Persistence of melt-bearing Archean lower crust for >200 million years - an example from the Lewisian Complex, NW Scotland

Tracking no: G46834R

Authors:

Rich Taylor (University of Cambridge), Tim Johnson (Curtin University), Chris Clark (Curtin University of Technology), and Richard Harrison (University of Cambridge)

Abstract:

Geochronological data in zircon from Archean tonalite-trondhjemite-tonalite (TTG) gneisses are commonly difficult to interpret. A notable example are TTG gneisses from the Lewisian Gneiss Complex (LGC), northwest Scotland, which have metamorphic zircon ages that define a more-or-less continuous spread through the Neoarchean, with no clear relationship to zircon textures. These data are generally interpreted to record discrete high-grade events at c. 2.7 Ga and c. 2.5 Ga, with intermediate ages reflecting variable Pb-loss. Although ancient diffusion of Pb is commonly invoked to explain such protracted age spreads, trace element data in zircon may permit identification of otherwise cryptic magmatic and metamorphic episodes. Although zircons from the TTG gneiss analyzed here show a characteristic spread of Neoarchean ages, they exhibit subtle but key step changes in trace element compositions that are difficult to ascribe to diffusive resetting, but which are consistent with emplacement of regionally-extensive bodies of mafic magma. These data suggest suprasolidus metamorphic temperatures persisted for 200 Myr or more during the Neoarchean. Such long-lived high-grade metamorphism is supported by data from zircon grains from a nearby monzogranite sheet. These preserve distinctive trace element compositions consistent with derivation from a mafic source, and define a well-constrained U-Pb zircon age of c. 2.6 Ga that is intermediate between the two previously proposed discrete metamorphic episodes. The persistence of melt-bearing lower crust for hundreds of millions of years was probably the norm during the Archean.

Persistence of melt-bearing Archean lower crust for >200 million years – an example from the Lewisian Complex, NW Scotland

Richard J. M. Taylor¹, Tim E. Johnson^{2,3}, Chris Clark², Richard J. Harrison¹

¹ Department of Earth Sciences, University of Cambridge, Cambridge, UK

² School of Earth and Planetary Sciences, Curtin University, Perth, Australia

³ State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan, China

ABSTRACT

Geochronological data in zircon from Archean tonalite–trondhjemite–tonalite (TTG) gneisses are commonly difficult to interpret. A notable example are TTG gneisses from the Lewisian Gneiss Complex (LGC), northwest Scotland, which have metamorphic zircon ages that define a more-or-less continuous spread through the Neoarchean, with no clear relationship to zircon textures. These data are generally interpreted to record discrete high-grade events at *c.* 2.7 Ga and *c.* 2.5 Ga, with intermediate ages reflecting variable Pb-loss. Although ancient diffusion of Pb is commonly invoked to explain such protracted age spreads, trace element data in zircon may permit identification of otherwise cryptic magmatic and metamorphic episodes. Although zircons from the TTG gneiss analyzed here show a characteristic spread of Neoarchean ages, they exhibit subtle but key step changes in trace element compositions that are difficult to ascribe to diffusive resetting, but which are consistent with emplacement of regionally-extensive bodies of mafic magma. These data suggest suprasolidus metamorphic temperatures persisted for 200 Myr or more during the Neoarchean. Such long-lived high-grade metamorphism is supported by data from zircon grains from a nearby monzogranite sheet. These preserve distinctive trace element compositions consistent with derivation from a mafic source, and define a well-constrained U–Pb zircon age of *c.* 2.6 Ga that is intermediate between the two previously proposed discrete metamorphic episodes. The persistence of melt-bearing lower crust for hundreds of millions of years was probably the norm during the Archean.

INTRODUCTION

The rates of cooling during high-grade metamorphism provide a first-order constraint on the geodynamic environment in which crustal rocks formed and were exhumed. For example, continental crust subducted to ultrahigh pressure during collisional orogenesis is generally exhumed rapidly and cools fast (Hermann et al., 2001; Rubatto and Hermann, 2001; Rubatto et al., 2001). By contrast, cooling of some granulite terranes may be slow (< 5 °C/Myr) and close-to-isobaric (Harley, 1985; Harley and Black, 1987; Harley, 1989; Mezger et al., 1991; Ashwal et al., 1999; Möller et al., 2000; Vry and Baker, 2006; Korhonen et al., 2013; Clark et al., 2018; Mitchell et al., 2019), implying formation near the base of continental crust that was never significantly overthickened and which experienced sustained high mantle heat flow (Sandiford and Powell, 1986; Bohlen, 1991).

The cooling rates of granulite terrains are difficult to constrain. At extreme temperature, most crustal rocks will undergo partial melting and melt loss. Loss of melt elevates the temperature at which solidification occurs during subsequent cooling (i.e. the solidus), restricting the temporal range over which melt crystallization (and zircon growth) can occur (Kelsey et al., 2008; Korhonen et al., 2013). These problems are exacerbated for ultrahigh temperature (UHT) rocks ($T > 900$ °C), where peak temperatures exceeded the closure temperature of most geochronometers, including zircon (Cherniak, 2010; Kelsey and Hand, 2015; Harley, 2016). In addition, Archean granulite terrains commonly record a complex polyphase tectonothermal history that may obscure their early evolution (e.g. Clark et al., 2018).

The Lewisian Gneiss Complex (LGC) of NW Scotland, part of the North Atlantic Craton, is a typical fragment of Archean lower crust, comprising mainly felsic gneisses representing deformed and metamorphosed plutonic rocks of the tonalite–trondhjemite–granodiorite (TTG) series. The rocks of the central region (Park and Tarney, 1987) record

UHT granulite facies (termed ‘Badcallian’) metamorphism (Park, 1970; Johnson and White, 2011; Feisel et al., 2018), although most were extensively retrogressed by subsequent amphibolite facies (termed ‘Inverian’) metamorphism (Evans, 1965; Wheeler et al., 2010; Zirkler et al., 2012). Although these have generally been considered to represent separate metamorphic episodes, we provide an alternative interpretation. Using U–Pb dating and the trace element composition of zircon, we propose that the lower crust in the LGC maintained suprasolidus conditions and underwent ultra-slow cooling rates of <2 °C/Myr during a protracted high-temperature episode that lasted from *c.* 2.7 to 2.5 Ga.

GEOLOGICAL SETTING

The TTG protoliths that dominate the LGC have emplacement ages that range from >3.0 Ga to *c.* 2.8 Ga, representing multiple generations of magma derived from partial melting of hydrous mafic protoliths (e.g. Friend and Kinny, 1995, 2001; Goodenough et al., 2013; MacDonald et al., 2015; Holdsworth et al., 2019). A significant and, to date, seemingly intractable problem is that U–Pb zircon data from central region gneisses show a continuous ‘smear’ of concordant metamorphic ages from *c.* 2.7 Ga to 2.5 Ga (Whitehouse and Kemp, 2010; Goodenough et al., 2013; MacDonald et al., 2015). This age spread has been interpreted either to reflect a late granulite facies metamorphic event at *c.* 2.5 Ga that partially reset Mesoarchean to Neoarchean magmatic ages (Friend and Kinny, 1995), or to record two discrete high-temperature metamorphic episodes, the so-called Badcallian and Inverian events, at *c.* 2.7 Ga and *c.* 2.5 Ga, respectively (Corfu et al., 1994; Crowley et al., 2015), with variable resetting due to Pb-loss, recrystallisation, and perhaps neocrystallization of zircon at *c.* 2.5 Ga (e.g. Whitehouse and Kemp, 2010; MacDonald et al., 2015). However, a discordant array of ages between two discrete Neoarchean tectonothermal events is

indistinguishable within uncertainty from a concordant array, and these data might instead record more-or-less continuous (re)crystallization of zircon over *c.* 200 Myr or more.

We present laser ablation split stream (LASS) zircon data from two samples from Scouriemore, the type locality for Archean metamorphism, in the central region (Assynt Terrane of Kinny et al. (2005)) of the LGC (Sutton & Watson, 1952; Fig. 1). Sample NWS17/6 is a tonalite gneiss from Geodh' Eanruig [UK Grid Reference NC 14338 44222], collected a few tens of meters from layered ultramafic–mafic granulites, part of a suite of similar bodies scattered throughout the central region (Johnson et al., 2012; Guice et al., 2018). Some 250 m further to the north, sample NWS17/7 is from a prominent foliated pink monzogranite sheet that cross-cuts an isoclinally-folded ultramafic–mafic body on the north side of Camas nam Buth [UK Grid Reference NC 14295 44665]. Petrographic images and descriptions are provided in the Data Repository.

RESULTS

Zircon Geochronology

In Fig. 2, analyses of core regions are shown as dashed ellipses and relative probability curves, whereas analyses from CL-bright rims or (in sample NWS17/6) uniform CL-bright grains with no core region, hereafter classified as ‘rims’, are shown as filled grey ellipses and relative probability curves. Uncertainties on individual spots are 2σ , and all analyses are within 6% of the concordia curve.

Tonalite Gneiss (NWS17/6)

Seventeen zircon analyses were undertaken encompassing all the textural types described below. Both cores and rims span almost the full range of ages observed here. Core

analyses have $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from 2802 ± 18 Ma to 2519 ± 73 Ma, in which U content ranges from 18 to 200 parts per million (ppm) and Th/U ratios are 0.2–1.0. Rim analyses have $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from 2765 ± 64 Ma to 2476 ± 89 Ma, with U contents from 8 to 47 ppm and Th/U ratios of 0.1–0.5. The generally lower U contents of (CL-brighter) rim analyses are reflected in larger age uncertainties. Younger core analyses typically have a brighter CL response and more diffuse patterns of oscillatory zoning.

Monzogranite Sheet (NWS17/7)

Twenty-seven zircon analyses were undertaken covering all textural types. The 18 core analyses cover a large age range. A single analysis with a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2934 ± 11 Ma is an outlier, with the ages of the remaining 17 grains ranging from 2773 ± 8 Ma to 2547 ± 19 Ma. U content ranges from 46 to 475 ppm with Th/U ratios of 0.2–1.2. Nine analyses from CL-brighter rims that were large enough to analyze form a well constrained age group with $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from 2619 ± 61 Ma to 2540 ± 170 Ma, for which U contents range from 16 to 82 ppm and Th/U ratios are relatively elevated (1.3–3.3). Although the generally lower U contents are associated with larger uncertainties, these nine analyses define a tightly-constrained population with a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2605 ± 10 Ma (95% confidence), and an MSWD of 0.72 (Figure 2B inset).

Zircon Trace Element Geochemistry

Figure 3 shows LASS trace element data for zircon grains from both samples. Methods and results are detailed in the Data Repository. As shown in Figure 4 and discussed below, we focus on those trace element data that most clearly highlight temporal variations in the composition of zircon.

133

134 ***Tonalite Gneiss (NWS17/6)***

135 Although the trace element compositions of all zircon grains from the tonalite are
136 similar (Fig. 3), plots of Yb versus Nb and Nb/Yb against age highlight three distinct time
137 periods: older than *c.* 2680 Ma (Group 1), between *c.* 2680 Ma and *c.* 2550 Ma (Group 2 –
138 grey fields on Figs 3 and 4b), and younger than *c.* 2550 Ma (Group 3). Although absolute
139 concentrations of Nb and Yb (both common igneous zircon trace element discriminants) for
140 each group overlap (Fig. 4A), Group 2 define a distinct array of Nb/Yb ratios (0.012–0.014)
141 that are significantly higher than those in groups 1 and 3 (0.006–0.009, with one outlier at
142 0.012; Fig. 4A,B).

143

144 ***Monzogranite Sheet (NWS17/7)***

145 Zircon grains from this sample show more dramatic variations in trace element
146 concentrations. In almost all cases, zircon cores with ages between *c.* 2800 and *c.* 2680 Ma
147 have trace element characteristics that are indistinguishable from Group 1 zircon in the
148 tonalite gneiss. However, the *c.* 2605 Ma rim analyses are clearly distinct for most trace
149 element values and ratios. Of particular note, significantly lower HREE concentrations in the
150 rims (see Fig. 2 of the Data Repository) are manifest in increased Gd/Yb (Fig. 4D) and
151 Nb/Yb ratios (Fig. 4E). In all instances, these changes record what is known as the ‘garnet
152 effect’ (Grimes et al., 2015).

153

154 **DISCUSSION**

155 **Zircon in the Tonalite Gneiss**

The studied tonalite gneiss records a continuous spread of zircon ages spanning more than 250 Myr, with little correlation between age and zircon texture. The cores of zircon grains show clear evidence for recrystallization (see Fig. 1C of the Data Repository), with most recording ages of *c.* 2.8–2.7 Ga. Thus, the spectrum of core dates most likely represents variably-disturbed protolith (magmatic) ages. The oldest zircon with a distinct metamorphic texture in the tonalite is 2765 ± 64 Ma, suggesting that temperatures sufficiently high to recrystallize zircon (i.e. granulite facies) had been reached by this stage.

Although variations in the Nb/Yb ratio in zircon are subtle, they are statistically significant. Figure 4c shows a variation diagram plotting Nb/Yb versus U/Yb (Grimes et al., 2015). Although designed for the interpretation of zircon from igneous rocks, there is no reason to assume this plot does not apply to melt-bearing metamorphic rocks. Despite scatter in the data, most analyses of Group 1 and 3 zircon (and the median of these data) lie in the field of continental crust (‘continental arc’ of Grime et al., 2005), whereas the majority of Group 2 zircon (and the median) plot within the mantle array (Fig. 4C). We suggest that Group 2 zircon grew from melts derived from more mafic protoliths, or from TTG crust modified by prolonged interaction with mafic magma. Prior to growth of Group 2 zircon (>2680 Ma), the trace element signatures suggest crystallization from melt derived from anatexis of the volumetrically-dominant TTG (Johnson et al. 2013). Subsequent to *c.* 2550 Ma (Group 3), the signal returns to this evolved (TTG-derived) signal. Together, these data are consistent with a switch from a compressional to an extensional regime, then back to compression, all of which caused reworking and partial melting of the crust.

Zircon in the Monzogranite Sheet

The trace element composition of zircon cores from the monzogranite sheet are indistinguishable from those of Group 1 zircon in the tonalite, suggesting they were entrained (as xenocrysts) from the TTG country rocks. The old (2934 Ma) core analysis likely preserves the minimum crystallization age of (some of) the TTG protoliths, consistent with previous studies (Friend and Kinny, 1995; MacDonald et al., 2015).

The trace element signatures of zircon rims in the monzogranite, in particular the flat middle to heavy REE patterns, indicate growth in the presence of garnet (Rubatto, 2002; Taylor et al., 2015; Taylor et al., 2016; Rubatto, 2017). Importantly, almost all TTG gneisses in the LGC lack garnet, whereas many of the mafic layers within the large ultramafic–mafic bodies contain abundant garnet, including those that crop-out a few meters below the monzogranite sheet (O’Hara, 1961; Johnson & White, 2010). Field evidence for in-situ partial melting of mafic granulites throughout the Assynt Terrane is ubiquitous (Johnson et al., 2012). We suggest that the monzogranite sheet was derived from low-volume partial melting of proximal garnet-bearing mafic layers that, on cooling, crystallized zircon at *c.* 2600 Ma on pre-existing inherited cores.

The Nature of Archean Lower Crust

These results have profound implications for interpreting data from the LGC. The well-constrained 2605 ± 10 Ma crystallization age of the monzogranite sheet (Fig. 3B) is conspicuous, corresponding to a temporal lull in metamorphic ages in the tonalite (Fig. 3A), but sitting between the commonly quoted ages for discrete *c.* 2.7 Ga (Badcallian) and *c.* 2.5 Ga (Inverian) metamorphic ‘events’. The zircon data from the tonalite support the general notion that the LGC was intruded by a suite of mafic magmas at or after *c.* 2.7 Ga, consistent with existing constraints (Cohen et al., 1991; Burton et al., 2000). Such bodies are common

throughout the central region (Bowes et al., 1964; Johnson et al., 2012, 2016; Guice et al., 2018), and would have provided substantial heat to help sustain granulite facies conditions in the deep crust. The age and trace element data of zircon from the monzogranite sheet, which are consistent with crystallization at *c.* 2600 Ma of melt derived from mafic protoliths, provide evidence in support of this interpretation.

Rather than two discrete high-grade metamorphic events, we interpret that rocks of the central region record a protracted tectonothermal episode during which the lower crust remained at high-temperature, and melt-bearing, for more than 200 million years, sustained by the input of mantle-derived magmas. We suggest that the pervasive (Inverian) amphibolite-facies retrogression recorded in rocks throughout the central region began with the crystallization of the final vestiges of H₂O-rich melt on cooling to the wet solidus at *c.* 2.5 Ga, coincident with the emplacement of pegmatites within the region (e.g. Corfu et al., 1994).

Such prolonged metamorphism is increasingly being recognized in the geological record through careful interpretation of coupled U–Pb and trace element data (e.g. Kelly and Harley, 2005; Korhonen et al., 2013; Clark et al., 2015, 2018; Harley, 2016; Taylor et al., 2016; Cavalcante et al., 2018). The extremely slow rate of cooling implied by our data have implications for mechanisms of heat loss, and require that the lower crust remained melt present and close to isostatic equilibrium for more than 200 Myr. We suggest that the protracted high-temperature history recorded by rocks of the LGC may be a feature common to rocks from the deeper levels of Archean crust, indicating that many Archean zircon ages may not simply record ancient Pb-loss, but are geologically meaningful.

ACKNOWLEDGEMENTS

TEJ acknowledges support from the State Key Laboratory for Geological Processes and Mineral Resources, China University of Geosciences, Wuhan (Open Funds GPMR201704 and GPMR201903). RJMT acknowledges salary support through NERC standard grant (NE/P002498/1). LASS data was collected at the John de Laeter Centre for Isotope Research in Western Australia. The authors thank Fernando Corfu, Simon Harley, and Bob Holdsworth for detailed and constructive reviews that helped improve the manuscript.

KEYWORDS: Archean; long-lived high-grade metamorphism; Lewisian Gneiss Complex; TTG gneiss; zircon; laser ablation split stream (LASS) petrochronology

FIGURE CAPTIONS

Figure 1. Simplified geological map showing the locality of the two studied samples near the village of Scourie, in the heart of the Lewisian Gneiss Complex, NW Scotland.

Figure 2. Tera-Wasserburg U–Pb/Pb–Pb plots for the TTG (sample NWS17/6; A) and monzogranite (sample NWS17/7 ; B). Although both samples define a continuous spread of ages between *c.* 2.8–2.5 Ga, the ages in sample NWS17/6 shows no clear correlation with zircon texture. Rims of zircon grains in sample NWS17/7 define a distinct population at *c.* 2.6 Ga.

Figure 3. Trace element characteristics of zircon from the two studied samples. The grey band highlights the age range of Group 2 zircon, as defined on the basis of Yb and Nb contents (see Fig. 4A). Notably, trace element data commonly measured in zircon, such as Ti contents and Th/U ratios, do not distinguish discrete age populations. The TTG age groups are discussed in more detail in relation to Figure 4.

Figure 4. Key trace element plots for zircon in the TTG (sample NWS17/6; A–C) and monzogranite (sample NWS17/7; D). (A) The Nb vs Yb composition of zircon from the tonalite shows two distinct trends to define three time periods. (B) The Nb/Yb ratio of zircon from the tonalite are lower for the oldest ages (Group 1), increase within the intermediate age period (Group 2), then return to lower values for the majority of analyses in age Group 3. (C) Discrimination diagram of U/Yb vs Nb/Yb for zircon from the tonalite shows that Group 2 zircon compositions overlap with the mantle array. (D) Monzogranite cores are similar to TTG zircon compositions, whereas the rim compositions are distinct and display a ‘garnet signature’, despite the lack of garnet in the rock.

REFERENCES

- Ashwal, L. D., Tucker, R. D., and Zinner, E. K., 1999, Slow cooling of deep crustal granulites and Pb-loss in zircon: *Geochimica et Cosmochimica Acta*, v. 63, no. 18, p. 2839-2851.
- Bohlen, S. R., 1991, On the formation of granulites: *Journal of Metamorphic Geology*, v. 9, no. 3, p. 223-229.
- Bowes, D. R., Wright, A. E., and Park, R. G., 1964, Layered intrusive rocks in the Lewisian of the North-West Highlands of Scotland: *Quarterly Journal of the Geological Society of London*, v. 120, no. 1-4, p. 153-192.
- Burton, K. W., Capmas, F., Birck, J. L., Allègre, C. J., and Cohen, A. S., 2000, Resolving crystallisation ages of Archean mafic-ultramafic rocks using the Re-Os isotope system: *Earth and Planetary Science Letters*, v. 179, no. 3-4, p. 453-467.
- Cavalcante, C., Hollanda, M. H., Vauchez, A., and Kawata, M., 2018, How long can the middle crust remain partially molten during orogeny?: *Geology*, v. 46, no. 10, p. 839-842.

- Cherniak, D., 2010, Diffusion in accessory minerals: zircon, titanite, apatite, monazite and xenotime: *Reviews in Mineralogy and Geochemistry*, v. 72, no. 1, p. 827-869.
- Clark, C., Healy, D., Johnson, T., Collins, A. S., Taylor, R. J., Santosh, M., & Timms, N. E., 2015, Hot orogens and supercontinent amalgamation: A Gondwanan example from southern India. *Gondwana Research*, v. 28, 1310-1328.
- Clark, C., Taylor, R. J., Kylander-Clark, A. R., and Hacker, B. R., 2018, Prolonged (> 100 Ma) ultrahigh temperature metamorphism in the Napier Complex, East Antarctica: AP etrochronological investigation of Earth's hottest crust: *Journal of Metamorphic Geology*.
- Cohen, A., O'Nions, R., and O'Hara, M., 1991, Chronology and mechanism of depletion in Lewisian granulites: *Contributions to Mineralogy and Petrology*, v. 106, no. 2, p. 142-153.
- Corfu, F., Heaman, L. M., and Rogers, G., 1994, Polymetamorphic evolution of the Lewisian complex, NW Scotland, as recorded by U-Pb isotopic compositions of zircon, titanite and rutile: *Contributions to Mineralogy and Petrology*, v. 117, no. 3, p. 215-228.
- Crowley, Q. G., Key, R., and Noble, S. R., 2015, High-precision U-Pb dating of complex zircon from the Lewisian Gneiss Complex of Scotland using an incremental CA-ID-TIMS approach: *Gondwana Research*, v. 27, no. 4, p. 1381-1391.
- Evans, C., 1965, Geochronology of the Lewisian basement near Lochinver, Sutherland: *Nature*, v. 207, no. 4992, p. 54.
- Feisel, Y., White, R. W., Palin, R. M., and Johnson, T. E., 2018, New constraints on granulite facies metamorphism and melt production in the Lewisian Complex, northwest Scotland: *Journal of Metamorphic Geology*, v. 36, no. 6, p. 799-819.
- Friend, C. R. L., and Kinny, P. D., 1995, New evidence for protolith ages of Lewisian granulites, northwest Scotland: *Geology*, v. 23, no. 11, p. 1027-1030.
- , 2001, A reappraisal of the Lewisian Gneiss Complex: Geochronological evidence for its tectonic assembly from disparate terranes in the Proterozoic: *Contributions to Mineralogy and Petrology*, v. 142, no. 2, p. 198-218.
- Goodenough, K. M., Crowley, Q. G., Krabbendam, M., and Parry, S. F., 2013, New U-Pb age constraints for the Laxford Shear Zone, NW Scotland: Evidence for tectono-magmatic processes associated with the formation of a Paleoproterozoic supercontinent: *Precambrian Research*, v. 233, p. 1-19.
- Grimes, C. B., Wooden, J. L., Cheadle, M. J., and John, B. E., 2015, "Fingerprinting" tectono-magmatic provenance using trace elements in igneous zircon: *Contributions to Mineralogy and Petrology*, v. 170, no. 5, p. 46.
- Guice, G. L., McDonald, I., Hughes, H. S. R., MacDonald, J. M., Blenkinsop, T. G., Goodenough, K. M., Faithfull, J. W., and Gooday, R. J., 2018, Re-evaluating ambiguous age relationships in Archean cratons: Implications for the origin of ultramafic-mafic complexes in the Lewisian Gneiss Complex: *Precambrian Research*, v. 311, p. 136-156.
- Harley, S. L., 1985, Garnet-orthopyroxene bearing granulites from enderby land, Antarctica: Metamorphic pressure temperature-time evolution of the archaean napier complex: *Journal of Petrology*, v. 26, no. 4, p. 819-856.
- , 1989, The origins of granulites: a metamorphic perspective: *Geological Magazine*, v. 126, no. 3, p. 215-247.
- , 2016, A matter of time: The importance of the duration of UHT metamorphism: *Journal of Mineralogical and Petrological Sciences*, v. 111, no. 2, p. 50-72.
- Harley, S. L., and Black, L. P., 1987, The Archaean geological evolution of Enderby Land, Antarctica: Evolution of the Lewisian and comparable Precambrian high grade terrains, p. 285-296.
- Hermann, J., Rubatto, D., Korsakov, A., and Shatsky, V. S., 2001, Multiple zircon growth during fast exhumation of diamondiferous, deeply subducted continental crust (Kokchetav Massif, Kazakhstan): *Contributions to Mineralogy and Petrology*, v. 141, no. 1, p. 66-82.

- Holdsworth, R. E., Morton, A., Frei, D., Gerdes, A., Strachan, R. A., Dempsey, E., Warren, C., and Whitham, A., 2019, The nature and significance of the Faroe-Shetland Terrane: Linking Archaean basement blocks across the North Atlantic: *Precambrian Research*, v. 321, p. 154-171.
- Johnson, T. E., Brown, M., Goodenough, K. M., Clark, C., Kinny, P. D., & White, R. W., 2016, Subduction or sagduction? Ambiguity in constraining the origin of ultramafic–mafic bodies in the Archean crust of NW Scotland. *Precambrian Research*, v. 283, 89-105.
- Johnson, T., and White, R., 2011, Phase equilibrium constraints on conditions of granulite-facies metamorphism at Scourie, NW Scotland: *Journal of the Geological Society*, v. 168, no. 1, p. 147-158.
- Johnson, T. E., Fischer, S., and White, R. W., 2013, Field and petrographic evidence for partial melting of TTG gneisses from the central region of the mainland Lewisian complex, NW Scotland: *Journal of the Geological Society*, v. 170, no. 2, p. 319-326.
- Johnson, T. E., Fischer, S., White, R. W., Brown, M., and Rollinson, H. R., 2012, Archaean intracrustal differentiation from partial melting of metagabbro-field and geochemical evidence from the central region of the Lewisian complex, NW Scotland: *Journal of Petrology*, v. 53, no. 10, p. 2115-2138.
- Kelly, N. M., and Harley, S. L., 2005, An integrated microtextural and chemical approach to zircon geochronology: Refining the Archaean history of the Napier Complex, east Antarctica: *Contributions to Mineralogy and Petrology*, v. 149, no. 1, p. 57-84.
- Kelsey, D. E., Clark, C., & 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, 199-212.
- Kelsey, D. E., and Hand, M., 2015, On ultrahigh temperature crustal metamorphism: Phase equilibria, trace element thermometry, bulk composition, heat sources, timescales and tectonic settings: *Geoscience Frontiers*, v. 6, no. 3, p. 311-356.
- Kinny, P. D., Friend, C. R. L., and Love, G. J., 2005, Proposal for a terrane-based nomenclature for the Lewisian Gneiss Complex of NW Scotland: *Journal of the Geological Society*, v. 162, no. 1, p. 175-186.
- Korhonen, F. J., Clark, C., Brown, M., Bhattacharya, S., and Taylor, R., 2013, How long-lived is ultrahigh temperature (UHT) metamorphism? Constraints from zircon and monazite geochronology in the Eastern Ghats orogenic belt, India: *Precambrian Research*, v. 234, p. 322-350.
- MacDonald, J. M., Goodenough, K. M., Wheeler, J., Crowley, Q., Harley, S. L., Mariani, E., and Tatham, D., 2015, Temperature-time evolution of the Assynt Terrane of the Lewisian Gneiss Complex of Northwest Scotland from zircon U-Pb dating and Ti thermometry: *Precambrian Research*, v. 260, p. 55-75.
- Mezger, K., Rawnsley, C., Bohlen, S., and Hanson, G., 1991, U-Pb garnet, sphene, monazite, and rutile ages: implications for the duration of high-grade metamorphism and cooling histories, Adirondack Mts., New York: *The Journal of Geology*, v. 99, no. 3, p. 415-428.
- Mitchell, R. J., Johnson, T. E., Clark, C., Gupta, S., Brown, M., Harley, S. L., and Taylor, R., 2019, Neoproterozoic evolution and Cambrian reworking of ultrahigh temperature granulites in the Eastern Ghats Province, India: *Journal of Metamorphic Geology*, v. 37 no. (7), p. 977-1006.
- Möller, A., Mezger, K., and Schenk, V., 2000, U-Pb dating of metamorphic minerals: Pan-African metamorphism and prolonged slow cooling of high pressure granulites in Tanzania, East Africa: *Precambrian Research*, v. 104, no. 3-4, p. 123-146.
- O'Hara, M. J., 1961, Zoned ultrabasic and basic gneiss masses in the early lewisian metamorphic complex at scourie, Sutherland: *Journal of Petrology*, v. 2, no. 2, p. 248-276.
- Park, R., 1970, Observations on Lewisian chronology: *Scottish Journal of Geology*, v. 6, no. 4, p. 379-399.

- 380 Park, R. G., and Tarney, J., 1987, The Lewisian complex: A typical Precambrian high-grade
381 terrain?, Geological Society Special Publication, Volume 27, p. 13-25.
- 382 Rubatto, D., 2002, Zircon trace element geochemistry: Partitioning with garnet and the link
383 between U-Pb ages and metamorphism: *Chemical Geology*, v. 184, no. 1-2, p. 123-138.
- 384 Rubatto, D., 2017, Zircon: The Metamorphic Mineral: *Reviews in Mineralogy and Geochemistry*,
385 v. 83, no. 1, p. 261-295.
- 386 Rubatto, D., and Hermann, J. r., 2001, Exhumation as fast as subduction?: *Geology*, v. 29, no. 1,
387 p. 3-6.
- 388 Rubatto, D., Williams, I. S., and Buick, I. S., 2001, Zircon and monazite response to prograde
389 metamorphism in the Reynolds Range, central Australia: *Contributions to Mineralogy
390 and Petrology*, v. 140, no. 4, p. 458-468.
- 391 Sandiford, M., and Powell, R., 1986, Deep crustal metamorphism during continental extension:
392 modern and ancient examples: *Earth and Planetary Science Letters*, v. 79, no. 1-2, p. 151-
393 158.
- 394 Taylor, R. J., Kirkland, C. L., and Clark, C., 2016, Accessories after the facts: Constraining the
395 timing, duration and conditions of high-temperature metamorphic processes: *Lithos*, v.
396 264, p. 239-257.
- 397 Taylor, R. J. M., Clark, C., Johnson, T. E., Santosh, M., and Collins, A. S., 2015, Unravelling the
398 complexities in high-grade rocks using multiple techniques – the Achankovil Zone of
399 southern India *Contributions to Mineralogy & Petrology*, v. 169, no. 5, p. 1-19.
- 400 Vry, J. K., and Baker, J. A., 2006, LA-MC-ICPMS Pb-Pb dating of rutile from slowly cooled
401 granulites: Confirmation of the high closure temperature for Pb diffusion in rutile:
402 *Geochimica et Cosmochimica Acta*, v. 70, no. 7, p. 1807-1820.
- 403 Wheeler, J., Park, R. G., Rollinson, H. R., and Beach, A., 2010, The Lewisian Complex: Insights
404 into deep crustal evolution, Volume 335, p. 51-79.
- 405 Whitehouse, M. J., and Kemp, A. I. S., 2010, On the difficulty of assigning crustal residence,
406 magmatic protolith and metamorphic ages to Lewisian granulites: Constraints from
407 combined in situ U-Pb and Lu-Hf isotopes, Volume 335, p. 81-101.
- 408 Zirkler, A., Johnson, T. E., White, R. W., and Zack, T., 2012, Polymetamorphism in the
409 mainland Lewisian complex, NW Scotland - phase equilibria and geochronological
410 constraints from the Cnoc an t'Sidhean suite: *Journal of Metamorphic Geology*, v. 30,
411 no. 8, p. 865-885.

Figure 1

Figure 2