Cooling and exhumation along the curved Albany-Fraser orogen, Western Australia

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ABSTRACT

The Albany-Fraser orogen of Western Australia exhibits a distinct 45° primary (preorogenic) curvature. Consequently, northwest-southeast compression during Mesoproterozoic orogeny was orthogonal to orogenic strike in the east of the orogen, but was oblique in the west. This produced different structural settings in the east and west of the orogen, with a greater component of dextral transpression in the west. We report new ⁴⁰Ar/³⁹Ar thermochronology from the east Albany-Fraser orogen, and compare these results to the cooling history of the west to examine how cooling varies between the differently striking domains of a curved orogen.

The ⁴⁰Ar/³⁹Ar analyses of hornblende, muscovite, and biotite grains encompass a range of metagneous and metasedimentary lithologies from two lithotectonic domains. The eastern Biranup Zone yields five hornblende cooling ages at ca. 1190 Ma and seven muscovite and biotite cooling ages between ca. 1171 and 1158 Ma. Hornblende and biotite in the southwestern Fraser Zone record cooling between ca. 1217 and 1205 Ma, and the central Fraser Zone reached ⁴⁰Ar/³⁹Ar biotite closure temperature at ca. 1157 Ma.

Slow 8.2–9.5 °C/m.y. cooling in the eastern Biranup Zone commenced 20 m.y. earlier than 22–33 °C/m.y. cooling in the west Albany-Fraser orogen. The differences in cooling rate are a result of the different structural settings in the east and west. However, similar mica ⁴⁰Ar/³⁹Ar cooling ages in the east and west record a convergence in cooling history. This suggests that exhumation had become increasingly decoupled from compressional tectonics, instead driven by more passive processes related to isostatic rebound and erosion.

INTRODUCTION

Exhumation controls when, where, and how rocks are exposed on the Earth’s surface. The cooling history of an orogen is strongly correlated with its exhumation history, i.e., rocks that are exhumed quickly from depth will also undergo fast cooling. Consequently, cooling rates provide a mechanism to understand the movement paths of lithotectonic packages. Cooling rates commonly vary within an orogen, and are not uniquely diagnostic of a specific exhumation mechanism (Ring et al., 1999). Nevertheless, knowledge of a region’s cooling history may aid in determining the drivers of the exhumation when considered together with other information, such as structure or metamorphism (Moore and England, 2001).

The structural setting within an orogen will affect which exhumation mechanisms operate and will consequently affect cooling rates, but previous studies have focused on comparisons between different orogens (e.g., Forbes et al., 2012; Ring et al., 1999; Willigers et al., 2002). However, no two orogens are identical, and the differing features may be those that most affect exhumation and cooling. These variables include upper or lower plate geometry (e.g., Ratschbacher et al., 1993), rheology (e.g., Gerya and Stöckhert, 2002), rock age (Mouthereau et al., 2013), and radiogenic heat production, all of which will determine the thermomechanical state of the lithosphere, and thereby influence structural development and exhumation (Charhon et al., 2009; Jamieson and Beaumont, 2013; McLaren et al., 2005). Climatic factors such as orographic rainfall-driven erosion or glaciation will also influence the tectonic evolution and exhumation of an orogen (e.g., Enkelmann et al., 2009; Koons et al., 2003), but are extremely difficult to ascertain in ancient orogens. In addition, there is a well-established correlation between orogenic age and apparent cooling rate that requires the secular evolution of the Earth to be incorporated into comparisons of cooling histories from different geological periods (Dunlap, 2000; Scibiorski et al., 2015; Willigers et al., 2002).

The Albany-Fraser orogen (AFO) of Western Australia is a Neoarchean to Mesoproterozoic orogen. It is characterized by a 45° change in strike from east to west as it curves around the margin of the Yilgarn Craton, although the principal direction of convergence during Mesoproterozoic orogeny is consistently northwest-southeast (Bodorkos and Clark, 2004b; Spaggiari et al., 2011). Consequently, the dominant deformation style varies, from craton-vergent thrusting in the east where convergence is at a high angle to the orogen, to dextral transpression in the west where convergence is more oblique (Beeson et al., 1988; Bodorkos and Clark, 2004b). Therefore, the significant curvature of the belt provides a rare opportunity to examine the effect of changing structural setting on the exhumation of rocks of comparable lithology and metamorphic grade.

In the west AFO, recent ⁴⁰Ar/³⁹Ar thermochronology established a history of extremely fast (22–33 °C/m.y.) and synorogenic cooling, inferred to be driven by the transpressional setting (Scibiorski et al., 2015). In the east AFO,
numerous high-temperature mineral age constraints are available (primarily U-Pb crystallization ages of zircon; Geological Survey of Western Australia, 2015), but published work on the cooling history is restricted to four ca. 1280–1220 Ma mineral ages from the Fraser Zone (biotite 40Ar/39Ar, Baksi and Wilson, 1980; biotite–whole-rock Rb-Sr, Fletcher et al., 1991; muscovite K-Ar and Rb-Sr, Wilson et al., 1959) and four ca. 1225–1140 Ma U-Pb titanite cooling ages from the Biranup and Fraser Zones (Kirkland et al., 2016). We use 40Ar/39Ar thermochronology to study cooling in the eastern part of the orogen, and compare these results to the cooling history of the west AFO. Differences in the timing and rate of cooling are discussed in the context of different structural settings.

GEOLOGICAL BACKGROUND

Tectonic Setting of the Albany-Fraser Orogen

The AFO extends for more than 1200 km along the southern and southeastern margins of the Yilgarn Craton of Western Australia (Fig. 1). During the two-stage Mesoproterozoic Albany-Fraser orogeny, the Neoarchean to Paleoproterozoic igneous and sedimentary rocks of the orogen were deformed and metamorphosed at high grades (Stage I: 1330–1260 Ma; Stage II: 1225–1140 Ma; Clark et al., 2000; Spaggiari et al., 2011). Previous interpretations attributed Stage I to the Mesoproterozoic suturing of the Yilgarn Craton to the Mawson and Gawler Cratons of East Antarctica and South Australia, with Stage II a result of later intracratonic reactivation (Bodorkos and Clark, 2004b; Clark et al., 2000). More recent evidence has suggested a continental rift or distal backarc setting for Stage I, and support for the intracontinental setting of Stage II, although the cause of this reactivation remains enigmatic (Smithies et al., 2015). However, regardless of tectonic setting, Stage II is responsible for the crustal architecture preserved throughout the orogen and its dominant metamorphic and structural fabrics; most earlier fabrics and mineral assemblages were replaced, or are preserved only as vestiges (Spaggiari et al., 2009).

The curvature of the AFO results in a 45° change in strike from east to west (Fig. 1). Most curved orogens are oroclines, orogens that undergo bending during orogeny (Carey, 1955; Weil and Sussman, 2004). However, the curvature of the AFO is primary, reflecting the margin of the Yilgarn Craton (Spaggiari et al., 2009). There is no structural evidence for the spatial accommodation of oroclinal bending, such as buckling or radial folding in the central hinge zone, or stretching in the eastern or western limbs (e.g., Weil, 2006). In addition, isotopic evidence suggests that the AFO formed in situ at the margin of the Yilgarn Craton (Kirkland et al., 2011), yet the Yilgarn Craton preserves no evidence of having been folded into its present-day configuration.

Structural studies in both the east and west AFO have independently concluded that deformation during Stage II was driven by northwest-directed compression (Beeson et al., 1988; Bodorkos and Clark, 2004b; Clark et al., 2000; Duebendorfer, 2002; Myers, 1995; Spaggiari et al., 2014b). In the east, shortening was at a high angle to the orogen, and Stage II deformation resulted in craton-vertgent thrusting, shearing, and folding, generally with a minor component of dextral transpression (Bodorkos and Clark, 2004b; Clark et al., 2000; Myers, 1995; Spaggiari et al., 2014b; Waddell et al., 2015).

Lithotectonic Subdivisions and Geochronology

The AFO is divided into two main tectonic components: the Archean Northern Foreland, and the dominantly Paleoproterozoic to Mesoproterozoic Kepe Kurl Booya Province, which in turn is subdivided into the Tropiciana, Biranup, Fraser, and Normalup Zones (Fig. 1; Spaggiari et al., 2014a). The Northern Foreland is the part of the Archean Yilgarn Craton intruded by Paleoproterozoic magmas and subsequently reworked by the Albany-Fraser orogeny (Spaggiari et al., 2015). Metamorphic grade and deformation intensity increase toward the south and southeast away from the cratonic margin, from greenschist to amphibolite facies (Beeson et al., 1988; Spaggiari et al., 2015). The Biranup and Normalup Zones are composed of ca. 1815–1630 Ma Paleoproterozoic orthogneisses and paragneisses, and were deformed at upper amphibolite to granulite facies during the Albany-Fraser orogeny, recorded by widespread metamorphic zircon growth (Beeson et al., 1988; Clark et al., 2000; Spaggiari et al., 2011). Phase equilibrium models suggest that Stage I pressure-temperature (P-T) conditions in the southeastern Biranup Zone were 700–850 °C and 5–7 kbar, increasing to 10 kbar; this was followed by Stage II metamorphism at 750–800 °C and 5–6 kbar (Bodorkos and Clark, 2004a). In the northeastern Biranup Zone, Stage II metamorphism reached 675–725 °C and 6.5–8.5 kbar (Kirkland et al., 2016). Granitic rocks of the ca. 1330–1280 Ma Recherche Supersuite and ca. 1200–1140 Ma Esperance Supersuite intrude the Biranup and Normalup Zones; these magmatic events are coeval with Stage I and Stage II of orogeny, respectively (Nelson et al., 1995; Pidgeon, 1990; Spaggiari et al., 2014a).

METHODS

We collected 25 samples across 170 km in the east AFO from the Northern Foreland, the Fraser Zone, and the Biranup Zone (Fig. 1). Sample descriptions and locations are summarized in Table 1; metamorphic assemblages show no evidence of any retrograde overprint. From these 25 samples, 13 hornblende, 3 muscovite and 22 biotite grains were analyzed using 40Ar/39Ar thermochronology. Single grains were step-heated by rastering a continuous laser over the sample, and Ar isotopes in the released gas were measured in static mode with a MAP 215–50 mass spectrometer. The 40Ar/39Ar analyses were performed at the Western Australian Argon Isotope Facility at Curtin University. Sample preparation and analytical methods are described in Appendix 1. Appendix DR1 contains Ar isotope data corrected for blanks, mass discrimination, and radioactive decay, with individual errors given at 1σ.

The criteria used to determine an age plateau follow Jourdan et al. (2009): plateaus must contain >70% of the total measured 39Ar; plateaus must contain at least 3 consecutive steps; and plateaus must satisfy a probability of fit (P) >0.05. Plateau ages are calculated from the mean of all plateau steps, weighted by the inverse variance of the analytical error of each step, and are reported with an uncertainty of 2σ. Miniplateaus are defined similarly, but contain 50%–70% of the measured 39Ar, and are less than 1 GSA Data Repository Item 2016219, Supplemental Figure 1, Supplemental Tables 1 and 2, and Appendix DRI, Ar/Ar data, is available at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org.
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Figure 1. (A) Simplified interpreted bedrock geology of the Albany-Fraser orogen with tectonic subdivisions. (B) Interpreted bedrock geology map of the east Albany-Fraser orogen, showing sample sites, new $^{40}$Ar/$^{39}$Ar thermochronology and existing Stage II (1225–1140 Ma) U-Pb zircon, monazite, and titanite geochronology. U-Pb zircon geochronology older than Stage II is not shown for clarity, except in the Fraser Zone where Stage I geochronology is shown. Abbreviations: BS—Buninyong Soak; CFZ—central Fraser Zone; FSZ—Fraser Shear Zone; GCG—Gwynne Creek Gneiss; GH—Gnamma Hill; HL—Harris Lake; LP—Leeuwin Province; LR—Lake Rivers; MBG—Mount Barren Group; MM—Malcolm Metamorphics; MRF—Mount Ragged Formation; PC—Ponton Creek; SF—Stirling Range Formation; SUR—south of Uraryie Rock; SWPC—southwest of Ponton Creek; SWUR—southwest of Uraryie Rock; UR—Uraryie Rock; WF—Woodline Formation; WH—Wyralinu Hill. Modified from Spaggiari et al. (2014a). Geochronology data are from Geological Survey of Western Australia (2015) and Kirkland et al. (2016).
Appendix DR1; samples either did not produce (16 grains). Inverse isochrons could not be calculated due to the highly radiogenic composition of the trapped Ar component.

RESULTS

The results for the 40Ar/36Ar analyses are listed in Table 2. In total, 38 grains were analyzed; 16 grains from 15 samples returned geologically significant plateau ages. Plateau graphs for these 16 grains are in Figure 2; the degassing spectra are generally flat and low in complexity. The remaining degassing spectra are in Appendix DR1; samples either did not produce a plateau (6 grains) or contained excess argon (16 grains). Inverse isochrons could not be calculated due to the highly radiogenic composition of the trapped Ar component.

40Ar/36Ar Plateau Ages by Domain

At the southern end of the Fraser Zone, two samples, EAF055B and EAF054, yielded hornblende and biotite plateau ages of 1217 ± 8 Ma and 1205 ± 4 Ma, respectively. A single sample 100 km to the northeast produced a younger biotite plateau age of 1157 ± 4 Ma (EAF046). Hornblende EAF052 from the Fraser Shear Zone produced a plateau age of 1234 ± 6 Ma.

In the Biranup Zone, five hornblendes from four samples give remarkably consistent plateau ages ranging from 1194 ± 6 Ma to 1190 ± 5 Ma, with a weighted mean of 1192 ± 2 Ma (samples EAF012, EAF017, EAF038, and EAF039B). Muscovites from samples EAF015, EAF022, and EAF027 give plateau ages ranging from 1177 ± 5 Ma to 1154 ± 5 Ma, decreasing over a distance of 12 km to the east. Four biotites produced plateau ages from 1171 ± 5 Ma to 1158 ± 5 Ma, with no apparent geographical trend (samples EAF018, EAF029, EAF037, and EAF039B).

Hornblende from sample EAF011 in the Northern Foreland contained excess argon, and did not return a geologically significant age.

Excess Argon

Excess argon is 40Ar that does not come from the in situ decay of 40K, or from the presence of atmospheric argon, and violates the assumption that all 40Ar in a sample is from one of these two sources (McDougall and Harrison, 1988). Excess argon is a common occurrence in argon thermochronology, particularly in metamorphic terranes, and is important to identify because it produces anomalously old mineral ages that do not represent the true cooling history of the sample (Harrison and McDougall, 1981; Kelley, 2002; Lapen and Dalrymple, 1976). The typical explanation for excess argon is a high ambient partial pressure of 40Ar (e.g., Foland, 1983), although inherited argon has also been suggested (McDougall and Harrison, 1988).

In most cases, excess 40Ar is easily identifiable due to its distribution in the mineral, typically producing degassing spectra with a saddle-shaped pattern, and a convergence toward supra-atmospheric values (40Ar/36Ar > 298) in the inverse isochron plot (40Ar/36Ar versus 39Ar/36Ar) (McDougall and Harrison, 1988). A more cryptic form of excess argon, in which the sample produces a geologically unrealistically old plateau age, was previously documented in metamorphic terranes (e.g., Batt et al., 2000; Foland, 1983; Rolland et al., 2009; Willigers et al., 2004).

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Table 1. Summary of Sample Locations, Lithology, and Analyzed Minerals

| Field site (Western Australia) | Sample   | Lithology       | Latitude   | Longitude   | Minerals analyzed |
|-------------------------------|----------|-----------------|------------|-------------|-------------------|
|                               |          |                 |            |             | Hb—hornblende; Ms—muscovite; Bt—biotite. |
| Northern Foreland             |          |                 |            |             |                   |
| Lake Rivers                   | EAF011   | amphibolite     | ~31.248134 | 123.259641  | 2                  |
| Fraser Zone                   |          |                 |            |             |                   |
| Central Fraser Zone           | EAF046   | metagranite     | ~31.4392643 | 123.538424  | 1                  |
| Wyralinu Hill                 | EAF054   | metadolerite    | ~32.0467930 | 122.795057  | 1                  |
| Wyralinu Hill                 | EAF055B  | metagranite     | ~32.0467930 | 122.795057  | 1                  |
| Gnana Hill                    | EAF060   | mafic granulite | ~32.18092198 | 122.697752  | 2                  |
| Gnana Hill                    | EAF061   | pelitic gneiss  | ~32.18092198 | 122.697752  | 2                  |
| Fraser fault zone             |          |                 |            |             |                   |
| Fraser fault zone             | EAF051   | granitic mylonite | ~31.58328398 | 123.267036  | 1                  |
| Fraser fault zone             | EAF052   | granitic mylonite | ~31.58328398 | 123.267036  | 1                  |
| Biranup Zone                  |          |                 |            |             |                   |
| Harris Lake                   | EAF021   | metacarbonate   | ~31.37133198 | 123.484967  | 2                  |
| Harris Lake                   | EAF022   | muscovite schist | ~31.31624803 | 123.482687  | 1                  |
| Harris Lake                   | EAF018   | metagranite     | ~31.30901302 | 123.483607  | 1                  |
| Harris Lake                   | EAF020-2 | quartzofeldspathic gneiss | ~31.30959196 | 123.483091  | 1                  |
| Buningonia Soak               | EAF027   | muscovite schist | ~31.35488701 | 123.433094  | 1                  |
| Buningonia Soak               | EAF029   | quartzofeldspathic gneiss | ~31.35488701 | 123.433094  | 1                  |
| Buningonia Soak               | EAF030   | gneissose amphibolite | ~31.35273898 | 123.434121  | 1                  |
| Urarrie Rock                  | EAF035   | metagranite     | ~31.15497301 | 123.413836  | 2                  |
| Urarrie Rock                  | EAF036   | granitic gneiss | ~31.17295001 | 123.413836  | 2                  |
| South of Urarrie Rock         | EAF017   | granitic gneiss | ~31.25792398 | 123.435165  | 3                  |
| Southwest of Urarrie Rock     | EAF015   | muscovite schist | ~31.27957201 | 123.369269  | 1                  |
| Southwest of Urarrie Rock     | EAF012   | metagranite     | ~31.28334001 | 123.360203  | 2                  |
| Ponton Creek                  | EAF038   | amphibolite     | ~30.90960000 | 123.642918  | 1                  |
| Ponton Creek                  | EAF039B  | biotite schist  | ~30.91100530 | 123.644351  | 1                  |
| Ponton Creek                  | EAF041   | migmatitic gneiss | ~30.91606969 | 123.645413  | 1                  |
| Ponton Creek                  | EAF042   | metagranodiorite | ~30.91338602 | 123.643762  | 3                  |
| Southwest of Ponton Creek     | EAF037   | quartzofeldspathic gneiss | ~31.04851998 | 123.454971  | 1                  |

Note: Hb—hornblende; Ms—muscovite; Bt—biotite.
Several of the analyzed samples contain excess argon (Table 2). Anomalously old plateau ages were readily identified in samples where a mineral with a low closure temperature (e.g., hornblende or muscovite) produced an apparent plateau age significantly older than a higher temperature event (e.g., U-Pb zircon age). Excess argon may also be identified by a lack of reproducibility of plateau ages from replicate analyses of a given sample. To this end, minerals were reanalyzed from several samples to check for the reproducibility of plateau ages. For example, sample EAF021 produced excess Ar in each sample. Despite excess argon contamination, it may be possible to extract geologically useful information from the inverse isochron plot.

### Table 2: Summary of 40Ar/39Ar Thermochronology Results from the Eastern Albany-Fraser Orogen, Western Australia

| Locality         | Sample | Lithology          | Mineral | Plateau characteristics | Excess argon | Zircon or titanite age | Zircon or titanite sample number |
|------------------|--------|--------------------|---------|-------------------------|--------------|------------------------|---------------------------------|
|                   |        |                    |         | Age (Ma, ±2σ) | 40Ar (%) | n | MSWD | P |                         |                               |
|                  |        |                    |         |                |              | | | | | | |
| **Northern Foreland** |        |                    |         |                |              | | | | | | |
| LR               | EAF011 | amphibolite        | Hb      | 1642 ± 13     | 50            | 0.53  | 0.71 | 1, 3 | 1287 ± 21     | 194791; zircon |
|                  |        |                    |         |                |              | | | | | | |
| **Fraser Zone**   |        |                    |         |                |              | | | | | | |
| CFZ              | EAF046 | metagranite        | Bt      | 1157 ± 4      | 99            | 5.00  | 0.41 |       |                 | |
|                  |        |                    |         |                |              | | | | | | |
| WH               | EAF054 | metadolerite       | Bt      | 1205 ± 4      | 98            | 4.00  | 0.35 |       |                 | |
|                  |        |                    |         |                |              | | | | | | |
| WH               | EAF055B| metagranite        | Hb      | 1217 ± 8      | 96            | 4.00  | 0.25 |       |                 | |
|                  |        |                    |         |                |              | | | | | | |
| GH               | EAF060 | mafic granite      | Hb      | np            | np            |       |     |       |                 | |
|                  |        |                    |         |                |              | | | | | | |
| GH               | EAF061 | pelitic gneiss     | Bt      | np            | np            |       |     |       |                 | |
|                  |        |                    |         |                |              | | | | | | |
| **Fraser Shear Zone** |        |                    |         |                |              | | | | | | |
| FSZ              | EAF051 | granitic mylonite  | Hb      | 1234 ± 6      | 74            | 4.00  | 0.39 |       |                 | |
|                  |        |                    |         |                |              | | | | | | |
| FSZ              | EAF052 | granitic mylonite  | Hb      | np            | np            |       |     |       |                 | |
|                  |        |                    |         |                |              | | | | | | |
| **Biranup Zone**  |        |                    |         |                |              | | | | | | |
| HL               | EAF021 | metanorite         | Bt      | 1557 ± 5      | 92            | 3.00  | 0.54 | 1, 3 | ca. 1185      | 194722; zircon |
|                  |        |                    |         |                |              | | | | | | |
| HL               | EAF022 | muscovite schist   | Ms      | 1160 ± 5      | 83            | 5.00  | 0.19 |       |                 | |
|                  |        |                    |         |                |              | | | | | | |
| HL               | EAF018 | metagranite        | Bt      | 1167 ± 4      | 97            | 5.00  | 0.34 |       |                 | |
|                  |        |                    |         |                |              | | | | | | |
| HL               | EAF020-2| quartzofeldspathic gneiss | Bt | 1182 ± 4 | 81 | 4 | 0.86 | 0.46 | 1 |
|                  |        |                    |         |                |              | | | | | | |
| BS               | EAF027 | muscovite schist   | Ms      | 1154 ± 5      | 99            | 8.00  | 0.13 |       |                 | |
|                  |        |                    |         |                |              | | | | | | |
| BS               | EAF029 | quartzofeldspathic gneiss | Bt | 1158 ± 4 | 74 | 4 | 0.82 | 0.48 |       | |
|                  |        |                    |         |                |              | | | | | | |
| BS               | EAF030 | gneissose amphibolite | Hb   | 1270 ± 7     | 82            | 5.00  | 0.91 | 3 | ca. 1185      | 194722; zircon |
|                  |        |                    |         |                |              | | | | | | |
| UR               | EAF035 | metagranite        | Bt      | 1210 ± 6      | 92            | 4.00  | 0.15 | 3 | 1162 ± 39     | 194726; zircon |
|                  |        |                    |         |                |              | | | | | | |
| UR               | EAF036 | granitic gneiss    | Hb      | 1191 ± 5      | 100           | 1.00  | 0.82 |       |                 | |
|                  |        |                    |         |                |              | | | | | | |
| SUR              | EAF017 | granitic gneiss    | Hb      | 1192 ± 4      | 95            | 4.00  | 0.39 | 2 |                 | |
|                  |        |                    |         |                |              | | | | | | |
| SWUR             | EAF015 | muscovite schist   | Ms      | 1177 ± 5      | 99            | 11.00 | 0.46 |       |                 | |
|                  | EAF012 | metagranite        | Hb      | 1194 ± 6      | 100           | 5.00  | 0.76 |       |                 | |
|                  |        |                    |         |                |              | | | | | | |
| PC               | EAF038 | amphibolite        | Hb      | 1192 ± 13     | 100           | 5.00  | 0.94 |       |                 | |
|                  |        |                    |         |                |              | | | | | | |
| PC               | EAF041 | biotite schist     | Bt      | 1169 ± 5      | 89            | 5.00  | 0.45 | 2, 3 | 1193 ± 9      | 194734; zircon |
|                  |        |                    |         |                |              | | | | | | |
| PC               | EAF042 | metagranodiorite   | Bt      | 1281 ± 4      | 95            | 10.00 | 0.10 | 2, 3 | 1193 ± 9      | 194734; zircon |
|                  |        |                    |         |                |              | | | | | | |
| SWPC             | EAF037 | quartzofeldspathic gneiss | Bt | 1171 ± 5 | 86 | 3 | 1.33 | 0.26 |       | |

Note: The rationales for identifying excess argon are: (1) inconsistent results from the same mineral at the same site; (2) biotite age is greater than hornblende or muscovite from the same site; (3) biotite or hornblende age is greater than published U-Pb zircon or titanite age from the same site. Hb—hornblende; Ms—muscovite; Bt—biotite; np—no plateau age; MSWD—mean square of weighted deviation; P—P-value; n—number of steps used in the plateau. Localities names correspond with those in Figure 1B: BS—Buningonia Soak; CFZ—Central Fraser Zone; FSZ—Fraser fault zone; GH—Gnamma Hill; HL—Harris Lake; LR—Lake River; PC—Ponton Creek; SUR—south of Uraryie Rock; SWPC—southwest of Ponton Creek; SWUR—southwest of Uraryie Rock; UR—Uraryie Rock; WH—Wyralinu Hill.
Figure 2. The $^{40}$Ar/$^{39}$Ar apparent age spectra of all analyses producing geologically significant plateau ages, with individual steps graphed against cumulative percentage of $^{39}$Ar released. Plateau age uncertainties are 2σ and are reported with the mean square of weighted deviates (MSWD) and probability (P). Thermochronological data tables and the remaining $^{40}$Ar/$^{39}$Ar apparent age spectra are in Appendix DR1. (Continued on following page.)
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Figure 2 (continued).

- **EAF0055B Hornblende**
  - 1217 ± 8 Ma
  - MSWD = 1.38, P = 0.25

- **EAF0052 Hornblende**
  - 1234 ± 6 Ma
  - MSWD = 1.00, P = 0.39

- **EAF27 Muscovite**
  - 1154 ± 5 Ma
  - MSWD = 1.59, P = 0.13

- **EAF029 Biotite**
  - 1158 ± 4 Ma
  - MSWD = 0.82, P = 0.48

- **EAF017 Hornblende**
  - 1192 ± 4 Ma
  - MSWD = 1.00, P = 0.39

- **EAF15 Muscovite**
  - 1177 ± 5 Ma
  - MSWD = 0.98, P = 0.46

- **EAF039B Biotite**
  - 1169 ± 5 Ma
  - MSWD = 0.45, P = 0.77

- **EAF037 Biotite**
  - 1174 ± 5 Ma
  - MSWD = 1.33, P = 0.26
isochron (Appendix DR1). The data from these samples are not geologically significant, and are not discussed further.

Mineral Closure Temperatures and Cooling Rates

The $^{40}$Ar/$^{39}$Ar analyses may record mineral crystallization ages, the last time a rock cooled through its mineral-specific closure temperature for argon diffusion, or hydrous recrystallization ages (McDougall and Harrison, 1988; Villa, 2016). Typical estimates of argon closure temperatures are $\sim$550 °C for hornblende, $\sim$425 °C for muscovite, and $\sim$350 °C for biotite (Harri-Villa, 2016). Typical estimates of argon closure temperatures (Dodson, 1973). A Monte Carlo simulation is a statistical technique that performs a calculation minimizing error correlations and gives a realistic final uncertainty. The distribution of cooling rates is strongly positively skewed, and is reported as a median with upper quartiles are a more robust measure of scale than the standard deviation. Inputs to the simulation and histograms of the results are in Appendix 2. Ms—muscovite; Bt—biotite.

### DISCUSSION

**Cooling and Exhumation in the East Albany-Fraser Orogen**

**Fraser Zone**

The new $^{40}$Ar/$^{39}$Ar thermochronology reported here provides evidence that the Fraser Zone was affected by metamorphism associated with Stage II (1225–1140 Ma) of the Albany-Fraser orogeny. The southwestern part of the Fraser Zone was at $\sim$550 °C ($^{40}$Ar/$^{39}$Ar hornblende closure temperature) at ca. 1217 Ma and cooled to 340 ± 26 °C (calculated $^{40}$Ar/$^{39}$Ar biotite closure temperature) by ca. 1205 Ma; the central Fraser Zone passed through $\sim$350 °C ($^{40}$Ar/$^{39}$Ar biotite closure temperature) at ca. 1157 Ma; and the Fraser Shear Zone records a hornblende cooling age of ca. 1234 Ma (Table 2). These results complement recent U-Pb titanite geochronology that suggests that the Fraser Zone was undergoing processes as high as 695–725 °C at 1205 ± 16 Ma, placing it into the mid-crust alongside the Biranup Zone (Kirkland et al., 2016). The agreement between the $^{40}$Ar/$^{39}$Ar and U-Pb data contributes to resolving a long-standing problem in the AFO: the effects of Stage II in the Fraser Zone had previously been unrecognized, due to the complete absence of Stage II ages in the U-Pb zircon geochronological record, despite the Fraser Zone juxtaposition between high-grade Stage II deformed rocks of the Biranup and Normalup Zones (Spaggiari et al., 2011). Cooling of the 200-km-long Fraser Zone was not homogeneous. By ca. 1205 Ma, the southwestern Fraser Zone had cooled at a rate of 17.5 ± 5.5/–3.3 °C/m.y. to $\sim$340 °C. In contrast, the 1157 Ma biotite cooling age 100 km to the northeast (sample EAF046) suggests that the central Fraser Zone did not cool to $\sim$350 °C for another 50 m.y. (Fig. 1). Faulting within the Fraser Zone may have resulted in this varying timing for exhumation, a common feature of orogenic exhumation (e.g., Cosca et al., 1992; Fügenschuh and Schmid, 2005). Alternatively, in Spaggiari et al. (2011) it was proposed that exhumation was driven by the lateral extrusion of the Fraser Zone to the southwest during early Stage II. The extrusion model is based on kinematic indicators for dextral movement in the Fraser Shear Zone and sinistral movement in the Newman Shear Zone, which form the northwest and northeast boundaries, respectively, of the Fraser Zone (Spaggiari et al., 2011).

The extrusive exhumation model requires that the Fraser and Newman Shear Zones were active simultaneously, either synchronous with or preceding the Fraser Zone cooling ages reported here. Although the deformation fabrics

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**TABLE 3. COOLING RATES FOR HORNBLENDE AND MICA COOLING AGE PAIRS FROM THE SAME LOCALITY IN THE EASTERN ALBANY-FRASER OROGEN**

| Locality             | Hornblende cooling age | Mica cooling age | Monte Carlo simulation |
|----------------------|------------------------|------------------|------------------------|
|                      | Sample                 | Cooling age (Ma, ±2σ) | Sample | Mineral | Cooling age (Ma, ±2σ) | Mica closure temperature (°C, ±2σ) | Cooling rate (°C/m.y., +Q37–Q1) |
| Biranup Zone         |                        |                   |             |        |                   |                                   |                               |
| Southwest of Urayrie Rock | EAF012               | 1194 ± 6          | EAF015      | Ms      | 1177 ± 5          | 410 ± 58                          | 8.2, +1.9/–1.5                   |
| Ponton Creek         | EAF038                 | 1192 ± 13         | EAF039B     | Bt      | 1169 ± 5          | 331 ± 24                          | 9.5, +2.4/–1.5                   |
| Fraser Zone          |                        |                   |             |        |                   |                                   |                               |
| Wyracului Hill       | EAF055B               | 1217 ± 8          | EAF054      | Bt      | 1205 ± 4          | 340 ± 26                          | 17.5, +5.5/–3.3                   |

Note: Cooling rates and closure temperatures were calculated using Monte Carlo simulation with 20,000 trials, in order to include all sources of uncertainty, minimize error correlations, and give a realistic final uncertainty. The distribution of cooling rates is strongly positively skewed, and is reported as a median with error defined by the lower and upper quartiles. The median is a better measure of the central tendency of a skewed population than the mean, and the lower and upper quartiles are a more robust measure of scale than the standard deviation. Inputs to the simulation and histograms of the results are in Appendix 2. Ms—muscovite; Bt—biotite.
in the Fraser and Newman Shear Zones have not been directly dated, the 1234 ± 6 Ma ⁴⁰Ar/³⁹Ar hornblende cooling age and the younger 1205 ± 16 Ma U-Pb titane age (22 km southwest) indicate a heterogeneous thermal history along the Fraser Shear Zone (Kirkland et al., 2016). In addition, it is difficult to reconcile the extrusion model with current thermal models of Stage II, where the Fraser Zone was cooler and thermally stronger than the surrounding, hotter Biranup and Normallup Zones.

**Eastern Biranup Zone**

Hornblende cooling ages across the sampled area of the eastern Biranup Zone are remarkably consistent. The region passed through ~550 °C (⁴⁰Ar/³⁹Ar hornblende closure temperature) at ca. 1190 Ma, followed by cooling to ~425–350 °C (⁴⁰Ar/³⁹Ar muscovite and biotite closure temperatures) between ca. 1175 and 1155 Ma (Table 2). Two cooling rates were calculated for the eastern Biranup Zone: ~8.2 ±1.9/–1.5 °C/m.y. southwest of Urayrie Rock, and ~9.5 ±2.4/–1.5 °C/m.y. at Ponton Creek, 50 km to the northeast along strike.

The timing of cooling is in the middle of Stage II of orogeny (1225–1140 Ma), which implies that the mid-crustal migmatized rocks of the Biranup Zone were already cooling from peak metamorphic conditions by ca. 1190 Ma. This is supported by the ca. 1206–1190 Ma zircon and titane U-Pb ages recording Stage II metamorphic mineral growth in the eastern Biranup Zone (Fig. 1; Geological Survey of Western Australia, 2015; Kirkland et al., 2016). Some of the zircon U-Pb geochronology from this region records ages younger than ca. 1185 Ma, but these data are not precise and may also be inaccurate, due to discordance (driven by common Pb content or by minor radiogenic Pb loss), small population sizes (n ≤ 3; due to insufficient overgrowths of datable size), and/or analyses forming no coherent age, possibly indicating prolonged metamorphic zircon growth. In Figure 1, these complex zircon populations are reported as a range defined by the individual analyses. Therefore, it is clear that the high-grade Stage II metamorphism (675–725 °C and 6.5–8.5 kbar in the Fly Dam Formation; Kirkland et al., 2016) that caused extensive metamorphic zircon growth within the Biranup Zone ceased by ca. 1190 Ma, and was followed by initially fast cooling to ~550 °C. The region then cooled to ~425–350 °C by ca. 1175–1155 Ma, at rates of 8.2–9.5 °C/m.y.

Cooling in the sampled area of the eastern Biranup Zone was contemporaneous with metamorphism and magmatism elsewhere in the orogen (Spaggiari et al., 2011). Widespread metamorphic zircon growth continued until at least ca. 1160 Ma throughout the orogen, and until ca. 1154 Ma in the central and southeastern Biranup Zone; Esperance Supersuite magmatism in the southeastern Biranup Zone and in the Normallup Zone continued until ca. 1140 Ma (Geological Survey of Western Australia, 2015; Smithies et al., 2015). Cooling in the northeastern Biranup Zone, therefore, preceded the end of Stage II of orogeny.

**Comparison to the West Albany-Fraser Orogen**

The comparison of cooling histories between the east and west AFO reveals a 20 m.y. difference in the timing of cooling through the ⁴⁰Ar/³⁹Ar hornblende closure temperature, but this difference disappears by the time the limbs of the orogen pass through the biotite ⁴⁰Ar/³⁹Ar closure temperature (Fig. 3). In the eastern Biranup Zone, hornblende cooling ages are ca. 1190 Ma; the western Biranup Zone and Normallup Zone cooled through hornblende closure temperatures 20 m.y. later, ca. 1170 Ma (Sciabich et al., 2015). However, muscovite and biotite cooling ages share a similar range and distribution: in the east, muscovite cooling ages range from 1175 to 1155 Ma and biotite cooling ages range from 1170 to 1160 Ma; in the west, muscovite cooling ages are ca. 1160 Ma and biotite cooling ages range from ca. 1170 to 1150 Ma (Fig. 3; Sciabich et al., 2015). The exceptions are the samples from the Fraser Shear Zone and from the southwestern end of the Fraser Zone, which record hornblende and biotite cooling ages 30–50 m.y. older than in the eastern Biranup Zone (Fig. 3).

Comparing cooling rates in the east and the west tells a similar story: cooling at ~8.2–9.5 °C/m.y. in the eastern Biranup Zone and ~17.5 °C/m.y. in the Fraser Zone is 2–4 times slower than the fast 22–33 °C/m.y. cooling of the western Biranup and Normallup Zones (inset in Fig. 3).

We consider the differences in the timing and rate of cooling along the orogen to be caused by differences in structural setting. The principal northwest-southeast convergence direction is oblique to the east-west–oriented west AFO, but is orthogonal to the east AFO; this geometry results in a greater component of transpression deformation to the west than in the east (Fig. 4). The northwest-southeast direction of convergence has been established from several structural studies in both the east AFO (Bodorkos and Clark, 2004b; Clark et al., 2000; Myers, 1995; Spaggiari et al., 2014b; Waddell et al., 2015) and the west AFO (Barquero-Molina, 2010; Beeson et al., 1988; Duebendorfer, 2002; Wetherley, 1998). Structural evidence includes the following: a pervasive northeast–southwest–striking foliation in the east AFO that strikes increasingly west-southwest–east-southeast toward the west (all listed studies); northeast–southwest–striking thrust and shear zones (all listed studies); kinematic indicators in these thrust and shear zones suggesting a combination of northwest thrusting, dextral shear, and southeast-up transport (Beeson et al., 1988; Duebendorfer, 2002; Myers, 1995; Wetherley, 1998); northwest-vergent folding (Barquero-Molina, 2010; Bodorkos and Clark, 2004b; Duebendorfer, 2002; Spaggiari et al., 2014b; Waddell et al., 2015; Wetherley, 1998); in the west AFO, conjugate shear sets suggesting dextral shearing (Beeson et al., 1988; Duebendorfer, 2002); and in the east AFO, duplexes and folded thrust sheets recording transport to the west-northwest over the margin of the Yilgarn Craton (Myers, 1995; Spaggiari et al., 2014b; Waddell et al., 2015).

**Difference in the Timing of Cooling**

Two possible explanations are considered for the 20 m.y. difference in ⁴⁰Ar/³⁹Ar hornblende cooling ages between the east (ca. 1190 Ma) and west AFO (ca. 1170 Ma). In the first hypothesis, while the east AFO is slowly exhuming at 1190 Ma, exhumation in the west AFO is negligible for 20 m.y. until a tipping point is reached that results in sudden fast exhumation. Possible reasons for this delay in cooling and the trigger for subsequent exhumation include a change in the dominant stress direction (e.g., Bodorkos and Clark, 2004b); the development of structures that facilitated exhumation; or crustal anatexis or melt intrusion, resulting in weakening of the crust and assisting shearing (e.g., Hollister, 1993). An alternative hypothesis is that the west AFO was already undergoing fast exhumation at 1190 Ma, but the top of the exhumed section is missing, so the cooling ages exposed at the surface are 20 m.y. younger. A consequence of and test for this second hypothesis is that the rocks exposed in the west AFO should have originated deeper within the crust than those in the east AFO. The three existing Stage II P-T models are insufficient to test this theory. Granulite facies pressure constraints of 6.5–8.5 kbar in the northeastern Biranup Zone and ~10 kbar in the southeastern Biranup Zone are from sites located 50–100 km from the margin of the Yilgarn Craton (Bodorkos and Clark, 2004a; Kirkland et al., 2016). These cannot be meaningfully compared with ~8 kbar in the amphibolite facies Mount Barren Group of the western Northern Foreland, which overlies the Yilgarn Craton (Wetherley, 1998).

**Difference in the Rate of Cooling**

In the east AFO, where deformation is dominated by craton-vergent thrusting and folding, relatively slow ~8.2–9.5 °C/m.y. cooling in the Biranup Zone fits with similar cooling records from other compressional orogens (e.g., Bingen et al., 2008; McLaren et al., 2002; Rivers,
The significance of the earlier initiation of ~17.5 °C/m.y. cooling in the Fraser Zone is as yet unresolved. Although the new 40Ar/39Ar thermochronology provides evidence that the Fraser Zone was thermally affected by Stage II orogeny, the extent of associated Stage II deformation is unknown and the Fraser Zone has no structural or lithological equivalents in the western part of the orogen (unlike the Northern Foreland, Biranup, and Normalup Zones, which span the length of the orogen).

The significantly faster exhumation of the west AFO is interpreted as a consequence of transpressional deformation in an obliquely compressional setting (Scibiorski et al., 2015). Although anomalously fast for Mesoproterozoic cooling, this may simply be due to the paucity of preserved cooling records from transpressional settings in the geological record (Scibiorski et al., 2015). Cooling rates of 22–33 °C/m.y. are not unusual when compared to other transpressional orogens (e.g., Batt et al., 2004; Cumacho and McDougall, 2000).

Numerical models of exhumation in transpressional orogens by Koons et al. (2003) showed that strain is initially partitioned into simple shear– and pure shear–dominated structures (e.g., the exhumation of granulites in southern Madagascar; Martelat et al., 1999), but may form a single oblique structure after thermal weakening of the upper crust. Due to the strike-slip component, faults and shear zones in transpressional settings may be steeper and extend to deeper crustal levels than in purely extensional or compressional settings (Fossen and Tikoff, 1998). These deep and steeply dipping fault and shear zones provide a conduit for the rapid uplift and exhumation of lower crustal rocks (Fossen and Tikoff, 1998). The contractional component of movement then allows a large amount of vertical transport to occur in a short space of time, resulting in rapid uplift and when combined with erosion, rapid exhumation.

Just as kinematics and strain vary along different segments of curved shear zones (Lin and Jiang, 2001), the different deformation styles along the AFO are a larger scale example of this variation (Fig. 4; Fossen and Tikoff, 1998; Tikoff and Teyssier, 1994). This coupled variance of deformation and cooling within a single orogen demonstrates the influence of the structural setting, controlled in the AFO by the curvature of the cratonic margin, on orogenic exhumation and cooling.

**Convergence of Mica Cooling Ages**

Successive periods in an orogen’s cooling history may reveal changes in exhumation mechanism (e.g., Favaro et al., 2015). By the time the eastern and western limbs of the AFO passed through muscovite 40Ar/39Ar closure temperature, differences in the timing of cooling...
had strongly decreased; by the time biotite closure temperature was reached, these differences had disappeared. In other words, with the exception of a biotite cooling age in the Fraser Zone and a muscovite cooling age in the eastern Biranup Zone, the range of mica $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages is uniform across the orogen (Fig. 3).

The convergence in cooling history between east and west suggests that exhumation was increasingly decoupled from compressional tectonics. The most likely candidates are simple isostatic uplift and erosion, processes that operate in all orogens (e.g., Gilchrist et al., 1994). Alternatively, prolonged residence of the orogen in the partial retention zone of biotite ($\sim 200–300$ °C) could also have resulted in the smoothing of cooling ages across the orogen due to partial resetting of the thermochronometer (e.g., Dunlap, 2000). This explanation requires nearly isothermal conditions over a long period of time, and therefore also requires that the orogen is tectonically quiescent, placing a lower age limit on the end of compressional tectonic activity. The convergence of muscovite and biotite cooling ages therefore marks the decreasing role of exhumation associated with compressional processes, and a transition to the more passive processes of isostatic uplift and erosion.

**CONCLUSIONS**

The 45° change in strike from east to west along the 1200 km AFO provides a rare opportunity to examine the effect of changing structural setting in a single orogen, on the cooling of rocks with comparable lithology and similar prograde metamorphic history. Cooling at 8.2–9.5 °C/m.y. in the eastern Biranup Zone, where deformation is dominated by northwest-southeast–directed thrusting and folding, is relatively slow. In contrast, fast 22–33 °C/m.y. cooling commenced 20 m.y. earlier in the transpressional west Albany-Fraser orogen. This difference is a result of the accommodation of the consistent northwest-southeast stress direction along the curved orogen. The convergence of cooling histories in the east and west is recorded by similar mica cooling ages across the orogen; this distribution suggests a decrease in exhumation driven by compression, and an increase in the role of more passive processes such as isostatic uplift and erosion.

**APPENDIX 1. DETAILED ANALYTICAL METHODS FOR $^{40}\text{Ar}/^{39}\text{Ar}$ THERMOCRONOLOGY**

Samples were crushed and sieved to separate the 125–250 µm fraction, which was washed in acetone to remove dust. Optically unaltered 125–250 µm grains of biotite (22 samples), muscovite (3 samples), and hornblende (13 samples) were separated by hand-picking under a binocular microscope.

Samples were loaded into 38 large wells of 3 aluminum discs measuring 1.9 cm in diameter and 0.3 cm in depth. These wells were bracketed by small wells containing either Fish Canyon sanidine (FCs), Hb3gr hornblende, or WA1ms muscovite, used as neutron flux monitors. The ages of these standards are: FCs, 28.294 Ma ± 0.13% (1σ) (Renne et al., 2011); Hb3gr, 108.10 Ma ± 0.11% (1σ) (Renne et al., 2011); WA1ms, 28614.2 Ma ± 0.055% (1σ) (Jourdan et al., 2014). To minimize nuclear interference reactions, the disc was C1 shielded, and irradiated for 40 h in the U.S. Geological Survey TRIGA nuclear reactor (Oregon, USA) in a central position.

The mean J values computed from the standard grains within the small pils are: FCs, 0.0012946 ± 0.00002986 (±0.19%); Hb3gr, 0.01086400 ± 0.00002607 (±0.24%); WA1ms, 0.00108550 ± 0.00002062 (±0.19%). Mean J values are calculated as the average and standard deviation of J values of the standard grains within each irradiation disc. An automated air pipette was used to monitor mass discrimination, which had a mean value of 1.00 ± 0.34 per Dalton (atomic mass unit) relative to an air ratio of 298.56 ± 0.31 (Lee et al., 2006). The correction factors for interfering isotopes were: ($^{132}\text{Ar}/^{39}\text{Ar}$)
These histograms represent probability distributions, within
the Australian Argon Isotope Facility at Curtin University. Sam-
pled for the testing of the Ar isotopes in two different
laser systems, by rastering a continuous Nd-YAG (IR, 1064
nm) laser over the sample for 1 min, to ensure homogenous
heating. The gas released from the sample was purified in a
stainless steel extraction line using two SAES AP10 get-
ters and one GPS filter. The Ar isotopes were measured in
static mode with a MAP 251-50 mass spectrometer (resolu-
tion 450; sensitivity 4 x 10⁻⁶ mol/V) with a Balzers SEV 217
electron multiplier using 9-10 cycles of peak hopping. Data
acquisition was performed with the Argus program written
by M.O. McDougall for a LabCalc computer. Raw data were processed using ArCalc software (Koppers, 2002), and ages were calculated using the decay constants
recommended by Renne et al. (2011). A blank was monitored
after every 4 steps, with a typical ⁴⁰Ar range of 3 x 10⁻⁸ to
10⁻⁹ mol. Appendix D1 contains Ar isotope data corrected for
blank, mass discrimination, and radioactive decay, with
individual errors given at the 2σ level.

In this section, the determination of the age plateau is as follows: plateaus must include at least 70% of the total measured ⁴⁰Ar, and plateaus should be distrib-
uted over at least 3 consecutive steps that agree at a 95%
confidence level and satisfy a probability of fit (P) of at least
0.05. Plateau ages in Table 2 and Figure 2 are given at the
2σ level, and are calculated using the mean of all plateau steps,
weighted by the inverse variance of their individual ana-
lytical errors. The errors on the plateau ages are ±20% of
the 2σ errors. Plateau ages include the 2σ errors, and are the true values of the closure temperature and
hornblende closure temperature and biotite closure tem-
perature after every 4 steps, with a typical ⁴⁰Ar range of 3 x 10⁻⁸ to
10⁻⁹ mol. Appendix D1 contains Ar isotope data corrected for
blank, mass discrimination, and radioactive decay, with
individual errors given at the 2σ level.

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