Preservation of basement architecture in zircon Hf isotope maps

Michael I. H. Hartnady, Christopher L. Kirkland

Abstract
Zircon Hf isotopic mapping has been proposed to image large-scale lithospheric architecture. Here we present zircon Hf isotope maps of the Proterozoic Albany–Fraser Orogen (AFO) in Western Australia, which records a protracted geological history in both extensional and compressional tectonic regimes. The spatial variation in Hf isotope composition of AFO granites is nearly orthogonal to the dominant crustal fabric. Although the $^{176}\text{Hf}/^{177}\text{Hf}$ compositions are too juvenile to represent direct melts of the Archaean basement, the variability in $^{176}\text{Hf}/^{177}\text{Hf}$ in these AFO magmatic rocks closely mimics the structure of the adjoining Yilgarn Craton. This orogen-parallel heterogeneity is best illustrated during earliest Palaeoproterozoic magmatic events, which are characterised by low Sr/Y ratios, consistent with tectonic models involving relatively uniform extension along the craton margin during the Palaeoproterozoic. These results demonstrate that regional-scale zircon Hf variability does not always image coeval lithospheric architecture, but may help illuminate deep basement structure in regions with complex deformation histories.

1 | INTRODUCTION

Crustal blocks of different age and heritage have distinct Nd and Hf isotopic signatures as a function of differences in the timing of fractionation from their mantle sources (Dickin & McNutt, 1989). Thus, spatial variations in isotopic signatures, so called isoscapes, may image major lithospheric boundaries (Mole et al., 2014) and crustal pathways for metal-rich mantle-derived magmas (Hou et al., 2015). Isotopic mapping using whole-rock Nd and zircon Hf isotope systems has been widely employed in Archaean terranes to track different lithotectonic blocks, understand the process of craton formation, and how these processes influence crustal metal fertility (Champion, 2013; Mole et al., 2014; Mole et al., 2019); thereby reducing exploration risk (Hagemann et al., 2016; Osei et al., 2021). However, these techniques have not been tested in younger terranes such as the Proterozoic orogenic belts that girdle many Archaean cratons; many of which were subject to high-T metamorphism (Harley, 1992) and potentially host a greater variety of magmatic source rocks and melt generation processes owing to the emergence of plate tectonics across the Archaean–Proterozoic transition (Keller & Schoene, 2012). The Albany–Fraser Orogen (AFO) is a Proterozoic orogenic belt that wraps around the southern and eastern margin of the Yilgarn Craton in Western Australia, and is relatively well-endowed in economic metal deposits such as the Tropicana gold deposit and Nova–Bollinger Ni–Cu magmatic sulphide deposit (Barnes et al., 2020; Crawford & Doyle, 2016). In this paper, we use U–Pb, Lu–Hf and O isotopes on inherited and magmatic zircon crystals from granites of the AFO, to image the modification of this ancient craton margin over both space and time, and test whether Hf isotopes...
are able to image mineralisation pathways along reworked craton margins.

2 | GEOLOGICAL SETTING

The Yilgarn Craton is one of the largest preserved remnants of Archaean continental crust on the planet and principally comprises granites and granitic gneisses with subordinate supracrustal belts (Figure 1a). The craton consists of several terranes, including, the Naranya and the South West Terranes to the west, the Youanmi Terrane in the centre and the Eastern Goldfields Super Terrane (EGST) across the Ida Fault in the east. The EGST has a pervasive NW-SW orientated linear fabric and gradients in whole rock Nd and zircon Hf maps have been correlated with gold and nickel mineralisation (Mole et al., 2014). Along the southern and eastern margin of the craton, this ancient fabric is cross-cut by the Proterozoic AFO, which wraps some 1,200 km around the margin of the Yilgarn Craton (Spaggiari et al., 2015). The belt reflects a protracted history of rifting and convergence with episodic magmatism from 1810 Ma to 1140 Ma (Clark et al., 2000; Hartnady et al., 2019). The AFO comprises several lithotectonic domains including the Northern Foreland, Biranup Zone, Normalup Zone and Fraser Zone (Figure 1b; Kirkland et al., 2011; Kirkland et al., 2015). Each zone has source rocks of Archaean heritage that have been variably reworked by Palaeoproterozoic and Mesoproterozoic magmatism (Smithies et al., 2015). The Eucla Basement (Madura and Coompana Provinces) lies to the east of the AFO and has a solely Proterozoic heritage with oceanic affnity (Hartnady et al., 2020; Spaggiari et al., 2018).

Together the igneous rocks of the AFO and Eucla Basement record a near continuous span of Proterozoic magmatic activity from 1850 to 1150 Ma (Hartnady et al., 2019; Kirkland et al., 2011; Kirkland et al., 2017).

3 | RESULTS

New laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) data are combined with published datasets to construct time sliced regional-scale zircon Hf isoscapes. Instrument and gridding parameters Appendix S1 and all analytical data are given in Appendices S2 and S3. Detailed petrology, zircon characterisation and U-Pb geochronology of these samples are provided in Appendix S4. An animation illustrating the Hf isotope evolution of the southern Yilgarn Craton and Albany–Fraser Orogen is provided in Appendix S5.

The first time slice (1810-1790 Ma; Figure 2a) shows a variation in εHf parallel to the orogen. Rocks in the northern Biranup and Tropicana Zones comprise reworked older crust, with εHf values ranging between −3.1 and −7.6. In contrast, more juvenile magmatism is found towards the south-western portion of the belt (εHf ~4.8 and 0.2). One sample with relatively evolved εHf of ~6.5 is found near the south-eastern edge of the Normalup Zone.

The second time slice (1770-1750 Ma; Figure 2b) is the least well sampled of the Palaeoproterozoic magmatic pulses. Nevertheless, magmatic rocks from this period also show an orogen-parallel variation in Hf isotope composition.

The third time slice (1710-1650 Ma; Figure 2c) represents the main phase of Palaeoproterozoic magmatism in the AFO. A strong orogen-parallel variation in εHf is observed in magmatic rocks from this period. The north-eastern portion of the belt is characterised by chondritic-to-sub-chondritic values (εHf ~8.8 to ~0.3). Much of the magmatism in the central Biranup Zone has chondritic-to-super-chondritic Hf values (εHf ~5.0 to ~1.5). Further to the south-west, these dominantly juvenile isotopic compositions give way to more sub-chondritic compositions (εHf ~6.3 to ~1.8). The south-western boundary between radiogenic and unradiogenic domains in the AFO corresponds with the extension of the Ida Fault in the Yilgarn Craton, and the boundary between the Youanmi Terrane and EGST.

The fourth time slice (1620–1400 Ma; Figure 2d) represents a period of magmatic quiescence in the AFO. However, this period corresponds to a period of magmatic activity in the adjacent Eucla Basement. This basement is characterised by almost exclusively super-chondritic signatures (εHf ~1.0 and +10.3).

The fifth time slice (1350–1260 Ma; Figure 2e) comprises the main period of orogenic magmatism during Stage I AFO. I-type and S-type granites associated with this magmatism (Recherche Supersuite) are
primarily found in the south-western portion of the Nornalup Zone and Fraser Zone (Kirkland et al., 2011; Smithies et al., 2015). These samples from the north-eastern portion of the belt have variable Hf isotopic compositions (εHf −14.0 to −1.7). A similar variability is also observed in granites and granitic gneiss from the south-western portion of the orogen (εHf −20.8 to −3.2).

The last time slice (1220–1140 Ma; Figure 2f) comprises magmatic rocks associated with the Esperance and Moodini Supersuites. These granitic rocks (AFO Stage II) represent a period of widespread intracontinental magmatism that post-dated the main period of collisional magmatism (Smithies et al., 2015). During this time period, magmatic rocks in the AFO have chondritic to sub-chondritic Hf isotope signatures and show spatial variation alike the Recherche Supersuite (1340–1260 Ma) magmatism. Overall, Esperance Supersuite magmatism is sub-chondritic (εHf −14.8 to −2.2). In contrast, Moodini Supersuite magmatism, to the east, exhibits predominantly super-chondritic Hf values (εHf −0.7 to +7.0).

The boundary between sub-chondritic and super-chondritic magmatism correlates with the Rodona Shear Zone, the major crustal scale structure separating the AFO from the Madura Province (Kirkland et al., 2017; Spaggiari et al., 2015; Spaggiari et al., 2018).

4 | DISCUSSION

Many previous isotopic mapping studies have shown gradients in zircon Hf isotope maps to correlate with large-scale structural features (Herrell et al., 2006). In such cases, regional-scale variation in isotopic signature is interpreted to reflect the first-order lithospheric-scale architecture (Champion & Cassidy, 2007;
Dickin & McNutt, 1989; Mole et al., 2012; Mole et al., 2014). In the isotopic maps of time-slices 4, 5, and 6 (Figure 2d-f) there is a strong gradient in isotopic signature between the AFO and the Eucla Basement, illustrating that the Rodona Shear zone is an important crustal-scale boundary separating largely autochthonous terranes of the AFO from allochthonous juvenile oceanic terranes (Kirkland et al., 2017; Spaggiari et al., 2018). However, in the AFO itself, the variation in isotopic signature is patchy and across all time slices the gradients are often orientated along NW-SE trends—nearly orthogonal to the regional-scale fabric of the orogen (Figure 2). In the Archaean Yilgarn Craton variations in Hf isotope compositions of zircon have been inferred to be a proxy for lithospheric thickness based partly on the spatial correlation between juvenile Hf isotope signatures, komatiite abundance, and base-metal fertility, which are typically associated with regions of lithospheric extension (Mole et al., 2014). In time slices 3 and 5 (Figure 2c,d), clusters of base-metal mineralisation in the AFO are associated with relatively juvenile zircon Hf isotope signature focussed around the southern part of the Fraser Zone, and are associated with mafic-ultramafic rocks (Barnes et al., 2020). However, similar base-metal clusters are also associated with relatively evolved Hf isotope signatures in high-grade gneisses in the Tropicana zone (Figure 3). Furthermore, if zircon Hf isotope variations track lithospheric thickness, then zircon Hf isotope composition should also correlate with chemical proxies for melting depth, such as Sr/Y ratios (Profeta et al., 2015). Palaeoproterozoic magmatism associated with the Biranup Orogeny shows strong orogen-parallel gradients in Hf isotope composition (Figure 2c). Yet, Palaeoproterozoic rocks associated with the Biranup Orogeny have low Sr/Y ratios (typically less than 10) irrespective of their Hf isotope composition (Figure 4), which taken at face value, imply melting depths <20 km (Profeta et al., 2015). Although a decrease in Sr/Y with SiO2 content in more evolved rocks may reflect magmatic differentiation processes, the least differentiated rocks (SiO2 = 50–70 wt%) have low Sr/Y indicating that their parental magmas likely intruded crust that was already relatively thin. Moreover, major gradients in Hf isotope composition of the Palaeoproterozoic granites are well correlated with terrane boundaries in the Yilgarn Craton, which also define crustal blocks of distinct age (Figure 4a, Figures S1–4); more evolved signatures of Palaeoproterozoic granites in the AFO correlate with extensions of the South West Terrane and Burtville and Yarmarna Terranes which are founded on ancient 3600–3200 Ma crust (Mole et al., 2019). Based on this evidence, it appears that the spatial variation in the isotope signatures of the Palaeoproterozoic granites reflects an original heterogeneity in the reworked craton margin and not the Palaeoproterozoic lithospheric architecture.

Although the spatial pattern for Palaeoproterozoic magmatism mimics the structure of the Archaean basement the range of εHf values that define magmatism in the AFO lie directly between those expected for crustal evolution arrays for the Archaean Yilgarn Craton (3600–2700 Ma), and more juvenile arrays for the
rocks from the Coompana and Madura Provinces further to the east (2000–1400 Ma). Accordingly, assuming bulk continental $^{176}\text{Lu}/^{177}\text{Hf}$, many analyses yield two-stage model ages between 2600 and 2000 Ma, which corresponds to a period of magmatic quiescence along the southern margin of the craton (Figure 5a).

Thus, it is unlikely that these granites are the product of melting Archaean basement material alone. Oxygen isotopes in zircon are sensitive to the degree of supracrustal material incorporated into the magma from which the zircon crystallised (Hawkesworth & Kemp, 2006). Therefore, oxygen isotopes may be used to discriminate granites derived purely through magmatic differentiation of mantle-derived melts from those formed through reworking of (or contamination by) pre-existing crust (Hawkesworth & Kemp, 2006). Filtering zircon Hf values by mantle-like oxygen isotope compositions, yields a distribution of model ages that is bimodal with peaks at c. 2700 Ma and c. 2000 Ma (Figure 5b) that better corresponds with known sources of juvenile magmatism in the Coompana Province and EGST respectively. These results indicate that the vertical Hf isotope arrays reflect mixing of reworked Archaean basement with younger juvenile material throughout.

---

**FIGURE 4** (a) Zircon initial $\varepsilon\text{Hf}$ map of 1710–1650 AFO granites with the orogen segmented into three zones (b) Sr/Y vs. SiO$_2$ for granites in the three zones. Crustal thickness estimate is based on calibration of Profeta et al., (2015). [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 5** (a) $\varepsilon\text{Hf}$ vs. crystallisation age for magmatic and inherited zircon from the Albany–Fraser Orogen and Eucla Basement colour coded by lithotectonic domain. Note that the range of $\varepsilon\text{Hf}$ values observed in each period of magmatism generally falls between the evolution arrays for the Yilgarn Craton and Proterozoic Eucla Basement (b) $\varepsilon\text{Hf}$ vs. crystallisation age for magmatic and inherited zircon from the Albany–Fraser Orogen for which oxygen isotope data are available. Grey circles denote zircon with supracrustal oxygen isotope compositions whereas blue squares denote zircon with mantle-like oxygen isotope compositions. [Colour figure can be viewed at wileyonlinelibrary.com]
the Palaeoproterozoic and Mesoproterozoic magmatism (Kirkland et al., 2011).

Previous studies have inferred a thinner crustal section in the Fraser Zone (central segment) of the AFO during the Palaeoproterozoic on the basis of their more juvenile Hf isotope signatures (Kirkland et al., 2016). However, these results indicate that during the Palaeoproterozoic addition of juvenile material must have been fairly uniform across the entire length of the orogen such that the inherent age variability in the Archaean basement was preserved in the spatial variation of Hf isotope composition from the Palaeoproterozoic granulites. Such uniform juvenile addition is consistent with tectonic models advocating for hyperextension of the southern and eastern margin of the Yilgarn Craton during the Palaeoproterozoic (e.g. Hartnady et al., 2019; Hartnady et al., 2020; Spaggiari et al., 2015).

5 | CONCLUSIONS

A dataset of >1700 individual analyses on 116 magmatic samples has been used to construct several Hf isoscapes for the Proterozoic AFO on the eastern margin of the Yilgarn Craton. Gradients in Hf isotope maps from Palaeoproterozoic granulites in particular are consistently orientated at a similar trend to the fabric of the adjoining Yilgarn Craton, and estimates of crustal thickness (based on Sr/Y ratios) imply a relatively shallow (~15–20 km) depth of melt generation along the length of the orogen, consistent with the development of extensional basins along the craton margin at this time (e.g. Spaggiari et al., 2015). The variation in Hf isotope composition of the Palaeoproterozoic granulites in the AFO does not image the Palaeoproterozoic lithospheric architecture, but rather preserves an image of the structure in the orogen’s Archaean substrate.

ACKNOWLEDGEMENTS

Financial support for this work was provided by the Minerals Research Institute of Western Australia (MRIWA), the Geological Survey of Western Australia, Curtin University, and Ponton Creek Minerals Pty Ltd as part of Project M470. Two anonymous reviewers are thanked for constructive comments that helped improve the manuscript. Klaus Mezger is thanked for editorial handling. L. Martin, C.V. Spaggiari, R.H. Smithies, B. McDonald and N. Evans are also thanked for support that helped facilitate this research. Open access publishing facilitated by Curtin University, as part of the Wiley - Curtin University agreement via the Council of Australian University Librarians. [Correction added on 2 July 2022, after first online publication: CAUL funding statement has been added.]

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

ORCID

Michael I. H. Hartnady https://orcid.org/0000-0001-5297-9925
Christopher L. Kirkland https://orcid.org/0000-0003-3367-8961

REFERENCES

Barnes, S. J., Taranovic, V., Miller, J. M., Boyce, G., & Beresford, S. (2020). Sulfide emplacement and migration in the Nova-Bollinger Ni-Cu-Co deposit, Albany-Fraser orogen, Western Australia. Economic Geology, 115(8), 1749–1776.

Champion, D. C. (2013). Neodymium depleted mantle model age map of Australia: explanatory notes and user guide. Record 2013/44. Canberra.

Champion, D. C., & Cassidy, K. F. (2007). An overview of the Yilgarn Craton and its crustal evolution. Geoscience Australia Record, 14, 8–13.

Clark, D. J., Hensen, B. J., & Kinny, P. D. (2000). Geochronological constraints for a two-stage history of the Albany-Fraser Orogen. Western Australia. Precambrian Research, 102(3–4), 155–183.

Crawford, A. J., & Doyle, M. G. (2016). Granulite-hosted gold: Tectonic setting and lithogeochemistry of the Tropicana Deposit, Western Australia. Economic Geology, 111(2), 395–420.

Dickin, A. P., & McNutt, R. H. (1989). Nd model age mapping of the southeast margin of the Archean foreland in the Grenville Province of Ontario. Geology, 17(4), 299–302.

Hagemann, S. G., Lisitsin, V. A., & Huston, D. L. (2016). Mineral system analysis: Quo vadis. Ore Geology Reviews, 76, 504–522.

Harley, S. L. (1992). Proterozoic granulite terranes. In Developments in Precambrian geology (Vol. 10, pp. 301–359). Elsevier.

Hartnady, M. I. H., Kirkland, C. L., Smithies, R. H., Poujol, M., & Clark, C. (2019). Periodic Palaeoproterozoic calc-alkaline magmatism at the southeast eastern margin of the Yilgarn Craton; implications for Nuna configuration. Precambrian Research, 332, 105400.

Hawkesworth, C. J., & Kemp, A. I. S. (2006). Using hafnium and oxygen isotopes in zircons to unravel the record of crustal evolution. Chemical Geology, 226(3), 144–162.

Herrell, M. K., Dickin, A. P., & Morris, W. A. (2006). A test of detailed Nd isotope mapping in the Grenville Province: delineating a duplex thrust sheet in the Kipawa–Mattawa region. Canadian Journal of Earth Sciences, 43(4), 421–432. https://doi.org/10.1139/e06-008

Hou, Z., Duan, L., Lu, Y., Zheng, Y., Zhu, D., Yang, Z., Yang, Z., Wang, B., Pei, Y., Zhao, Z., et al. (2015). Lithospheric architecture of the Lhasa terrane and its control on ore deposits in the Himalayan-Tibetan orogen. Economic Geology, 110(6), 1541–1575.

Keller, C. B., & Schoene, B. (2012). Statistical geochemistry reveals disruption in secular lithospheric evolution about 2.5 Gyr ago. Nature, 485(7399), 490–493.

Kirkland, C. L., Smithies, R. H., Spaggiari, C. V., Wingate, M. T. D., Quentin De Gromard, R., Clark, C., Gardiner, N. J., & Belousova, E. A. (2017). Proterozoic crustal evolution of the Eucla basement, Australia: Implications for destruction of oceanic crust during emergence of Nuna. Lithos, 278, 427–444.

Kirkland, C. L., Spaggiari, C. V., Johnson, T. E., Smithies, R. H., Daniššik, M., Evans, N., Wingate, M. T. D., Clark, C., Spencer, C., Mikkucki, E., & McDonald, B. J. (2016). Grain size matters: Implications for element and isotopic mobility in titanite. Precambrian Research, 278, 283–302.

Kirkland, C. L., Spaggiari, C. V., Pawley, M. J., Wingate, M. T. D., Smithies, R. H., Howard, H. M., Tyler, I. M., Belousova, E. A., & Poujol, M. (2011). On the edge: U-Pb, Lu-Hf, and Sm-Nd data suggests reworking of the Yilgarn craton margin during formation of the Albany-Fraser Orogen. Precambrian Research, 187(3–4), 223–247.

Kirkland, C. L., Spaggiari, C. V., Smithies, R. H., Wingate, M. T. D., Belousova, E. A., Greau, Y., Sweetapple, M. T., Watkins, R., Tessalina, S., & Creaser, R. (2015). The affinity of Archaean crust on
the Yilgarn Albany-Fraser Orogen boundary: Implications for gold mineralisation in the Tropicana Zone. *Precambrian Research*, 266, 260–281.

Mole, D. R., Fiorentini, M. L., Thebaud, N., Cassidy, K. F., McCuaig, T. C., Kirkland, C. L., Romano, S. S., Doublier, M. P., Belousova, E. A., Barnes, S. J., et al. (2014). Archean komatiite volcanism controlled by the evolution of early continents. *Proceedings of the National Academy of Sciences*, 111(28), 10083–10088.

Mole, D. R., Fiorentini, M. L., Thebaud, N., McCuaig, T. C., Cassidy, K. F., Kirkland, C. L., Wingate, M. T. D., Romano, S. S., Doublier, M. P., & Belousova, E. A. (2012). Spatio-temporal constraints on lithospheric development in the southwest-central Yilgarn craton, Western Australia. *Australian Journal of Earth Sciences*, 59(5), 625–656.

Mole, D. R., Kirkland, C. L., Fiorentini, M. L., Barnes, S. J., Cassidy, K. F., Issac, C., Belousova, E. A., Hartnady, M., & Thebaud, N. (2019). Time-space evolution of an Archean craton: A Hf-isotope window into continent formation. *Earth-Science Reviews*, 196, 102831.

Osei, K. P., Kirkland, C. L., & Mole, D. R. (2021). Nd and Hf isoscapes of the Yilgarn Craton, Western Australia and implications for its mineral systems. *Gondwana Research*, 92, 253–265. https://doi.org/10.1016/j.gr.2020.12.027

Profeta, L., Ducea, M. N., Chapman, J. B., Paterson, S. R., Gonzales, S. M. H., Kirsch, M., Petrescu, L., & DeCelles, P. G. (2015). Quantifying crustal thickness over time in magmatic arcs. *Scientific Reports*, 5(1), 1–7.

Smithies, R. H., Spaggiari, C. V., & Kirkland, C. L. (2015). Building the crust of the Albany-Fraser Orogen: constraints from granite geochemistry (p. 150). Geological Survey of Western Australia.

Spaggiari, C. V., Kirkland, C. L., Smithies, R. H., Wingate, M. T. D., & Belousova, E. A. (2015). Transformation of an Archean craton margin during Proterozoic basin formation and magmatism: The Albany-Fraser Orogen, Western Australia. *Precambrian Research*, 266, 440–466.

Spaggiari, C. V., Smithies, R. H., Kirkland, C. L., Wingate, M. T. D., England, R. N., & Lu, Y. (2018). Buried but preserved: The Proterozoic Arubiddy Ophiolite, Madura Province, Western Australia. *Precambrian Research*, 317, 137–158.

**SUPPORTING INFORMATION**

Additional supporting information may be found in the online version of the article at the publisher’s website.

**How to cite this article**: Hartnady, M. I. H., & Kirkland, C. L. (2022). Preservation of basement architecture in zircon Hf isotope maps. *Terra Nova*, 34, 441–448. [https://doi.org/10.1111/ter.12607](https://doi.org/10.1111/ter.12607)