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High-grade metamorphism flying under the radar of accessory minerals

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ABSTRACT

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INTRODUCTION

Uranium-bearing accessory minerals are common in crustal rocks and widely used to constrain the timing and duration of igneous, metamorphic, and deformation events. Petrochronology using minerals with a high U/Pb ratio (high-U/Pb) enables important linkages between age records and petrological processes (e.g., Kohn et al., 2017); nevertheless, these records may be incomplete, especially in mafic rocks where high-U/Pb minerals may be lacking. Zircon and monazite, for instance, may not be stable together, such that single stages are recorded by one or the other depending on rock composition (Kooijman et al., 2017) and some stages may not be recorded at all (Kelsey et al., 2008; Yakymchuk and Brown 2014; Kohn et al., 2015). Additionally, in rocks with a polymetamorphic history, linkages between accessory mineral petrochronology and a sample's petrological record may be ambiguous (e.g., Dragovic et al., 2016). Herein, we demonstrate that direct dating of the petrogenetic indicator mineral garnet can provide crucial time constraints for poorly recorded metamorphic processes in high-pressure (HP) polymetamorphic mafic rocks.

The southeastern Rae craton (northern Canada; Fig. 1A) exemplifies a polymetamorphic amphibolite- to granulite-facies region (Berman et al., 2007) where U-bearing accessory minerals have been used to constrain the timing of numerous tectonometamorphic events that occurred between initial crust formation at 2.7–2.6 Ga to stabilization after 1.82 Ga (Fig. 1B; e.g., Berman et al., 2013; Bethune et al., 2013; Dumond et al., 2015). HP (>13 kbar) relict assemblages in mafic rocks that remained intact after 1.9 Ga pervasive deformation and recrystallization are argued to have crystallized during collisional orogenesis at 2.55 and/or 1.9 Ga (e.g., Flowers et al., 2008; Martel et al., 2008). However, these assemblages have only been dated indirectly by U-Pb zircon (e.g., Baldwin et al., 2004; Flowers et al., 2008) or monazite in metasedimentary rocks adjacent to the undated HP mafic units (Dumond et al., 2017). Importantly, the highest metamorphic pressures are commonly preserved by mineral assemblages within mafic units (e.g., O'Brien et al., 2001; Carswell et al., 2003; Baldwin et al., 2004), so direct dating of their crystallization ages is necessary for ascertaining accurate reconstructions of their tectonic histories. To better evaluate the timing and nature of HP metamorphism during the complex history of the Rae craton, we have dated two texturally distinct garnet generations in a HP mafic granulite. Using Lu-Hf garnet geochronology with complementary petrological modeling, garnet dates presented herein correspond to a HP stage that has remained largely undetected in the U-Pb mineral record of the southeastern Rae craton.

REGIONAL GEOLOGY AND SAMPLE CONTEXT

Southern Rae craton basement comprises Neoarchean (ca. 2.7–2.5 Ga) intermediate gneiss and intrusions with minor mafic gneiss metamorphosed between 2.60 and 2.50 Ga (e.g., Davis et al., 2015; Dumond et al., 2015; Regis et al., 2017). The Arrowsmith orogeny (Fig. 1B) mainly affected the northwestern margin of the southern Rae craton from 2.54 to 2.28 Ga (e.g., Berman et al., 2013). From 2.28 to 2.00 Ga, regional extension is manifested by sedimentation, anorthosite magmatism, and formation of mafic dikes (Rainbird et al., 2010; Card et al., 2014; Regan et al., 2017). These processes did not favor zircon growth (Fig. 1B), and, thus, their records are dwarfed by those of other events. Widespread 1.94–1.89 Ga regional metamorphism during the Taltson and Snowbird orogenies (Fig. 1B; Berman et al., 2007; Bethune et al., 2013) preceded melt generation and exhumation facilitated by crustal-scale shear zones that occurred between 1.90 and 1.76 Ga (Flowers et al., 2006; Mahan et al., 2006; Regis et al., 2017; Thiessen et al., 2018).

To better understand the aforementioned HP relicts, we analyzed a mafic granulite (sample

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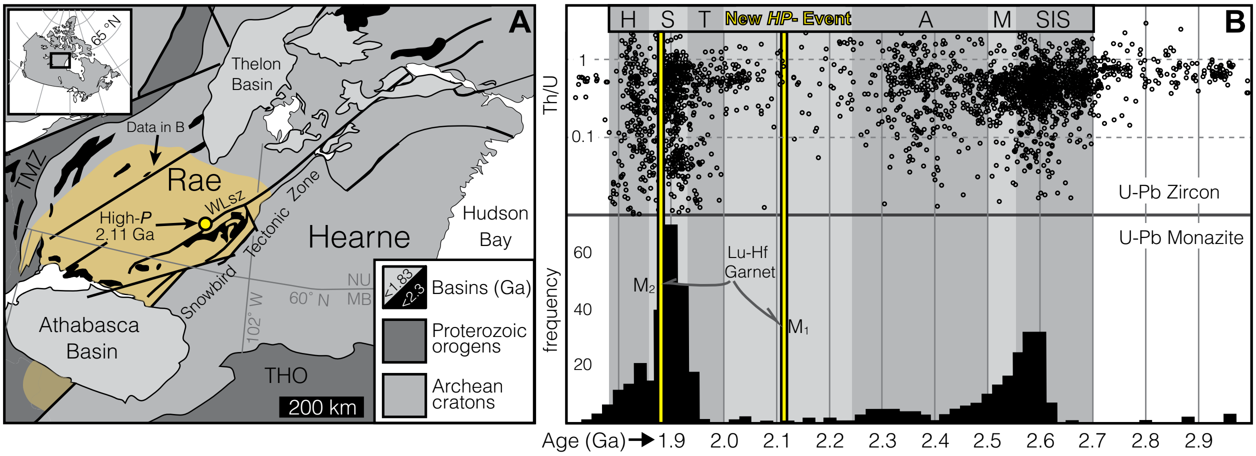


Figure 1. A: Precambrian geology west of Hudson Bay, northern Canada. Yellow circle is location of Rae craton mafic-granulite sample studied herein at latitude 60.7224°N and longitude 104.0179°W. Thick black lines show major crustal-scale shear zone. TMZ—Taltson magmatic zone; WLsz—Wholdaia Lake shear zone; THO—Trans-Hudson orogen; NU—Nunavut; MB—Manitoba. B: Upper plot: Non-detrital crustal U-Pb zircon dates (black open circles) and corresponding Th/U values. Lower plot: Monazite U-Pb dates (black histograms). U-Pb data are from within outlined tan-colored area in A (see Data Repository [see footnote 1] for references). Recognized tectonic phases (SIS—Snow Island Suite; M—MacQuoid; A—Arrowsmith; T—Taltson; S—Snowbird; H—Trans-Hudson) and durations are highlighted as gray fields. High-pressure (HP) event refers to newly analyzed data presented herein. Yellow bars represent Lu-Hf garnet dates for M_1 and M_2 metamorphic assemblages. Note comparative lull in orogenesis recorded by zircon and monazite between 2.28 and 2.0 Ga.

15ET249) that has comparable metamorphic assemblages to other HP (>13 kbar) rocks preserved in the southern Rae craton (e.g., Baldwin et al., 2004; Mahan et al., 2008). Our sample was collected from a belt of highly-tectonized granulite units within the Wholdaia Lake shear zone (Thiessen et al., 2018), a >300-km-long crustal-scale shear zone that exhumed mid- to lower-crustal rocks adjacent to the Snowbird tectonic zone (STZ) between 1.90 and 1.86 Ga. Sample 15ET249 from this study has 2.6 and 1.9 Ga U-Pb zircon age components and contains a rare relict metamorphic domain (M_1) that was not recrystallized at 1.9 Ga during pervasive ductile shearing along the Wholdaia Lake shear zone.

PETROGRAPHY AND MINERAL COMPOSITIONS

The M_1 domain contains coarse-grained, granoblastic garnet + clinopyroxene + quartz + ilmenite ± plagioclase with >5-mm-diameter garnet porphyroblasts (Fig. 2A). These minerals typically display polygonal boundaries and do not preserve a solid-state tectonic fabric. Garnet (Grt_1) occurs as a roughly equant porphyroblast with an irregular outer margin surrounded by 1-mm-diameter Grt_1 fragments suggesting a larger initial crystal size by at least 10 vol% (Fig. 2A). Major element composition profiles in Grt_1 are generally flat; however, Grt_1 margins and two internal fractures have relatively low Mn (Fig. 2B), suggesting a locally focused secondary equilibration event, which is the opposite of what is expected for resorbed garnet margins (e.g., Kohn and Spear, 2000). Lutetium concentrations vary between 0.5 and 2.5 ppm across Grt_1; the higher concentrations correlate with zones of low Mn (Fig. 2B). Plagioclase is closely associated with Grt_1 grain boundaries and was likely produced during decompression and Grt_1 consumption. Amphibole occurs along fractures and is considered a late, retrograde phase.

The M_2 domain envelops the M_1 domain and consists of a fine-grained <1 mm granoblastic-polygonal assemblage of garnet + plagioclase + clinopyroxene + quartz + ilmenite + titanite (Fig. 2A), which defines a prominent gneissic foliation. Quartz occurs as lobate inclusions in garnet (Grt_2) or within interstitial spaces. Major element compositions are generally homogeneous within all major phases and are comparable to M_1 phase compositions (Table DR1 in the GSA Data Repository[1]).

PHASE EQUILIBRIUM MODELING AND GARNET CHRONOLOGY

Pressure-temperature (P-T) isochemical phase diagrams were constructed (Fig. 3; Figs. DR2–DR3 in the Data Repository) for sample 15ET249 to constrain equilibrium conditions recorded by M_1 and M_2. We segmented the thin section into the two texturally distinct domains and combined modal phase proportions with their representative compositions to calculate independent effective bulk compositions for each domain (Table DR1). Based on the calculated stable equilibrium assemblage field of the observed major silicates Grt_1 and clinopyroxene (>1 vol%) and complemented by isomodes for garnet (originally ~35 vol% or higher assuming resorption) and plagioclase (initially plagioclase free), minimum P-T conditions for the M_1 assemblage are 12 ± 1 kbar and >700 °C (Fig. 3). Accessory rutile was not preserved in the M_1 assemblage and may have been lost during pervasive overprinting in the ilmenite stability field. However, it should be noted that the stability of minor phases is not accurately predicted with this technique (e.g., Forshaw et al., 2019). Three 1–3 mm fragments of the Grt_1 porphyroblast shown in Figure 2, together with a M_1 matrix clinopyroxene, were subjected to Lu-Hf analysis, yielding a statistically valid isochron regression (Fig. 3; Table DR2) with an apparent age of 2111 ± 3 Ma (mean square weighted deviation [MSWD] = 0.41). The M_2 assemblage equilibrated at P-T conditions of 8–11 kbar and >750 °C (Fig. DR3). Lu-Hf analyses of two separates of clean, single 1 mm Grt_2 crystals, with no anchoring mineral or whole-rock point, lay along a 1.87 Ga reference isochron and yield a two-point date of 1870 ± 40 Ma (Fig. 3), which is within error of metamorphic zircon age components in the same sample (1890 ± 33 Ma; Thiessen et al., 2018).

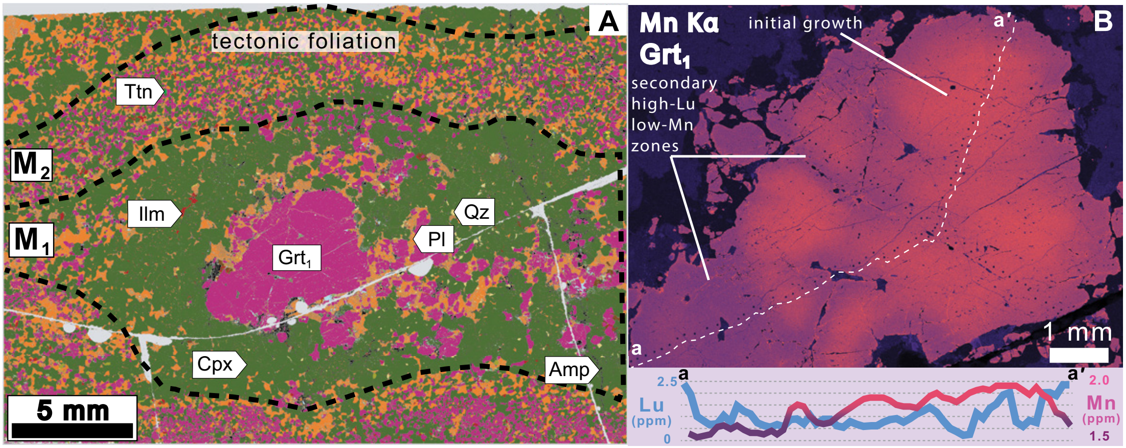
DISCUSSION

M_1 and M_2—Together, Yet 230 Million Years Apart

Major and minor element concentrations provide no evidence for the presence of multiple age domains in Grt_2. The crystals are large enough to be unaffected by $^{176}Hf^*$ (radiogenic Hf) diffusion, which would have required temperatures of at least 900 °C (Smit et al., 2013). Although evidence of diffusive uptake of Lu in these grains

[1]GSA Data Repository item 2019207, methods and supporting data for phase equilibrium modeling and major element determinations; Lu-Hf isotope analyses; and trace element determinations of garnet, is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

Figure 2. A: Thin-section scanning electron microscope phase map highlighting coarse-grained M_1 relict assemblage with retrograde plagioclase after garnet and finer-grained tectonic foliation in the M_2 domain. Amp—amphibole; Cpx—clinopyroxene; Grt_1—garnet; Ilm—ilmenite; Pl—plagioclase; Qz—quartz; Ttn—titanite. B: Mn chemical map of M_1 garnet from A, showing homogeneous high-Mn core (2.1 wt% Mn) with later crosscutting and rimming low-Mn domains (1.4 wt% Mn) reflecting garnet growth followed by reequilibration or recrystallization or new growth. Coupled Lu and Mn compositional profiles are shown that correspond with traverse line a to a′ that represents transect of laser pits across porphyroblast. Fragments of M_1 garnet porphyroblast pictured were dated by Lu-Hf geochronology.



is lacking, such an effect remains possible (Bloch et al., 2015), and thus, the Lu-Hf date for M_2 may be subject to slight "younging", which in extreme cases, may be a few tens of millions of years (Smit et al., 2013). Regardless, the ca. 1.87 Ga date for Grt_2 overlaps metamorphic zircon ages obtained from this sample (1890 ± 33 Ma; Thiessen et al., 2018) and is consistent with the time of regional metamorphism (1.92–1.89 Ga; Martel et al., 2008) and shearing along the Wholdaia Lake shear zone (1.90–1.86 Ga; Thiessen et al., 2018). The date is slightly older than the age for Wholdaia Lake shear zone footwall anatexis (1845–1824 Ma; Regis et al., 2017), which immediately preceded exhumation documented by ^{40}Ar-^{39}Ar hornblende ages of 1840–1769 Ma (Regis and Kellett, 2018).

The Grt_1 Lu-Hf age provides a striking new result, distinct from previously recognized zircon age components for this sample (2.6 and 1.9 Ga). For several reasons, the 2.11 Ga Grt_1 date likely reflects primary growth rather than resetting or mixing with older 2.6 Ga garnet. Significant diffusive loss of $^{176}Hf^*$ is unlikely, as closure temperatures (>1000 °C) for the grain size of Grt_1 are well beyond the peak estimated temperature, even when considering an unrealistically slow cooling rate of 2 °C/m.y. (Smit et al., 2013). Also, diffusive reuptake of Lu as observed by Kelly et al. (2011) is not evident. However, we do observe small increases in Lu toward the rim and within healed fractures (Fig. 2B), but they do not display typical Rayleigh fractionation patterns and are, therefore, likely secondary features. Furthermore, the low-Mn Grt_1 rims and fractures are not typical features for resorbed garnet, in which Mn usually is enriched due to diffusive reuptake. The reason for the coupled low Mn and higher Lu is unclear, yet this feature appears to be part of Grt_1. The higher Lu concentrations in the Grt_1 rim and fractures correspond to those obtained from the solution analyses (Table DR2), which could indicate that the 2111 ± 3 Ma age is skewed toward the rims. However, the sampled 1–3 mm garnet fragments may preferentially preserve core domains over rims given the irregular and fragile outer margins of Grt_1 (Fig. 2). Even if the isochron age is skewed toward the volumetrically significant rim domains, the analyzed fragments include both core and rim isotopic values that together yield a precise age with no resolvable scatter indicating that both features formed at 2111 ± 3 Ma. Also, age skewing due to dissolution of inclusions rich in ^{176}Hf is unlikely due to the high Lu/Hf ratios obtained (Table DR2). It is possible that the 2.11 Ga Lu-Hf age is the result of mixing between Lu-enriched domains (possible 1.87 Ga M_2) and a 2.6 Ga core. Such extreme age mixing or partial resetting has been described in the literature (Herwartz et al., 2011; Dragovic et al., 2016), and has yielded a high degree of scatter for the calculated isochrons. If affected by these processes, similar degrees of scatter should be expected for Grt_1 considering that each data point consisted of large fragments (>1 mm), each presumably with variable proportions of Lu-rich material. However, this scatter is not observed; the Grt_1 isochron is remarkably precisely constrained. This may not theoretically exclude a mixing hypothesis but sets such an unrealistic number of exact requirements to the volume and concentration of the mixing components that this option is considered highly implausible. Age skewing due to diffusive gain of Lu (Bloch et al., 2015) is also possible especially because we observe a Lu enrichment along fractures and rims of M_1 garnet. However, if diffusive gain occurred well after initial M_1 garnet growth, then notable scatter should be seen in the M_1 isochron reflecting distinct Lu/Hf domains, which is not observed. Lastly, we note that the current decay constant uncertainties for ^{176}Lu (Söderlund et al., 2004) do not facilitate overlap of the M_1 Lu-Hf and U-Pb ages determined for this sample. Thus, we conclude that 2111 ± 3 Ma very closely approximates the time of growth of M_1, including Lu/Mn heterogeneities observed in Grt_1, at pressures of 12 kbar or higher.

Decoupling of Lu-Hf and U-Pb Chronometers

Microtextural analyses and petrologic modeling of sample 15ET249 reveal a two-stage evolution separated by ~230 m.y. with high-grade garnet growth at 2111 ± 3 Ma and 1870 ± 40 Ma. The sample preserves U-Pb zircon populations at 2.6 and 1.9 Ga, while no concordant 2.11 Ga zircon dates occur (Thiessen et al., 2018). Lu-Hf garnet and U-Pb mineral dates are commonly offset due to their growth along distinct intervals of a single *P-T* path or owing to their contrasting responses to reequilibration of petrological assemblages (e.g., Smit et al., 2014). Zircon growth within HP mafic granulites is predicted to occur mainly upon cooling and decompression rather than during prograde metamorphism (Kohn et al., 2015) due to the breakdown of Zr-bearing phases. Because the M_1 assemblage is anhydrous, cooling alone at 2.11 or 1.9 Ga may not have been sufficient to liberate Zr and grow new zircon. Additionally, metamorphic zircon within sample 15ET249 at 1.9 Ga is interpreted as recrystallized rather than neocrystallized (Thiessen et al., 2018). This suggests that minimal Zr was liberated during the 1.9 Ga M_2 event and that deformation may have been necessary for recrystallization and isotopic resetting along 2.6 Ga zircon rims and, thus, may explain the lack of zircon recrystallization during the static M_1 event.

High-pressure metamorphism at 2111 ± 3 Ma occurred during an interval of time when no major tectonic events have been recognized within the southern Rae craton (Fig. 1B); however, rare igneous events dated at 2.1 Ga possibly related to regional (failed) rifting have been documented (Card et al., 2014; Regan et al.,

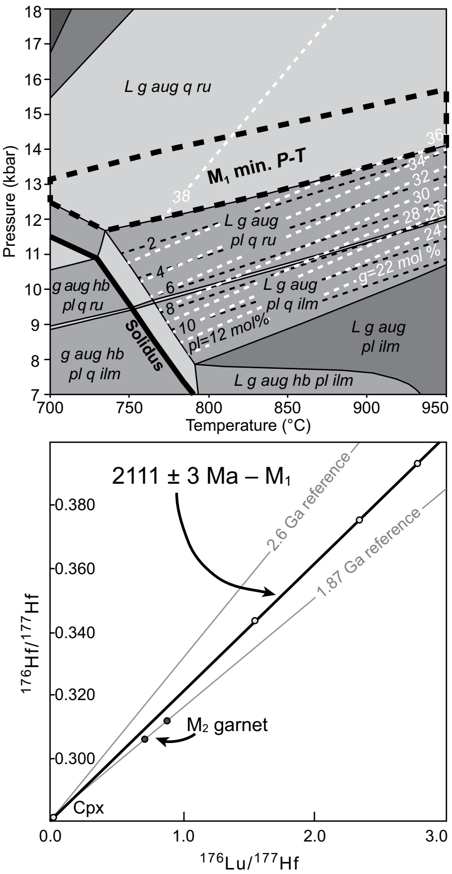


Figure 3. Upper plot: Pseudosection of M_1 domain showing minimum pressure-temperature (*P-T*) estimates of 12 kbar and >700 °C. Peak pressure corresponds to plagioclase-free garnet-clinopyroxene assemblage and is supported by >34 mol% equivalent garnet (now partially resorbed to 24%—see Fig. 2A). Assemblages for all fields are listed in Figure DR2 (see footnote 1). Abbreviations: L—melt; g—garnet; aug—clinopyroxene (augite); q—quartz; ru—rutile; pl—plagioclase; hb—amphibole (hornblende); ilm—ilmenite. Lower plot: Lu-Hf isochron for M_1 assemblage (2111 ± 3 Ma, three ~~Grt±~~ garnet separates from one crystal plus one matrix M_1 clinopyroxene [Cpx], yellow dots). Reference isochrons for 1.87 Ga and 2.6 Ga with same initial Lu/Hf as the M_1 isochron are represented in light gray. Blue dots refer to M_2 garnet separates.

2017). Regardless, the M_1 assemblage is an example of a refractory mafic granulite in thickened lower crust that has persisted through extreme metamorphic cycles (e.g., Cutts and Smit, 2018) and preserves a unique age component that is absent in the zircon age record.

The 2.11 Ga garnet age highlights a need to reexamine the timing of similar HP events in polymetamorphic terranes where growth decoupling of U-Pb accessory minerals and garnet in mafic granulites may have occurred. The results obtained here show that substantial improvements and reevaluations of tectonic models dealing with the HP evolution of the southern Rae craton can be made through garnet chronology, and that further work to discern the nature and extent of 2.1 Ga metamorphism is required. This study also highlights how a major metamorphic process within the lower crust can remain undetected if the affected rocks do not co-stabilize U-Pb accessory minerals and have been subsequently extensively deformed.

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REFERENCES CITED

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, https://doi.org/10.1007/s00410-004-0572-4.

Berman, R.G., Davis, W.J., and Pehrsson, S., 2007, Collisional Snowbird tectonic zone resurrected: Growth of Laurentia during the 1.9 Ga accretionary phase of the Hudsonian orogeny: Geology, v. 35, p. 911–914, https://doi.org/10.1130/G23771A.1.

Berman, R.G., Pehrsson, S., Davis, W.J., Ryan, J.J., Qui, H., and Ashton, K.E., 2013, The Arrowsmith orogeny: Geochronological and thermobarometric constraints on its extent and tectonic setting in the Rae craton, with implications for pre-Nuna supercontinent reconstruction: Precambrian Research, v. 232, p. 44–69, https://doi.org/10.1016/j.precamres.2012.10.015.

Bethune, K.M., Berman, R.G., Rayner, N., and Ashton, K.E., 2013, Structural, petrological and U-Pb SHRIMP geochronological study of the western Beaverlodge domain: Implications for crustal architecture, multi-stage orogenesis and the extent of the Taltson orogen in the SW Rae craton, Canadian Shield: Precambrian Research, v. 232, p. 89–118, https://doi.org/10.1016/j.precamres.2013.01.001.

Bloch, E., Ganguly, J., Hervig, R., and Cheng, W., 2015, ^{176}Lu-^{176}Hf geochronology of garnet I: Experimental determination of the diffusion kinetics of Lu^{3+} and Hf^{4+} in garnet, closure temperatures and geochronological implications: Contributions to Mineralogy and Petrology, v. 169, 12, https://doi.org/10.1007/s00410-015-1109-8.

Card, C.D., Bethune, K.M., Davis, W.J., Rayner, N., and Ashton, K.E., 2014, The case for a distinct Taltson orogeny: Evidence from northwest Saskatchewan, Canada: Precambrian Research, v. 255, p. 245–265, https://doi.org/10.1016/j.precamres.2014.09.022.

Carswell, D.A., Tucker, R.D., O'Brien, P.J., and Krogh, T.E., 2003, Coesite micro-inclusions and the U/Pb age of zircons from the Hareidland Eclogite in the Western Gneiss Region of Norway: Lithos, v. 67, p. 181–190, https://doi.org/10.1016/S0024-4937(03)00014-8.

Cutts, J.A., and Smit, M.A., 2018, Rates of deep continental burial from Lu-Hf garnet chronology and Zr-in-rutile thermometry on (ultra)high-pressure rocks: Tectonics, v. 37, p. 71–88, https://doi.org/10.1002/2017TC004723.

Davis, W.J., Pehrsson, S.J., and Percival, J.A., 2015, Results of a U-Pb zircon geochronology transect across the southern Rae craton, Northwest Territories, Canada: Geological Survey of Canada Open File 7655, 74 p., https://doi.org/10.4095/295610.

Dragovic, B., Guevara, V.E., Caddick, M.J., Baxter, E.F., and Kylander-Clark, A.R.C., 2016, A pulse of cryptic granulite-facies metamorphism in the Archean Wyoming Craton revealed by Sm-Nd garnet and U-Pb monazite geochronology: Precambrian Research, v. 283, p. 24–49, https://doi.org/10.1016/j.precamres.2016.07.010.

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, https://doi.org/10.1111/jmg.12150.

Dumond, G., Williams, M.L., Baldwin, J.A., and Jercinovic, M.J., 2017, Backarc origin for Neoarchean ultrahigh-temperature metamorphism, eclogitization, and orogenic root growth: Geology, v. 45, p. 943–946, https://doi.org/10.1130/G39254.1.

Flowers, R.M., Mahan, K.H., Bowring, S.A., Williams, M.L., Pringle, M.S., and Hodges, K.V., 2006, Multistage exhumation and juxtaposition of lower continental crust in the western Canadian Shield: Linking high-resolution U-Pb and $^{40}Ar/^{39}Ar$ thermochronology with pressure-temperature-deformation paths: Tectonics, v. 25, TC4003, https://doi.org/10.1029/2005TC001912.

Flowers, R.M., Bowring, S.A., Mahan, K.H., Williams, M.L., and Williams, I.S., 2008, Stabilization and reactivation of cratonic lithosphere from the lower crustal record in the western Canadian shield: Contributions to Mineralogy and Petrology, v. 156, p. 529–549, https://doi.org/10.1007/s00410-008-0301-5.

Forshaw, J.B., Waters, D.J., Pattison, D.R.M., Palin, R.M., and Gopon, P., 2019, A comparison of observed and thermodynamically predicted phase equilibria and mineral compositions in mafic granulites: Journal of Metamorphic Geology, v. 37, p. 153–179, https://doi.org/10.1111/jmg.12454.

Herwartz, D., Nagel, T.J., Münker, C., Scherer, E.E., and Froitzheim, N., 2011, Tracing two orogenic cycles in one eclogite sample by Lu-Hf garnet chronometry: Nature Geoscience, v. 4, p. 178–183, https://doi.org/10.1038/ngeo1060.

Kelly, E.D., Carlson, W.D., and Connelly, J.N., 2011, Implications of garnet resorption for the Lu-Hf garnet geochronometer: An example from the contact aureole of the Makhavinekh Lake Pluton, Labrador: Journal of Metamorphic Geology, v. 29, p. 901–916, https://doi.org/10.1111/j.1525-1314.2011.00946.x.

Kelsey, D.E., Clark, C., and Hand, M., 2008, Thermobarometric modelling of zircon and monazite growth in melt-bearing systems: Examples using model metapelitic and metapsammitic granulites: Journal of Metamorphic Geology, v. 26, p. 199–212, https://doi.org/10.1111/j.1525-1314.2007.00757.x.

Kohn, M.J., and Spear, F., 2000, Retrograde net transfer reaction insurance for pressure-temperature estimates: Geology, v. 28, p. 1127–1130, https://doi.org/10.1130/0091-7613(2000)28<1127:RNTRIF>2.0.CO;2.

Kohn, M.J., Corrie, S.L., and Markley, C., 2015, The fall and rise of metamorphic zircon: The American Mineralogist, v. 100, p. 897–908, https://doi.org/10.2138/am-2015-5064.

Kohn, M.J., Engi, M., and Lanari, P., eds., 2017, Petrochronology: Methods and Applications: Berlin, Boston, Walter de Gruyter, Reviews in Mineralogy and Geochemistry, v. 83, 575 p., https://doi.org/10.1515/9783110561890.

Kooijman, E., Smit, M.A., Ratschbacher, L., and Kylander-Clark, A.R.C., 2017, A view into crustal evolution at mantle depths: Earth and Planetary Science Letters, v. 465, p. 59–69, https://doi.org/10.1016/j.epsl.2017.02.032.

Mahan, K.H., Goncalves, P., Williams, M.L., and Jercinovic, M.J., 2006, Dating metamorphic reactions and fluid flow: Application to exhumation of high-*P* granulites in a crustal-scale shear zone, western Canadian Shield: Journal of Metamorphic Geology, v. 24, p. 193–217, https://doi.org/10.1111/j.1525-1314.2006.00633.x.

Mahan, K.H., Goncalves, P., Flowers, R., Williams, M.L., and Hoffman-Setka, D., 2008, The role of heterogeneous strain in the development and preservation of a polymetamorphic record in high-*P* granulites, western Canadian Shield: Journal of Metamorphic Geology, v. 26, p. 669–694, https://doi.org/10.1111/j.1525-1314.2008.00783.x.

Martel, E., van Breemen, O., Berman, R.G., and Pehrsson, S., 2008, Geochronology and tectonometamorphic history of the Snowbird Lake area, Northwest Territories, Canada: New insights into the architecture and significance of the Snowbird tectonic zone: Precambrian Research, v. 161, p. 201–230, https://doi.org/10.1016/j.precamres.2007.07.007.

O'Brien, P.J., Zotov, N., Law, R., Khan, M.A., and Jan, M.Q., 2001, Coesite in Himalayan eclogite and implications for models of India-Asia collision: Geology, v. 29, p. 435–438, https://doi.org/10.1130/0091-7613(2001)029<0435:CIHEAI>2.0.CO;2.

Rainbird, R.H., Davis, W.J., Pehrsson, S.J., Wodicka, N., Rayner, N., and Skulski, T., 2010, Early Paleoproterozoic supracrustal assemblages of the Rae domain, Nunavut, Canada: Intracratonic basin development during supercontinent break-up and assembly: Precambrian Research, v. 181, p. 167–186, https://doi.org/10.1016/j.precamres.2010.06.005.

Regan, S.P., Grohn, L.J., Williams, M.L., Chiarenzelli, J., Jercinovic, M., Cousens, B., Aspler, L.B., and Mahan, K.H., 2017, The Snowbird tectonic zone LIP: Implications for an aborted rift origin: Geological Society of America Abstracts with Programs, v. 49, no. 6, https://doi.org/10.1130/abs/2017AM-302135.

Regis, D., and Kellett, D.A., 2018, ^{40}Ar/^{39}Ar hornblende and biotite cooling ages for metamorphic rocks from the southern Rae craton, Northwest Territories: Geological Survey of Canada Open File 8438, 73 p., https://doi.org/10.4095/311217.

Regis, D., Martel, E., Davis, W.J., and Pehrsson, S.J., 2017, U-Pb zircon geochronology of metaplutonic rocks across the southern Rae province, Northwest Territories: Geological Survey of Canada Open File 8254, 37 p., https://doi.org/10.4095/302772.

Smit, M.A., Scherer, E.E., and Mezger, K., 2013, Lu-Hf and Sm-Nd garnet geochronology: Chronometric closure and implications for dating petrological processes: Earth and Planetary Science Letters, v. 381, p. 222–233, https://doi.org/10.1016/j.epsl.2013.08.046.

Smit, M.A., Ratschbacher, L., Kooijman, E., and Stearns, M.A., 2014, Early evolution of the Pamir deep crust from Lu-Hf and U-Pb geochronology and garnet thermometry: Geology, v. 42, p. 1047–1050, https://doi.org/10.1130/G35878.1.

Söderlund, U., Patchett, P.J., Vervoort, J.D., and Isachsen, C.E., 2004, The ^{176}Lu decay constant determined by Lu-Hf and U-Pb isotope systematics of Precambrian mafic intrusions: Earth and Planetary Science Letters, v. 219, p. 311–324, https://doi.org/10.1016/S0012-821X(04)00012-3.

Thiessen, E.J., Gibson, H.D., Regis, D., and Pehrsson, S.J., 2018, Deformation and extensional exhumation of 1.9 Ga high-pressure granulites along the Wholdaia Lake shear zone, south Rae craton, Northwest Territories, Canada: Lithosphere, v. 10, p. 641–661, https://doi.org/10.1130/L704.1.

Yakymchuk, C., and Brown, M., 2014, Behaviour of zircon and monazite during crustal melting: Journal of the Geological Society, v. 171, p. 465–479, https://doi.org/10.1144/jgs2013-115.

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