Can microplate rotation drive subduction inversion?

L.E. Webb[1]*, S.L. Baldwin[1], T.A. Little[2], P.G. Fitzgerald[1]
[1]Syracuse University, Earth Sciences, Syracuse, New York 13244, USA
[2]Victoria University of Wellington, Earth Sciences, P.O. Box 600, Wellington 6140, New Zealand

ABSTRACT

We propose a model for the exhumation of Late Miocene coesite-eclogite in the Woodlark Rift of Papua New Guinea. Reorganization within the obliquely convergent Australian–Pacific plate boundary zone led to formation of the Woodlark microplate. Counterclockwise rotation of the microplate relative to the Australian plate resulted in extensional reactivation of a subduction thrust (subduction inversion) and the exhumation of high- and ultrahigh-pressure (HP-UHP) rocks within the Australian–Woodlark plate boundary zone. The model invokes plate tectonic processes to drive rapid exhumation and predicts spatial and temporal patterns of exhumation to assess its applicability to HP-UHP terranes worldwide.

Keywords: ultrahigh-pressure, exhumation, microplate rotation, subduction inversion.

INTRODUCTION

Subduction of continental crust to mantle depths and its subsequent exhumation are fundamental geologic processes. Case studies indicate that exhumation from ultrahigh-pressure (UHP) conditions may occur at rates as fast as subduction (i.e., cm yr^{-1}; Rubatto and Hermann, 2001). The discovery of Late Miocene coesite-eclogite in Papua New Guinea (Baldwin et al., 2008) provides an unprecedented opportunity to examine mechanisms for rapid exhumation from UHP conditions to the surface in an active tectonic setting.

The present-day tectonic setting of Papua New Guinea (Fig. 1) is characterized by rapid (10–11 cm yr^{-1}) oblique convergence between the Australian and Pacific plates (Johnson and Molnar, 1972), resulting in the formation of several microplates (Tregoning et al., 1998; Wallace et al., 2004). A NW–SE transition along the Papuan Peninsula from a convergent plate boundary to a divergent plate boundary is associated with counterclockwise rotation of the Woodlark microplate relative to the Australian plate (Wallace et al., 2004). The divergent segment in the southeast, the Woodlark Rift, is undergoing a W–E transition from rifting to seafloor spreading and the oldest preserved oceanic crust is ~6 Ma (Taylor et al., 1995, 1999).

High-pressure (HP) and UHP rocks in eastern Papua New Guinea are inferred to have formed during Cenozoic subduction of the Australian continental margin northward beneath a Late Paleocene–Early Eocene island arc and oceanic crust, and mantle of the Papuan Ultramafic Belt (Davies, 1980a; Worthing, 1988; Davies and Warren, 1992). While timing of subduction is poorly constrained, P-T-t data for coesite-eclogite require a low geothermal gradient (< 8 °C km^{-1}) during the Late Miocene (Monteleone et al., 2007; Baldwin et al., 2008). Geophysical data support the existence of a continental slab, contiguous with the Papuan Peninsula, dipping N–NE beneath the Papuan Ultramafic Belt (Finlayson et al., 1977). The presence of a Late Miocene (7.9 Ma; Monteleone et al., 2007) coesite-eclogite in the D'Entrecasteaux Islands indicates that some rocks were subducted to depths ≥ 90 km (T ≥ 650 °C, P ≥ 27 kbar; Baldwin et al., 2008). Isotopic and geochemical data are consistent with in situ metamorphism of the mafic eclogites and felsic hosts (Baldwin et al., 2004; Monteleone et al., 2007; Baldwin and Ireland, 1995).

The HP-UHP rocks are found in the lower plates of metamorphic core complexes distributed along the Australian-Woodlark plate boundary (Davies, 1980a,b; Davies and Warren, 1988; Worthing, 1988; Hill and Baldwin, 1993; Little et al., 2007; Appleby, 1996; Peters, 2007). Footwall blueschist, eclogite, migmatite, gneiss, and Pliocene granodiorite are juxtaposed against an upper plate consisting of the Papuan Ultramafic Belt, unmetamorphosed sediments, and volcanic rocks (Davies and Warren, 1988; Hill et al., 1992; Hill, 1994, Little et al., 2007). Exhumation of HP-UHP rocks was facilitated by top-to-the-N (or NE), kilometer-scale ductile shear zones and normal faults on the northern flanks of the antiformal domes (Davies and Warren, 1988; Hill, 1994; Little et al., 2007). Stretching lineations in mylonites on Normanby Island and in gneisses on the eastern part of Fergusson Island trend N or NNE, roughly parallel to 3.6–0.5 Ma plate motion vectors (Fig. 1B), reflecting exhumation from ~4–2 Ma (Hill and Baldwin, 1993; Baldwin et al., 1993). Lineations in the lower plate on Misima Island (Peters, 2007) also trend parallel to Pliocene plate motion vectors. While these metamorphic tectonites yield Middle-Late Miocene $^{40}Ar/^{39}Ar$ ages (Baldwin et al., 2006), a time for which there is no published plate solution, the Miocene plate motion vectors were probably not significantly different from those of the Pliocene (Goodliffe, 1998). Lineations in gneisses in the domes on Goodenough and western Fergusson Islands (Hill, 1994) are more variable and locally are oblique to the Pliocene plate motion vector. On the northern dip-slope of the Dayman Dome, an incipient metamorphic core complex (Davies and Warren, 1988), lineations trend approximately parallel to the present-day Woodlark–Australia plate motion vector. Available data indicate that structures associated with exhumation are still active (Abers, 2001).

MICROPLATE ROTATION MODEL

A model for the exhumation of HP-UHP rocks in Papua New Guinea is proposed (Fig. 2). Counterclockwise rotation of the Woodlark microplate relative to the Australian plate drives exhumation of the subducted Australian margin via reactivation of the subduction thrust at the base of the Papuan Ultramafic Belt as a normal-sense shear zone. An arc length is determined based on the distance from the pole of rotation (radius) and the amount of relative rotation (α) between the upper and lower plates. Where motion is dip-slip, the arc length is related via the dip angle to exhumation. In other words, horizontal plate motion locally results in normal-sense reactivation of the subduction thrust and unbending of the lower plate as it is exhumed. This concept is supported by the megamullioned and domal morphology and apparent rolling-hinge style kinematics of shear zones on Normanby Island (Little et al., 2007) and the Dayman Dome (Davies and Warren, 1988). The term "subduction inversion" is used to denote the exhumation of the subduction complex due to the normal-sense reactivation of the subduction thrust.

MICROPLATE ROTATION MODEL PREDICTIONS

Evidence for microplate rotation should be recorded in along-strike structural transitions along the plate boundary (e.g., extensional–strike-slip–compressional in Papua New Guinea; Wallace et al., 2004). Segments of the exhumed lower plate may also be offset by transform faults (e.g., Hill, 1994) that plot as small circles about the pole of rotation (e.g., Little et al., 2007). The model predicts regional trends in stretching lineations in the exhumed lower plate that parallel relative plate motion vectors of the upper plate. The model also predicts peak metamorphic field gradients recorded by exhumed rocks and radiometric ages associated with subduction inversion (Fig. 2). Such trends are emergent in the growing thermochronologic data set from Papua New Guinea (Monteleone et al., 2007; Baldwin et al., 1993, 2006).

*Current address: University of Vermont, Geology, Burlington, Vermont, USA; lewebb@uvm.edu.

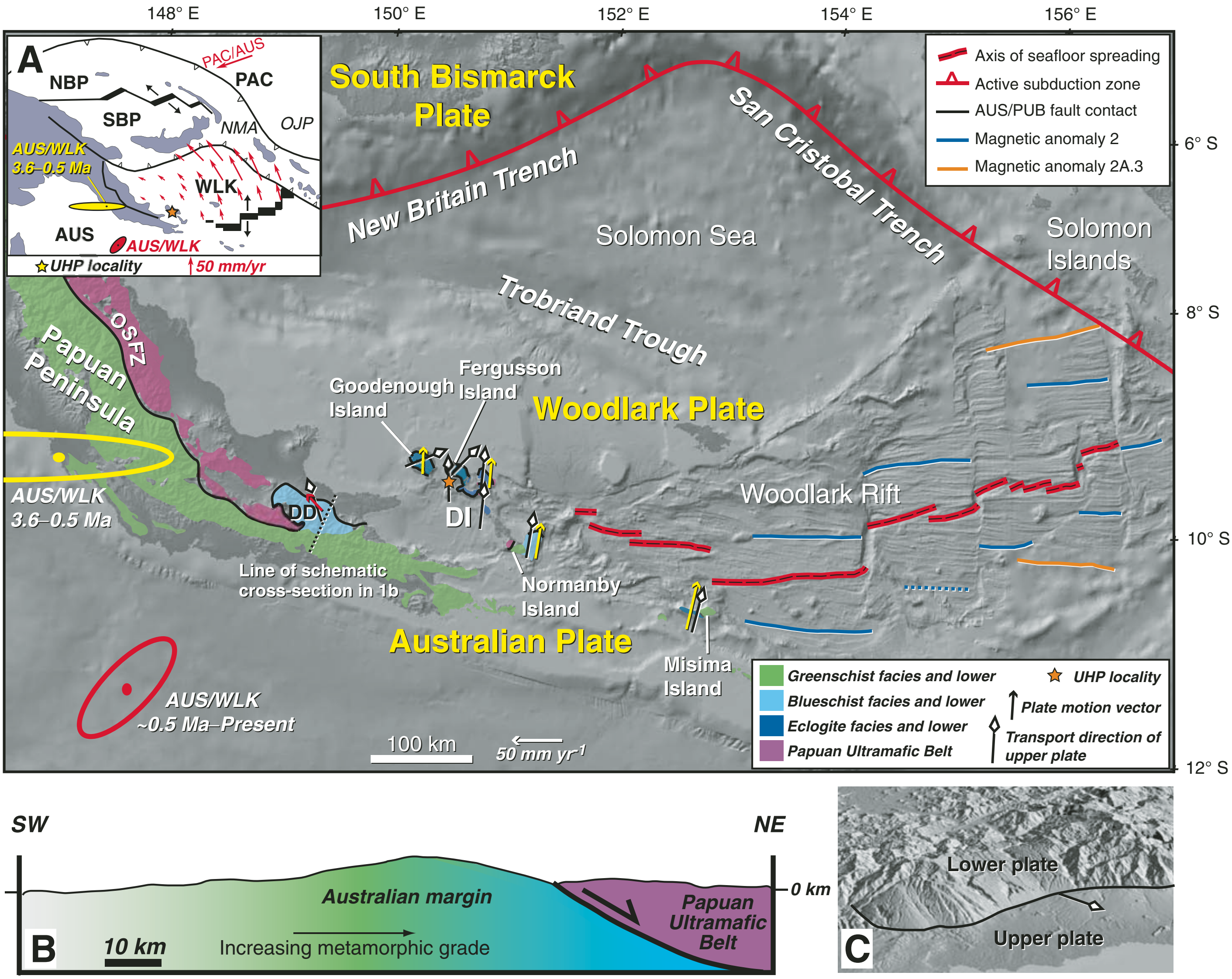

Figure 1.A: Simplified tectonic map of eastern Papua New Guinea. Digital elevation model was created using GeoMapApp (http://www.GeoMapApp.org). Geologic overlay is simplified from Davies (1980a). Pole of rotation for 3.6–0.5 Ma (Taylor et al., 1999) and present-day pole of rotation (Wallace et al., 2004) are shown with error ellipses. AUS—Australian plate; DD—Dayman Dome; DI—D'Entrecasteaux Islands; OSFZ—Owen Stanley fault zone; PUB—Papuan Ultramafic Belt. Magnetic anomalies from Taylor et al. (1999); chron 2A.3 is dashed where inferred. Woodlark plate motion vectors relative to Australia are color coded relative to the 3.6–0.5 Ma (yellow) and present-day (red) poles of rotation. Transport directions of upper plate are based on our field observations and Little et al. (2007). Inset: Tectonic setting of HP-UHP rocks within the present day Australian-Pacific plate boundary zone. AUS—Australian plate; NBP—North Bismarck plate; SBP—South Bismarck plate; NMA—Northern Melanesian Arc; OJP—Ontong Java Plateau; PAC—Pacific plate; WLK—Woodlark plate. B: Schematic cross section across the Papuan Peninsula (after Davies, 1980b). C: GeoMapApp image of an oblique aerial view of the Dayman Dome detachment fault. No vertical exaggeration; view is from the NNE.

Subduction inversion is predicted to be associated with normal-sense, non-coaxial shear where extension is mainly accommodated along the reactivated subduction thrust. Removal of overburden likely results in localized partial melting and could enhance buoyancy of the slab (e.g., Auzanneau et al., 2006). If negative buoyancy is retained at the former leading edge, the slab is likely under tension, and some degree of coaxial stretching, particularly at deeper structural levels, may occur. As subduction inversion transitions to rifting of the Australian margin, partial melting, magmatism and doming progressively dominate as the Australian lithosphere is attenuated and ultimately ruptures, giving way to seafloor spreading (Fig. 3). While exhumation from HP-UHP conditions to the surface can apparently be attributed to two phases (subduction inversion followed by rifting of the slab), the entire exhumation process represents a continuum in an evolving plate boundary zone.

To assess whether the model can explain rapid exhumation from UHP conditions, we compare predicted exhumation rates with published data. We consider the case of the 7.9 Ma coesite-eclogite exhumed on Fergusson Island. Given the orientation of shear zone lineations and that apatite fission track ages from Fergusson Island are on the order of 0.5 Ma or older, we test the model relative to the 3.6–0.5 Ma pole of rotation (radius ~380 km). The subduction thrust dips 10–40° to the N-NE based on geologic and geophysical studies (Davies, 1980b; Finlayson et al., 1977), a range that encompasses the ~30° N-dipping normal faults on the D'Entrecasteaux Islands (Hill, 1994) and in the Woodlark Rift (Abers, et al., 1997). Applying the average rotation rate from 3.6 to 0.5 Ma of ~4.2° m.y.$^{-1}$ (Taylor et al., 1999) throughout the time interval from 7.9 to 0.5 Ma (i.e., 7.4 m.y. of fault slip) yields an $\alpha = 31°$ and, consequently, an arc length of ~206 km. Using these values, we calculate an average exhumation rate of 0.49 cm

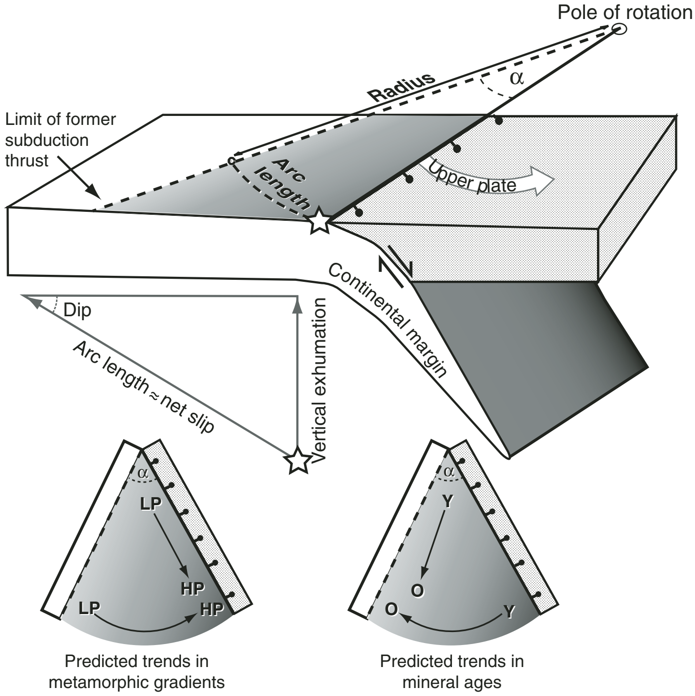

Figure 2. Microplate rotation model for subduction inversion (see text for explanation). The grayscale gradient schematically represents the subduction zone metamorphic gradient recorded in crustal rocks. Pie-slice diagrams represent plan views of the exhumed slab; arrows indicate predicted trends in peak metamorphic gradients and mineral ages for a given mineral and isotopic system (with equivalent *P-T*-D context). LP—lower pressure; HP—higher pressure; Y—younger; O—older.

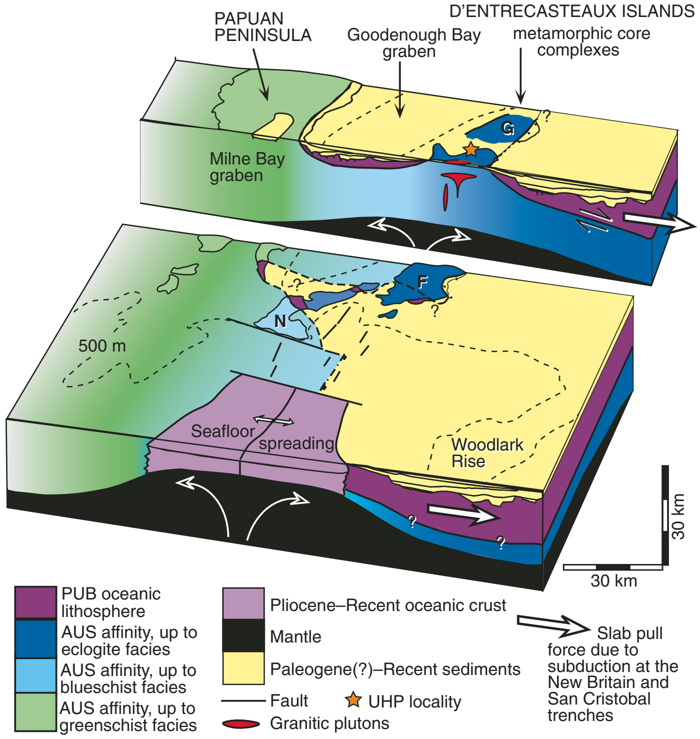

Figure 3. Present-day three-dimensional block diagram of D'Entrecasteaux Islands modified after Hill et al. (1995). G—Goodenough; F—Fergusson; N—Normanby; PUB—Papuan Ultramafic Belt; AUS—Australian plate.

yr^{-1} for a fault dip of 10°, and 1.8 cm yr^{-1} for a fault dip of 40°. Exhumation from UHP conditions (> 90 km), however, is only predicted in this case for a fault dip > 25°, which corresponds to exhumation rates > 1.2 cm yr^{-1} and agrees well with the published average exhumation rate of > 1.1 cm yr^{-1} (Monteleone et al., 2007). The corresponding slip rate is > 2.6 cm yr^{-1}, within the range of horizontal extension rates near the seafloor-spreading rift tip (~20–40 mm yr^{-1} at 151.5°E; Abers, 2001).

DISCUSSION

Rotation of the Woodlark microplate and extension in the Woodlark Rift is related to slab-pull forces associated with subduction of the Solomon Sea lithosphere at the New Britain and San Cristobal trenches (Weissel et al., 1982; Hall, 2001). The inception of subduction there resulted from collision of the Ontong Java plateau with the Northern Melanesian Arc System in the Late Miocene–Pliocene (Coleman and Kroenke, 1981; Petterson et al., 1999; Mann and Taira, 2004), or perhaps as early as Early Miocene (Hall, 2002). Implicit in the microplate rotation hypothesis is that the Solomon Sea region constitutes part of the Woodlark microplate. There is no land above sea level north of the Trobriand Trough, so an independent Solomon Sea microplate cannot be ruled out. However, GPS and seismological data from the greater Pacific-Australian Plate boundary zone are best explained by inclusion of the Solomon Sea as part of the Woodlark microplate, and velocities on the Woodlark microplate fit a rigid plate model well (Wallace et al., 2004).

Are HP-UHP rocks of Papua New Guinea exhumed via a unique geologic process? Millions of years from now, will rifting and seafloor spreading overprint the evidence for subduction inversion? Or, will the HP-UHP rocks be sandwiched in an arc-continent collision zone between the Australian and South Bismarck plates that obscures their true subduction-exhumation history? Papua New Guinea is most likely not geologically unique except for the fact that subduction inversion is 'caught in the act.' The overall structural geometry in Papua New Guinea—asymmetric domes bounded by normal-sense shear zones with stretching lineations that record the relative rotation between upper and lower plates—bears resemblance to the Hong'an–Dabie UHP terrane where trends in metamorphic gradients (Hacker et al., 2004) are similar to those predicted by the microplate rotation model, and lineations record a change in ductile flow inferred to reflect rotation of the slab relative to the upper plate during exhumation (Hacker et al., 2000). Given that subduction inversion in Papua New Guinea is related to slab-pull forces at the New Britain and San Cristobal trenches, a 2-D version of the microplate rotation model also bears similarities to the slab extraction model for the Adula Nappe in the Central Alps (Froitzheim et al., 2003). Because all plates rotate, the microplate rotation model has potential to provide insight into 3-D mechanisms for rapid exhumation of UHP rocks in other regions.

CONCLUSIONS

Counterclockwise rotation of the Woodlark microplate resulted in subduction inversion at the Australian-Woodlark plate boundary and the exhumation of HP-UHP rocks in eastern Papua New Guinea. This neotectonic example provides the basis for a 3-D model in which the magnitude of exhumation is a function of the relative rotation between upper and lower plates, the distance from the pole of rotation, and the geometry of the subduction zone. The model provides a mechanism for rapid exhumation to the surface and testable hypotheses by which to assess its applicability to the exhumation of HP/UHP terranes preserved in the geologic record.

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REFERENCES CITED

Abers, G.A., 2001, Evidence for seismogenic normal faults at shallow dips in continental rifts, in Wilson, R.C.L., Whitmarsh, R.B., Taylor, B., and Froitzheim, N., ed., Non-volcanic rifting of volcanic margins: a comparison of evidence from land and sea: The Geological Society of London Special Publication 187, p. 305–318.

Abers, G.A., Mutter, C.Z., and Fang, J., 1997, Shallow dips of normal faults during rapid extension: Earthquakes in the Woodlark-D'Entrecasteaux rift system, Papua New Guinea: Journal of Geophysical Research, v. 102, p. 15,301–15,317, doi: 10.1029/97JB00787.

Appleby, K., 1996, New model for controls on gold-silver mineralization on Misima Island: Minerals Engineering, v. 48, p. 33–36.

Auzanneau, E., Vielzeuf, D., and Schmidt, M.W., 2006, Experimental evidence of decompression melting during exhumation of subducted continental crust: Contributions to Mineralogy and Petrology, v. 152, p. 125–148, doi: 10.1007/s00410–006–0104–5.

Baldwin, S.L., and Ireland, T.R., 1995, A tale of two eras: Pliocene-Pleistocene unroofing of Cenozoic and late Archean zircons from active metamorphic core complexes, Solomon Sea, Papua New Guinea: Geology, v. 23, p. 1023–1026, doi: 10.1130/0091–7613(1995)023<1023:ATOTEP>2.3.CO;2.

Baldwin, S.L., Lister, G.S., Hill, E.J., Foster, D.A., and McDougall, I., 1993, Thermochronologic constraints on the tectonic evolution of active metamorphic core complexes, D'Entrecasteaux Islands, Papua New Guinea: Tectonics, v. 12, p. 611–628, doi: 10.1029/93TC00235.

Baldwin, S.L., Monteleone, B., Webb, L.E., Fitzgerald, P.G., Grove, M., and Hill, E.J., 2004, Pliocene eclogite exhumation at plate tectonic rates in eastern Papua New Guinea: Nature, v. 431, p. 263–267, doi: 10.1038/nature02846.

Baldwin, S.L., Webb, L.E., Monteleone, B., Little, T.A., Fitzgerald, P.G., Peters, K., and Chappell, J.L., 2006, Continental crust subduction and exhumation: Insights from eastern Papua New Guinea: Geochimica et Cosmochimica Acta, v. 70, Supplement, p. A31, doi: 10.1016/j.gca.2006.06.171.

Baldwin, S.L., Webb, L.E., and Monteleone, B.D., 2008, Late Miocene coesite-eclogite exhumed in the Woodlark Rift: Geology, v. 36, p. 735–738, doi: 10.1130/G25144A.1.

Coleman, P.J., and Kroenke, L.W., 1981, Subduction without volcanism in the Solomons island arc: Geo-Marine Letters, v. 1, p. 129–134, doi: 10.1007/BF02463330.

Davies, H.L., 1980a, Crustal structure and emplacement of ophiolite in southeastern Papua New Guinea: Colloques Internationaux du C.N.R.S, Volume 272, p. 17–33.

Davies, H.L., 1980b, Folded thrust fault and associated metamorphics in the Suckling-Dayman Massif, Papua New Guinea: American Journal of Science, v. 280, p. 171–191.

Davies, H.L., and Warren, R.G., 1988, Origin of eclogite-bearing, domed, layered metamorphic complexes (core complexes) in the D'Entrecasteaux Islands, Papua New Guinea: Tectonics, v. 7, p. 1–21, doi: 10.1029/TC007i001p00001.

Davies, H.L., and Warren, R.G., 1992, Eclogites of the D'Entrecasteaux Islands: Contributions to Mineralogy and Petrology, v. 112, p. 463–474, doi: 10.1007/BF00310778.

Finlayson, D.M., Drummond, B.J., Collins, C.D.M., and Connelly, J.B., 1977, Crustal structures in the region of the Papuan Ultramafic Belt: Physics of the Earth and Planetary Interiors, v. 14, p. 13–29, doi: 10.1016/0031–9201(77)90043–7.

Froitzheim, N., Pleuger, J., Roller, S., and Nagel, T., 2003, Exhumation of high- and ultrahigh-pressure metamorphic rocks by slab extraction: Geology, v. 31, p. 925–928, doi: 10.1130/G19748.1.

Goodliffe, A., 1998, The Rifting of Continental and Oceanic Lithosphere: Observations from the Woodlark Basin [Ph.D. thesis]: Honolulu, Hawaii, University of Hawaii at Manoa.

Hacker, B.R., Ratschbacher, L., Webb, L.E., McWilliams, M., Ireland, T.R., Calvert, A., Dong, S., Wenk, H.-R., and Chateigner, D., 2000, Exhumation of ultrahigh-pressure continental crust in east-central China: Late Triassic-Early Jurassic tectonic unroofing: Journal of Geophysical Research, v. 105, p. 13,339–13,364, doi: 10.1029/2000JB900039.

Hacker, B.R., Ratschbacher, L., and Liou, J.G., 2004, Subduction, collision, and exhumation in the Qinling-Dabie Orogen: The Geological Society of London Special Publication 226, p. 157–175.

Hall, R., 2001, Cenozoic reconstructions of SE Asia and the SW Pacific: changing patterns of land and sea, in Metcalfe, I., Smith, J.M.B., Morwood, M. & Davidson, I.D., ed., Faunal and Floral Migrations and Evolution in SE Asia-Australasia: Lisse, Swets & Zeitlinger, p. 35–56.

Hall, R., 2002, Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: computer-based reconstructions and animations: Journal of Asian Earth Sciences, v. 20, p. 353–434, doi: 10.1016/S1367–9120(01)00069–4.

Hill, E.J., 1994, Geometry and kinematics of shear zones formed during continental extension in eastern Papua New Guinea: Journal of Structural Geology, v. 16, p. 1093–1105, doi: 10.1016/0191–8141(94)90054-X.

Hill, E.J., and Baldwin, S.L., 1993, Exhumation of high-pressure metamorphic rocks during crustal extension in the D'Entrecasteaux region, Papua New Guinea: Journal of Metamorphic Geology, v. 11, p. 261–277, doi: 10.1111/j.1525–1314.1993.tb00146.x.

Hill, E.J., Baldwin, S.L., and Lister, G.S., 1992, Unroofing of active metamorphic core complexes in the D'Entrecasteaux Islands, Papua New Guinea: Geology, v. 20, p. 907–910, doi: 10.1130/0091–7613(1992)020<0907:UOAMCC>2.3.CO;2.

Hill, E.J., Baldwin, S.L., and Lister, G.S., 1995, Magmatism as an essential driving force for formation of active metamorphic core complexes in eastern Papua New Guinea: Journal of Geophysical Research, v. 100, p. 10,441–10,452, doi: 10.1029/94JB03329.

Johnson, T., and Molnar, P., 1972, Focal mechanisms and plate tectonics of the southwest Pacific: Journal of Geophysical Research, v. 77, p. 5000–5032, doi: 10.1029/JB077i026p05000.

Little, T.A., Baldwin, S.L., Fitzgerald, P.G., and Monteleone, B.M., 2007, A young metamorphic core complex on Normanby Island, D'Entrecasteaux Islands, Papua New Guinea: Continental rifting processes near the Woodlark spreading ridge: Tectonics, v. 26, p. doi:10.1029/2005TC001911.

Mann, P., and Taira, A., 2004, Global tectonic significance of the Solomon Islands and Ontong Java Plateau convergent zone: Tectonophysics, v. 389, p. 137–190, doi: 10.1016/j.tecto.2003.10.024.

Monteleone, B.D., Baldwin, S.L., Webb, L.E., Fitzgerald, P.G., Grove, M., and Schmitt, A., 2007, Evidence for late Miocene to Pliocene HP metamorphism in eclogites from the D'Entrecasteaux Islands, SE Papua New Guinea: Journal of Metamorphic Geology, v. 25, p. 245–265, doi: 10.1111/j.1525–1314.2006.00685.x.

Peters, K., 2007, Exhumation of high-pressure metamorphic rocks by low-angle normal faulting at Misima Island, Woodlark rift, Papua New Guinea [Master's thesis]: Wellington, New Zealand, Victoria University of Wellington.

Petterson, M., Babbs, T., Neal, C., Mahoney, J., Saunders, A., Duncan, R., Tolia, D., Magu, R., Qopoto, C., Mahoa, H., and Natogga, D., 1999, Geological-tectonic framework of Solomon Islands, SW Pacific: crustal accretion and growth within an intra-oceanic setting: Tectonophysics, v. 301, p. 35–60, doi: 10.1016/S0040–1951(98)00214–5.

Rubatto, D., and Hermann, J., 2001, Exhumation as fast as subduction?: Geology, v. 29, p. 3–6, doi: 10.1130/0091–7613(2001)029<0003:EAFAS>2.0.CO;2.

Taylor, B., Goodliffe, A.M., Martinez, F., and Hey, R., 1995, Continental rifting and initial sea-floor spreading in the Woodlark Basin: Nature, v. 374, p. 534–537, doi: 10.1038/374534a0.

Taylor, B., Goodliffe, A.M., and Martinez, F., 1999, How continents break up: Insights from Papua New Guinea: Journal of Geophysical Research, v. 104, p. 7497–7512, doi: 10.1029/1998JB900115.

Tregoning, P., Lambeck, K., Stolz, A., Morgan, P., McClusky, S.C., van der Beek, P., McQueen, H., Jackson, R.J., Little, R.P., Laing, A., and Murphy, B., 1998, Estimation of current plate motions in Papua New Guinea from Global Positioning System observations: Journal of Geophysical Research, v. 103, p. 12,181–12,203, doi: 10.1029/97JB03676.

Wallace, L.M., Stevens, C., Silver, E., McCaffrey, R., Loratung, W., Hasiata, S., Stanaway, R., Curley, R., Rosa, R., and Taugaloidi, J., 2004, GPS and seismological constraints on active tectonics and arc-continent collision in Papua New Guinea: Implications for mechanics of microplate rotations in a plate boundary zone: Journal of Geophysical Research, v. 109, doi: 10.1029/2003JB002481.

Weissel, J.K., Taylor, B., and Karner, G.D., 1982, The opening of the Woodlark Basin, subduction of the Woodlark spreading system, and the evolution of northern Melanesia since mid-Pliocene time: Tectonophysics, v. 87, p. 253–277, doi: 10.1016/0040–1951(82)90229–3.

Worthing, M.A., 1988, Petrology and tectonic setting of blueschist facies metabasites from the Emo metamorphics of Papua New Guinea: Australian Journal of Earth Sciences, v. 35, p. 159–168.

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