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# Backarc origin for Neoarchean ultrahigh-temperature metamorphism, eclogitization, and orogenic root growth

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## ABSTRACT

**Contraction of continental crust during orogeny results in elevated topography at the surface and a root at depth. Thermomechanical models suggest that root growth is enhanced by thickening of thermally softened thin lithosphere. A >400 km$^2$ region of Archean gneiss in the Athabasca granulite terrane in the Canadian shield contains abundant mafic sills with mid-oceanic ridge basalt–like chemistry. Heat from the sills facilitated melting of supracrustal host rocks along a prograde pressure-temperature (*P-T*) path culminating at *P* > 1.4 GPa and *T* > 950 °C in the Neoarchean. A basalt sill, converted to eclogite near the base of the domain, exhibits positive Eu anomalies consistent with plagioclase accumulation at a shallow crustal level prior to burial. Eclogite facies metamorphism previously dated as 1.90 Ga is here revised to 2.54 Ga based on existing zircon dates from the sill and new monazite dates from the paragneiss that hosts the sill. The results suggest that upper crustal materials were thermally softened in a backarc setting prior to burial to lower crustal levels during orogenic root growth.**

## INTRODUCTION

Contraction of continental crust during mountain building leads to surface uplift and growth of deep crustal roots. Root survival depends on the amount of isostatic rebound that occurs when contraction ceases, and is a function of erosional unloading at the surface (Fischer, 2002), metamorphic reactions that densify the lower crust and inhibit rebound (Williams et al., 2014), and the magnitude of foundering of lower crust into the mantle (Ducea, 2011). Roots are well documented seismically in modern and ancient orogens, e.g., the Southern Alps in New Zealand (Scherwath et al., 2003) and the Trans-Hudson orogen in the Canadian Shield (Lucas et al., 1993). Deeply exhumed field examples of crustal roots, however, are rare and include parts of the Western Gneiss region (Dewey et al., 1993) and the Bohemian Massif (Schulmann et al., 2005).

Thermomechanical models for root growth emphasize the importance of thermal softening prior to thickening, a situation that is most likely in continental rift zones or backarc settings (Thompson et al., 2001). Tectonic burial of a hot backarc provides a mechanism for ultrahigh-temperature (UHT) metamorphism due to an elevated geothermal gradient and >800 °C Moho temperature that result from high mantle heat flux across thin lithosphere (Currie and Hyndman, 2006). Models of root growth achieve UHT conditions at high pressure (*P*) when thickening occurs across a narrow 100-km-wide zone with a hot 35 °C/km initial geotherm that is enhanced by additional heat supplied from below (model HH100 in Thompson et al., 2001).

We present evidence for Neoarchean eclogitization near the base of a buried backarc basin, now preserved as the Upper Deck domain in the western Canadian shield (Fig. 1). Our results are consistent with the modeling of Thompson et al. (2001) and provide evidence for crustal root growth associated with high-*P* metamorphism of mid-oceanic ridge basalt (MORB)–like mafic intrusions. Intraplating of these intrusions facilitated partial melting and UHT metamorphism of peraluminous supracrustal host rocks (Dumond et al., 2015). We use Th–U–total Pb monazite petrochronology to constrain the timing of high-*P* melting preserved in felsic granulite paragneiss in contact with a previously dated eclogite sill that yielded U-Pb zircon dates of 2.54 Ga and 1.90 Ga (Baldwin et al., 2004). These results are combined with bulk-rock geochemistry for mafic granulites and eclogite near the base of the Upper Deck to infer a backarc origin for a Neoarchean orogenic root.

## BACKGROUND

The >400 km$^2$ and >50-km-wide Upper Deck domain is part of the >20,000 km$^2$ Athabasca granulite terrane in the western Canadian shield (Figs. 1A and 1B). The domain consists of (1) garnet-rich kyanite (Ky) + potassium feldspar (Kfs) ± orthopyroxene (Opx) ± sillimanite (Sil) felsic granulite gneisses (mineral abbreviations after Bucher and Frey, 2002), (2) centimeter- to kilometer-scale sills and dikes of garnet (Grt) + clinopyroxene (Cpx) + plagioclase (Pl) + quartz (Qtz) ± hornblende (Hbl) mafic granulite gneisses, and (3) a sill of eclogite as much as 15 m thick near the base of the domain (Snoeyenbos et al., 1995; Fig. 1B). Field relationships indicate that the felsic granulite gneisses were produced by partial melting of a biotite (Bt) bearing metasedimentary protolith during intrusion of a mafic magma intraplate, now represented by the mafic granulites and eclogite (Dumond et al., 2015).

Peak conditions for the Upper Deck are constrained by phase equilibria modeling of felsic granulite bulk compositions indicating temperature, *T* > 950 °C during a period of prograde crustal thickening from *P* < 0.8 GPa to *P* > 1.4 GPa (Dumond et al., 2015). Existing *P-T* data for the mafic granulites and eclogite are consistent with these pressures (Baldwin et al., 2003, 2007). Constraints on the timing of metamorphism and deformation in the Upper Deck include zircon and monazite dates from felsic granulites that record partial melting, garnet growth, and lower crustal flow at 2.61–2.52 Ga (Baldwin et al., 2006; Dumond et al., 2015). Monazite inclusions in high-Ca garnet constrain the timing of UHT–high-*P* metamorphism at 2.58–2.52 Ga (Dumond et al., 2015). The felsic granulites contain polyphase inclusions of Bt + Pl + Qtz + rutile (Rt) included in high-Ca garnet, indicating that partial melting via the reaction Bt + Pl + Qtz → Grt + Kfs + melt occurred at high *P* (>1.4 GPa; Dumond et al., 2015). The ca. 1.9 Ga monazite dates in the felsic granulites are inferred to indicate crustal reactivation during a second lower *P* granulite facies event (Dumond et al., 2015). Zircon dates from the mafic granulites and eclogite span 2.54–1.89 Ga (Baldwin et al., 2003, 2004). A zircon U-Pb isotope dilution–thermal ionization spectrometry (ID-TIMS) date of 1.904 Ga was obtained (Baldwin et al., 2004) for the eclogite that was reinforced by ca. 1.9 Ga in situ sensitive high-resolution ion microprobe (SHRIMP) dates on zircon included in clinopyroxene in a single thin section from a second

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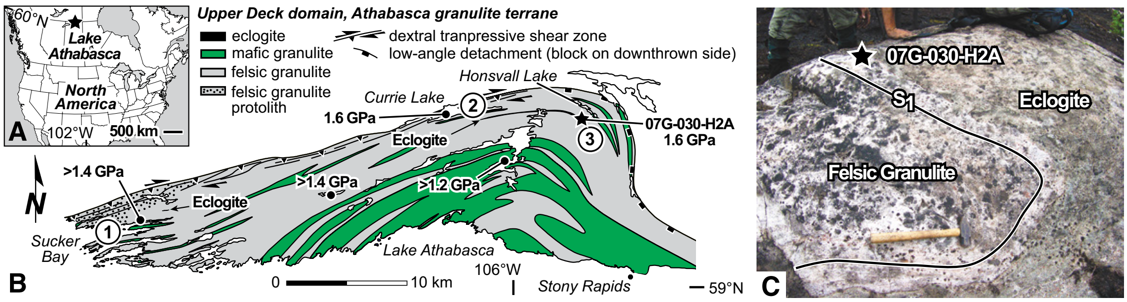


**Figure 1. A: Location of the Athabasca granulite terrane (star) in northern Saskatchewan, Canada. B: Geologic map of the Upper Deck domain; pressure estimates are modified from Dumond et al. (2015). Circled locations were sampled for mafic granulite and eclogite. C: Folded contact between felsic granulite and eclogite with location of sample 07G-030-H2A.v**

sample. Single zircon grains from the same sample, however, produced a high-precision ID-TIMS U-Pb discordia with intercepts at 2.54 Ga and 1.91 Ga (Baldwin et al., 2004), consistent with a polymetamorphic origin for zircon in the eclogite and similar to zircon U-Pb discordia documented in Upper Deck mafic granulites (Baldwin et al., 2003).

## NEW FIELD OBSERVATIONS FROM THE DATED ECLOGITE LOCALITY

A wildfire in A.D. 2006 burned several hundred square kilometers of the Upper Deck and revealed new exposures of the eclogite sill. Field observations in 2007 showed that the eclogite and the host felsic granulite gneiss share a penetrative gently southwest-dipping foliation. The foliation and the contact between the two rocks is folded (Fig. 1C), with retrograde sapphirine occurring axial planar to the fold in both rock types. These concordant observations at the original sample locality negate the discordant relationships inferred by Baldwin et al. (2004), and require that the felsic granulite and eclogite had a shared history prior to folding and sapphirine growth.

## MONAZITE PETROCHRONOLOGY OF THE ECLOGITE HOST ROCK

Monazite petrochronology is a rapidly advancing field in continental tectonics with the goal of linking monazite dates to specific metamorphic processes and deformation events (e.g., Mottram et al., 2014). Here we present results from 07G-030-H2A (Figs. 1C and 2; see the GSA Data Repository[1]), a garnet-rich sapphirine-bearing felsic granulite paragneiss in contact with the eclogite dated by Baldwin et al. (2004); Baldwin et al. (2015) obtained *P-T* conditions of $P > 1.4$ GPa and $T > 800$ °C for a similar rock adjacent to the eclogite.

Inclusions of resorbed Bt + Pl occur in garnet, consistent with garnet growth via a fluid-absent biotite melting reaction such as Bt + Pl + Qtz → Grt + Kfs + melt (Vielzeuf and Montel, 1994). Biotite inclusions are Ti rich (to 5.52 wt% $TiO_2$; Table DR1 in the Data Repository), as expected for residues of UHT melting (Cesare et al., 2003). Garnet grains are zoned with low-Ca cores (grossular, $Grs_4$) that grade into high-Ca rims ($Grs_{20}$; Fig. 2B; Table DR1). Similar observations were documented for felsic granulites in the western Upper Deck (Dumond et al., 2015) and attributed to garnet growth during prograde loading at 800 to >950 °C and 0.8 to >1.4 GPa. Garnet grains in the eclogite contact zone display symplectite textures and evidence for breakdown to coronae of Opx + Pl during subsequent decompression (Figs. 2A and 2B; Table DR1; Baldwin et al., 2007).

[1]GSA Data Repository item 2017313, analytical methods, Table DR1 (electron probe microanalyzer major element analyses for garnet and biotite), Table DR2 (electron probe microanalyzer monazite analyses), Table DR3 (mafic rock bulk compositions), Figure DR1 (reaction textures and setting of monazite grain 3-m7), Figure DR2 (setting of monazite grains not in the field of view of Fig. 2B), Figure DR3 (monazite consistency standard results), and Figure DR4 (mafic rock bulk composition plots), is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.

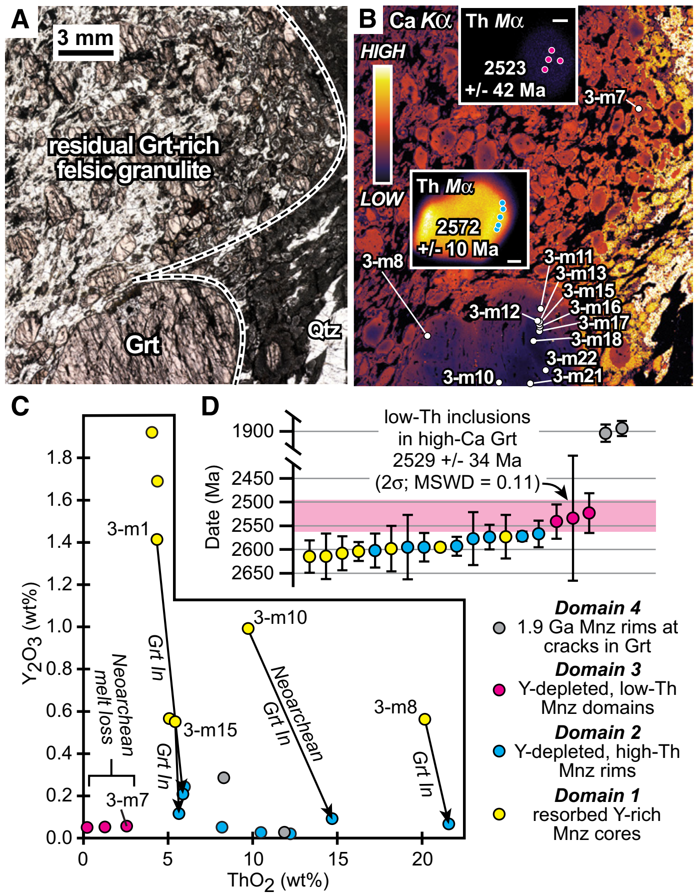


**Figure 2. A: Photomicrograph of sample 07G-030-H2A showing retrogressed cuspate-lobate contact zone between felsic granulite and eclogite (Grt—garnet; Qtz—quartz). B: Calcium *K*α map with locations of analyzed monazite (Mnz) grains. Insets for grains 3-m7 and 3-m8 are simultaneously processed Th *M*α maps of monazite inclusions in garnet with weighted mean Th-U-total Pb electron microprobe dates (after Williams et al., 2006). Scale bars in each inset are 5 µm long. C: $ThO_2$ versus $Y_2O_3$ plot for all 20 analyzed domains. Arrows connect Neoarchean high-Y core and low-Y rim domains from the same monazite grain. See Figure DR2 (see footnote 1) for grains 3-m1 and 1-m1, which are not in the field of view. D: Vertical error bar plot with weighted mean monazite dates at the 95% confidence interval. MSWD—mean square of weighted deviates.**

Monazite grains occur only as inclusions in garnet (Fig. 2B). Four compositionally defined monazite domains were identified based on X-ray mapping (Fig. 2C; Fig. DR2). Domain 1 corresponds to resorbed high-Y monazite cores dated as 2.61–2.57 Ga (Fig. 2C). Domain 2 consists of Y-depleted, high-Th monazite rims dated as 2.60–2.57 Ga (Figs. 2B and 2C). Several grains consist partly or entirely of domain 3 defined by Y-depleted, low-Th monazite dated as 2.54–2.52 Ga (Figs. 2B and 2C). Domain 3

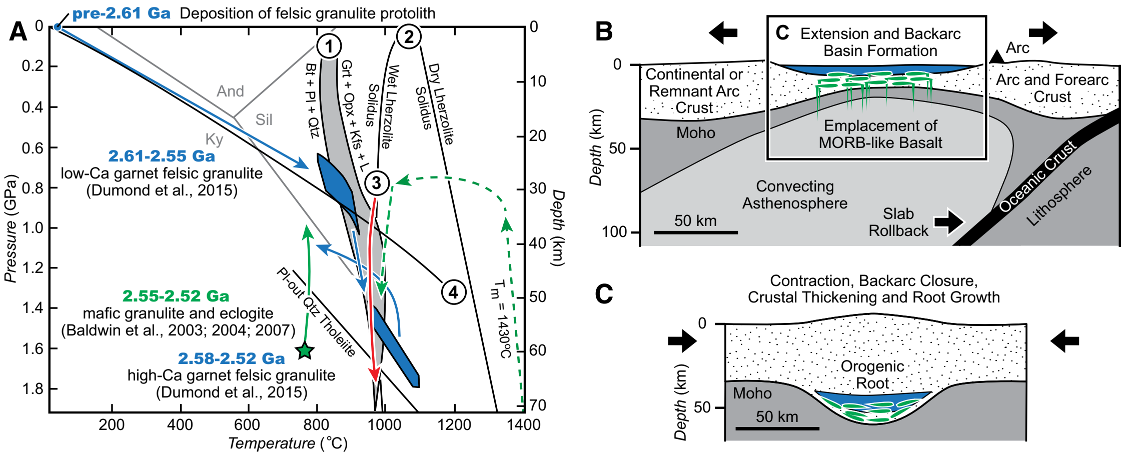


**Figure 3. A: Pressure-temperature-time (*P-T-t*) paths for Upper Deck domain (Canada) granulites and the eclogite. The blue felsic granulite path is from Dumond et al. (2015). The solid green mafic granulite and eclogite path is from Baldwin et al. (2003, 2007). The dashed green path is the inferred path for the mafic granulite and eclogite protoliths with mid-oceanic ridge basalt (MORB) like basalt generated by decompression melting of fertile lherzolite. A 1430 °C mantle adiabat ($T_m$) is shown for reference (Green et al., 2014). 1—Stability field for fluid-absent biotite melting of metagraywacke (Vielzeuf and Montel, 1994). 2—Solidi for fertile lherzolite (Green et al., 2014). 3—Model *P-T* path HH100 of Thompson et al. (2001). 4—Hot backarc geotherm modeled for 35-km-thick crust and 50-km-thick lithosphere (Currie and Hyndman, 2006). And—andalusite; Sil—sillimanite; Ky—kyanite; Pl—plagioclase; Bt—biotite; Grt—garnet; Opx—orthopyroxene; Kfs—potassium feldspar; L—liquid. B: Model for emplacement of MORB-like basalt into extended backarc lithosphere (modified from Collins, 2002). C: Burial of Upper Deck backarc toward the base of thickened crust, coincident with an inferred orogenic root ca. 2.55–2.52 Ga prior to decompression.**

occurs locally as inclusions in high-Ca garnet (e.g., grains 3-m7 in Fig. 2B; 1-m1 in Figs. DR2A–DR2C). Three analyses of domain 3 yield a weighted mean date of 2529 ± 34 Ma (2σ, mean square of weighted deviates = 0.11), and provide a maximum constraint on the timing of high-Ca garnet growth and high-*P* metamorphism (Fig. 2D). Domain 4 consists of monazite rims on Neoarchean cores that are adjacent to cracks in garnet connected to the matrix and dated as 1.90–1.89 Ga (Fig. 2C; Figs. DR2D–DR2G). Domain 4 rims display embayed compositional zoning indicative of dissolution-reprecipitation of preexisting monazite (Harlov et al., 2011; Fig. DR2G).

## MAFIC ROCK GEOCHEMISTRY

Bulk geochemistry is reported for mafic granulite and eclogite collected near the base of the Upper Deck to constrain their petrogenetic history (Fig. 1B; Fig. DR4; Table DR3). Mafic granulite samples have compositions similar to tholeiitic basalts. Eclogite samples have high-alumina basalt compositions. All samples define a tholeiitic trend on an AFM diagram ($Na_2O + K_2O$, $FeO_{Total}$, MgO; Fig. DR4A). A spider diagram for all samples normalized to average primitive continental arc andesite shows that Upper Deck samples are depleted in the large ion lithophile elements with respect to primitive arc rocks (Rb, Ba, K, and Sr; Fig. DR4B). The mafic granulites are enriched in Ti, Y, and the heavy rare earth elements (REEs; Dy, Yb, and Lu; Fig. DR4B). Eclogite samples are depleted in all elements with respect to primitive continental arc andesite (Fig. DR4B). None of the samples have an arc affinity, and instead define positively sloping patterns that are similar to primitive MORB (Fig. DR4B).

Mafic granulites exhibit flat REE patterns that overlap with primitive MORB (Fig. DR4C). The eclogite samples tend to have negatively sloping patterns due to light REE enrichment and many have positive Eu anomalies indicative of plagioclase accumulation (Fig. DR4C). For comparison, 85 backarc basalt compositions were retrieved from EarthChem PetDB (www.earthchem.org; accessed 17 October 2015). The results show that Upper Deck mafic granulites and some of the eclogites have REE patterns similar to backarc basalts (cf. Figs. DR4C and DR4D).

## DISCUSSION

### Monazite Petrochronology and Implications for Interpreting Zircon Geochronology

Monazite and garnet are the only Y-bearing phases in 07G-030-H2A and the depletion in Y observed in monazite can be attributed to garnet growth during partial melting and resorption of high-Y domain 1 monazite (Dumond et al., 2015). Crystallization of Y-depleted domain 2 monazite from melt therefore occurred in the presence of garnet at 2.60–2.57 Ga (Fig. 2C). Melt loss is required to preserve residual garnet-rich bulk compositions derived from partial melting (White and Powell, 2002). Thorium in monazite is a proxy for melt loss in peraluminous partially molten rocks whereby Th partitions into monazite as it crystallizes from the melt (Dumond et al., 2015). As melt was lost from the system, less Th was available to partition into monazite (Dumond et al., 2015). Low-Th domain 3 monazite grains included in high-Ca garnet are interpreted to have crystallized after 2.57 to 2.52 Ga at high pressure and after significant melt loss (Figs. 2B and 2C). Rare ca. 1.9 Ga domains adjacent to cracks in garnet are inferred to record dissolution-reprecipitation of Y-depleted high-Th Neoarchean monazite after high-*P* metamorphism and possibly during a second granulite facies event (Fig. 2C; Fig. DR2; Baldwin et al., 2006; Dumond et al., 2015). The occurrence of Neoarchean high-*P* garnet in the eclogite host rock is inconsistent with the 1.90 Ga age interpreted for eclogite metamorphism by Baldwin et al. (2004) and is more consistent with the oldest concordant U-Pb date of 2.54 Ga obtained for zircon via ID-TIMS.

### Inferring a Backarc Basin Setting

Modern continental margin backarc basins include the Okinawa Trough and the Sea of Japan (Letouzey and Kimura, 1986; Lee et al., 2001). These basins can have depocenters >10 km in thickness (Lee et al., 2001) and contain both MORB-like and arc-like basalts emplaced during backarc basin spreading (Taylor and Martinez, 2003). Field occurrences of roots that resulted from thickening of hot backarcs should thus have appreciable amounts of basin fill and basalt. The Upper Deck is characterized by a locally 10-km-thick succession of metasedimentary rocks and MORB-like basaltic intrusions, although some of this amount is due to tectonic thickening (Dumond et al., 2015). Most of the eclogite samples display light REE enrichment and positive Eu anomalies consistent with plagioclase accumulation at shallow crustal levels (<1.0 GPa; Baldwin et al., 2004). We infer that contraction, closure, and tectonic burial of a hot backarc basin provided the conditions necessary to (1) facilitate UHT metamorphism, (2) attain $P > 1.4$ GPa, and (3) locally achieve eclogite facies. The minor amount of eclogite in the Upper Deck is attributed to variations in bulk composition that precluded most of the mafic rocks from crossing the garnet granulite–eclogite transition (Ringwood, 1975).

## P-T-t Paths for the Felsic Granulite and Eclogite During Orogenic Root Growth

Existing constraints on the *P-T-t* paths for rocks of the Upper Deck include (1) deposition of the felsic granulite protolith prior to 2.61 Ga, (2) prograde burial to ~0.8 GPa and $T > 800$ °C at 2.61–2.55 Ga, and (3) loading to $P > 1.4$ GPa at $T > 950$ °C (blue path in Fig. 3A; Dumond et al., 2015). The dashed green path in Figure 3A illustrates the preferred path for the mafic granulites and eclogite, which originated as MORB-like basalts derived from decompression melting during backarc extension (Figs. 3A and 3B). Following shallow crustal emplacement, both the felsic and mafic rocks would have shared a similar burial *P-T* path culminating at $P$ = 1.4–1.6 GPa at 2.58–2.52 Ga, marking the onset of crustal root growth (Figs. 3A and 3C). This path is similar to the HH100 path modeled by Thompson et al. (2001) for thickening of hot thin lithosphere across a narrow 100-km-wide zone to produce an orogenic root (red path in Fig. 3A).


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### REFERENCES CITED


Baldwin, J.A., Bowring, S.A., and Williams, M.L., 2003, Petrological and geochronological constraints on high pressure, high temperature metamorphism in the Snowbird tectonic zone, Canada: Journal of Metamorphic Geology, v. 21, p. 81–98, doi:10.1046/j.1525-1314.2003.00413.x.

Baldwin, J.A., Bowring, S.A., Williams, M.L., and Williams, I.S., 2004, Eclogites of the Snowbird tectonic zone: Petrological and U-Pb geochronological evidence for Paleoproterozoic high-pressure metamorphism in the western Canadian Shield: Contributions to Mineralogy and Petrology, v. 147, p. 528–548, doi:10.1007/s00410-004-0572-4.

Baldwin, J.A., Bowring, S.A., Williams, M.L., and Mahan, K.H., 2006, Geochronological constraints on the evolution of high-pressure felsic granulites from an integrated electron microprobe and ID-TIMS geochemical study: Lithos, v. 88, p. 173–200, doi:10.1016/j.lithos.2005.08.009.

Baldwin, J.A., Powell, R., Williams, M.L., and Goncalves, P., 2007, Formation of eclogite, and reaction during exhumation to mid-crustal levels, Snowbird tectonic zone, western Canadian Shield: Journal of Metamorphic Geology, v. 25, p. 953–974, doi:10.1111/j.1525-1314.2007.00737.x.

Baldwin, J.A., Powell, R., White, R.W., and Štípská, P., 2015, Using calculated chemical potential relationships to account for replacement of kyanite by symplectite in high pressure granulites: Journal of Metamorphic Geology, v. 33, p. 311–330, doi:10.1111/jmg.12122.

Bucher, K., and Frey, M., 2002, Petrogenesis of metamorphic rocks: Berlin, Springer, 341 p., doi:10.1007/978-3-662-04914-3.

Cesare, B., Cruciani, G., and Russo, U., 2003, Hydrogen deficiency in Ti-rich biotite from anatectic metapelites (El Joyazo, SE Spain): Crystal-chemical aspects and implications for high-temperature petrogenesis: American Mineralogist, v. 88, p. 583–595, doi:10.2138/am-2003-0412.

Collins, W.J., 2002, Hot orogens, tectonic switching, and creation of continental crust: Geology, v. 30, p. 535–538, doi:10.1130/0091-7613(2002)030<0535:HOTSAC>2.0.CO;2.

Currie, C.A., and Hyndman, R.D., 2006, The thermal structure of subduction zone back arcs: Journal of Geophysical Research, v. 111, B08404, doi:10.1029/2005JB004024.

Dewey, J.F., Ryan, P.D., and Andersen, T.B., 1993, Orogenic uplift and collapse, crustal thickness, fabrics and metamorphic phase changes: The role of eclogites, *in* Harris, N.B.W., and Neary, C.R., eds., Magmatic processes and plate tectonics: Geological Society of London Special Publication 76, p. 325–343, doi:10.1144/GSL.SP.1993.076.01.16.

Ducea, M.N., 2011, Fingerprinting orogenic delamination: Geology, v. 39, p. 191–192, doi:10.1130/focus022011.1.

Dumond, G., Goncalves, P., Williams, M.L., and Jercinovic, M.J., 2015, Monazite as a monitor of melting, garnet growth, and feldspar recrystallization in continental lower crust: Journal of Metamorphic Geology, v. 33, p. 735–762, doi:10.1111/jmg.12150.

Fischer, K.M., 2002, Waning buoyancy in the crustal roots of old mountains: Nature, v. 417, p. 933–936, doi:10.1038/nature00855.

Green, D.H., Hibberson, W.O., Rosenthal, A., Kovács, I., Yaxley, G.M., Falloon, T.J., and Brink, F., 2014, Experimental study of the influence of water on melting and phase assemblages in the upper mantle: Journal of Petrology, v. 55, p. 2067–2096, doi:10.1093/petrology/egu050.

Harlov, D.E., Wirth, R., and Hetherington, C.J., 2011, Fluid-mediated partial alteration in monazite: The role of coupled dissolution-reprecipitation in element redistribution and mass transfer: Contributions to Mineralogy and Petrology, v. 162, p. 329–348, doi:10.1007/s00410-010-0599-7.

Lee, G.H., Kim, H.J., Han, S.J., and Kim, D.C., 2001, Seismic stratigraphy of the deep Ulleung Basin in the East Sea (Japan Sea) back-arc basin: Marine and Petroleum Geology, v. 18, p. 615–634, doi:10.1016/S0264-8172(01)00016-2.

Letouzey, J., and Kimura, M., 1986, The Okinawa Trough: Genesis of a back-arc basin developing along a continental margin: Tectonophysics, v. 125, p. 209–230, doi:10.1016/0040-1951(86)90015-6.

Lucas, S.B., Green, A., Hajnal, Z., White, D., Lewry, J., Ashton, K., Weber, W., and Clowes, R., 1993, Deep seismic profile across a Proterozoic collision zone: Surprises at depth: Nature, v. 363, p. 339–342, doi:10.1038/363339a0.

Mottram, C.A., Warren, C.J., Regis, D., Roberts, N.M.W., Harris, N.B.W., Argles, T.W., and Parrish, R.R., 2014, Developing an inverted Barrovian sequence: Insights from monazite petrochronology: Earth and Planetary Science Letters, v. 403, p. 418–431, doi:10.1016/j.epsl.2014.07.006.

Ringwood, A.E., 1975, Composition and petrology of the Earth's mantle: New York, McGraw-Hill, 618 p.

Scherwath, M., Stern, T., Davey, F., Okaya, D., Holbrook, W.S., Davies, R., and Kleffmann, S., 2003, Lithospheric structure across oblique continental collision in New Zealand from wide-angle P wave modeling: Journal of Geophysical Research, v. 108, 2566, doi:10.1029/2002JB002286.

Schulmann, K., Kroner, A., Hegner, E., Wendt, I., Konopasek, J., Lexa, O., and Stipska, P., 2005, Chronological constraints on the pre-orogenic history, burial and exhumation of deep-seated rocks along the eastern margin of the Variscan orogen, Bohemian Massif, Czech Republic: American Journal of Science, v. 305, p. 407–448, doi:10.2475/ajs.305.5.407.

Snoeyenbos, D.R., Williams, M.L., and Hanmer, S., 1995, Archean high-pressure metamorphism in the western Canadian Shield: European Journal of Mineralogy, v. 7, p. 1251–1272, doi:10.1127/ejm/7/6/1251.

Taylor, B., and Martinez, F., 2003, Back-arc basin basalt systematics: Earth and Planetary Science Letters, v. 210, p. 481–497, doi:10.1016/S0012-821X(03)00167-5.

Thompson, A.B., Schulmann, K., Jezek, J., and Tolar, V., 2001, Thermally softened continental zones (arcs and rifts) as precursors to thickened orogenic belts: Tectonophysics, v. 332, p. 115–141, doi:10.1016/S0040-1951(00)00252-3.

Vielzeuf, D., and Montel, J.M., 1994, Partial melting of metagreywackes. Part I. Fluid-absent experiments and phase relationships: Contributions to Mineralogy and Petrology, v. 117, p. 375–393, doi:10.1007/BF00307272.

White, R.W., and Powell, R., 2002, Melt loss and the preservation of granulite facies mineral assemblages: Journal of Metamorphic Geology, v. 20, p. 621–632, doi:10.1046/j.1525-1314.2002.00206_20_7.x.

Williams, M.L., Jercinovic, M.J., Goncalves, P., and Mahan, K., 2006, Format and philosophy for collecting, compiling, and reporting microprobe monazite ages: Chemical Geology, v. 225, p. 1–15, doi:10.1016/j.chemgeo.2005.07.024.

Williams, M.L., Dumond, G., Mahan, K.H., Regan, S.P., and Holland, M., 2014, Garnet-forming reactions in felsic orthogneiss: Implications for densification and strengthening of the lower continental crust: Earth and Planetary Science Letters, v. 405, p. 207–219, doi:10.1016/j.epsl.2014.08.030.



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