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The origin and geochemical evolution of the Woodlark Rift of Papua New Guinea

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ABSTRACT

Geochemical, isotopic, and geochronologic data for exhumed rocks in the Woodlark Rift of Papua New Guinea (PNG) allow a tectonic link to be established with the Late Cretaceous Whitsunday Volcanic Province (WVP) of northeastern Australia. Most of the metamorphic rocks in the Woodlark Rift have Nd isotopic compositions ($\varepsilon_{Nd} = +1.7$ to $+6.2$) similar to the Nd isotopic compositions of rocks in the WVP ($\varepsilon_{Nd} = +1.3$ to $+6.6$; Ewart et al., 1992), and contain inherited zircons with 90 to 100 Ma U–Pb ages that overlap the timing of magmatism in the WVP. None of the metamorphic rocks in the Woodlark Rift have the highly evolved Hf and Nd isotopic compositions expected of ancient continental crust. Magmas were erupted in the WVP during the middle Cretaceous as eastern Gondwana was rifted apart. The protoliths of felsic and intermediate metamorphic rocks in the Woodlark Rift are interpreted to be related to the magmatic products produced during this Cretaceous rifting event. Some mafic metamorphic rocks exposed in the western Woodlark Rift (eclogites and amphibolites) are not related to the WVP and instead could have originated as basaltic lavas crystallized from mantle melts at (U)HP depths in the Late Cenozoic, or as fragments of Mesozoic aged oceanic lithosphere.

Isotopic and elemental comparisons between basement gneisses and Quaternary felsic volcanic rocks demonstrate that felsic lavas in the D'Entrecasteaux Islands did not form solely from partial melting of metamorphic rocks during exhumation. Instead, the isotopic compositions and geochemistry of Quaternary felsic volcanic rocks indicate a significant contribution from the partial melting of the mantle in this region. When combined with geophysical data for the western Woodlark Rift, this suggests that future seafloor spreading will commence south of Fergusson Island, and west of the present-day active seafloor spreading rift tip.

1. Introduction

Active plate boundary zones, such as the Woodlark Rift of southeastern Papua New Guinea, provide natural laboratories where lithospheric processes can be studied. Here, a late Mesozoic subduction complex (Zirakparvar et al., 2011) with a history of arc-continent collision and (U)HP metamorphism (Baldwin et al., 2012) is rifting apart as seafloor spreading in the Woodlark Rift has propagated westward towards the Papuan Peninsula for the last 6 Ma (Taylor et al., 1995). One major question about the evolution of the Woodlark Rift is the tectonic origin and history of the (U)HP to subgreenchist-facies metamorphic rocks exposed along the southern margin of the Woodlark Rift. Understanding the origin of these rocks is important for reconstructing the history of the Woodlark Rift, which in turn has implications not only for understanding plate boundary processes, but also provides constraints on the Late Mesozoic—Cenozoic evolution of the Australian (AUS)–Pacific (PAC) plate boundary zone.

Following the Late Cretaceous breakup of Gondwana, fragments of the former eastern Australian margin, now found in Papua New Guinea, were tectonically overprinted and metamorphosed during late Mesozoic and Cenozoic arc continent collisions (Hall, 2002; Schellart et al., 2006; Davies, 2012). Lithosphere that was once part of the active eastern Australian margin also comprises many of the submarine plateaus and rises in the southwestern Pacific (e.g., the Lord Howe and Chatham rises, Queensland, Challenger, and Campbell plateaus, and Norfolk Ridge; Lister and Etheridge, 1989; Veevers et al., 1991; Gaina et al., 1998a,b; Veevers, 2000, 2004; Cluzel et al., 1999, 2001; Betts et al., 2002; Schellart et al., 2006; Tulloch et al., 2009; Cluzel et al., 2010a,b). We test the hypothesis that metamorphic rocks exposed along the southern margin of the Woodlark Rift were derived from the eastern Australian margin (Davies and Warren, 1988). New geochronological and isotopic data from metamorphic rocks in the Woodlark Rift are presented and compared to existing data sets from geologic provinces of the eastern Australian continental margin, as well as rifted fragments of the former Australian margin now found isolated in the Pacific (Fig. 1).

Results allow us to link metamorphic rocks in the Woodlark Rift with an early Cretaceous volcano-sedimentary succession (the

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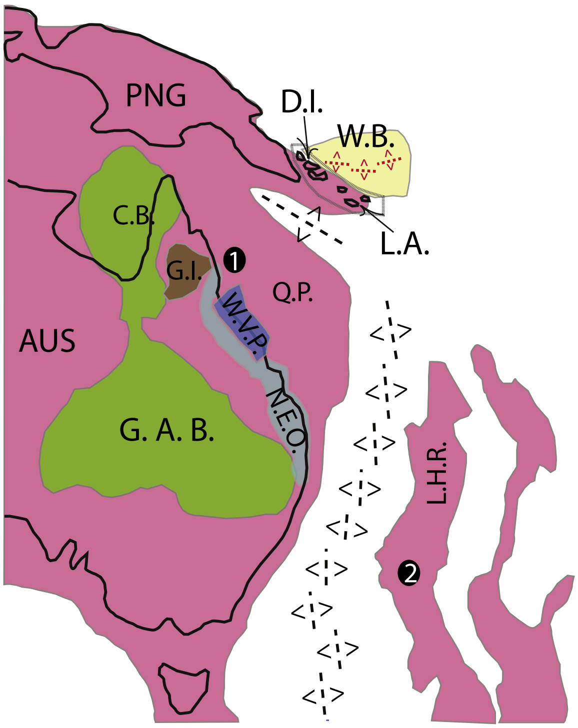

Fig. 1. Schematic representation of present-day configuration of geologic provinces along the eastern Australian continental margin used for isotopic, geochemical, and geochronologic comparisons drawn in this study: Carpentaria (C.B.) and Great Artesian (G.A.B.) basins, Georgetown Inlier (G.I.), New England Orogen (N.E.O.), Whitsunday Volcanic Province (W.V.P.), Queensland Plateau (Q.P.), Lord Howe Rise (L.H.R.), Woodlark Basin (W.B.), and rocks in the D'Entrecasteaux Islands (D.I.) and Louisiade Archipelago (L.A.). Study area, which is along the southern rifted margin of the Woodlark Basin (termed Woodlark Rift in text), is outlined in gray box. Numbered circles indicate the location of drill core samples investigated by Mortimer et al. (2008): 1 = xenoliths in ODP824-825; 2 = xenoliths in NORFANZ 85. The present day ε_{Nd} values of rocks in these provinces, including sources of data, are listed below. Georgetown Inlier (Black and McCulloch, 1990): *Proterozoic granitoids* = ε_{Nd} −12 to −25; *Silurian–Devonian granitoids* = ε_{Nd} −11 to −20; *Permian granitoids* = ε_{Nd} −6 to −15. Lord How Rise (Mortimer et al., 2008): *schist and greywacke* = ε_{Nd} −11 to −7. New England Orogen (Hensel et al., 1985): *granites and sediments* = ε_{Nd} −20 to −10. Queensland Plateau (Mortimer et al., 2008): *schist and sandstone* = ε_{Nd} −10 to −8. Whitsunday Volcanic Province (Ewart et al., 1992): *Cretaceous bimodal volcanic suite* = ε_{Nd} +1.3 to +6.6. Metamorphic rocks along southern rifted margin of Woodlark Basin (this study): *D'Entrecasteaux Islands gneisses* = ε_{Nd} +1.7 to +4.3; *D'Entrecasteaux Islands eclogites* = ε_{Nd} +2.8 to +6.2; *Louisiade Archipelago schists* = ε_{Nd} +1.8 to +2.4, one sample ε_{Nd} −3.4.

Whitsunday Volcanic Province, or WVP) found along the present-day eastern continental margin of Australia (Bryan et al., 1997). This correlation extends the known paleogeographic extent of the northern end of a >2500 km long rift system that occupied the eastern margin of Gondwana during the Cretaceous (Bryan et al., 1997) and identifies another dispersed fragment of former eastern Australian crust in the southwestern Pacific.

Cretaceous rifting in eastern Australia during the breakup of Gondwana occurred within the site of a long-lived active margin, amalgamated from exotic terranes, arc magmas, and fragments of continental lithosphere (Bryan et al., 1997). The bimodal magmatic products of Cretaceous rifting in eastern Gondwana, which we demonstrate are the protoliths of metamorphic rocks now exposed in the Woodlark Rift, do not appear to have incorporated the highly evolved geochemical and isotopic characteristics of Precambrian aged Australian continental lithosphere (Ewart et al., 1992). This important relationship and the results from this study indicate that fragments of crust that have rifted away from Australia since the Late Cretaceous and are now found dispersed throughout the southwest Pacific need not have a highly evolved continental lithospheric geochemical signature to demonstrate that they are tectonically related to the former eastern Australian margin in Gondwana.

The present day tectonic setting of the Woodlark Rift – a subduction complex being rifted apart – provides an active analog to study the lithologic records of passive margin development. In the western Woodlark Rift, where rifting is currently focused, there is a close spatial and temporal relationship between the exhumation of formerly subducted continental lithosphere and the eruption of felsic volcanics (Baldwin et al., 2012). Representative samples of these evolved volcanic rocks from within the rift were analyzed for comparison with the metamorphic rocks in order to assess whether partial melting of formerly subducted continental lithosphere during exhumation has produced the felsic volcanics in the western Woodlark Rift. We will demonstrate below that the felsic volcanic rocks have not inherited the isotopic and trace element signature of the metamorphic basement and instead have juvenile isotopic compositions reflecting a mantle origin.

2. Geology of the Woodlark Rift and samples analyzed

Metamorphic rocks are exposed on islands along the southern rifted margin of the Woodlark Rift and west of the active seafloor spreading rift tip (Fig. 2). Metamorphic grade decreases steadily eastward along the strike of this margin from (U)HP in the D'Entrecasteaux Islands (Davies and Warren, 1988; Hill et al., 1995; Baldwin et al., 2008), to upper amphibolite facies on Misima Island, and finally to sub-greenschist facies in the Louisiade Archipelago (Smith, 1973; Smith and Pieters, 1973; Smith et al., 1973). The predominant bulk composition of metamorphic rocks in the region is felsic to intermediate, but mafic bulk compositions (e.g., eclogite and amphibolite) frequently occur associated with the felsic and intermediate metamorphic rocks.

Prior to this study the pre-Late Cenozoic history of metamorphic rocks in the Woodlark rift was known only from a few studies (Baldwin and Ireland, 1995; Zirakparvar et al., 2011). It had been hypothesized that the felsic and intermediate metamorphic rocks originated as part of the eastern Australian margin in Gondwana, rifted away from Australia during the Early Cretaceous breakup of eastern Gondwana and Late Mesozoic opening of the Coral Sea Basin (Davies and Warren, 1988). Marine sediments from the Trobriand Basin (Fig. 2) contain 2.78 Ga zircons (in igneous and metamorphic clasts; Baldwin and Ireland, 1995) and the data presented here allow us to explore this possible connection with Australia. Metamorphism of these rocks could have occurred during the Early Cenozoic obduction of the Papuan Ultramafic Belt (PUB), now exposed on the Papuan peninsula (Milsom, 1973; Davies, 1980; Jacques and Chappel, 1980; Davies and Warren, 1988; Lus et al., 2004), and during subsequent collision and subduction events. This possibility is supported by the fact that an episode of ~68 Ma garnet growth (Zirakparvar et al., 2011) is preserved in a metamorphic core complex (MCC) bounding shear zone in the western Woodlark Rift (Little et al., 2012). A more detailed description of the geology of the rocks in the different parts of the rift is provided below.

2.1. (U)HP and amphibolite facies rocks in the D'Entrecasteaux and Misima Islands

The western apex of the V-shaped Woodlark Rift is a zone of active extension ahead of seafloor spreading in the Woodlark Rift (Abers, 1991; Taylor et al., 1995, 1999; Wallace et al., 2004; Little et al., 2007). The D'Entrecasteaux Islands (Fig. 1), in the western Woodlark Rift, contain MCCs with complexly deformed (U)HP to amphibolite facies rocks comprising their lower plates (Davies and Warren, 1988; Little et al., 2007; Baldwin et al., 2008). The upper-plate rocks of the D'Entrecasteaux Islands MCCs, which consist of mafic and ultramafic rocks, are geochemically and petrographically similar to the

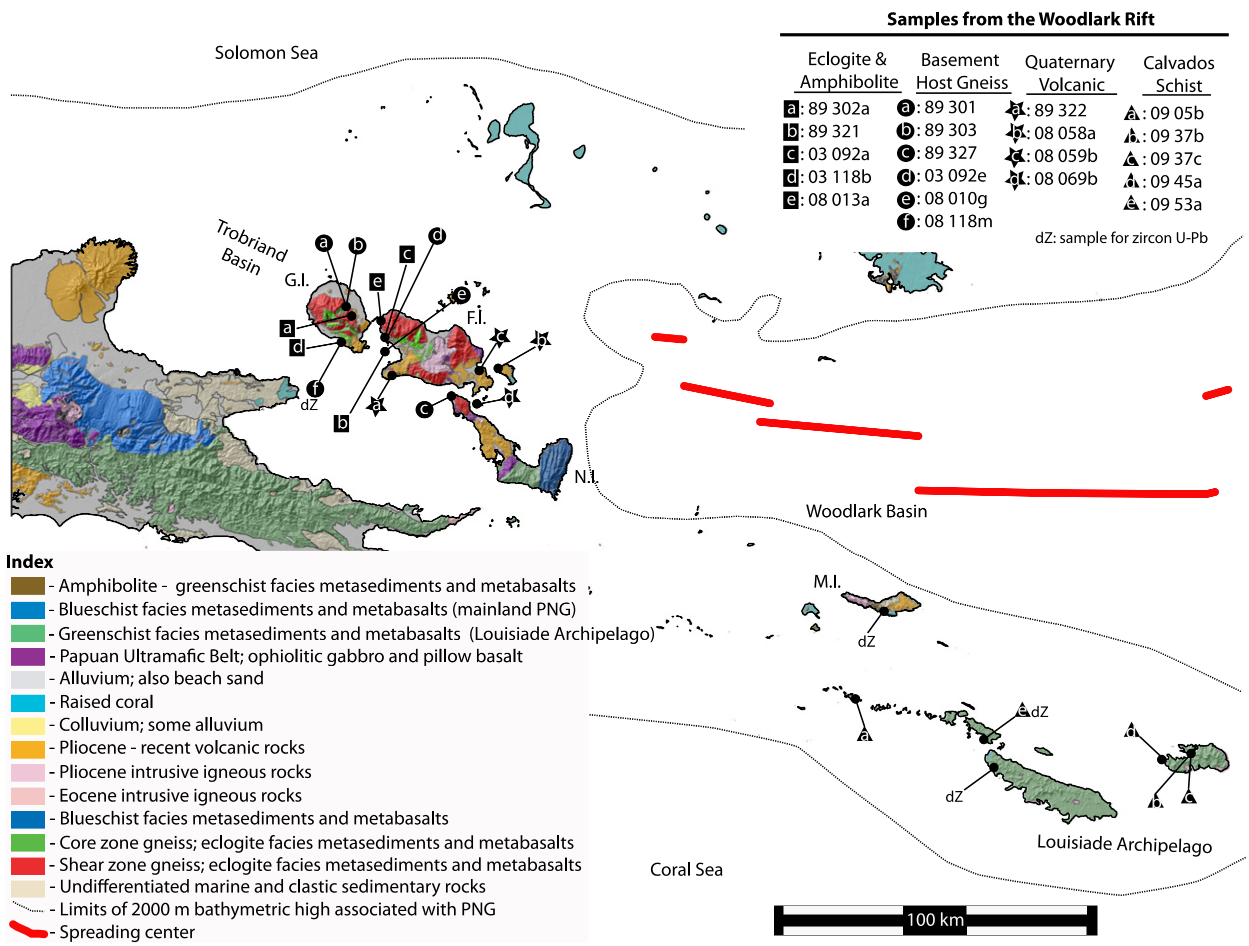

Fig. 2. Geologic map of southeastern Papua New Guinea with sample locations. Symbols used to denote individual samples within different lithological units are used throughout remaining figures. G.I. = Goodenough Island; F.I. = Fergusson Island; N.I. = Normamby Island; M.I. = Misima Island.

basalts and gabbros of the PUB (Davies and Warren, 1988; Little et al., 2007). Lower plate rocks are separated from upper plate rocks by km-scale shear zones and brittle detachment faults (Davies and Warren, 1988; Hill, 1994; Little et al., 2007).

The lower plates consist of mafic eclogite, including coesite eclogite (Baldwin et al., 2008), boudins and dikes encapsulated in felsic to intermediate gneiss (Davies and Warren, 1988). Zircon U–Pb dating (Monteleone et al., 2007) and garnet Lu–Hf dating (Zirakparvar et al., 2011) on coesite eclogite (Baldwin et al., 2008), as well as P–T constraints (Baldwin et al., 2004; Baldwin et al., 2008) show that these rocks were situated at a depth of greater than 90 km as recently as ~8 Ma and possibly even younger (Gordon et al., 2010; Brownlee et al., 2011; Ellis et al., 2011). Also relevant to this study is a ~7 Ma Lu–Hf garnet age determined for a coesite eclogite (sample 89321 in this study) that was interpreted to record the time when a basaltic partial melt of the mantle, associated with rising asthenosphere ahead of rifting in the Woodlark Rift, crystallized at UHP conditions within formerly subducted continental crust (Zirakparvar et al., 2011).

K/Ar, ^{40}Ar/^{39}Ar, and fission track dating techniques applied to the lower plate rocks have documented an extremely rapid (e.g., ≥100 °C/m.y.) cooling and exhumation history (Davies and Warren, 1988; Baldwin and Hill, 1993; Baldwin et al., 1993). Based on dominant top-E shear fabrics in the (U)HP terrane, Little et al. (2012) emphasized the role of westward extrusive flow, decoupled from coeval N–S Woodlark–Australia plate motion in the upper crust of the rift, to explain rapid and near-isothermal ascent from mantle depths, abundant syndeformational partial melting, and symmetrical gneiss dome structures within the Woodlark Rift. Final exposure of the (U)HP terrane resulted from minor erosion and slip on late-stage active normal faults. Thermo-mechanical models emphasized a complex feedback between diapirism and rifting to exhume (U)HP rocks in the Woodlark Rift (Ellis et al., 2011).

The high topography of the D'Entrecasteaux Islands is supported by a seismic Moho that is elevated by 10–15 km and is now located at ~20 km beneath these islands, indicating that sub-continental mantle lithosphere in this region has been replaced by asthenosphere (Abers et al., 2002). The emplacement and crystallization of basalt at UHP conditions within subducted continental lithosphere at ~7 Ma may have occurred in response to this asthenospheric upwelling (Zirakparvar et al., 2011). Seismic velocities and densities of the (U)HP terrane, based on predicted mineral assemblages, suggest a dominantly mafic composition below ~20 km depth in the D'Entrecasteaux Islands (Brownlee et al., 2011). In the D'Entrecasteaux Islands, seismic activity (Abers, 1991), young geomorphology (Miller et al., 2012), and Plio—Pleistocene ^{40}Ar/^{39}Ar mineral cooling ages (Baldwin et al., 1993), all suggest that exhumation of lower-plate rocks occurred during Plio—Pleistocene to Holocene time and may still be active.

Misima Island is located ~150 km southeast of the D'Entrecasteaux Islands, on the southern margin of the Woodlark rift (Fig. 2). The island is roughly bisected by a low angle normal fault (Peters et al., 2004; Peters, 2007). The western half of the island is the footwall of this fault and contains amphibolite-facies felsic to mafic gneisses intruded by granodiorite plutons. The lower plate is juxtaposed against greenschist-facies schists, unmetamorphosed sedimentary and volcanic rocks, and basalts comprising the upper plate.

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$^{40}Ar/^{39}Ar$ apparent ages from the lower plate of Misima Island indicate cooling through amphibole Ar closure between ~10 and 15 Ma (Baldwin et al., 2008). Partial melting of the metamorphic basement in the Misima Island lower plate appears to have occurred contemporaneously with MCC formation (Appleby et al., 1996). Lu–Hf dating of dynamically recrystallized garnets in an amphibolite gneiss from the lower plate of the Misima Island MCC yielded an age of ~12 Ma (Zirakparvar et al., 2011).

Quaternary volcanism in the D'Entrecasteaux Islands is bimodal (Smith and Johnson, 1981; Smith, 1982; Smith and Clarke, 1991; Stolz et al., 1993). Seafloor spreading in the D'Entrecasteaux Islands has produced basaltic and peralkaline rhyolitic volcanism throughout the region. Calc-alkaline rhyolitic volcanics are commonly associated with MCC dome bounding faults (Smith, 1982). The close spatial and temporal relationship between the basalt-peralkaline rhyolite suite and the calc-alkaline rhyolites, as well as the degree of crustal contamination in these lavas, is not well understood.

2.2. Subgreenschist facies rocks in the Louisiade Archipelago

The ~45 islands of the remote Louisiade Archipelago extend over >160 km along the southeastern most margin of the Woodlark Rift. Geologic investigations in the 1970s (Smith, 1973; Smith and Pieters, 1973; and Smith et al., 1973) were conducted by the Australian Bureau of Mineral Resources, Geology, and Geophysics on a reconnaissance basis. The Louisiade Archipelago was also visited in 2009, when samples were collected for this study. The most abundant rocks in the archipelago are the subgreenschist-facies metasedimentary rocks of the Calvados Schist and minor basalt and diorite dikes that intrude the schist. In some locations, notably on Rossel and Sudest Islands, more extensive outcrops of basalt, gabbro, and serpentinite are also present.

The dominant structures in the Louisiade Archipelago are related to progressive deformation and folding resulting in S_1–S_3 foliation development under prehnite–pumpellyite to greenschist-facies conditions (Webb et al., 2009). Deformation was associated with NE–SW compression and SE–NW extension, such that these fabrics may record a history related to convergence with minimal overprinting during rifting. The age and contact relationships of mafic magmatic rocks that intrude the Calvados Schist are currently unknown, so the details of tectonic affinity of magmatic rocks in the Louisiade Archipelago are presently unclear (Webb et al., 2009). Currently, the only published geochronology for rocks of the Louisiade Archipelago is a K/Ar whole rock date of ~11 Ma on a pyroxene andesite from the western part of the island chain (Smith, 1973).

Exhumation of the Calvados Schist may be intricately related to continental rifting prior to the onset of seafloor spreading in the Woodlark Rift (Webb et al., 2008). Protoliths include siltstone, shale, sandstone, pebbly sandstone, and minor conglomerate. However, the Louisiade Archipelago is not currently located near an elevated source region for these sediments. It is possible that the source of the sedimentary protoliths of the Calvados Schist was separated from the sediments during the opening of the Coral Sea in the Eocene (Weissel and Watts, 1979).

2.3. Samples analyzed and rational

The Hf and Nd isotopic and REE compositions of representative examples of exposed metamorphic rock types in the Woodlark Rift (i.e., amphibolite-facies to (U)HP gneisses and eclogites from the D'Entrecasteaux Islands, subgreenschist-facies schists from the Louisiade Archipelago) were determined in order to establish their origin. U–Pb dating of zircons from amphibolite gneisses in the D'Entrecasteaux and Misima islands as well as from samples of the Calvados schist in the Louisiade Archipelago was also performed. In order to ascertain whether partial melting of the metamorphic basement rocks in the D'Entrecasteaux Islands is the source of Quaternary rhyolitic–andesitic volcanism, the isotopic (Hf and Nd) and geochemical (REE) compositions of these volcanic rocks were determined for comparison with the metamorphic basement rocks. Sample descriptions are summarized in Table 1. Sample locations are shown in Fig. 2.

3. Analytical methods

3.1. Major and trace elements

Rock samples were crushed using jaw-crushers at the Washington State University (WSU) GeoAnalytical Facility. The procedures of Johnson et al. (1999) and Knacck et al. (1994) were followed, respectively, for XRF and ICP-MS analyses. Representative aliquots of the crushed rocks (20–30 g) were obtained using a rotating splitter and powdered in agate ball mills. Aliquots of powder (3.5 g) were mixed with 7 g of a lithium tetraborate flux and fused in graphite crucibles at ~1000 °C for XRF analyses. The resulting beads were then reground in tungsten-carbide shatter boxes and fused again at ~1000 °C. For ICP-MS analyses, 2 g powder aliquots were mixed with 2 g of lithium tetraborate flux and fused under the same conditions as for the XRF aliquots. These beads for ICP-MS trace element analysis were then reground in Fe shatter boxes and dissolved using a $HF/HNO_3/HClO_4$ acid mixture. Major and trace element data are presented in full in an electronic supplementary data file as well as in Figs. 3, 5, and 6.

3.2. Hf and Nd isotopes

Whole rock samples were powdered in an agate mortar and dissolved using a 10:1 HF/HNO_3 mixture in steel-jacketed Teflon bombs in an oven at 160 °C for 4–5 days at the WSU Radiogenic Isotope Facility. All samples analyzed for isotopic compositions were spiked with a mixed ^{176}Lu–^{180}Hf and ^{149}Sm–^{150}Nd tracer in order to determine accurate parent/daughter ratios. Lutetium, Hf, Sm, and Nd were separated from the same solutions following methods described in Vervoort and Blichert-Toft (1999) and Vervoort et al. (2004). The isotopic compositions of these elements were analyzed on a ThermoFinnigan Neptune™ multi-collector inductively coupled mass spectrometer (MC-ICP-MS) at WSU according to procedures described in Vervoort et al. (2004).

During the course of this study the following isotopic values were measured for the Ames Nd and JMC 475 Hf standards: $^{142}Nd/^{144}Nd = 1.141713 \pm 40$, $^{143}Nd/^{144}Nd = 0.512120 \pm 16$, $^{145}Nd/^{144}Nd = 0.348418 \pm 14$, $^{148}Nd/^{144}Nd = 0.241557 \pm 20$, $^{150}Nd/^{144}Nd = 0.236341 \pm 26$ (2σ SD, n = 18); $^{176}Hf/^{177}Hf = 0.282152 \pm 20$, $^{178}Hf/^{177}Hf = 1.467243 \pm 60$, $^{180}Hf/^{177}Hf = 1.886840 \pm 24$ (2σ SD, n = 24). Both the Hf and Nd isotope measurements were normalized to the accepted values for these standards (e.g., $^{143}Nd/^{144}Nd = 0.512138$, $^{176}Hf/^{177}Hf = 0.282160$). For the calculation of epsilon Nd and Hf values we used $^{143}Nd/^{144}Nd_{chur\ (0)} = 0.512630$, $^{147}Sm/^{144}Nd_{chur(0)} = 0.1960$, $^{176}Hf/^{177}Hf_{chur(0)} = 0.282785$, and $^{176}Lu/^{177}Hf_{chur(0)} = 0.0336$ (Bouvier et al., 2008). The Hf and Nd isotopic data are presented in full in Table 2 and diagrammatically in Fig. 4.

3.3. U–Pb zircon dating

Zircons for U–Pb geochronology were isolated from rock samples using standard crushing and mineral separation procedures. Grains handpicked under a binocular microscope were mounted in epoxy along with standards, polished to expose their centers, carbon-coated, and cathodoluminescence images were obtained using with an SEM at Syracuse University. U–Pb zircon analyses of polished grain mounts from samples 03118m and 041198 were conducted using the UCLA Cameca IMS 1270 ion microprobe. U–Pb zircon analyses of polished grain mounts from samples 0906b and 09053a were performed by LA-ICP-MS at Washington State

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Table 1
Samples analyzed in this study grouped according to lithostratigraphic units presented in Fig. 2. Additional information (lithology, structural context, types of analyses performed) is provided for each sample. Refer to Fig. 2 for sample locations. Summary of samples from PNG.

Sample	Lat/long	Lithology	Location, previous P-T-D constraints, and other information
D'Entrecasteaux Islands: eclogites and amphibolites			
89302E	S 9.323611 E 150.275	Mafic eclogite	Goodenough Island. Zr in rutile: 718°–8258 °C; U–Pb zircon: 2.94 ± 0.41 Ma (Monteleone et al., 2007).
89321	S 9.488663 E 150.461681	Coesite eclogite	Tumabaguna Island. Zr in rutile: 612°–740 °C; Ti in zircon: 650°–680 °C; U–Pb zircon: 7.9 ± 1.9 Ma; Gt-omph-pheng barom: 18–26 kbar (Monteleone et al., 2007). Lu–Hf garnet age = 7.1 ± 0.9 Ma (Zirakparvar et al., 2011).
03092A	S 9.464070 E 150.455992	Mafic eclogite	Fergusson Island. Zr in rutile: 633°–719 °C; U–Pb zircon: 7.0 ± 1 Ma (Monteleone et al., 2007).
03118B	S 9.481301 E 150.250316	Mafic eclogite	Goodenough Island. Zr in rutile: 677°–817° C; U–Pb zircon: 2.09 ± 0.49 Ma; Jadeite barom: > 14 kbar (Monteleone et al., 2007).
08013A	S 9.383212 E 150.444813	Amphibolite	Fergusson Island.
D'Entrecasteaux Islands: basement gneisses			
89327	S 9.650534 E 150.738250	Foliated granodiorite	Guletabutabu Island. K/Ar potassium Feldspar: 1.91 Ma (Baldwin et al., 1993).
03092E	S 9.464070 E 150.455992	Felsic gneiss	Fergusson Island. Felsic host of sample 03092a.
08010G	S 9.487828 E 150.462938	Felsic gneiss	Tumabaguna Island.
08118M	S 9.481594 E 150.250314	Felsic gneiss	Goodenough Island. Felsic host of sample 03118b (unpub.). U–Pb dating of zircon via SIMS also performed for this sample.
89301	S 9.320120 E 150.27642	Felsic gneiss	Goodneough Island.
89303	S 9.319203 E 150.274610	Felsic gneiss	Goodenough Island.
D'Entrecasteaux Islands: quaternary calc-alkaline volcanic rocks			
89322	S 9.636757 E 150.447834	Andesite	Fergusson Island. K–Ar whole rock age: 0.79 Ma (Baldwin et al., 1993).
08058A	S 9.594528 E 150.953599	Rhyolitic-dacite	Fergusson Island.
08059B	S 9.595549 E 150.896360	Obsidian	Fergusson Island.
08069B	S 9.739680 E 150.863747	Obsidian	Dobu Island.
Louisiade Archipelago: subgreenschist facies metasediments			
09005B	S 11 5.647′ E 152 35.639′	Schist	Strongly deformed fine grained schist cut by basalt dikes.
09053A	S 11 16.451′ E 153 9.868′	White mica schist	Strongly crenulated fine grained white mica schist. U–Pb zircon dating via LA-ICP-MS also performed for this sample.
09037C	S 11 18.528′ E 154 3.482′	Dark gray metasediment	Dark gray fine grained metasediment in proximity to body of basalt.
09045A	S 11 21.930′ E 153 58.451′	Schist	Strongly crenulated fine grained schist in fault contact with serpentinite.
09037B	S 11 18.528′ E 154 3.482′	Light gray metasediment	Light gray fine grained metasediment in proximity to body of basalt.
Samples for U–Pb Zircon dating only (no isotopic data or geochemical data available)			
09006B	S 11 15.873′ E 153 6.231′	Schist	Louisiade Archipelago. Strongly crenulated metapelite; only U–Pb zircon dating via LA-ICP-MS performed for this sample.
04119A	S 10.687106 E 152.673239	Amphibolite gneiss	Misima Island. $^{40}Ar/^{39}Ar$ amphibole: 13.25 ± 0.81 Ma (unpub.); only U–Pb zircon dating via SIMS performed for this sample.

University. Details of the analytical protocols for the SIMS and LA-ICP-MS analyses follow.

3.3.1. LA-ICP-MS

All LA-ICP-MS U–Pb measurements were made using a New Wave Nd: YAG UV 213-nm laser coupled to a ThermoFinnigan Element 2 single collector, double-focusing, magnetic sector ICP-MS. Operating procedures and parameters are only outlined briefly here; for full details see Chang et al. (2006). Laser spot size and repetition rate were 30 μm and 10 Hz, respectively. The sample aerosol was delivered to the plasma in He and Ar carrier gasses. Individual analyses were preceded by a several second blank, and consisted of 300 sweeps (lasting ~35 s) through masses 204, 206, 207, 208, 232, 235, and 238. Time dependent mass fractionation, which is linear over the short time of the analysis, was corrected by regressing the time series data to the intercept at t = 0. Time-independent fractionation, which is the largest source of uncertainty in LA-ICP-MS U–Pb measurements, was corrected by normalizing U/Pb and Pb/Pb ratios of the unknowns to standards. In this study, we used two standards to monitor fractionation: Peixe, with an age of 564 Ma (Dickinson and Gehrels, 2003), and FC-1, with an age of 1099 Ma (Paces and Miller, 1993). Peixe was used as our primary standard to correct the LA-ICP-MS U-Pb data reported here; FC1 was used as the secondary standard to monitor the accuracy of the corrections.

3.3.2. Ion microprobe

Ion microprobe $^{238}U/^{206}Pb$ zircon age measurements were made using a Cameca ims 1270 high resolution, high sensitivity ion microprobe in the UCLA SIMS laboratory (http://sims.ess.ucla.edu/). Resolution of mass interferences within the mass range analyzed was possible due to the high mass resolution (~4500) of this instrument. A 12.5 kV primary ^{16}O-beam with a ~20 nA current and ~25 μm beam diameter were used for sputtering of sample material. Zircon standard AS3 was mounted with the unknowns. Prior to analysis, mounts were lightly polished to remove the carbon coating that had been applied for SEM CL imaging, cleaned with dilute HCL, and coated with a ~30 nm Au film. Intensities of monatomic U+, Th+, and Pb+ ions and $^{94}Zr_2O+$ and UO+ molecular ions were measured with a discrete dynode electron multiplier in peak jumping mode. Individual analyses consisted of 15 cycles with 15 s count times. O_2 flooding at 3×10^{-5} Torr was applied to the sample surface to enhance Pb yield. In-house software (ZIPS) at the UCLA SIMS laboratory was used to reduce the raw data.

4. Overview of analytical results

This section provides an overview of the major element data, REE, and isotopic characteristics of the twenty-one samples in the four lithostratigraphic units (eclogite and amphibolite, gneiss, felsic volcanics, and subgreenschist facies metasediment) from the Woodlark Rift examined in this study. The results of U–Pb zircon dating for four metamorphic rock samples are also presented below. See Table 1 for sample descriptions, Fig. 2 for sample locations, and Table 2 for Hf and Nd isotopic data. Measured whole rock major element, REE, and U–Pb zircon data are presented in the electronic supplementary

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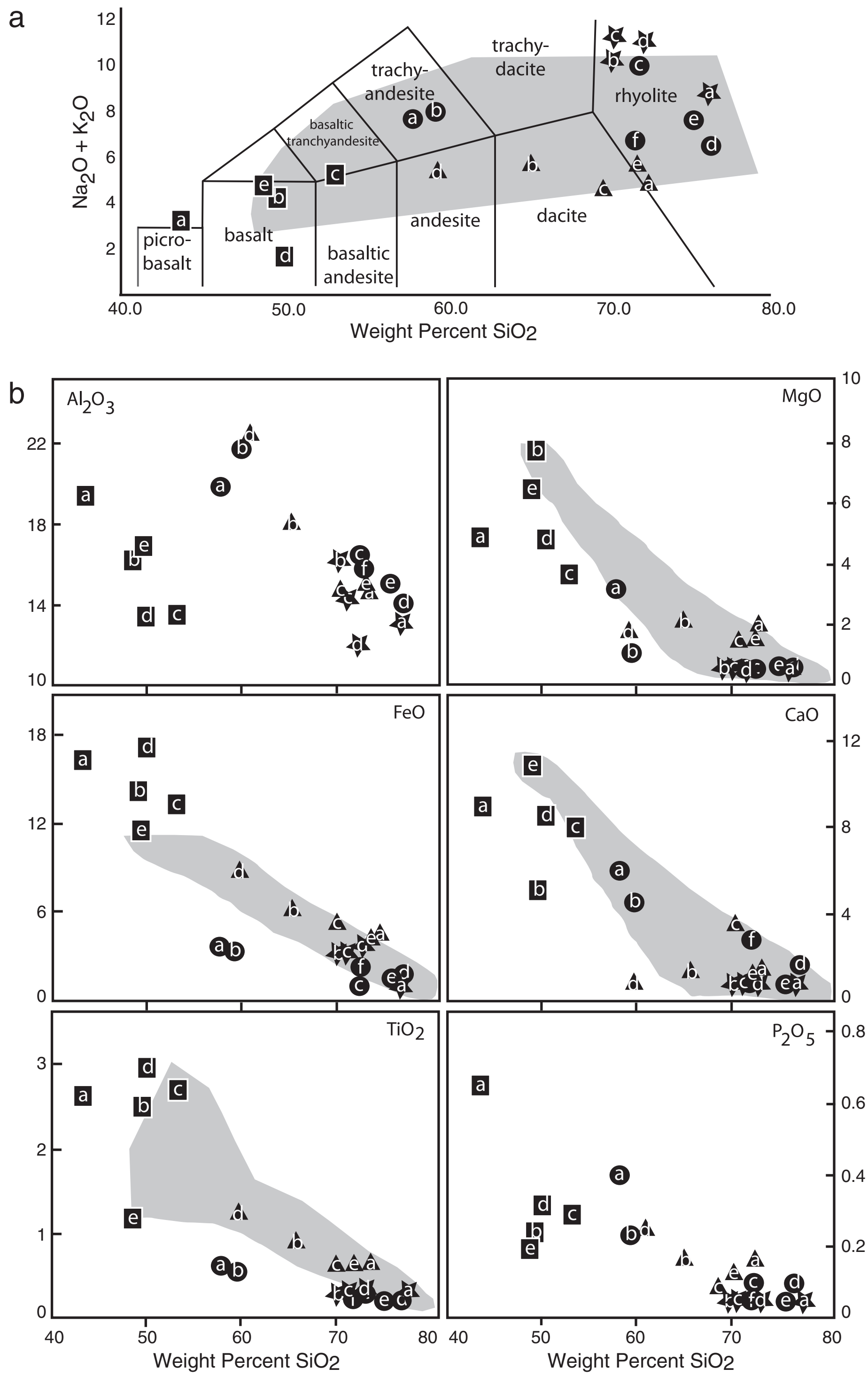

Fig. 3. a. Total alkalis versus SiO_2 for samples analyzed in this study. Symbols for individual samples are as in Fig. 2. Gray field in background is the range of compositions of volcanic rocks in the Whitsunday Volcanic Province, Northeastern Australia (reference data from Ewart et al., 1992). b. Major element compositions of samples analyzed in this study plotted as weight percents of elemental oxides versus SiO_2. Symbols for individual samples are as in Fig. 2. Gray fields in background are the range of compositions of volcanic rocks in the Whitsunday Volcanic Province (where shown, reference data from Ewart et al., 1992).

data file, which also contains additional data not specifically discussed in the text.

4.1. Major element characteristics

The major element compositions of the rocks sampled from the Woodlark Rift are plotted on a diagram of total alkalis versus silica (Fig. 3) as well as Harker variation diagrams (Fig. 3b). The reason for plotting all of the samples (including metamorphic rocks) from the Woodlark Rift on diagrams traditionally used for magmatic rocks is to illustrate the wide range of bulk compositions exhibited by the Woodlark Rift samples and to make comparisons between the rocks in the Woodlark Rift and their potential protoliths in the WVP. These comparisons are reserved for the discussion section of this paper.

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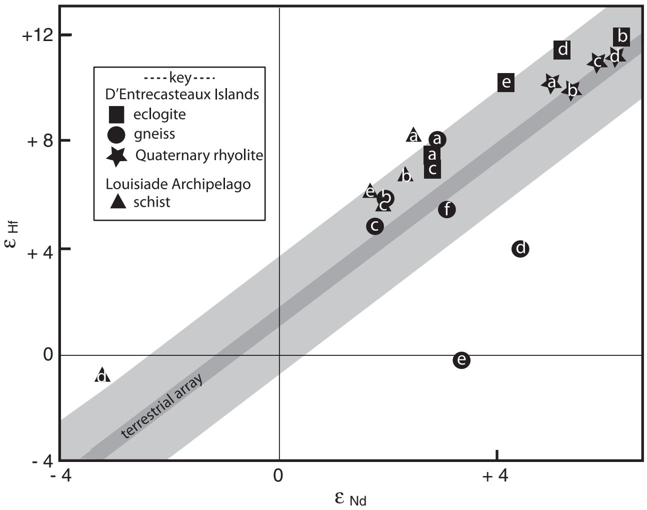

Fig. 4. ε_{Hf} vs ε_{Nd} isotopic compositions for samples from the Woodlark Rift. Gray line is the 'terrestrial array' from Vervoort et al. (2011).

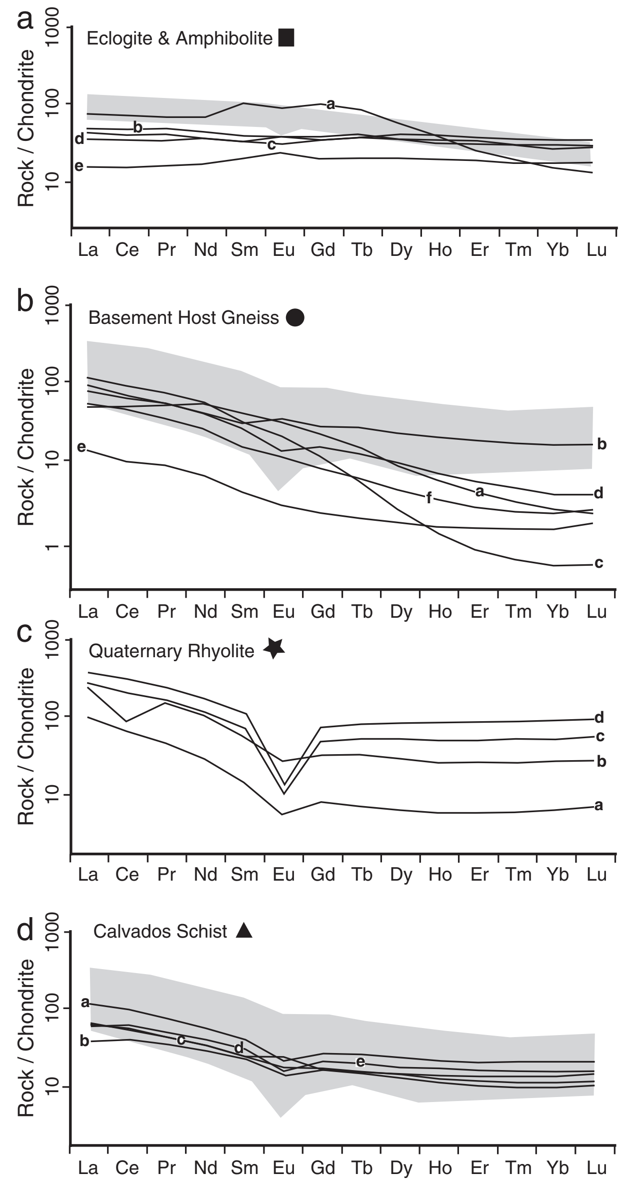

Fig. 5. Chondrite-normalized (McDonough and Sun, 1995) REE variation diagrams for: a) eclogites and amphibolites in the D'Entrecasteaux Islands, with field for Whitsunday Volcanic Province basalts and gabbros in gray (Ewart et al., 1992); b) basement gneisses in the D'Entrecasteaux Islands, with field for Whitsunday Volcanic Province rhyolites and andesites in gray (Ewart et al., 1992); c) Quaternary volcanic rocks in the D'Entrecasteaux Islands; and d) subgreenchist-facies metasedimentary rocks from the Louisiade Archipelago, with field for Whitsunday Volcanic Province rhyolites and andesites in gray (Ewart et al., 1992). Letters adjacent to each REE pattern correspond to individual samples identified in Fig. 2.

4.2. Whole rock Hf & Nd isotopic and REE characteristics

4.2.1. Eclogites and amphibolites in the D'Entrecasteaux Islands

The five eclogite and amphibolite samples from the D'Entrecasteaux Islands have ε_{Nd} values between +2.8 and +6.2, and ε_{Hf} values between +6.8 and +10.8. The Hf and Nd isotopic compositions of these five samples are well correlated with one another, and plot linearly on a diagram of ε_{Hf} vs ε_{Nd} (Fig. 4). Chondrite-normalized REE patterns of the eclogites and amphibolites are predominantly flat (Fig. 5a). A notable exception to this is one sample with enrichment of the MREE and depletion of the HREE; this sample also has lower ε_{Hf} and ε_{Nd} values than many of the other eclogite and amphibolite samples.

4.2.2. Felsic and intermediate gneisses in the D'Entrecasteaux Islands

The six samples of felsic and intermediate gneisses from the D'Entrecasteaux Islands exhibit ε_{Nd} values between +1.7 and +4.3, and ε_{Hf} values between −0.6 and +7.4. The Hf and Nd isotopic compositions of these six samples are not well correlated and have far more variation in ε_{Hf} (>8 ε_{Hf} units) than in ε_{Nd} (<4 ε_{Nd} units) (Fig. 4). The gneisses also have highly variable chondrite normalized REE patterns, some of which are characterized by extreme depletion of the HREE (Fig. 5b).

4.2.3. Quaternary felsic volcanic rocks in the D'Entrecasteaux Islands

The four samples of Quaternary felsic volcanic rocks from the D'Entrecasteaux Islands have a narrow range of ε_{Nd} (+5.0 to +6.1) and ε_{Hf} (+9.5 to +10.8) values (Fig. 4). These, along with two eclogite and amphibolite samples, have the most radiogenic Hf and Nd compositions of all samples analyzed from the Woodlark Rift. The chondrite-normalized REE patterns of these Quaternary felsic volcanic rocks are similar and exhibit LREE enrichment, flat HREEs, and pronounced negative Eu anomalies (Fig. 5c).

4.2.4. Subgreenschist facies calvados schist in the Louisiade Archipelago

Four subgreenschist-facies metasedimentary samples from the Louisiade Archipelago have a narrow range of ε_{Nd} (+1.8 to +2.4) and ε_{Hf} (+5.1 to +7.7) values (Fig. 4); a fifth sample has less radiogenic Hf and Nd isotopic compositions ($\varepsilon_{Nd}=-3.4$, $\varepsilon_{Hf}=-1.2$). The chondrite-normalized REE patterns of the subgreenschist-facies metasedimentary rocks are very similar, with slightly enriched LREEs, flat HREEs, and slight negative Eu anomalies (Fig. 5d).

4.3. U–Pb zircon results

The $^{206}Pb/^{238}U$ dates for the ion microprobe U–Pb zircon analyses of 03118m and 04119a are presented in Fig. 7 as probability density curves. Most of the zircon grains from sample 03118m have oscillatory-zoned cores that are mantled by dark CL overgrowths; data presented here are for analyses that targeted cores of zircons. The dates determined on the cores of zircons from sample 03118m range from ~110 to ~30 Ma, but it is possible that the young ages from this sample (e.g., <70 Ma) result from mixing of analysis of older cores and younger overgrowths formed during metamorphism. Zircons from sample 04119a, a gneiss from the lower plate (i.e., western end) of Misima Island, have an internal morphology similar to zircons from sample 03118m, except that they lack the dark CL

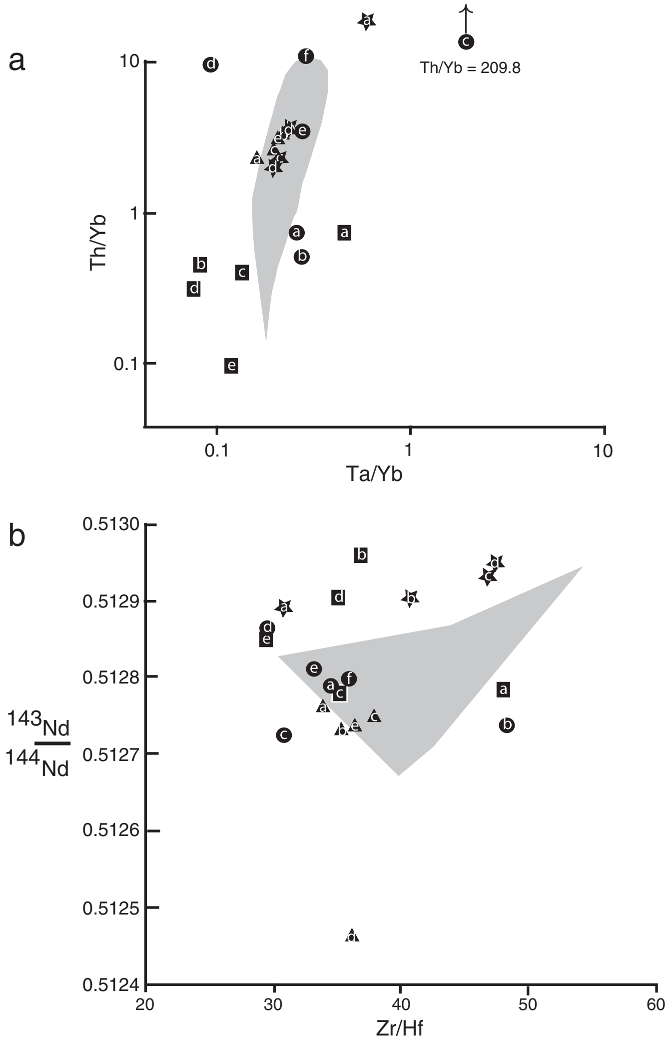

Fig. 6. a. Plot of Th/Yb versus Ta/Yb for samples analyzed in this study. Symbols for individual samples are as in Fig. 2. Gray field in background is the range of compositions of volcanic rocks in the Whitsunday Volcanic Province, Northeastern Australia (reference data from Ewart et al., 1992). b. Plot of $^{143}Nd/^{144}Nd$ versus Zr/Hf for samples analyzed in this study. Symbols for individual samples are as in Fig. 2. Note that the Nd isotopic data for samples analyzed in this study is presented in Table 2. Gray field in background is the range of compositions of volcanic rocks in the Whitsunday Volcanic Province, Northeastern Australia (reference data from Ewart et al., 1992).

overgrowths of 03118m. Ion microprobe analyses of the cores in this sample revealed a nearly homogeneous ~100 Ma population (Fig. 7).

Zircon from two samples of the Calvados Schist (0906b and 0953a) in the Louisiade Archipelago was dated using U–Pb LA-ICP-MS. The results are presented here as probability density curves of the single grain $^{206}Pb/^{238}U$ dates from these samples (Fig. 7b). We analyzed 96 zircons from 0906b, but we were only able to analyze 37 grains from 0953a. Both of these samples contain zircons with similar grain morphologies and internal grain structure under CL. The large laser spot size (~30 μm diameter and ~20–30 μm depth) made it difficult to target specific domains within zircons. The results from both samples are similar to one another and are characterized by a prominent early to middle Cretaceous zircon population (e.g., 120 to 90 Ma; Fig. 7b). Of the 96 grains analyzed in sample 0906b, only a few zircons fell outside of the 90 to 120 Ma age range. One grain yielded an ~600 Ma age and another an ~1.1 Ga age (not shown on Fig. 7b). All of the zircons analyzed in 0953a had ages between ~200 and ~90 Ma, with the majority of the analyses clustering at ~100 Ma.

5. Discussion

5.1. Protoliths of metamorphic rocks in the Woodlark Rift

There are several lines of evidence, including Nd and Hf isotopic, U–Pb zircon geochronologic, and trace element data, which support a tectonic link between metamorphic rocks on the southern margin of the Woodlark Rift and the Cretaceous Whitsunday Volcanic Province (WVP) in northeastern Queensland (Fig. 1). This connection is especially strong for the amphibolite facies to (U)HP basement gneisses in the D'Entrecasteaux Islands and the subgreenschist facies metasediments in the Louisiade Archipelago.

The WVP is currently situated along the rifted Australian passive margin and was active from ~120 to ~90 Ma (Bryan et al., 1997). The WVP lies at the northern end of a >900 km long continental rift that marked the eastern margin of Gondwana during the Cretaceous. It is estimated that greater than 105 km^3 of volcanic rocks was erupted in the WVP, much of which was either eroded and transported westward into Australia's Great Artesian and Otway/Gippsland basin systems (Bryan et al., 1997) or rifted away from Australia during the Late Mesozoic and Early Cenozoic.

It is important to note that magmatism in the WVP spanned a wide range of bulk compositions. In Fig. 3a and b the fields for the major element compositions of magmas in the WVP are shown in gray (Ewart et al., 1992). Comparison of the major element compositions for the Woodlark Rift samples with data from the WVP indicates that many of the eclogites and amphibolites, and some of the basement gneisses from the Woodlark Rift are not compositionally similar to the WVP. While the evidence discussed below favors an origin for the basement gneisses and the metasediments in Woodlark Rift that are uniformly related to the WVP, the deviation of major element compositions exhibited by the eclogites and amphibolites and some of the basement gneisses in the D'Entrecasteaux Islands as compared to the WVP highlights the importance of a potentially more complex origin for the eclogites and amphibolites (see Section 5.2), as well as processes that have operated during the Late Cenozoic opening of the Woodlark Rift (see Section 5.3).

The connection between the felsic and intermediate metamorphic rocks in the Woodlark Rift and the WVP in northeastern Australia is most evident when the Nd isotopic data from the Woodlark Rift samples is compared with available Nd isotopic data for rocks in the various geologic provinces currently found along the eastern Australian margin (e.g., caption of Fig. 1). The range of Nd isotopic compositions for Cretaceous basalts, andesites, and rhyolites comprising the WVP ($\varepsilon_{Nd} = +1.3$ to $+6.6$, Ewart et al., 1992) bracket the range of Nd isotopic compositions displayed by all but one of metamorphic rock samples from the Woodlark Rift ($\varepsilon_{Nd} = +1.7$ to $+6.2$). The only sample from the Woodlark Rift that does not fall within this range of values is a sample of the Calvados Schist from the Louisiade Archipelago (0945a), which has an ε_{Nd} of -3.4. This schist also has the most unradiogenic Hf isotopic composition ($\varepsilon_{Hf} = -0.8$) of all the samples analyzed, but it still does not have the strongly unradiogenic Hf and Nd isotopic signature expected of the exposures of Archean or Proterozoic continental crust currently exposed near the WVP (Fig. 1).

The Nd isotopic compositions of all the metamorphic samples from the Woodlark Rift are much more juvenile than any of the Paleozoic and Precambrian metamorphic and magmatic basement rocks currently exposed near the WVP, both on- and offshore (Fig. 1). These onshore exposures include late Paleo- to Mesoproterozoic metamorphic and magmatic rocks northeast of the WVP in the Georgetown Inlier (Whithall and Mackenzie, 1980; Black and McCulloch, 1984, 1990; McDonald et al., 1997), and Late Paleozoic and early Mesozoic granites south of the WVP in the New England Fold Belt. Offshore exposures include rocks recovered via drill core from the Queensland Plateau (ODP824-825) and Lord Howe Rise

Table 2
Hf and Nd isotopic results. The uncertainties on the $^{176}Hf/^{177}Hf$ and $^{143}Nd/^{144}Nd$ values shown in this table are the within-run 2 sigma ($\times 10^{-6}$).
Measured whole rock trace/REE and major elements in supplemental data file.
U–Pb zircon results in supplemental data file.

Sample	$^{176}Lu/^{177}Hf$	±	$^{176}Hf/^{177}Hf$	±	Lu ppm	Hf ppm	ε_{Hf}	±	$^{147}Sm/^{144}Nd$	$^{143}Sm/^{144}Nd$	±	Sm ppm	Nd ppm	ε_{Nd}	±
D'Entrecasteaux Islands: eclogites and amphibolites															
89302a	0.0147	3	0.282984	3	0.296	2.86	7.0	0.2	0.2395	0.512783	5	12.1	30.6	2.8	0.1
89321	0.0229	5	0.283107	5	0.610	3.77	11.4	0.4	0.2179	0.512958	8	3.43	9.52	6.2	0.2
03092A	0.0184	4	0.282977	4	0.757	5.83	6.8	0.2	0.1817	0.512781	6	4.74	15.8	2.8	0.1
03118b	0.0297	6	0.283091	6	0.798	3.81	10.8	0.4	0.1852	0.512902	6	5.37	17.5	5.2	0.2
08013A	0.0330	7	0.283056	7	0.438	1.88	9.6	0.3	0.2083	0.512851	10	2.71	7.86	4.2	0.1
D'Entrecasteaux Islands: basement gneisses															
89327	0.0003	1	0.282908	9	0.011	6.10	4.3	0.2	0.1050	0.512725	8	4.42	25.4	1.7	0.1
03092E	0.0065	1	0.282887	12	0.095	2.09	3.6	0.1	0.1223	0.512860	8	3.80	18.8	4.3	0.2
08010G	0.0019	1	0.282767	10	0.037	2.81	−0.6	0.02	0.1067	0.512808	5	0.526	2.99	3.3	0.1
08118M	0.0024	1	0.282925	11	0.054	3.14	4.9	0.2	0.1095	0.512796	10	2.06	11.4	3.1	0.1
89301	0.0061	1	0.282995	5	0.048	1.11	7.4	0.3	0.0229	0.512783	5	4.72	124	2.8	0.1
89303	0.0047	1	0.282941	3	0.096	2.91	5.5	0.2	0.1154	0.512738	8	2.14	11.2	1.9	0.1
D'Entrecasteaux Islands: quaternary calc-alkaline volcanic rocks															
08059B	0.0089	2	0.283081	7	1.35	21.4	10.5	0.4	0.1230	0.512935	10	9.79	48.2	5.8	0.2
08069B	0.0091	2	0.283091	7	2.12	32.9	10.8	0.4	0.1254	0.512951	7	14.3	68.8	6.1	0.2
89322	0.0068	1	0.283058	7	0.190	3.95	9.7	0.3	0.0958	0.512894	9	2.12	13.4	5.0	0.2
08058A	0.0085	2	0.283053	7	0.661	11.1	9.5	0.3	0.1103	0.512910	7	7.70	42.2	5.3	0.2
Louisiade Archipelago: Subgreenchist Facies Metasediment															
0953a	0.0091	2	0.282928	10	0.264	4.11	5.1	0.1	0.1276	0.512734	5	3.27	15.5	1.9	0.1
0905b	0.0138	3	0.283002	10	0.358	3.69	7.7	0.3	0.1416	0.512760	8	3.44	14.7	2.4	0.03
0937c	0.0087	2	0.282961	8	0.244	3.99	6.2	0.2	0.1329	0.512751	9	3.29	14.9	2.2	0.1
0945a	0.0097	2	0.282750	6	0.534	7.79	−1.2	0.04	0.1391	0.512464	6	5.49	23.9	−3.4	0.1
0937b	0.0121	2	0.282945	6	0.395	4.63	5.7	0.2	0.1663	0.512730	8	2.69	9.77	1.8	0.1

(NORFANZ 85), considered to be extensions of the New England Fold Belt (Mortimer et al., 2008).

The range of present-day ε_{Nd} values of the Proterozoic granites and volcanic rocks in the Georgetown Inlier (Black and McCulloch, 1984, 1990), and granites and associated metasedimentary rocks in the New England Fold Belt (Hensel et al., 1985) and its offshore extensions (Mortimer et al., 2008), is shown in comparison with the Nd isotopic data from the WVP and the rocks in the Woodlark Rift in the caption of Fig. 1. It is clear that the Nd isotopic compositions of the Woodlark Rift metamorphic rocks, even including the single sample with an ε_{Nd} value of −3.4, are more similar to the WVP than to any of the areas of older crust exposed in eastern Australia both on- and offshore (Fig. 1).

There are currently no whole rock Hf isotopic data for the WVP reported in the literature and therefore it is not possible to directly compare the Hf isotopic compositions of rocks in the Woodlark Rift and the WVP. The Hf isotopic compositions of the metamorphic rocks from the Woodlark Rift are consistent with their Nd isotopic compositions (e.g., Vervoort et al., 1999) and, as was the case with Nd results, none of the metamorphic rocks have the highly evolved Hf isotopic compositions expected of ancient (i.e. Paleoproterozoic or Archean) crust. The overall juvenile Hf isotopic compositions of the metamorphic rocks from the Woodlark Rift are consistent with a tectonic affinity related to Cretaceous aged mantle derived magmas.

The isotopic evidence for the connection between the rocks in the Woodlark Rift and the Cretaceous WVP is also supported by the U–Pb data for zircons from the metamorphic rocks in the Woodlark Rift. The four samples with U–Pb zircon dates represent both (U)HP to amphibolite facies basement gneisses in D'Entrecasteaux and Misima islands, as well as the subgreenschist-facies metasediments in the Louisiade Archipelago. The dominant zircon age population in all four samples (Fig. 7 and b), collected over a distance of ~250 km (Fig. 2) is 100 to 90 Ma. We interpret this data to indicate that either the rocks with sedimentary protoliths in the Woodlark Rift originated as part of the WVP, where the peak of volcanic activity occurred between 132 and 95 Ma (Bryan et al., 1997), or that another Cretaceous magmatic province was the dominant source for the rocks in the Woodlark Rift with sedimentary protoliths (Fig. 8). The occurrence of zircons with Precambrian U–Pb ages (Baldwin and Ireland, 1995; this study) in the Woodlark Rift is not surprising given the fact that exposures of Precambrian aged crystalline rocks occur along the present day eastern Australian continental margin (Fig. 1). It is not currently possible, however, to further refine the source for the older zircons in the Woodlark Rift due to the fact that few older zircons have been documented and, as in the case with this study, represent an insignificant population as compared to the Cretaceous aged grains.

5.2. Additional protoliths of eclogites and amphibolites in the D'Entrecasteaux Islands

Unlike the basement gneisses in the D'Entrecasteaux Islands, the data gathered in this study indicates that the mafic eclogites and amphibolites found in the D'Entrecasteaux Islands are not all simply metamorphosed WVP magmas with mafic bulk compositions. Based on Lu–Hf garnet analyses Zirakparvar et al. (2011) suggested that the eclogites and amphibolites in the D'Entrecasteaux Islands could have originated as: 1) partial mantle melts intruded into formerly subducted lithosphere and crystallized at depth during the earliest phases of rifting in the Woodlark Rift; 2) as fragments of the Mesozoic-aged upper plate of the subduction complex that were entrained when these rocks were subducted; or 3) as basalts that intruded the Cretaceous rifted margin of east Gondwana that was subsequently subducted and metamorphosed. The Nd isotopic and REE compositions of the eclogites and amphibolites in the Woodlark Rift and the basalts from the WVP overlap and therefore do not help to resolve these three possibilities. It is likely that all three processes can be used to explain the variety (Davies and Warren, 1992) of eclogites and amphibolites exhumed along with the felsic and intermediate host gneisses in the D'Entrecasteaux Islands.

The coesite eclogite sample, interpreted to have originated as a mantle-derived basaltic melt that crystallized at ~7 Ma at (U)HP

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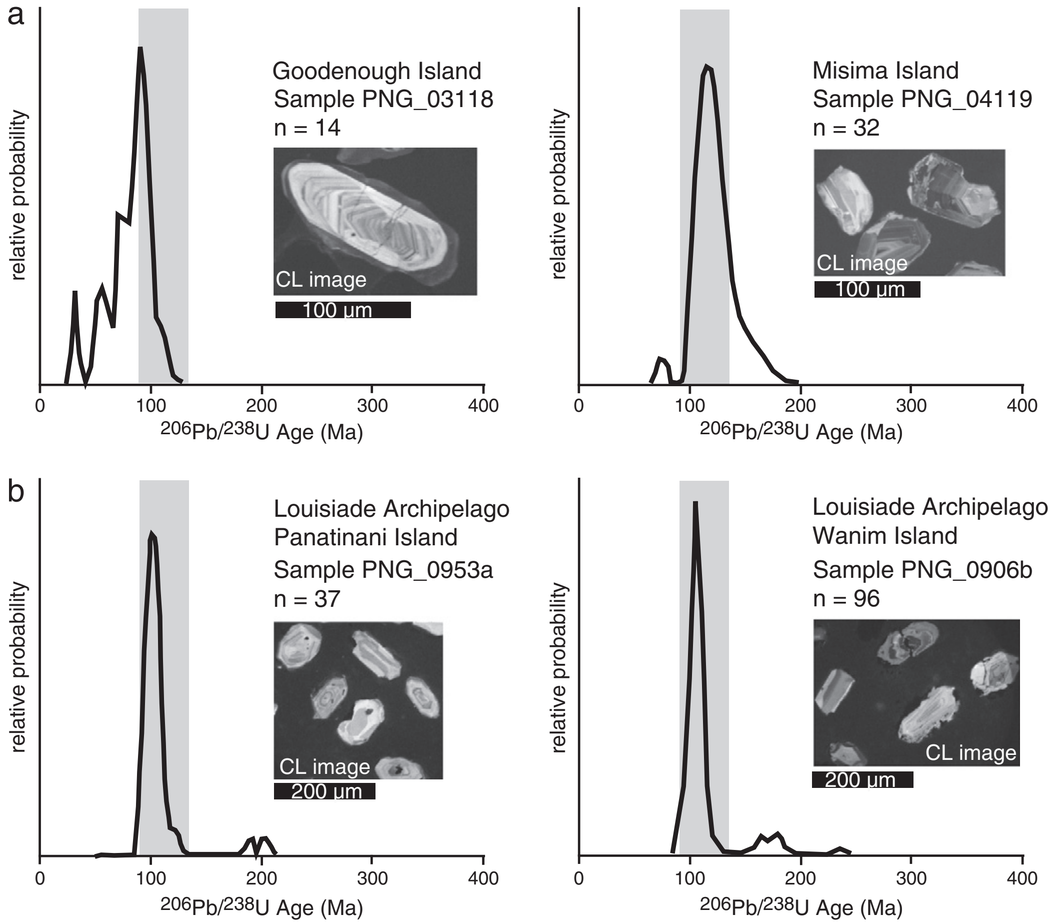

Fig. 7. a. Results of ion microprobe U–Pb zircon dating. Probability density curves for $^{206}Pb/^{238}U$ single grain ages for individual analyses of zircons from samples 03118m and 04119b. Solid gray bar is the age range of magmatism in the WVP (Bryan et al., 1997). Representative examples of zircon cathodoluminescence images from each sample are shown as insets within the probability density curves. b. Results of LA-ICP-MS U–Pb zircon dating. Probability density curves for $^{206}Pb/^{238}U$ single grain ages for individual analyses of zircons from samples 0906b and 09053a. Solid gray bar is the approximate age range of magmatism in the WVP (Bryan et al., 1997). Representative examples of zircon cathodoluminescence images from each sample are shown as insets within the probability density curves.

conditions (Zirakparvar et al., 2011), was also examined in this study (eclogite sample 89321). This sample has the most radiogenic Hf and Nd isotopic compositions of all metamorphic rocks analyzed (Fig. 4), and it may be possible that the less radiogenic eclogites and amphibolites are, in fact, metamorphosed WVP equivalents (similar to the gneisses and schists), or captured fragments of oceanic lithosphere comprising the upper plate of the Mesozoic forearc and initially metamorphosed at ~68 Ma (Zirakparvar et al., 2011). Many eclogite and amphibolite samples have FeO, MgO, CaO, and TiO_2 contents that are outside the range of values for magmatic rocks in the WVP (Fig. 3b) as well as REE patterns that are not similar to WVP basalts and gabbros (Fig. 5a). More work is necessary to determine which eclogites and amphibolites formed via these various processes. However, this uncertainty does not detract from the correlation between the felsic and intermediate metamorphic rocks in the Woodlark Rift and the Cretaceous WVP in northeastern Australia.

5.3. Partial melting of the metamorphic basement and the mantle source of quaternary felsic volcanics in the D'Entrecasteaux Islands: current location of the rift tip

Late Cenozoic (U)HP exhumation in the D'Entrecasteaux Islands was accompanied by intrusion and deformation of felsic and intermediate granodiorite plutons yielding Quaternary crystallization and cooling ages (Baldwin et al., 1993; Hill et al., 1995; Little et al., 2012). From a geochemical perspective, partial melting during exhumation is evident when the Hf and Nd isotopic compositions (Fig. 4) and REE characteristics (Fig. 5) of the D'Entrecasteaux Islands gneisses are compared with those of the Calvados Schist in the Louisiade Archipelago. If both the D'Entrecasteaux Islands gneisses and Louisiade Archipelago Calvados Schist are derived from the Cretaceous WVP (Fig. 8), the observation that the gneisses are strongly HREE depleted (Fig. 5b) compared to the Calvados Schist (Fig. 5d), but have Hf and Nd isotopic compositions overlapping those of the Calvados Schist (Fig. 4), can be explained by partial melting of the gneissic rocks in the recent past such that the gneisses and metasediments have not yet evolved to markedly different Hf and Nd isotopic compositions.

The geochemical evidence for partial melting of the basement gneisses during rock exhumation in the D'Entrecasteaux Islands is also evident in a comparison of the Th/Yb versus Ta/Yb (Fig. 6) and $^{143}Nd/^{144}Nd$ versus Zr/Hf (Fig. 6b) of the basement gneisses with those of the metasediments in the Louisiade Archipelago and the rocks in the WVP. The Th/Yb versus Ta/Yb and $^{143}Nd/^{144}Nd$ versus Zr/Hf values for representative bulk compositions of WVP magmas (Ewart et al., 1992) are shown as gray fields in Fig. 6a and b. On these figures, the Louisiade Archipelago metasediments plot within or very close to the fields for the WVP magmas, whereas many of the D'Entrecasteaux Islands basement gneiss samples plot well outside of the WVP fields. A good example of this behavior is basement gneiss sample PNG89327 (denoted as circle labeled 'C') that exhibits high Ta/Yb and extremely high Th/Yb (Fig. 6), as well as lower $^{143}Nd/^{144}Nd$ and Zr/Hf (Fig. 6b) than the other metamorphic rocks samples and the WVP. The fact that all but one of the Louisiade

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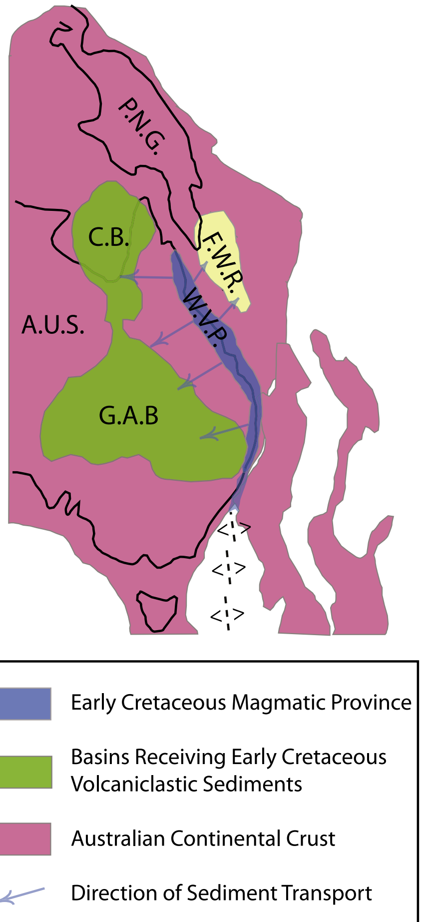

Fig. 8. Tectonic reconstruction of the eastern Australian margin during the early Cretaceous. Data gathered in this study indicate a tectonostratigraphic link between metamorphic rocks now exposed in the Woodlark Rift and the Cretaceous aged Whitsunday Volcanic Province, a bimodal volcanic suite related to the breakup of east Gondwana and the initiation of the eastern Australian passive margin. The basement gneisses in the D'Entrecasteaux Islands and the subgreenschist facies metasediments in the Louisiade Archipelago probably originated as volcanogenic sediments shed off of this Cretaceous volcanic province. C.B. = Carpentaria Basin, G.A.B. = Great Artesian Basin, F.W.R. = future Woodlark Rift, W.V.P. = Whitsunday Volcanic Province.

Archipelago metasedimentary samples plot close to each other and within/near the WVP fields in Fig. 6a and b whereas the D'Entrecasteaux Islands basement gneisses are widely scattered on these diagrams can be best explained by the effects of elemental fractionation during high degrees of partial melting in the D'Entrecasteaux Islands.

With the geologic and geochemical evidence for partial melting of the felsic and intermediate basement gneisses in the D'Entrecasteaux Islands, it stands to reason that some of the Quaternary aged felsic lavas erupting in the western Woodlark Rift may be the extrusive equivalents of these partially melted basement rocks. In order to test this possibility, we analyzed four Quaternary felsic (rhyolitic) volcanic rocks (Fig. 2, Table 1) from the D'Entrecasteaux Islands. Some of the basement gneisses have bulk compositions that are similar to the Quaternary aged felsic volcanic rocks (Fig. 3a and b). However, the Hf and Nd compositions (Fig. 4) of the basement gneisses ($\varepsilon_{Hf} = -0.6$ to $+7.4$; $\varepsilon_{Nd} = +1.7$ to $+4.3$) are less radiogenic than any of the Quaternary volcanic ($\varepsilon_{Hf} = +9.5$ to $+10.8$; $\varepsilon_{Nd} = +5.0$ to $+6.1$) rocks we analyzed. The chondrite-normalized REE patterns of the basement gneisses (Fig. 5b) and those of the Quaternary volcanic rocks (Fig. 5c) are also significantly different from one another. These two observations suggest that the Quaternary felsic volcanic rocks are not entirely derived from partial melting of the basement gneisses in the western Woodlark Rift.

The isotopic and REE compositions of the gneisses and Quaternary volcanics in the D'Entrecasteaux Islands are markedly different despite the spatial and temporal proximities of the basement rocks to the volcanic eruptive centers in the D'Entrecasteaux Islands. These volcanic rocks do not appear to have formed entirely as the extrusive equivalent of partial melts of gneisses; instead, the more juvenile isotopic compositions and negative Eu anomalies of the Quaternary felsic volcanic rocks indicate that they are fractionated mantle melts and have remained *mostly* uncontaminated from the melting metamorphic basement during their ascent to the surface. Perhaps these felsic lavas are the more fractionated equivalents of peralkaline rift-related basalts in the Woodlark Rift (e.g., Smith, 1982). The presence of these Quaternary mantle-sourced volcanic rocks in the D'Entrecasteaux Islands indicates that the zone of crustal thinning and asthenospheric upwelling, associated with the westward propagating seafloor spreading rift-tip, extends to the southern coast of Fergusson Island in the D'Entrecasteaux Islands region of the Woodlark Rift.

6. Conclusions

Geochemical, geochronologic and isotopic data from the Woodlark Rift was used to reveal the evolution of metamorphic rocks (sub-greenschist facies to (U)HP) from their protoliths as Cretaceous volcanoclastic sediments derived from a >900 km long magmatic province within the eastern margin of Gondwana (Bryan et al., 1997), through subduction and metamorphism north and east of Australia during the late Mesozoic (Zirakparvar et al., 2011), and finally to exhumation during rifting in the Woodlark Rift. Isotopic, REE, and geochronologic data for the metamorphic and volcanic units at the western end, and along the southern-rifted margin, of the Woodlark Rift indicate the following:

1) (U)HP to amphibolite facies basement gneisses and subgreenschist-facies metasediments in the Woodlark Rift can be correlated with Cretaceous-aged volcaniclastic sediments of the Whitsunday Volcanic Province (WVP), northeastern Queensland (Fig. 8). The eclogites and amphibolites in the D'Entrecasteaux Islands, while possibly related to the WVP, may also be derived from the mantle or as fragments of the subduction complex where the Cretaceous volcaniclastic sediments were initially subducted in the Late Mesozoic.
2) Quaternary felsic volcanic rocks in the D'Entrecasteaux Islands have not inherited the isotopic or geochemical signature of the metamorphic basement despite being erupted within a zone of active continental extension where partial melting of the metamorphic basement is evident. These Quaternary volcanic rocks are highly fractionated and mostly uncontaminated mantle melts, an observation that when combined with geophysical data for the region, suggests that seafloor spreading will commence adjacent to Fergusson Island if crustal thinning due to rifting continues in this region.

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Appendix A. Supplementary data

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