; Cluzel et al., 2001) suggesting that at ca. 88 Ma, Poya and Pouebo were consanguineous parts of the ENCB (Eissen et al., 1998). The opening of this back-arc basin during the Cretaceous would lead to a migration of arc magmatism to the east of the Norfolk Ridge (Schellart et al., 2006), and consequently, a reduced input of volcaniclastic material (and hence, Cretaceous zircons) into the sedimentary depocentre on the edge of the Norfolk Ridge, which later formed the Koumac Unit and lowest grade sections of the Diahot Blueschists. The easternmost (high grade) Diahot Blueschists (PP12, RT7-9b) and metasediments of the PEM originally formed in deeper marine and more distal environments, which collected a high abundance of ca. 85 Ma igneous–derived zircons (Fig. 4d, e), but very little old detrital zircon. Hafnium isotope signatures of volcanic zircons (εHf +6 to +9) indicate that the source(s) of the subduction system between 135 and 85 Ma remained relatively constant, and likely was associated with ongoing opening of the ENCB

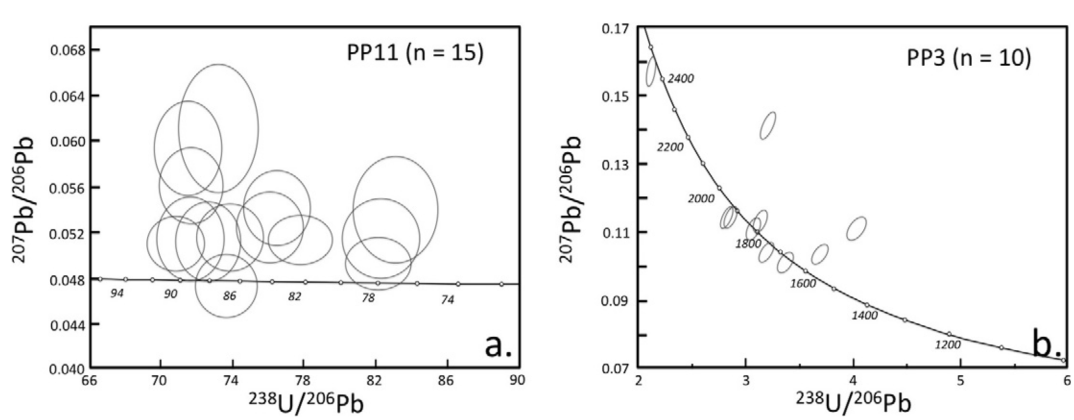

Fig. 7. Tera-Wasserburg diagram of felsic eclogite in sample PP11 (meta-rhyolite) and PP3 (jadeitite). PP11 meta-igneous sample shows a considerable natural spread of zircon ages.

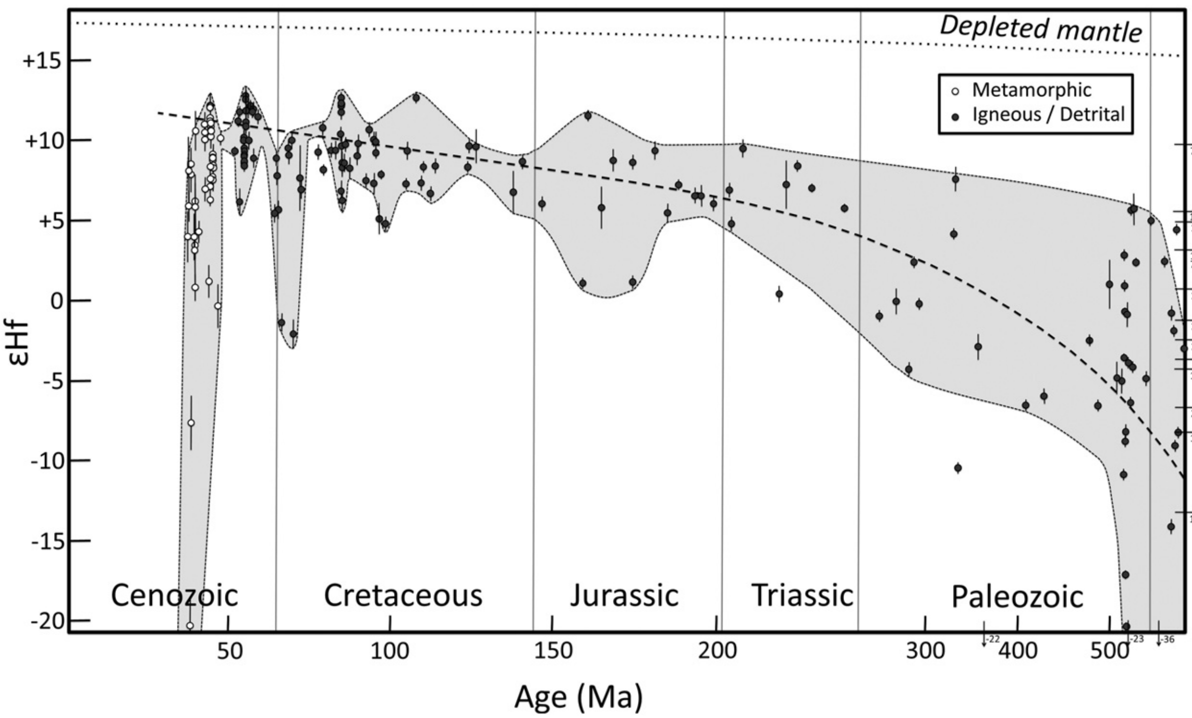

Fig. 8. Hafnium isotopic signature of zircons with their respective ages (circles) and error bars. The gray zone represents the extent of εHf variation during the Phanerozoic for detrital samples, metavolcanic eclogites and metamorphic rims. The dashed line represents the main Phanerozoic trend for detrital zircons, similar to external orogenic systems of Collins et al. (2011). The depleted mantle evolution is provided as a dotted line.

(Fig. 13). This interpretation implies that the protolithic variation in the metamorphic units is the product of deposition in varying environments (proximal versus distal) environments in the ENCB.

The interpretation of the period between 80 and 55 Ma remains unclear in the zircon record. The age of metavolcanic eclogite (sample 3105) and detrital zircon grains in sample PP12 show that there was some igneous activity in the region at around 67 and 78 Ma (Figs. 4e, 5b). Contemporaneous magmatic activity in the region has been recorded from dredged volcanic rocks from the Lord Howe Rise (74 Ma, Higgins et al., 2011) and volcanic arc activity from the Solomon Islands (71 to 63 Ma, Tejada et al., 1996; Tapster et al., 2014) but no direct relationship can be identified. The drop in εHf from +10 to ca. +6 at the end of the Cretaceous (Fig. 10) is an indication of a change in the tectonic regime. Variations in mantle source or early rifting could explain lower εHf values and would coincide with the opening of the Tasman Sea and the Coral Sea. However, a short-lived subduction flip of an oceanic crust carrying Gondwana-derived turbiditic sediments or the closure of a marginal back-arc basin could also produce the observed isotopic shift, and be responsible for the volcaniclastic protoliths of the PEM.

In the Eocene, a new east-dipping subduction zone is developing inside the ENCB, creating the Loyalty Arc and initiating the shortening of the ENCB into the residual South Loyalty Basin (Crawford et al., 2003). The subduction of back-arc basalts similar to the Poya Terrane produces arc magmas with the highest εHf ($+10.5 \pm 1.7$) recorded in the Norfolk Ridge. There is no direct evidence that the Loyalty Arc was already active in the earliest Eocene (Eissen et al., 1998) but felsic dykes preserved in the ultramafic ophiolite (52–53 Ma, Cluzel et al., 2006, 2016) and metamorphic sole (55 Ma; Soret et al., 2016) show similar ages and are interpreted as supra-subduction melts and fluids interacting in the

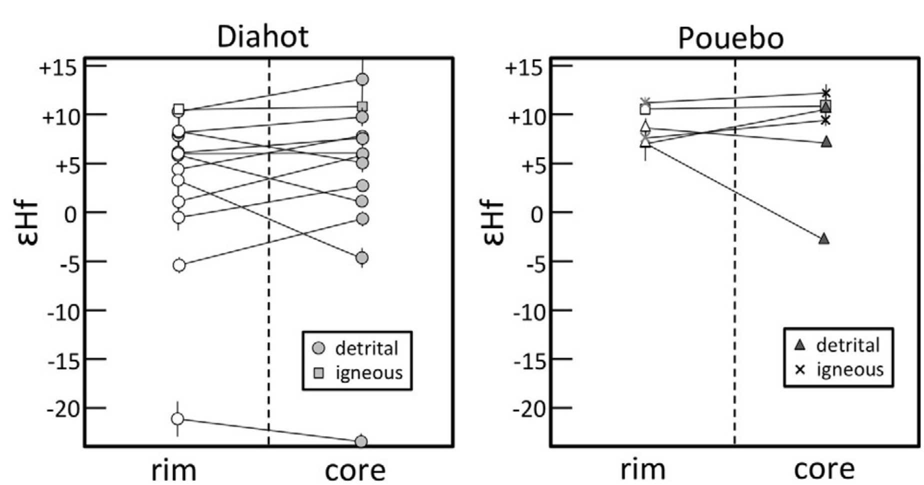

Fig. 9. Hafnium isotopes relationships between rims and cores in single zircons for various samples from the Diahot Blueschists and Pouebo Eclogite Mélange. Zircon rims from the eclogitic samples tend to have homogenous εHf values, whereas zircon rims from the blueschist samples have a wide variation of εHf values that, to some extent, corresponds to the εHf of the zircon core.

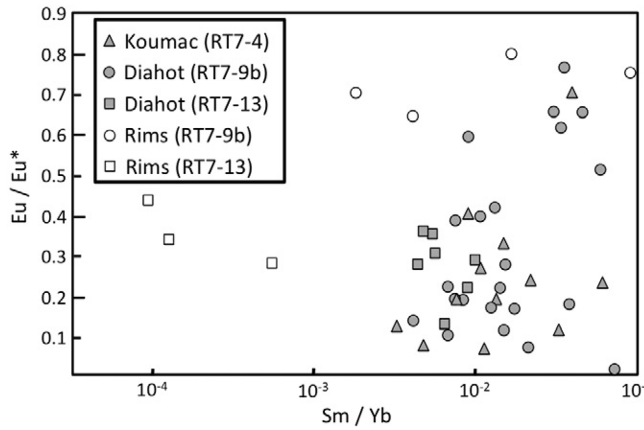

Fig. 10. Sm/Yb versus Eu/Eu* of zircons, where Eu* is calculated as (Sm + Gd)/2. Filled symbols are zircon cores and open symbols are rims. The rim zones tend to have lower Sm/Yb and less pronounced Eu anomalies than the core zones.

fore-arc lithospheric mantle (Pirard et al., 2013). The volcanism created in this subduction zone is the direct source for Eocene protoliths of the PEM.

As the Eocene convergent zone becomes well established, sections of the subducting ENCB oceanic crust adjacent to the Norfolk Ridge reaches eclogite-facies metamorphism at 44 Ma, as recorded in the metamorphic rims of zircons grains in eclogitic metasediments of the PEM (Spandler et al., 2005a). However, the range of metamorphic ages from 44 to 37 Ma indicates a protracted, and/or episodic, high-pressure history and a complex multistage exhumation. Some eclogites evidenced an exhumation rate higher than 10 mm/yr between 2.4 GPa and 0.8 GPa, while most of the exhumation of the belt from 0.8 GPa occurred at a slower rate of ~5 mm/yr based on dating of blueschist zircon rims, mica and apatite (Baldwin et al., 2007). Retrograde metamorphism of the belt was more widespread and extensive during this latter exhumation episode (Rawling and Lister, 2002; Vitale Brovarone and Agard, 2013), possibly due to the protracted time period and greater permeability at shallower levels (Manning and Ingebritsen, 1999), providing enhanced influx of retrogressive hydrothermal/metamorphic fluids.

6. Conclusions

The zircon record of the high-pressure metamorphic sequence of northern New Caledonia informs us on the local geological history and process of formation of these rocks, their origin and the broader geodynamic history of the region.

- Non-mafic metamorphic rocks preserve a zircon record with a maximum depositional age from the Late Cretaceous to the early Cenozoic. Lithologies show increasingly distal features from the Norfolk

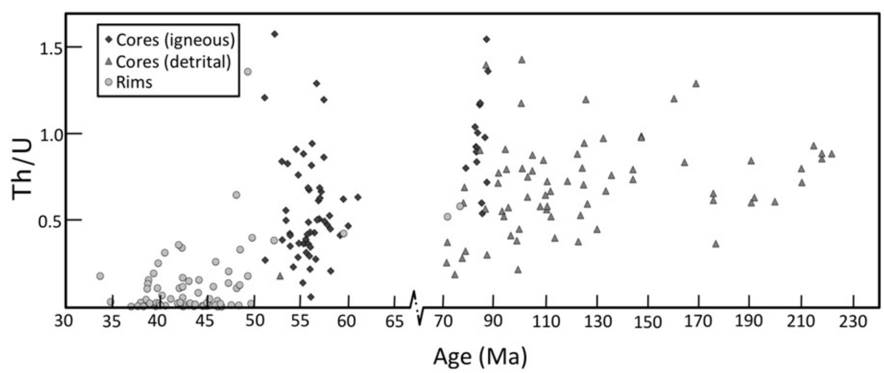

Fig. 11. Th/U versus age of zircon domains. The Mesozoic and Cenozoic zircons show a wide range of Th/U values (0.2 to >2) for detrital and igneous cores. Metamorphic cores (37 to 45 Ma) show low to very low Th/U ratio (<0.1). Intermediate Th/U values (>0.2) between 37 and 53 Ma may be due to mixed sampling of core and rim regions during laser ablation analysis.

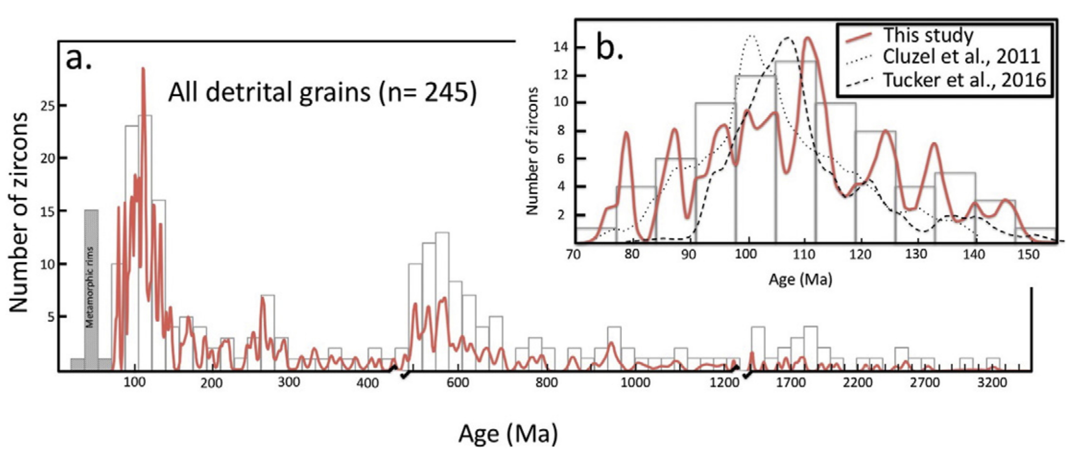

Fig. 12. a. Histogram distribution and probability density plot of all zircons collected in samples of the Koumac Unit, Diahot Blueschists and Pouebo Eclogite Mélange. Metamorphic rims are displayed in the dashed columns (<60 Ma) and have not been included in the probability density curve. b. Inset shows the detrital zircon distribution and probability density plot in the Cretaceous, indicative of the magmatic activity in the Whitsundays volcanic province. A comparison with detrital zircons in New Caledonia (Cluzel et al., 2011) and in the Eromanga Basin (Tucker et al., 2016) is displayed as discontinuous lines. Ages are $^{238}U/^{206}Pb$ data.

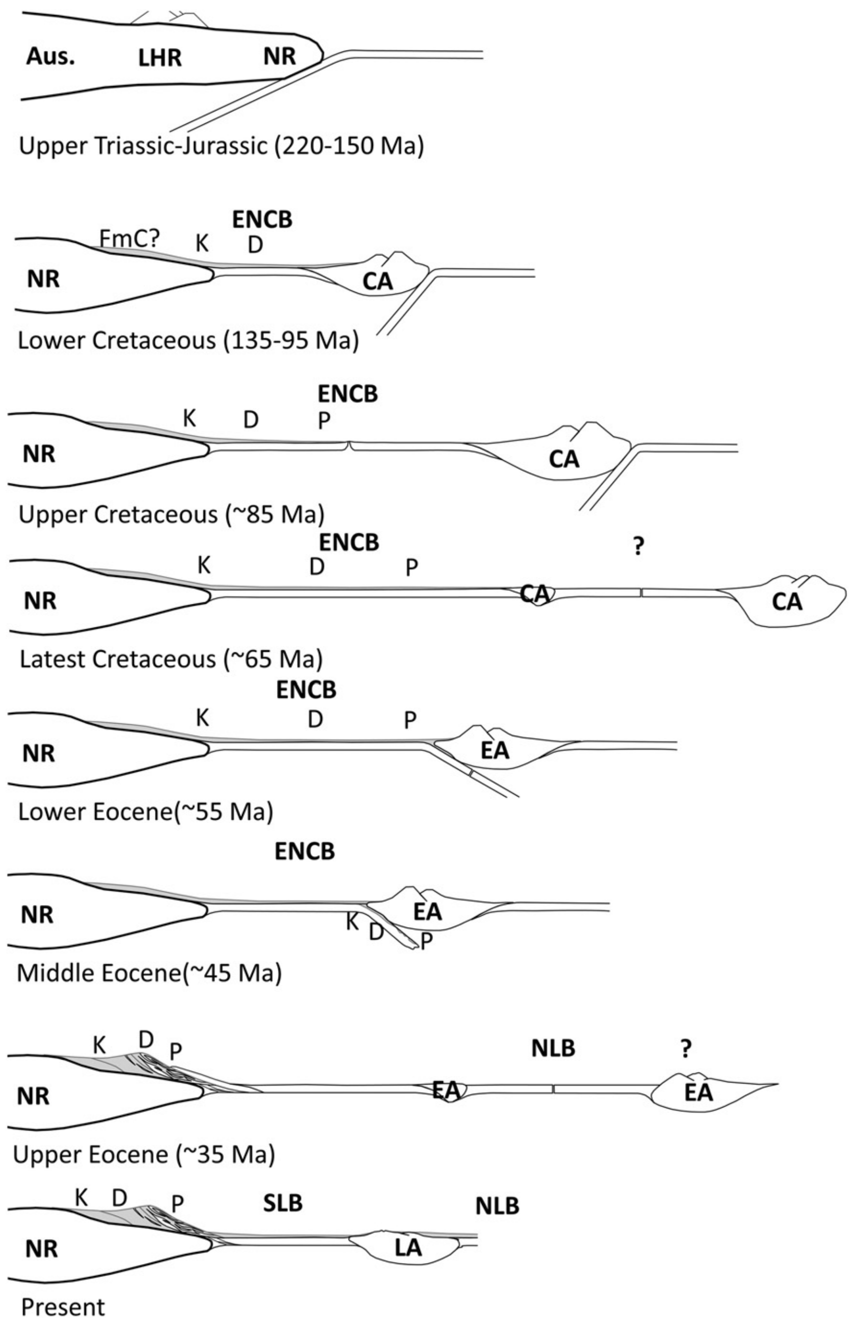

Fig. 13. Development of the Norfolk Ridge (NR) and surrounding basins during the Mesozoic and early Cenozoic showing a long-lasting west-dipping subduction zone in the Mesozoic, producing continental arc magmatism in the Lord Howe Rise (LHR) with the possible existence of short-lived basins (not represented) during the Triassic and Jurassic. Initiation of roll-back after 135 Ma produces an hypothetic arc (Cretaceous arc (CA)) (possibly preserved in the Vitiaz Arc; Falloon et al., 2014) and the development of the East New Caledonia Basin (ENCB) that collect Norfolk Ridge sediments to form Formation à Charbons (FmC), Koumac (K) Unit and Diahot (D) Blueschists. In the Upper Cretaceous, the ENCB is spreading and PEM (P) sediments also start to accumulate in deeper part of the basin. A subduction flip occurs in the Eocene, possibly initiating on the margin of the previous arc and forming a new arc that will become the Loyalty Arc (LA). The ENCB, carrying protoliths of the Pouebo, Diahot and Koumac Units, is progressively subducted in the Loyalty trench during the Eocene while forming a fore-arc crust that will become the South Loyalty Basin (SLB) and New Caledonia ophiolite (Pirard et al., 2013). The current situation has Pouebo, Diahot and Koumac thrusted onto the Norfolk Ridge with a remnant of the ENCB forming the South Loyalty Basin, separated from the North Loyalty Basin (NLB) by the eroded Loyalty Arc.

Ridge from the west (Diahot) to the east (Pouebo). While Diahot Blueschists shows detrital zircon signature characteristics of proximal sedimentary basin to eastern Australia and the Norfolk Ridge basement, the PEM mostly contains metavolcanic rocks produced in an environment distal from continental sources, where Late Cretaceous and Eocene magmatic arc(s) are the main sediment source.

- Detrital zircons populations in metasediments of all metamorphic grades have affinities to continental materials from Proterozoic to Permian terranes of Eastern Australia, that were likely recycled in Mesozoic sedimentary basins adjacent to the Norfolk Ridge. The abundance of volcanic-derived Mesozoic zircons is interpreted to be linked to the development of magmatic arcs on the margin of Gondwana.
- The Late Cretaceous zircons record events associated with the fragmentation of the nearby Phoenix Plate and a change in the geodynamics of the eastern Gondwana margin. A west-dipping subduction system was present in the vicinity of the Norfolk Ridge and formed the East New Caledonia Basin until ca. 85 Ma as recorded in metavolcaniclastic eclogite samples. In the early Eocene, a new east-dipping subduction appeared in the basin and formed the Loyalty

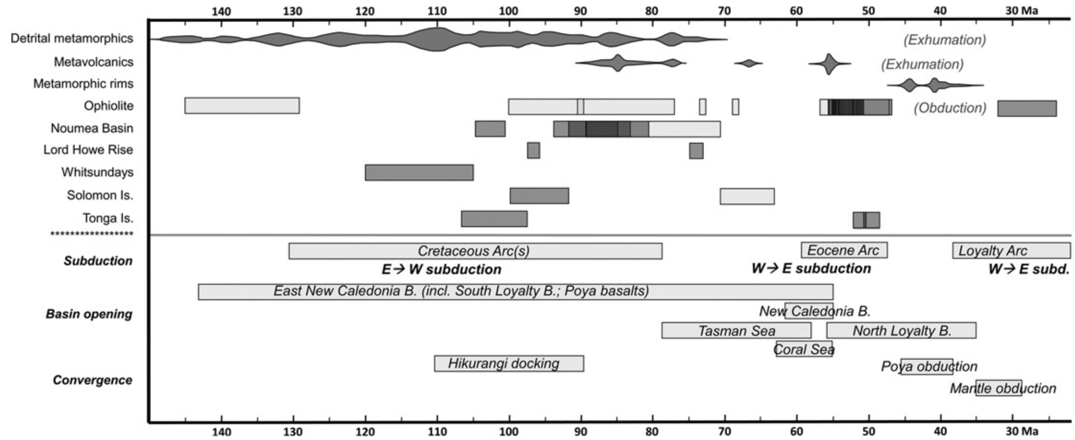

Fig. 14. Schematic representation of geodynamic events and timing of magmatic events in the south west Pacific. Detrital metamorphics, metavolcanics and metamorphic rims lines show the relative abundance of zircons found at a specific age. Overlapping data (with darker gray) show different dating techniques and higher abundance of magmatic activity for the displayed time period. Data are from Auzende et al., 2000; Bryan et al., 1997; Carroué, 1972; Cluzel et al., 2001, 2005, 2006, 2011; Collot et al., 1987; Crawford et al., 2003; Eissen et al., 1998; Espirat, 1963; Falloon et al., 2014; Launay et al., 1982; Meffre et al., 2012; Mortimer et al., 2008; Nicholson et al., 2011 Paris, 1981; Prinzhofer, 1981; Schellart et al., 2006; Sdrolias et al., 2004; Tapster et al., 2014; and Whattam et al., 2008.

volcanic arc. The progressive change throughout the Mesozoic and Cenozoic in hafnium isotopes shows increasingly radiogenic zircons interpreted as a waning of continental influence in subducted materials.

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