Lu–Hf garnet geochronology applied to plate boundary zones: Insights from the (U)HP terrane exhumed within the Woodlark Rift

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ABSTRACT

High-pressure and ultra-high-pressure (U)HP metamorphic rocks occur in many of the world’s major orogenic belts, suggesting that subduction of continental lithosphere is a geologically important process. Despite the widespread occurrence of these rocks, relatively little is known about the timescales associated with (U)HP metamorphism. This is because most (U)HP terranes are tectonically overprinted and juxtaposed against rocks with a different history. An exception to this are the Late Miocene (U)HP metamorphic rocks found in the Woodlark Rift of southeastern Papua New Guinea. This region provides a rare opportunity to study the garnet Lu–Hf isotopic record of (U)HP metamorphism in a terrane that is not tectonically overprinted.

In order to constrain the timing of garnet growth relative to the history of (U)HP metamorphism and the region north and east of Australia during late Mesozoic/early Cenozoic time.

1. Introduction

In the past two decades, Lu–Hf garnet geochronology has been used to gain insight into the history of polymetamorphosed terranes (Anckiewicz et al., 2004; 2007; Berger et al., 2005; Blichtert-Toft and Frei, 2001; Cheng et al., 2008; Corrie et al., 2010; Duchene et al., 1997; Kylander-Clark et al., 2007; Lagos et al., 2007; Lapen et al., 2003; Scherer et al., 2000; Skora et al., 2006 and Zirakparvar et al., 2010). It is not uncommon for a particular region to yield a range of Lu–Hf garnet ages, often older than coexisting garnet Sm–Nd, U–Pb zircon, and 40Ar/39Ar ages. In some cases, the Lu–Hf garnet age range can be interpreted with respect to the spatial and temporal evolution of the metamorphic terrane thereby providing insight into the evolution of complex plate boundary zones.
This paper presents the first Lu–Hf garnet results on eclogite and garnet amphibolites from the youngest known (U)HP terrane in the Woodlark Rift of southeastern Papua New Guinea (PNG) (Baldwin et al., 2004). Late Miocene eclogites, including an ~8 Ma coesite eclogite (Baldwin et al., 2008; Monteleone et al., 2007), are exposed in the lower-plates of active metamorphic core complexes (MCC) in the D’Entrecasteaux Islands. The young age of high pressure and ultrahigh pressure (U)HP rocks in southeastern PNG provides an opportunity to study the entire (U)HP metamorphic path – from subduction to exhumation – in a terrane that has not been re-incorporated into an orogen with subsequent tectonic, metamorphic, or thermal overprinting (Baldwin et al., 2004; Monteleone et al., 2007).

The Lu–Hf garnet isochron ages are combined with garnet Lu and major element concentrations to ascertain whether the ages reflect garnet growth or isotopic closure following growth. This approach has been successfully used in other UHP terranes (Anzckiewicz et al., 2007; Cheng et al., 2008; Konrad-Schmolke et al. 2008; Skora et al., 2006), and allows for a geologically consistent interpretation. Results for two samples yield the youngest Lu–Hf garnet ages yet reported in the literature.

Results from the western Woodlark Basin support previous geochronological evidence for Late Cretaceous–Paleocene obduction of the Papuan Ultramafic Belt (Davies, 1980; Lus et al., 2004) in southeastern PNG, as well as Late Miocene (U)HP metamorphism in the D’Entrecasteaux Islands (Monteleone et al., 2007). The garnet Lu–Hf isochron age from the Misima Island MCC records dynamic recrystallization during Late Miocene amphibolite facies metamorphism on the southern-rifted margin of the Woodlark Rift. These results have implications not only for Cenozoic tectonics of southeastern PNG, but also for the interpretation of Lu–Hf garnet ages and Lu concentration profiles from (U)HP rocks exhumed within complex plate boundary zones.

2. Geology of the Woodlark Rift

Much of PNG is thought to have originated as part of the northern Australian rifted passive margin, having separated from Australia during the Late Mesozoic opening of the Coral Sea Basin (Weissel and Watts, 1979) and Early Cretaceous breakup of East Gondwana. The present northern limit of Australian continental crust is not known, but remnants of Archean basement occur within the fold and thrust belt on the PNG mainland (Hill and Hall, 2003) and in the Trobriand Basin (Baldwin and Ireland, 1995).

Rates of plate tectonic motion in the vicinity of southeastern PNG are generally high (cm/yr), and are related to microplate formation resulting from oblique convergence between the Pacific and Indo-Australian plates (Cooper and Taylor, 1987; Curtis, 1973; Johnson and Molnar, 1972; Schellart et al., 2006; Taylor et al., 1995; Wallace et al., 2004). The Papuan peninsula is an active zone of arc continent collision, but in the eastern-most part of PNG, where plate motion becomes extensional, eastward extensions of the Papuan peninsula have stretched, separated, and subsided since at least 6 Ma. This has occurred as the seafloor spreading rift tip propagated westward forming the Woodlark Basin (Taylor et al., 1995).

The western apex of the V-shaped Woodlark Basin is a zone where seafloor spreading transitions into continental rifting (Abers, 1991; Little et al., 2007; Taylor et al., 1995). The D’Entrecasteaux Islands (Fig. 1), in the western Woodlark Basin, contain MCCs with complexly deformed (U)HP to amphibolite facies rocks in their lower plates (Baldwin et al., 2008; Davies and Warren, 1988; Little et al., in press). Lower plate rocks are separated from upper plate rocks, which consist of metamorphosed mafic and ultramafic rocks, by km-scale ductile shear zones and brittle detachment faults (Davies and Warren, 1988; Hill, 1994). 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). U–Pb dating of zircon formed at (U)HP conditions in a coesite eclogite (sample 89321 in this study), indicates that the high-grade basement rocks crystallized at ~8 Ma, but the onset, prograde history, or duration of (U)HP metamorphism is unknown.

The poly metamorphic basement exposed in the lower plates of the D’Entrecasteaux Islands MCCs have been recognized as one of the most recently unroofed MCCs on Earth (Baldwin et al., 1993; Hill, 1994), Zircon U–Pb dating and P–T constraints (Baldwin et al., 2004; Baldwin et al., 2008; Monteleone et al., 2007) show that these rocks were at a depth of greater than 90 km as recently as ~8 Ma. K/Ar, 40Ar/39Ar, and fission track dating techniques applied to the lower plate rocks have documented an extremely rapid (e.g., > 100 °C/myr.) cooling history occurring within the past five million years (Baldwin et al., 1993). In the D’Entrecasteaux Islands, seismic activity (Abers et al., 2002), geomorphology, and 40Ar/39Ar mineral cooling ages, all suggest that final exhumation of lower-plate rocks to the surface occurred during Plio-Pleistocene to Holocene time and may still be active (Baldwin et al., 1993; Baldwin and Hill, 1993).

Metamorphic grade decreases steadily eastward along strike of the southern-rifted margin of the Woodlark Rift from (U)HP in the D’Entrecasteaux Islands (Baldwin et al., 2008), to upper amphibolite facies on Misima Island (Appleby et al., 1996), and finally to sub-greenschist facies in the Louisiade Archipelago (e.g., Davies and Warren, 1988; and Smith, 1973a,b; Smith and Pieters, 1973). Misima Island (Fig. 1), located ~150 km southeast of the D’Entrecasteaux Islands, is roughly bisected by a low angle normal fault (Peters et al., 2004). 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. 40Ar/39Ar apparent ages from the lower plate of Misima Island indicate cooling through Ar closure between 15.1 and 9.8 Ma for amphibole and 8.0–7.6 Ma for biotite (Baldwin et al., 2008). Biotite 40Ar/39Ar ages are concordant with U–Pb zircon crystallization ages for granodiorites emplaced during MCC exhumation (Appleby et al., 1996). 40Ar/39Ar data for lower plate rocks of the Misima Island MCC indicates that cooling occurred 4 to 8 Ma earlier than in the D’Entrecasteaux Islands (8 to 7 Ma; Baldwin et al., 2008). The apparent westward younging of 40Ar/39Ar ages along the southern margin of the Woodlark Rift suggests that MCCs formed in response to westward propagation of the Woodlark Rift (Baldwin et al., 2008; Little et al., 2007).

The (U)HP to sub-greenschist facies rocks in the Woodlark Rift may have first been metamorphosed during an episode of Eocene arc-continent collision (Davies and Warren, 1988). The primary evidence for this collision is the Papuan Ultramafic Belt (PUB) on the Papuan peninsula, a succession of Cretaceous oceanic crustal slices emplaced southward onto the leading edge of the rifted Australian margin during the early to middle Eocene (Davies, 1970; Jacques and Chappell, 1980; Lus et al., 2004; Milsom, 1973). Constraints for the Late Paleocene–Early Eocene timing of ophiolite emplacement are based on 40Ar/39Ar amphibole crystallization ages from the metamorphic sole of the PUB (Lus et al., 2004). The upper-plane rocks of the D’Entrecasteaux Islands MCCs are geochemically and petrographically similar to the basalts and gabbros of the PUB (Davies and Warren, 1988; Little et al., 2007). Gabbro recovered from the Moresby Seamount during DOP Leg 180 yielded a 207Pb/206Pb age of 66.4 ± 1.5 Ma indicating PUB remnants occur in close proximity to the active seafloor spreading rift tip (Monteleone et al., 2001).

3. Analytical techniques

Three samples from MCCs in the eastern and western parts of the Woodlark Rift were selected for Lu–Hf garnet geochronology (Fig. 1). These were selected to encompass a range of garnet-bearing lithologies from the D’Entrecasteaux and Misima Island MCCs. They
include coesite eclogite from the lower plate and garnet amphibolite from the shear zone carapace of the D’Entrecasteaux Island MCCs, and garnet amphibolite in the lower plate of the Misima Island MCC. Garnets were characterized via LA-ICP-MS and WDS to examine the distribution of select trace and major elements as described below.

For Lu–Hf geochronology, multiple garnet and whole-rock fractions, each consisting of 200–250 mg of material, from each sample were dissolved in the radiogenic isotope clean laboratory at Washington State University. All of the garnet and some of the whole-rock fractions in this study were dissolved using partial dissolution, whereas a few of the whole rocks were also dissolved using high-pressure bombs. Partial dissolution was intended to dissolve the bulk of the sample without dissolving zircon, whereas full dissolution was intended to dissolve the entire sample including zircon (King et al., 2007). The partial dissolution technique, also known as ‘table-top dissolution’, consisted of dissolving the samples in a mixture of concentrated HF/HNO$_3$ (10:1) in closed Savillex™ capsules on hot plates at 150 °C for 24 to 48 h.

Whole-rock fractions subjected to the full dissolution technique were digested in high-pressure, steel-jacketed, Teflon vessels (‘Parr style bombs’) at 160 °C for five to seven days. The fluoride solutions from both techniques were converted to chlorides using H$_2$BO$_3$ and HCl (Zirakparvar et al., 2010). A mixed $^{176}$Lu–$^{180}$Hf tracer was then added to the solutions and allowed to equilibrate on a hot plate for a minimum of 24 h. Samples were then dried down, re-dissolved, and centrifuged in preparation for chromatographic separations. The protocols for dissolution, spiking, chemical separations, and analyses used in garnet Lu–Hf geochronology are fully discussed in Cheng et al. (2008). The protocol used for separation of Lu and Hf is based on procedures described by Patchett and Tatsumoto (1980), Vervoort and Patchett (1996), Vervoort and Blichert-Toft (1999), and Munker et al. (2001).

Lu–Hf isotopic analyses were performed on a ThermoFinnigan™ Neptune MC-ICP-MS at Washington State University. Hf and Lu were dissolved in dilute (2%) HNO$_3$ and aspirated into the instrument via an Aridus desolvating nebulizer (garnet Hf) or a standard Teflon low-flow (50 µL/min) nebulizer (Lu and whole-rock Hf) in conjunction with a dual quartz spray chamber. Analyses were made in static mode and consisted of 75, 8-second integrations for Hf and 30, 8-second integrations for Lu. During the course of this study the following isotope values were measured on the JMC475 Hf standard: $^{176}$Hf/$^{177}$Hf = 0.282150 ± 8, $^{178}$Hf/$^{177}$Hf = 1.467221 ± 46, and $^{180}$Hf/$^{177}$Hf = 1.886831 ± 74 (n = 17). These values compare favorably with the accepted values for JMC 475: $^{176}$Hf/$^{177}$Hf = 0.282160, $^{178}$Hf/$^{177}$Hf = 1.467170, and $^{180}$Hf/$^{177}$Hf = 1.886660 (Vervoort and Blichert-Toft, 1999). Final Hf isotope values were adjusted slightly relative to these values using a linear correction following mass bias and interference corrections.

Natural Yb present in the samples was used to correct for mass fractionation in the Lu measurements following the method, and using the values, reported in Vervoort et al. (2004). Lu and Hf concentrations and $^{176}$Lu/$^{177}$Hf ratios were subsequently determined by isotope dilution. All regressions for Lu–Hf isochrons were calculated using Isoplot/Ex (Ludwig, 2003) and a $^{176}$Lu decay constant of 1.867 $\times$ 10$^{-11}$ (Scherer et al., 2001; Soderlund et al., 2004). Present-day CHUR values of $^{176}$Hf/$^{177}$Hf = 0.282785 and $^{176}$Lu/$^{177}$Hf = 0.0336 (Bouvier et al., 2008) were used in the calculation of epsilon (ε) Hf values.

The $^{176}$Hf/$^{177}$Hf, $^{176}$Lu/$^{177}$Hf ratios, Lu and Hf concentrations, and present-day epsilon (ε) Hf values for all samples analyzed in this
study are reported in Table 1. Uncertainty on the $^{176}$Hf/$^{177}$Hf ratio given in Table 1 is the internal precision of the Hf isotope measurement determined by within-run statistics (2σ standard error). For the regression of isochrons and calculation of ages, however, we used uncertainties of 0.5% for the $^{176}$Lu/$^{177}$Hf and, for the $^{176}$Hf/$^{177}$Hf ratios, within-run errors combined in quadrature with a systematic uncertainty of 0.01% (1σ Hf unit). Within-run error is a determination of the precision of the measurements during the course of a single analysis, but does not provide an estimate of the accuracy of the measurement. Accuracy is estimated by repeat measurements of a solution of known isotopic composition such as the JMC 475 standard.

Sources from natural geologic samples, however, are not perfectly elementally pure and often have small but measurable amounts of interfering species and other elements that present difficult to quantify matrix effects. This is particularly true for garnet samples with very low Hf abundances and high REE contents, such as those analyzed in this study. Using error determined only from within-run statistics or repeated measurement of the JMC475 standard underestimate the total uncertainty in the measurement of Hf poor geologic samples and will result in isochrons with unrealistically high MSWD values.

The distribution of Lu in garnet porphyroblasts was determined using laser-ablation ICP-MS at Washington State University. Garnets were analyzed using a NewWave Nd-YAG laser (λ = 213 nm), operating at ~10 J/cm² and 10 Hz, with a 10–15 μm spot size. Ablated material was carried in purified He gas to the plasma source of a ThermoFinnigan Element2 single collector, magnetic sector mass spectrometer. Only Lu results are presented here. Analyses were conducted in low-resolution mode (m/Δm = 300) using an analog mode for $^{29}$Si and pulse counting for $^{175}$Lu. Data were screened using Glitter software to remove portions of the analysis biased by inclusions. Detection limits were ≤0.25 ppm. Analyses were standardized against glass made from USGS rock standard BCR2-G using $^{29}$Si as an internal standard.

Element maps of garnet using WDS (Fe, Mg, Mn, and Ca) were obtained using the Cameca SX-100 electron microprobe operating at 15 kV, at the Rensselaer Polytechnic Institute.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Lu ppm</th>
<th>Hf ppm</th>
<th>ε Hf</th>
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| PNG 89321 | 0.283097±20 | (ε Hf)7.1 Ma = 11.2 | 7.1 ± 0.7 Ma (MSWD = 1.1) and an initial $^{176}$Hf/$^{177}$Hf of 0.283097 ± 20 (ε Hf = 11.2). An important aspect in interpreting the 7 Ma Lu–Hf age from the coesite eclogite is to determine the origin of the homogeneous distribution of Lu in garnet. If Lu was initially homogeneously distributed the ~7 Ma Lu–Hf age records garnet growth. Alternatively, if the homogeneous distribution is due to re-equilibration of Lu, the ~7 Ma Lu–Hf age records isotopic closure.

In published examples of eclogite garnets lacking Lu zoning due to thermal re-equilibration, major elements are also homogeneously distributed (e.g. Cheng et al., 2008). This is not the case for the ~7 Ma coesite eclogite, as the garnet we examined via X-ray mapping from this sample contains a pronounced off-center oscillatory zone of high Ca and low Mg. Furthermore, this relict off-center oscillatory zone is truncated at the garnet grain boundary, suggesting that garnets in this sample experienced partial resorption during the reaction to form the current mineral assemblage. If re-equilibration is called upon to explain the homogeneous distribution of Lu in the coesite eclogite garnets, this mechanism must have left Ca and Mg zoning undisturbed. Available thermometry indicates crystallization temperatures that did not exceed ~760 °C therefore, re-equilibration seems unlikely.

An alternative explanation to re-equilibration is that Lu zoning was never present in garnets from the coesite eclogite. This could occur if garnet crystallized as a primary igneous phase in a magmatic system above the Lu blocking temperature. The Ca and Mg zoning in the garnet may have formed initially as garnet crystallized from a partial melt of the mantle. If this garnet-bearing partially crystallized melt was intruded into cold continental crust at UHP conditions, its metamorphic assemblage could have crystallized directly from the partial melt when it crystallized rapidly at UHP conditions. This near-instantaneous crystallization could have essentially frozen the distribution of Lu and major elements in garnet. The ~7 Ma Lu–Hf age from the coesite eclogite is concordant with a previously reported U–Pb zircon age from this sample, interpreted as the time when zircon crystallized at UHP conditions (Monteleone et al., 2007), further suggesting rapid crystallization and isotopic closure.
The coesite eclogite’s mafic bulk composition suggests that this partial melt was basaltic, which would have had a solidus above the closure temperature of the Lu–Hf system. The emplacement of basaltic melts into subducted continental lithosphere at ~7 Ma is also consistent with the tectonic evolution of the Woodlark Rift (see discussion below). Our preferred interpretation of the ~7 Ma Lu–Hf age from the coesite eclogite is that this age records the time of isotopic closure when this sample crystallized at UHP conditions. The ~7 Ma Lu–Hf age records the end of garnet growth, which corresponds to the time when the (U)HP mineral assemblage formed in this sample.

4.2. Garnet amphibolite in shear zone carapace

Sample 0620d (Fig. 1) is a medium- to coarse-grained amphibolite gneiss from the shear zone carapace on northern Goodenough Island. It contains large (1–2 cm), partially-retrogressed, garnet porphyroblasts in an amphibole + biotite + quartz + feldspar matrix. The large garnets in this sample are mantled by a matrix of preferentially oriented amphiboles and surrounded by pressure shadows composed of quartz and plagioclase (Little et al., in press). The rims of these large garnet porphyroblasts are partially retrogressed to amphibole.

Major element X-ray maps (Fig. 3a) of a large garnet porphyroblast from this sample do not show strong zoning. There appears to be a gradation from high Ca, Mg, and Fe, but low Mn, from the rim to the core of the imaged garnet. Of these elements, Mg is the most strongly zoned. Mg is enriched in a thin uneven concentric band within the garnet rim. The concentration of Lu was measured along a rim to rim transect through a ~1.5 cm diameter garnet porphyroblast in this sample, revealing an abrupt increase in Lu concentration in the apparent core region of the garnet.

A linear regression for sample 0620d (Fig. 3b) using five garnet fractions and one Savillex-dissolved, garnet-free whole-rock fraction
consisting mostly of amphibole yields an age of 65.8 ± 6.0 (MSWD = 68) and a poorly defined initial $^{176}$Hf/$^{177}$Hf of ~0.282630 ($\varepsilon_{Hf}(65.8 \text{ Ma}) = -4$). A separate regression excluding the two garnet fractions with the highest $^{176}$Lu/$^{177}$Hf ratios, which plot clearly below the regression for the other four analyses yields a more precise age of 68.0 ± 3.6 (MSWD = 8.4) and an initial $^{176}$Hf/$^{177}$Hf of ~0.282560 ($\varepsilon_{Hf}(68.0 \text{ Ma}) = -6$). This is our preferred age for this sample and the oldest determined in this study. The Lu enriched garnet core is consistent with prograde growth zoning, giving rise to our interpretation that the ~68 Ma age records garnet growth during a Late Cretaceous/Early Paleocene metamorphic event. The age discrepancy between these two regressions, however, indicates there is some complexity in the Lu–Hf isotope systematics of these large garnet porphyroblasts (see below). While the isochron ages are concordant, these regressions illustrate the sensitivity of results based on the choice of fractions used for isochron age determination.

The large ~68 Ma garnet porphyroblasts in this sample are hosted within the Pleistocene shear zone carapace (Baldwin et al., 1993; Hill, 1994) of the D’Entrecasteaux Islands MCCs. These large garnet porphyroblasts are strongly mantled by a mylonitic fabric, a further indication that these porphyroblasts pre-date development of the shear zone gneiss. The outermost regions of the large garnet porphyroblasts in this sample are assumed to be in textural equilibrium with amphibole in the rock matrix, and major element X-ray maps reveal only very weak compositional gradients throughout the large garnet. These two observations support the possibility that thermal equilibration and partial retrogression occurred in these garnets, probably related to formation of the shear zone carapace for the D’Entrecasteaux Islands MCCs during the late Cenozoic. However, the Lu–Hf isotopic systematics remained undisturbed during mylonitization.

The ~68 Ma Lu–Hf garnet age from this sample indicates that the Lu–Hf isotopic systematics in garnets have largely remained closed...
since the time of initial garnet growth. It is possible that the large size of the garnet porphyroblasts coupled with the concentration of Lu in their cores, shielded the Lu from thermal equilibration during the late Cenozoic formation of the shear zone. It is somewhat surprising that the two garnet fractions with the highest Lu/Hf ratios have Hf isotopic compositions below the regression for the remaining garnet fractions. The cores of the garnets are enriched in Lu, suggesting that garnet fractions with high Lu/Hf ratios might represent the core that should yield an older age. The slightly younger age and higher MSWD obtained if these two high Lu/Hf fractions are included could indicate complex Lu–Hf behavior in these large garnets. This complexity, however, is not severe enough to significantly impact the isochron age, as both regressions yielded Lu–Hf ages that are within error of each other.

4.3. Garnet amphibolite from the southern-rifted margin

Sample 04148a (Fig. 1) is a fine-grained amphibolite gneiss from western Misima Island on the southern rifted margin of the Woodlark Rift. This rock is composed of garnet + quartz + amphibole + minor clinopyroxene + plagioclase. It contains elongate garnet layers (up to 4 mm in length) comprised of aggregates of sub-millimeter polygonal and inequigranular garnet grains. There are currently no P-T constraints for this sample, but results from elsewhere in the lower plate of the Misima Island MCC indicate upper-amphibolite facies to lower eclogite facies metamorphic conditions (i.e., P = 12–16.5 kbar; T = 750–810 °C; Peters, 2007). Major element maps obtained across one of the garnet layers reveal complex zoning (Fig. 4a). Individual garnet grains making up the elongate garnet layers can be grouped into two categories based on the distribution of Ca, Mg, Fe, and Mn, but cannot be distinguished from one another optically. The upper-right hand region of the layer shown in Fig. 4a is populated by garnets that have rims with higher Mn than their cores. The lower-left hand region of the layer has garnet grains with the opposite relationship (i.e., cores enriched in Mn relative to their rims). Fe, Mg, and Ca exhibit the inverse behavior to Mn. Between these two chemically distinct regions of the layer, there is a zone where major element variation within individual garnet grains is highly variable.

The elongate garnet layers in this sample are part of a penetrative stretching lineation, and these textures are similar to those that have been documented to record high strain conditions where dynamic recrystallization and diffusion creep in garnet accommodated deformation (Storey and Prior, 2005; Terry and Heidelbach, 2004). This includes the complex sub-millimeter scale major element zoning in individual garnet grains, the presence of elongate layers that define a stretching lineation in the amphibolite, and the overall arrangement of garnet grains in the layers.

The concentration of Lu was measured across three garnet layers, but we observed no systematic variation in Lu (Fig. 4a). The analytical spot size of the LA-ICP-MS Lu analysis is larger than many of the individual garnet crystals making up the garnet layers in this sample. Because of this, it was not possible to determine if concentration variations exist within individual garnet grains.

A linear regression using four garnet separates, a pyroxene and an amphibole separate, and a bomb-dissolved whole rock fraction (sample 04148a; Fig. 4b) yields a Lu–Hf age of 12.8 ± 3.4 Ma (MSWD = 2.0) with an initial 176Hf/177Hf of 0.283080 ± 34 (ε 176Hf/177Hf = 10.7). A second isochron excluding the bomb dissolusion whole rock yields an age of 11.2 ± 2.1 Ma (MSWD = 0.64) with an initial 176Hf/177Hf of 0.283099 ± 23 (ε 176Hf/177Hf = 11.3).

The element maps from the Misima Island garnet amphibolite show that individual garnet crystals making up the elongate layers do not all have the same composition. Garnets for Lu–Hf analysis were picked under plane light, where it is not possible to distinguish between garnet grains with different compositions. It is possible that different age populations were mixed together during the picking process. Another difficulty arises from not knowing whether the concentration of Lu changes within the individual garnet grains. Mixing between two garnet age populations, however, would be expected to result in considerable scatter on the isochron diagram, and should be recognizable. The ~12 Ma Lu–Hf age indicates either the Lu–Hf isotopic system of pre-existing garnets was reset during recrystallization, or any pre-existing garnets do not pre-date recrystallization by more than a few million years and is therefore beyond analytical resolution. The ~12 Ma Lu–Hf garnet isochron age most likely records the time when the garnet layers formed in this sample, possibly associated with dynamic recrystallization.

5. Discussion

5.1. Tectonic implications of Lu–Hf ages

Samples in this study yield different Lu–Hf garnet ages, and it is appropriate to address the tectonic implications of the Lu–Hf ages from the two regions (D’Entrecasteaux Islands and Misima Island) separately.

5.1.1. Western Woodlark Rift (D’Entrecasteaux Islands Region)

We interpret the ~68 Ma Lu–Hf garnet age from the shear zone gneiss (0620d) as dating garnet growth during a Late Cretaceous metamorphic event. The Lu–Hf garnet age for this sample is within error of the upper range (~65 to ~56 Ma) of K–Ar and amphibole 40Ar/39Ar apparent ages reported by Lus et al. (2004) from granulites in the metamorphic sole of the early Mesozoic Papuan Ultramafic Belt (PUB) on mainland PNG, and with ~66.4 Ma zircon from inferred PUB remnants in close proximity to the active seafloor spreading rift tip (Monteleone et al., 2001). The presence of ~68 Ma prograde garnet preserved in the Pleistocene shear zone carapace bounding the Goodenough Island MCC (Baldwin et al., 1993) suggests that this sample may have initially formed during metamorphism associated with ophiolite obduction in southeastern PNG (Davies and Jacques, 1984).

Following ~68 Ma garnet growth, the next event recorded by garnets in the D’Entrecasteaux Islands is crystallization of the coesite eclogite at ~7 Ma. We propose that the coesite eclogite crystallized directly from a basaltic partial melt of the upper mantle, and that the ~7 Ma Lu–Hf garnet age records the time of this event (Fig. 5a). How (U)HP metamorphism at ~7 Ma relates to obduction of the PUB is unknown, but (U)HP metamorphism predates sea floor spreading in the Woodlark Basin.

Seismic observations of the MCCs in the D’Entrecasteaux Islands reveal that crustal thinning in the western Woodlark Rift is compensated by upwelling mantle with anomalously low density (Abers et al., 2002). High elevations in the D’Entrecasteaux Islands are currently supported by buoyant mantle, and the seismic Moho beneath this region is elevated by 10–15 km (Abers et al., 2002). P-wave anomalies in the D’Entrecasteaux Islands also indicate that the sub-continental mantle lithosphere has been replaced by asthenosphere (Abers et al., 2002). The early stages of asthenospheric upwelling and consequent partial melting appears to have occurred at ~7 Ma; a record of this is preserved in garnets from the coesite eclogite.

Crystallization of basaltic melts at UHP conditions, at ~7 Ma in the D’Entrecasteaux Island region, was subsequently followed by the onset of rapid exhumation from the UHP depths in this region (Fig. 5b). This is supported by the fact that cooling ages from the MCCs in this region are only a few m.y. younger than the ~7 Ma Lu–Hf and U–Pb zircon ages recording crystallization of the coesite eclogite (Baldwin et al., 1993). Little is known about the tectonic evolution of the region between the time of obduction at ~68 Ma and crystallization of the coesite eclogite at ~7 Ma.

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5.1.2. Eastern Woodlark Rift (Misima Island Region)

The tectonic context of the ~12 Ma Lu–Hf garnet age of the Misima Island amphibolite is less certain. The ~12 Ma garnets strongly resemble dynamically recrystallized garnet found in retrogressed eclogites (Storey and Prior, 2005) from the Glenelg–Attadale Inlier of NW Scotland. According to these authors, garnet in rocks with evidence for dynamic recrystallization can be a mixture of the garnet originally present and garnet that formed in response to deformation. This is because the grain boundaries of pre-existing garnet porphyroblasts, experiencing diffusion-accommodated grain boundary sliding, become progressively recrystallized, while at the same time additional garnets form adjacent to the pre-existing grains. It is not possible to rule out the possibility that the ~12 Ma Lu–Hf age from this sample is a mixed age, although the preferred interpretation is that this age records dynamic recrystallization of garnet at ~12 Ma.

Middle Miocene granitic, granodioritic, and dioritic igneous rocks as well as high-K volcanic rocks occur in the southeastern parts of the Papuan peninsula and on the southern- and northern-rifted margins of the Woodlark Basin (Ashley and Flood, 1981; Smith, 1973a,b; Smith and Davies, 1976). The widespread occurrence of middle-Miocene igneous rocks in southeastern PNG has been cited as evidence for active subduction of oceanic lithosphere beneath PNG during middle Miocene time, and the ~12 Ma age could result from middle Miocene-aged subduction related metamorphism in this region (Fig. 5c). It is...
possible that this middle Miocene metamorphism was not widespread, and not recorded elsewhere in the Woodlark Rift. Alternatively, the ~12 Ma age may record recrystallization in response to ongoing oblique convergence between the Australian and Pacific plates during Middle Miocene times, and may not be related to subduction (e.g. Hill and Hall, 2003).

Another alternative for producing the ~12 Ma garnet age is that garnet originated in a manner similar to the formation of the ~7 Ma coesite eclogite. The onset of seafloor spreading in the Woodlark Basin occurred at 6 Ma (Taylor et al., 1995), but presumably crustal thinning and asthenospheric upwelling preceded lithospheric rupture by at least a few m.y. The ~12 Ma Lu–Hf garnet age from the Misima Island sample could thus record the arrival of hot asthenospheric material into the lower crust ahead of the earliest phase of rifting in the eastern reaches of the Woodlark Rift. The protolith of the ~12 Ma garnet amphibolite may have experienced recrystallization as a result of asthenospheric upwelling, or it is possible that the ~12 Ma garnet amphibolite crystallized directly from a partial melt associated with the rising asthenosphere. More work is needed to fully understand the tectonic implications of dynamic recrystallization of garnet on Misima Island at ~12 Ma.

**5.1.3. Tectonic summary**

Lu–Hf garnet ages indicate that the metamorphic history of garnet bearing rocks exhumed in the Woodlark Rift dates back to an episode of Late Cretaceous ophiolite obduction. Following Late Cretaceous tectonic collision responsible for producing the ~68 Ma garnets, now preserved in the Pleistocene shear zone carapace of the Goodenough Island MCC, little is known about the tectonic evolution of ophiolite exhumed in the Woodlark Rift. The relationship between garnet growth in the eastern Woodlark Rift to those in the western Woodlark Rift is presently unclear.

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Fig. 5. a) Schematic diagram illustrating the proposed mechanism for the origin of the ~7 Ma coesite eclogite in the D’Entrecasteaux Islands. We propose that the coesite eclogite crystallized from an asthenospheric melt that was injected into cold subducted continental lithosphere. This occurred during the early phases of rifting in the region. b) Schematic diagram illustrating the structural context of the ~7 and ~68 Ma garnets in the D’Entrecasteaux Islands. Note that the ~7 Ma garnets are found in the core zone whereas the ~68 Ma garnets are found in the shear zone carapace. The seismic Moho is currently located ~26–29 km below the D’Entrecasteaux Islands region (Abers et al., 2002). c) Series of schematic tectonic cross-sections illustrating the possible tectonic environment for dynamic recrystallization of garnet on Misima Island. The relationship between garnet growth in the eastern Woodlark Rift to those in the western Woodlark Rift is presently unclear.
Middle Miocene subduction-related igneous rocks in PNG, as well as the occurrence of ~12 Ma garnet amphibolite on Misima Island.

Rifting in the Woodlark Basin is currently focused in an area of former continental subduction. Asthenospheric upwelling associated with this rifting has resulted in hot material from the mantle becoming entrapped within cold continental lithosphere where it crystallized at UHP conditions (Fig. 5a). In the D’Entrecasteaux Islands, this apparently occurred at ~7 Ma, only a few m.y. before rapid exhumation. The emplacement of hot asthenospheric material into the former subduction complex does not appear to have resulted in widespread recrystallization and isotopic resetting, as is evidenced by the preservation of the large ~68 Ma garnet porphyroblasts currently found in the shear zone carapace (Fig. 5b).

5.2. Implications for the interpretation of Lu-Hf garnet ages

The pristine nature and young age of the coesite eclogite sample provides a rare opportunity to study the Lu-Hf isotopic record of (U)HP metamorphism in a garnet that has not yet been overprinted. The age from this sample corresponds to the time when this sample crystallized at (U)HP conditions. We did not detect prograde Lu zoning in garnets from this sample, suggesting that there is no record of initial garnet growth, and only the time when the (U)HP mineral assemblage crystallized is preserved in the Lu-Hf isotopic systematics. In assessing the robustness of our assertion that Lu is homogeneously distributed in garnets from the coesite eclogite we compared our results to those of Skora et al. (2006). These authors determined trace element profiles across the exact cores of eclogite garnets that were prepared by X-ray tomography so as to ensure a perfectly central cut. They documented an extremely narrow central peak for Lu (as well as Yb and Tm) that would have gone unrecognized if the garnets had not been cut across their exact centers. Since X-ray tomography was not used in this study to ensure garnets in the coesite eclogite were cut across their exact centers, we cannot rule out the possibility that an exceptionally small zone of high Lu has gone undocumented in garnets from the ~7 Ma coesite eclogite.

It is important to note, however, that the average Lu concentrations for LA-ICP-MS spot analyses (Fig. 2a) and those determined by isotope dilution (Table 1) for the garnet fractions used to construct the isochron diagrams are in good agreement with one another. This agreement is an indication that there is probably not an undocumented region of high Lu in garnets from the coesite eclogite, as this region would be expected to raise the Lu concentration for the isochron fractions. The confidence with which garnet trace element profiles can be interpreted is clearly an important consideration in assessing the meaning of Lu-Hf garnet ages. If our interpretation of the ~7 Ma age is correct, the homogeneous distribution of Lu in garnets from the coesite eclogite indicates that thermal re-equilibration is not the only way to produce a garnet lacking Lu zoning.

Another important consideration for interpreting Lu-Hf garnet ages from (U)HP metamorphic terranes arises out of the relationship between the three samples examined from the Woodlark Rift. The young age and homogeneous distribution of Lu in garnets from the ~7 Ma coesite eclogite stand in stark contrast to the presence of Lu-Hf eclogite stand in stark contrast to the presence of Lu-Hf garnets from the (U)HP metamorphic terranes. We did not detect prograde Lu zoning in garnets from the ~7 Ma age is correct, the homogeneous distribution of Lu in garnets from the Woodlark Rift. The fact that three different Lu-Hf isotopic ages were obtained on garnet bearing metamorphic rocks exhumed within this active transient plate boundary zone illustrates the utility of the Lu-Hf system for piecing together the history of a tectonically complex region. However, it is somewhat disappointing that results cannot be used to constrain the onset or duration of (U)HP metamorphism, an objective at the outset of this study.

Results illustrate the potential for preservation of multiple generations of garnet in metamorphic rocks exhumed within transient plate boundary zones. It is not uncommon for Lu-Hf garnet ages from a particular region to span several tens of m.y. (e.g. Cheng et al., 2008; Kylander-Clark et al., 2007) to hundreds of m.y. (e.g. Zirakparvar et al., 2010). In cases where a large gap in the Lu-Hf ages is not apparent between the different samples from a particular region, as in the samples from the Woodlark Rift, it might be easy to mistakenly attribute the ages as all being related to the same tectonic event. This could potentially lead to the development of erroneous tectonic models, especially in the case of terranes that have been re-incorporated into an orogen with the possibility of subsequent tectonic, metamorphic, and/or thermal overprintng.

6. Conclusions

Garnet Lu–Hf ages determined in this study provide valuable insights into the tectonic evolution of garnet bearing rocks exhumed within the Woodlark Rift, as well as the interpretation of garnet ages from geologically complex regions:

1) The oldest garnets dated in the Woodlark Rift yielded a Lu–Hf age of ~68 Ma. We infer these garnets grew during Latest Cretaceous metamorphism that occurred during southward obduction of the Papuan Ultramafic Belt (Davies and Jacques, 1984; Lus et al., 2004).

2) The youngest Lu–Hf garnet age of ~7 Ma from a coesite eclogite records crystallization at UHP conditions. This occurred when a garnet-bearing partial melt intruded subducted continental crust during asthenospheric upwellung in the earliest stages of rifting in the western Woodlark Rift.

3) The ~12 Ma Lu–Hf garnet age from the lower plate of the Misima Island MCC, on the southern rifted margin, records dynamic recrystallization during amphibolite facies metamorphism. There are several possible tectonic interpretations of this ~11 Ma garnet Lu–Hf age.

4) Preservation of Lu–Hf isotopic systematics that record garnet growth at ~68 Ma, despite incorporation into a Pleistocene crustal scale shear zone indicates that the Lu–Hf garnet geochronometer can resist isotopic resetting during intense deformation and metamorphism. Results indicate that unambiguous tectonic interpretations of garnet Lu–Hf isotopic ages from metamorphic rocks exhumed within transient plate boundary zones may be difficult to extract, especially in cases where garnet bearing rocks have been subsequently incorporated into an orogen during tectonism unrelated to the events that formed them.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.epsl.2011.06.016.

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