Late Miocene coesite-eclogite exhumed in the Woodlark Rift

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ABSTRACT

Late Miocene–Pliocene eclogites were exhumed in the Woodlark Rift of eastern Papua New Guinea, an actively extending region west of the Woodlark Basin seafloor spreading center. We report the discovery of coesite in late Miocene eclogite from the lower plate of one of the D'Entrecasteaux Islands metamorphic core complexes within the Woodlark Rift. Zircon crystallization temperatures (650–675 °C) and ^{238}U/^{206}Pb age (ca. 8 Ma), and rutile thermometry (695–743 °C) combined with garnet-pyroxene thermometry (600–760 °C) and garnet-pyroxene-phengite barometry (18–27 kbar), indicate that the coesite-eclogite was exhumed from mantle depths (≥90 km) to the Earth's surface at plate tectonic rates (cm yr^{-1}). This late Miocene coesite-eclogite is the youngest exhumed ultrahigh-pressure (UHP) rock on Earth, and its preservation ahead of the westward-propagating seafloor spreading center forces reevaluation of models for UHP exhumation, as well as the geologic and tectonic evolution of the Woodlark Rift.

Keywords: coesite-eclogite, ultrahigh-pressure exhumation, Woodlark Rift.

INTRODUCTION

One of the most exciting frontiers in the field of continental dynamics in recent decades concerns the formation and exhumation of ultrahigh-pressure (UHP) rocks. With the discovery of UHP polymorphs of silica (coesite; Chopin, 1984; Smith, 1984) and carbon (diamond; Nasdala and Massone, 2000; Sobolev and Shatsky, 1990) in collisional orogens came the realization that buoyant continental crust can be subducted to mantle depths and subsequently exhumed to the Earth's surface. The number and volume of known UHP terranes indicate that subduction and exhumation of continental crust has had a major impact on Earth's evolution, including the recycling of continental crust, and the exchange of material between the crust and mantle (Chopin, 2003; Liou et al., 2004).

Coesite, the high-pressure polymorph of silica, and the primary indicator mineral of UHP metamorphism, requires high pressure/temperature (*P*/*T*) conditions for its formation. Coesite inclusions occur in mechanically strong minerals (e.g., garnet, omphacite, zircon; Gillet et al., 1984). While some coesite inclusions are untransformed (Tabata et al., 1998), most exhibit partial transformation to palisade quartz. The volume increase resulting from the coesite-quartz transition results in rupture and radial fracturing of the host grain (Van der Molen and van Roermund, 1986). In cases where partial transformation has occurred, petrographic observations target potential relict coesite that can be positively confirmed by laser Raman spectroscopy (Boyer et al., 1985; Gillet et al., 1984). In this paper we present the first evidence, and new *P-T* constraints, for coesite-eclogite exhumed in the Woodlark Rift, and discuss implications for models of HP-UHP rock exhumation.

PRESSURE-TEMPERATURE-TIME EVOLUTION OF COESITE-ECLOGITE IN THE WOODLARK RIFT

Variably retrogressed eclogite facies rocks have long been recognized (Davies and Ives, 1965) in the lower plates of metamorphic core complexes (Davies and Warren, 1988, 1992; Hill and Baldwin, 1993) exposed in the D'Entrecasteaux Islands (Fig. 1), in the active Woodlark Rift of eastern Papua New Guinea. Structural and field evidence (Hill, 1994; Hill and Baldwin, 1993), combined with U-Pb, trace element, and rare earth element (REE) data (Baldwin and Ireland, 1995; Baldwin et al., 2004; Monteleone et al., 2007) indicate that mafic eclogites and their felsic host gneisses were metamorphosed together under eclogite facies conditions from the late Miocene to Pliocene.

The eclogite studied (89321c; Fig. 1) was sampled from a locality in which mafic eclogites were previously described as xenoliths in weakly foliated leucogranite (e.g., Davies and Warren, 1988; Fig. 2 in Monteleone et al., 2007). However, a return to this locality in January 2008 revealed significant new outcrop, inferred to result from tsunami waves triggered by the 1 April 2007 magnitude 8.1 Solomon Islands earthquake. Additional observations revealed that mafic eclogites occur as boudins within strongly foliated and isoclinally folded garnet-bearing quartzo-feldspathic host gneisses. Amphibolite rinds encapsulate the eclogite boudins, the protolith of which appears to have been mafic dikes. Pegmatite occurs in strain shadows surrounding the amphibolite rinds, as well as in veins within the host gneiss.

Previous studies of retrogressed eclogite from this locality reported garnet-pyroxene temperatures ranging from ~700 to 750 °C and minimum pressures of ~17–19 kbar based on the jadeite content of omphacite (Davies and Warren, 1992; Hill and Baldwin, 1993). In situ U-Pb ion probe analyses of zircon inclusions in garnet from the sample studied (89321) yielded a ^{238}U/^{206}Pb age of 7.9 ± 1.9 Ma (2σ), and, together with in situ ion probe trace element and REE chemistry on zircon and garnet pairs, indicate zircon growth under eclogite facies conditions (Monteleone et al., 2007).

The eclogite investigated preserves a peak assemblage of garnet + omphacite + rutile + phengite + SiO_2. Within the matrix, rutile is rimmed by retrograde titanite and is intergrown with ilmenite. Anhedral garnet contains inclusions of omphacite, rutile, and zircon. Petrographic observations revealed a 150 × 200 μm SiO_2 inclusion at the center of a radial fracture pattern in its omphacite host (Fig. 2). Cathodoluminescence imaging shows that the SiO_2 inclusion is polymineralic with angular, fractured, darker regions surrounded by rims of polycrystalline quartz exhibiting palisade texture (Fig. 2 inset). The SiO_2 inclusion also hosts a zircon. Raman spectroscopy of the SiO_2 inclusion confirms the presence of both coesite and α-quartz (Fig. 3). Five Raman spectra yielded diagnostic Raman bands (Liu et al., 1997) for coesite at 520, 354–356, 270, and 176 cm^{-1}, and for quartz, at 463–465 cm^{-1}.

The omphacite host of the partially transformed coesite inclusion and surrounding garnet and phengite were used to constrain the *P-T* path of this sample using garnet-pyroxene-phengite barometry (Ravna and Terry, 2004) and garnet-pyroxene thermometry (Ravna, 2000). The assemblage and corresponding mineral compositions are assumed to reflect an equilibrium volume preserved when the coesite-eclogite was at (or near) UHP conditions. These thermobarometers yielded temperatures of 600–760 °C and pressures of 18–27 kbar. Given uncertainties regarding the oxidation state of Fe in garnet and omphacite, and the potential for post-peak Fe-Mg volume diffusion during retrograde HP metamorphism, [Zr] in rutile and [Ti] in zircon thermometry was used to further constrain temperatures attained by this coesite-eclogite. Both rutile inclusions (e.g., in omphacite; Fig. 2) and matrix rutile were analyzed. Rutile temperatures, determined using Tomkins et al.'s (2007) calibration that accounts for the pressure effect on [Zr] in rutile, yield temperatures from 695 to 743 °C (assuming $P = 28$ kbar; Fig. 4). No systematic temperature differences were observed for matrix versus inclusion populations. In comparison, thermometry based on [Ti] in zircon (Ferry and Watson, 2007; Watson et al., 2006) yielded temperatures of 650–675 °C (Fig. 4). These are interpreted as zircon crystallization temperatures in this sample.

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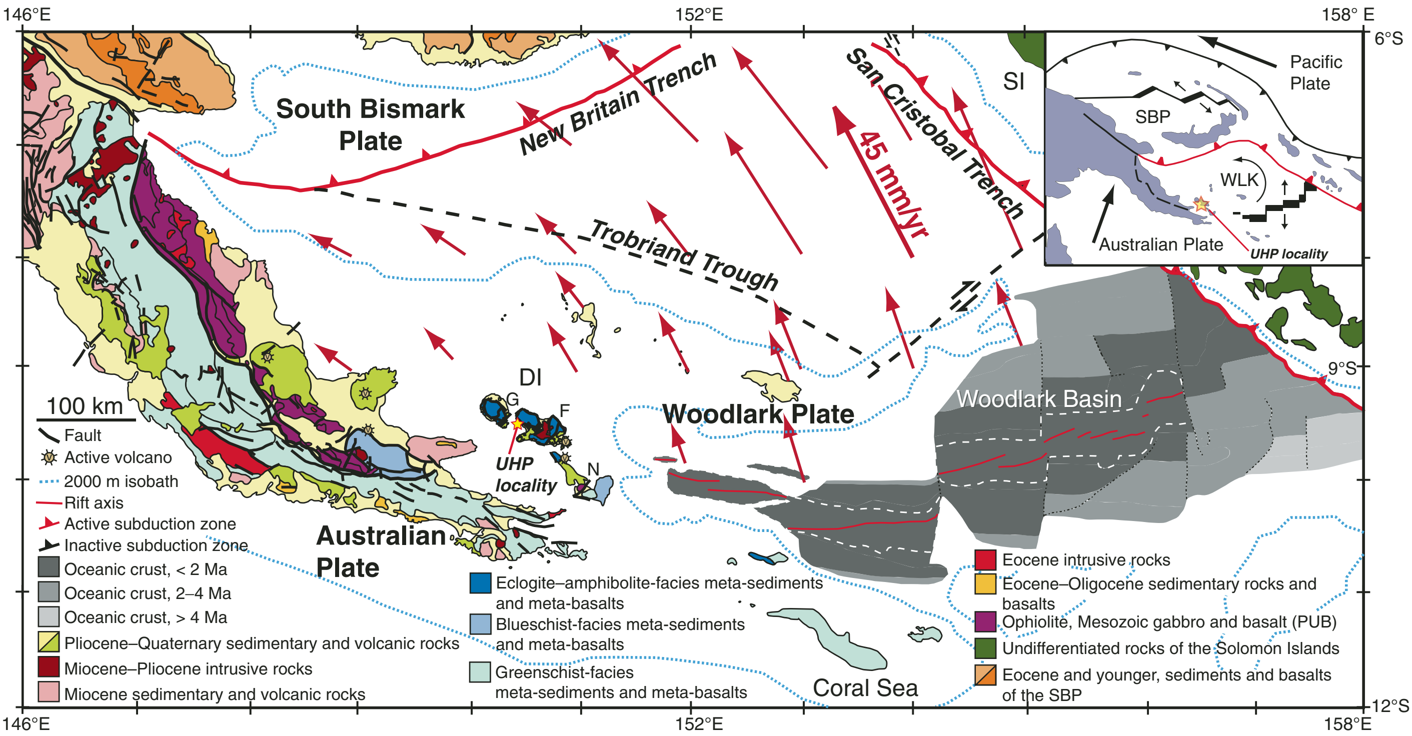

Figure 1. Tectonic and geologic map of eastern Papua New Guinea (Baldwin et al., 2004). Asterisk indicates coesite-eclogite locality (9°29′0″S, 150°27′40″E). Red arrows indicate present-day plate motion vectors (Wallace et al., 2004). White dashed line indicates Bruhnes chron. Inset shows microplates of Australian-Pacific plate boundary zone. Abbreviations: WLK—Woodlark plate; SBP—South Bismarck plate; UHP—ultrahigh pressure. Map: DI—D'Entrecasteaux Islands; G—Goodenough Island; F—Fergusson Island; N—Normanby Island; PUB—Papuan ultramafic belt. After Baldwin et al. (2004).

The combined textural and mineral composition data set is used to assess the HP–UHP history preserved in the coesite-eclogite (Figs. 2 and 4). At 7.9 ± 1.9 Ma zircon crystallized under eclogite facies conditions, at temperatures of 650–675 °C (i.e., below the closure temperature for Pb diffusion in zircon and below the closure temperature for Ti diffusion in zircon [Cherniak et al., 2007; Cherniak and Watson, 2000]). Available data indicate that only one population of zircon grew at this time. In other words, ^{238}U/^{206}Pb ages, trace element, and REE analyses do not reveal the presence of inherited zircons or zircons that grew during amphibolite facies retrogression (Monteleone et al., 2007). The presence of preserved coesite indicates that the eclogite reached depths of >90 km during UHP metamorphism. Coesite encapsulated a zircon and was encapsulated by omphacite (Fig. 2). The inferred late Miocene geothermal gradient was ≤8 °C km^{-1} (Fig. 4).

The omphacite host insulated the coesite, enabling it to remain dry (Mosenfelder et al., 2005), while the outer rind of the eclogite block was retrogressed under amphibolite facies conditions during exhumation. The quartzo-feldspathic host gneiss underwent partial melting during exhumation, and pegmatite formed in strain shadows surrounding the amphibolite rind of the coesite-eclogite. Temperatures had decreased to <500 °C (Fig. 6 in Baldwin et al., 1993) by 3.5 Ma, as indicated by muscovite ^{40}Ar/^{39}Ar apparent ages from pegmatite in strain shadows surrounding the amphibolite rind. Apatite fission track data from the quartzo-feldspathic host gneiss indicate cooling to below ~120 °C by 0.6 Ma (Baldwin et al., 1993). These data, together with coesite-eclogite zircon age and crystallization temperatures, suggest an increase in apparent cooling rate (i.e., ~35 °C m.y.$^{-1}$ from 8 Ma to 3.5 Ma, ~135 °C m.y.$^{-1}$ from 3.5 Ma to present) during rapid (cm yr^{-1}) exhumation from mantle depths to the surface.

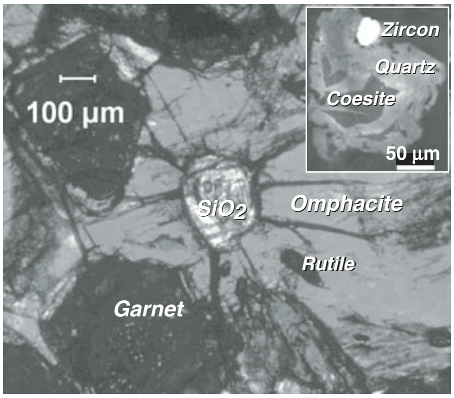

Figure 2. Photomicrograph of coesite-eclogite (sample 89321c). Inset: cathodoluminescence image of the SiO_2 inclusion showing partial transformation of coesite to palisade quartz.

IMPLICATIONS FOR MODELS OF HP-UHP ROCK EXHUMATION

Since the late Miocene, exhumation of the lower plates of the D'Entrecasteaux Islands metamorphic core complexes, including coesite-eclogite, was facilitated by movement on kilometer-scale mylonitic shear zones (Hill, 1994), and likely aided by transport associated with decompression partial melting of the quartzo-feldspathic host gneiss (Auzanneau et al., 2006). Thus *P-T*-time data for coesite-eclogite provide important new constraints on geodynamic models for the evolution of the Australian-Woodlark plate boundary zone.

Vertical extrusion of ductile lower crust within a volcanic arc has been previously proposed as a mechanism by which the D'Entrecasteaux core complexes accommodate extension (Martinez et al., 2001). Three lines of evidence now call into question this model for HP–UHP exhumation in the Woodlark Rift. (1) Receiver function studies indicate that the crust beneath Goodenough and northwest Fergusson Islands is currently 26–29 km thick (Abers et al., 2002). Vertical exhumation of coesite-eclogite from mantle depths is unlikely, because this would require that the crust was at one time >115 km thick, values far exceeding the thickest continental

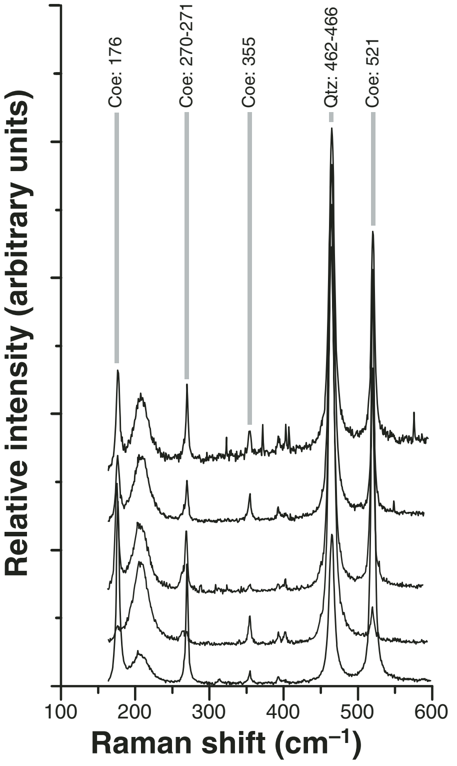

Figure 3. Representative Raman spectra for SiO_2 inclusion. Diagnostic Raman bands for coesite at 520, 354–356, 270, and 176 cm^{-1} and diagnostic Raman bands for quartz at 463–465 cm^{-1} are indicated (Liu et al., 1997). See also Table DR1 in the GSA Data Repository.[1]

crust known on Earth (Wittlinger et al., 2004). (2) Vertical fabrics are not preserved within eclogites and their felsic host gneisses (Hill, 1994; Little et al., 2007). (3) Temperatures, much greater than are indicated by the thermometry presented here, would be encountered within the mantle during transport of the ca. 8 Ma coesite-eclogite from >90 km depths. This would lead to changes in the composition and textures of garnet-pyroxene-phengite-rutile assemblages in the coesite-eclogite, which are not observed. A vertical extrusion model is also inconsistent with the preservation of blueschist facies assemblages nearby in the footwall of the Normanby Island metamorphic core complex (Little et al., 2007).

Our preferred model for HP-UHP exhumation proposes that microplate formation and rotation (Wallace et al., 2004) within the obliquely convergent Australian-Pacific plate boundary zone resulted in rifting that exploits a former subduction thrust (Little et al., 2007; Webb et al., 2005). In this model, northward subduction of the thinned Australian passive continental margin beneath a late Paleocene–early Eocene island arc led to HP–UHP metamorphism of the continental margin and southward obduction of the Papuan Ultramafic Belt (Davies, 1980). Subsequent rifting reactivated inherited structural fabrics, including the original subduction thrust (Davies and Warren, 1988; Little et al., 2007). Rotation of the Woodlark microplate facilitated tectonic exhumation by removing upper plate rocks from above these previously subducted rocks (Webb et al., 2005) and resulted in exhumation of retrogressed eclogites (Baldwin et al., 2004; Monteleone et al., 2007), including coesite-eclogite, within the lower plates of the D'Entrecasteaux Islands metamorphic core complexes (Fig. 1).

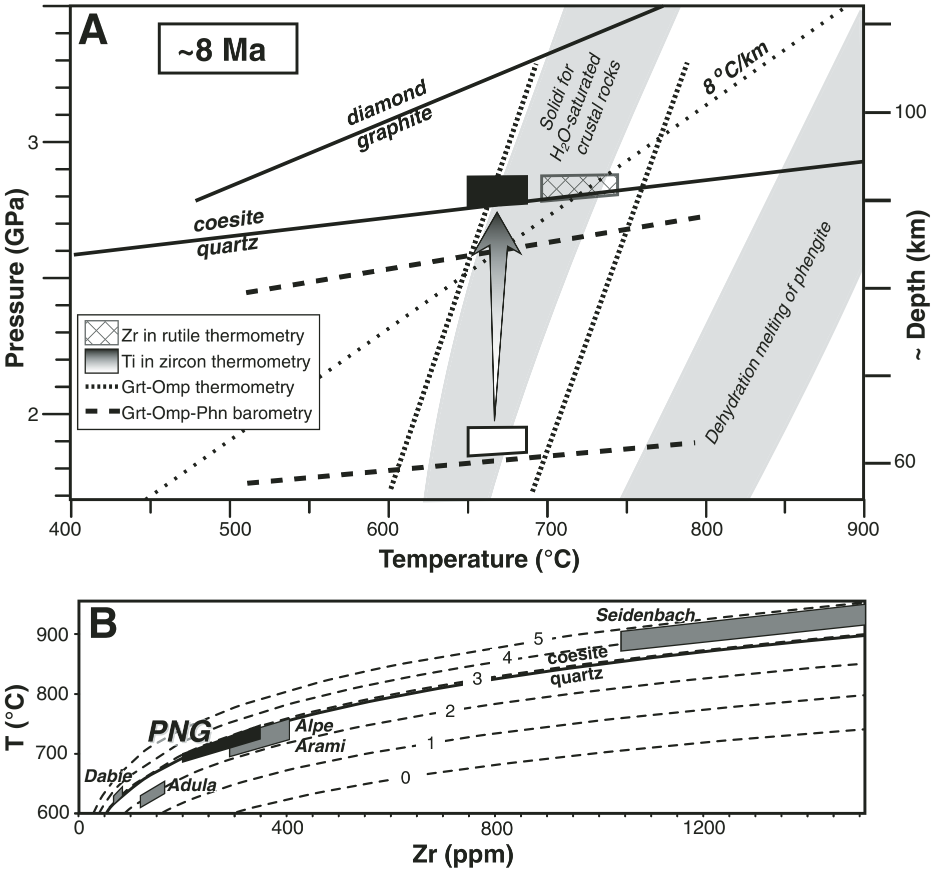

Figure 4. A: Late Miocene pressure-temperature constraints for coesite-eclogite. Quadrilateral defined by maximum and minimum intersections of garnet-pyroxene Fe^{+2}-Mg cation exchange thermometry (Ravna, 2000) and garnet-pyroxene-phengite barometry (Ravna and Terry, 2004). White and black boxes bracket minimum and maximum temperature estimates based on [Ti] in zircon data from five in situ ion microprobe analyses on two zircon grains, assuming no pressure effect exists for the calibration of [Ti] in zircon thermometer (Ferry and Watson, 2007; Watson et al., 2006). White box and arrow indicate pressures associated with zircon crystallization under high-pressure conditions. Black box indicates minimum pressures of zircon crystallization under ultrahigh-pressure (UHP) conditions. Cross-hachured box indicates minimum and maximum temperatures based on [Zr] in rutile thermometry, assuming *P* = 28 kbar, for 16 rutile grains that occur as inclusions and in the matrix (Tomkins et al., 2007). *P-T* fields indicating solidi for H_2O-saturated crustal rocks and dehydration melting of phengite after (Hacker, 2006). Grt-Omp-Phn—garnet-omphacite-phengite. B: Papua New Guinea (PNG) coesite-eclogite rutile thermometry compared with rutile data from other UHP terranes (after Tomkins et al., 2007). Dashed lines indicate pressure (GPa) contours. Electron probe and ion probe data are presented in Tables DR2 and DR3 (see footnote 1).

In comparison with older UHP terranes, structures that have facilitated exhumation in the Woodlark Rift are still active, or have been minimally overprinted by younger and unrelated deformation. The region thus provides an unprecedented natural laboratory for assessing exhumation processes associated with the rapid plate boundary zone transition from convergence to rifting and ultimately seafloor spreading.

CONCLUSIONS

The discovery of coesite in late Miocene eclogite, exhumed in the active Woodlark Rift, provides the first evidence for UHP

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[1] GSA Data Repository item 2008184, materials and methods for Raman spectroscopy, electron probe, and ion probe analyses; and Tables DR1–DR3 (Raman spectroscopy, electron probe, and ion probe data), is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

metamorphism in eastern Papua New Guinea. This is the youngest known coesite-eclogite on Earth, and its exhumation from mantle depths (≥90 km) occurred at plate tectonic rates. Preservation of HP–UHP rocks, ahead of the westward-propagating Woodlark Basin seafloor spreading center, requires reevaluation of the geologic and tectonic evolution of the Woodlark Rift.

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