Linking thermodynamic modelling, Lu–Hf geochronology and trace elements in garnet: new $P-T-t$ paths from the Sevier hinterland

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ABSTRACT Major element, trace element and Lu–Hf geochronological data from amphibolite facies pelitic schist in the Raft River and Albion Mountains of northwest Utah and southern Idaho indicate that garnet grew during increasing pressure, interpreted to be the result of tectonic burial and crustal thickening during Sevier orogenesis. Garnet growth was interrupted by hiatuses interpreted from discontinuities in major element zonation. Pressure–temperature paths were determined from the pre-hiatus portions of the garnet chemical zoning profiles and indicate an increase of ~2 kbar and ~50 °C in the western Raft River Mountains. Garnet Lu–Hf dates of 150 ± 1 Ma in the western Raft River Mountains and 138.7 ± 0.7 Ma and 132 ± 5 Ma in the southern Albion Mountains indicate the timing of garnet growth. Lutetium garnet zoning profiles indicate that the Lu–Hf ages are biased towards the post-hiatus or outer pre-hiatus segments, indicating that the determined ages likely post-date the recorded $P-T$ path history or date the tail end of the paths. Crustal thickening associated with Sevier orogenesis in the western Raft River Mountains thus began slightly before 150 ± 1 Ma, in the Late Jurassic. This study shows that integrating $P-T$ paths determined from garnet growth zoning with Lu–Hf garnet geochronology and in situ garnet trace element analyses is an effective approach for interpreting and dating deformation events in orogenic belts.

Key words: garnet Lu–Hf geochronology; petrochronology; $P-T-t$ path; Sevier orogen; trace elements.

INTRODUCTION

The timing of thrusting within the Sevier orogenic belt of the North American Cordillera has been primarily constrained by cross-cutting relationships and syn-orogenic sedimentary deposits (e.g. Heller et al., 1986; DeCelles, 2004). Amphibolite facies pelitic schists from the Raft River, Albion and Grouse Creek mountains of northwest Utah and southern Idaho provide a unique opportunity to study the tectonic evolution of the Sevier hinterland through garnet geochemistry and geochronology (Harris et al., 2007; Wells et al., 2012; Hoisch et al., 2014). Garnet has been identified as a critical mineral for linking small-scale petrological processes to large-scale orogenic processes because of its usefulness both as a geochronometer and for recording changes in $P-T$ conditions during its growth. Understanding the trace element zoning and petrological context of minerals used for geochronology has become paramount in interpreting the dates, durations and $P-T-t$ histories of tectonic events (e.g. Anczkiewicz et al., 2007; Lagos et al., 2007; Cheng et al., 2008; Endo et al., 2009; Corrie et al., 2010; Kylander-Clark et al., 2013; Mottram et al., 2014), as evidenced by the increasingly popular use of the term ‘petrochronology’.

Documentation of trace element zoning is critical for interpreting garnet geochronology, particularly with respect to Lu zoning in applications of Lu–Hf geochronology. The partitioning of Lu and other heavy rare earth elements (HREE) during garnet growth may be described as a simple Rayleigh fractionation process (e.g. Hollister, 1966), resulting in HREE profiles that decrease from core to rim (e.g. Lapen et al., 2003; Skora et al., 2006; Anczkie-
wicz et al., 2007; Kohn, 2009). However, multiple studies have shown that the distribution of Lu and other rare earth elements (REE) in garnet is not always this straightforward (e.g. Otamendi et al., 2002; Yang & Rivers, 2002; King et al., 2004; Skora et al., 2006; Kohn, 2009; Moore et al., 2013). Consequently, Rayleigh distribution cannot be assumed for compatible elements such as the middle and heavy REEs in garnet.

Anomalous HREE+Y zoning in garnet has been reported from numerous rock types from a wide variety of tectonic settings (e.g. Otamendi et al., 2002; Yang & Rivers, 2002; King et al., 2004; Moore et al., 2013) using in situ techniques such as secondary ionization mass spectrometry and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). Workers have documented near-rim Lu increases (e.g. Lagos et al., 2007) and HREE-Y annuli in garnet (e.g. Yang & Rivers, 2002; Moore et al., 2013). Interpretations of these phenomena include: the breakdown of a HREE-phase (e.g. Gieré et al., 2011); open-system behaviour during garnet growth (e.g. Corrie et al., 2010); changes in garnet growth rate and diffusion rates (e.g. Skora et al., 2006; Moore et al., 2013); post-growth-hiatus resorption (e.g. Yang & Rivers, 2002), and retrograde rim dissolution (Kohn, 2009).

In this study, we present new P–T paths, Lu–Hf dates, and in situ trace element zoning for garnet from amphibolite facies pelitic schist from the Raft River–Albion–Grouse Creek metamorphic core complex of the western United States. This study links subtle changes recorded in major element zoning in garnet with more obvious changes in trace element zoning to interpret a reaction history (e.g. Konrad-Schmolke et al., 2008). We also evaluate the distribution of trace elements in garnet (e.g. Lu) to interpret the significance of Lu–Hf garnet dates with respect to the P–T paths derived from garnet from the same rocks. The resultant P–T–t paths provide insight into the timing of early, previously undated tectonic events within the hinterland of the Sevier orogen, and provide a basis for evaluating the relationship between major and trace element zoning and Lu–Hf garnet geochronology.

GEOLOGICAL SETTING AND SAMPLE DESCRIPTION

The Raft River, Albion and Grouse Creek mountains are located in northwest Utah and southern Idaho, within the hinterland of the Late Mesozoic to Early Cenozoic Sevier orogenic belt (Fig. 1). Together they comprise one continuous exposure of amphibolite facies Barrovian metamorphic rocks that were exhumed in the Miocene along flanking low-angle normal faults (Wells et al., 2000; Egger et al., 2003). They belong to a discontinuous north-trending belt with similar exposures of metamorphic rocks in the western United States that have been termed ‘Cordilleran metamorphic core complexes’ (e.g. Crittenden et al., 1980).

The Raft River–Albion–Grouse Creek metamorphic core complex consists of Archean basement overlain by a tectonically thinned sequence of metasedimentary rocks of Neoproterozoic to Permian age, designated the Raft River Mountains sequence (Compton, 1972; Miller, 1983; Wells, 1997; Wells et al., 1998; Hoisch et al., 2002; Yanke et al., 2014). The Neoproterozoic schist of Mahogany Peaks, the unit sampled in this study, is located in the footwall of the Basin-Elba fault (Fig. 1), the only major thrust fault preserved in the region (Miller, 1983). The schist of Mahogany Peaks was sampled from two general localities: (i) outcrops ~100 m apart in the Raft River Mountains (LHRR10D, LHRR10I); and (ii) outcrops ~3 km apart in the Albion Mountains (THAL4E, THAL6B) (Fig. 1). Previous work has yielded P–T paths from the two Albion Mountains samples (THAL4E and THAL6B), which record an overall pressure increase of ~3 kbar (Harris et al., 2007).

The Raft River Mountains samples LHRR10D and LHRR10I contain quartz, muscovite, biotite, staurolite and garnet. Porphyroblastic garnet (up to 4 mm) and staurolite (~3–12 mm) are subidioblastic. Biotite is also porphyroblastic and up to 5 mm in size. Garnet and some staurolite grains have quartz inclusions concentrated in their cores and have relatively inclusion-free rims. Minor chloritization of some garnet and staurolite grains is also present. The fine-grained matrix (LHRR10D: ~100–500 μm; LHRR10I: ~50–300 μm) is composed primarily of quartz and muscovite. Apatite, xenotime and allanite are present in the matrix and as inclusions in garnet, staurolite and biotite. Small grains of graphite occur in the matrix. Minor deformation is indicated by the undulose extinction of quartz and weakly developed strain shadows around garnet and staurolite.

Samples LHRR10D and LHRR10I are classed as high-alumina pelitic schists, in which biotite is a late crystallizing phase relative to garnet. Garnet growth is interpreted from major element zoning to have occurred through two distinct reactions, separated by a reaction period in which garnet was partially consumed. Petrographically, the only evidence of a complex garnet growth history is a concentric birefringence zoning pattern observed in some staurolite grains in sample LHRR10D that is truncated by adjacent garnet, suggesting that staurolite was consumed as garnet grew. We interpret that this occurred during the earliest stage of retrogradation, which partially reversed the reaction that brought biotite into the assemblage (approximately garnet + chlorite = staurolite + biotite).

Detailed descriptions of samples THAL4E and THAL6B are reported in Harris et al. (2007). Like LHRR10D and LHRR10I, both samples are high-alumina pelitic schist. THAL4E contains garnet, staurolite, muscovite, paragonite, quartz and kyanite.
and THAL6B contains garnet, staurolite, muscovite, biotite, paragonite, plagioclase and quartz. Accessory phases in both samples include graphite, ilmenite, apatite and rutile. Garnet from these samples shares a similar reaction history as described above for THRR10D and THRR10I, with a growth hiatus preserved in the garnet profile.

MINERAL CHEMISTRY

Major element geochemistry

Major element maps of garnet (Mg, Fe, Mn and Ca; Fig. 2) were produced using an Oxford Instruments Energy Dispersive System attached to the JSM-6480LV Scanning Electron Microscope at Northern Arizona University. Trace element maps (Y and Ti) were acquired using the electron microprobe in Washington State University’s Geoanalytical Lab. Locations for microprobe traverses across garnet were chosen based on the major element maps (Fig. 2) to pass through the centre of the garnet concentric zoning, avoid inclusions and capture as much of the rim as possible. Spot analyses of garnet along line traverses and of matrix minerals were acquired using the Cameca MBX electron microprobe at Northern Arizona University using an accelerating voltage of 15 kV (Appendix S1). For garnet traverses, a spot size of 1 μm was used. A spot size of 5 μm was used to collect matrix mineral compositions. Points along garnet line traverses were spaced ~20 μm apart. Major element traverses across garnet from samples LHRR10D and LHRR10I are shown in Fig. 3.

Trace element geochemistry

Trace elements were analysed along linear traverses in one garnet grain from each sample dated by
Lu–Hf, using the SHRIMP-RG at Stanford University. The following garnet crystals were analysed: LHRR10I garnet grain 3, THAL6B garnet grain 1 and THAL4E garnet grain 2. SHRIMP-RG analyses followed the procedures outlined by Mazdab (2009). A 1.83 nA primary O$_2^-$ ion beam resulting in a spot diameter of ~15 µm was used. Approximately 30 points were analysed across each garnet grain, chosen to correspond roughly to the locations of microprobe line traverses from which garnet P–T paths were generated in this and previous studies (Harris et al., 2007). Each analysis was acquired over 535 s. The following isotopes were analysed: $^{30}$Si, $^{139}$La, $^{140}$Ce, $^{146}$Nd, $^{147}$Sm, $^{153}$Eu, $^{156}$Gd, $^{159}$Tb, $^{163}$Dy, $^{165}$Ho, $^{166}$Er, $^{169}$Tm, $^{172}$Yb and $^{175}$Lu. Concentrations were determined relative to the in-house garnet reference material Garnet28, using $^{30}$Si as a normalizing mass. Two sigma errors for Lu analyses are ~10%, based on a 95% confidence interval of the counting statistics for Lu, $2\sigma$ variability in analyses of the reference material, and assuming 2% error from microprobe values of the Si concentration in garnet. Typical $2\sigma$ errors for other elements range from 5 to 10%, depending on the concentration of the element. Representative acquisition parameters for SHRIMP-RG analyses can be found in Appendix S2.

A second trace element traverse was performed on garnet grain 3 from sample THAL4E using LA-ICP-MS at The Pennsylvania State University, using a spot size of 65 µm, a beam energy density of ~11 J cm$^{-2}$ and a repetition rate of 10 Hz. Each analysis was acquired over 160 s, which consisted of 30 s of background collection during laser warm-up, 60 s of dwell time during ablation and 60 s of wash-out. The following isotopes were analysed: $^{43}$Ca, $^{139}$La, $^{140}$Ce, $^{146}$Nd, $^{147}$Sm, $^{153}$Eu, $^{157}$Gd, $^{159}$Tb, $^{163}$Dy, $^{165}$Ho, $^{166}$Er, $^{169}$Tm, $^{172}$Yb and $^{175}$Lu. Trace element concentrations were determined relative to the glass reference material NIST SRM612, using $^{43}$Ca as a normalizing mass. Average $2\sigma$ errors for individual Lu analyses are 6%; average $2\sigma$ errors for Yb analyses are 5%.

Zoning profiles for trace elements are plotted in Figs 4–6 and S1. Trace element data were collected in each garnet along the same traverse used to collect major element data. P–T paths were produced from the major element data in this study (as described below) and in the study of Harris et al. (2007).

**Raft River Mountains sample LHRR10I**

Trace element concentrations in garnet 3 from sample LHRR10I are shown in Fig. 4. The core (zone 1) of garnet 3 has high HREE+Y concentrations that decrease towards the rim, consistent with Rayleigh-type behaviour (e.g. Hollister, 1966). A near-rim annulus in HREE+Y (zone 2), visible in the Y element map (Fig. 2) and the Lu and Y zoning profiles (Fig. 4a,b), occurs towards the garnet rim and coincides with the beginning of post-hiatus garnet growth, as identified in the major element zoning (Figs 3 & 4c).

**Albion Mountains samples THAL4E, THAL6B**

Rare earth element and Y zoning profiles for garnet grain 2 from sample THAL4E (Fig. S1) are symmetrical with relatively flat cores and near-rim peaks.
which, as in sample LHRR10I, coincide with a previously interpreted garnet growth hiatus that was identified in the major element zoning profiles (Harris et al., 2007). This zoning profile does not appear to be the result of simple Rayleigh fractionation that is expected for compatible trace elements in garnet, which would yield HREE+Y profiles that decrease from core to rim (e.g. Lapen et al., 2003; Skora et al., 2006; Anczkiewicz et al., 2007; Kohn, 2009). It is possible that HREE+Y in this rock were fractionated as expected from the onset of garnet growth, but the initial stages of fractionation were not recorded in garnet grain 2.

The hypothesis that garnet grain 2 does not record the initial stage of garnet growth in the rock is supported by the composite P–T path constructed by Harris et al. (2007) from three garnet profiles within the same thin section. The composite P–T path indicates that garnet grain 2 records only the latest segment of garnet growth, based on the correlation of $X_{\text{Sps}}$ values. To test the validity of this hypothesis, a trace element traverse was performed using LA-ICP-MS across garnet grain 3 from sample THAL4E (Fig. 5). Garnet grain 3 records the first segment of garnet growth documented in the composite P–T path of Harris et al. (2007). The trace element traverse for garnet grain 3 shows HREE+Y decreasing from the garnet core to the growth hiatus as expected (Fig. 5a,b, zone 1), and a peak in HREE+Y at the onset of rim growth (zone 2), similar to that observed in LHRR10I.

Garnet grain 1 from sample THAL6B reveals high concentrations of HREE+Y in the core of the garnet (Fig. 6; zone 1), which are interpreted to be the result of Rayleigh fractionation. A secondary annulus in HREE+Y occurs towards the rim of the garnet (zone 2) and corresponds very closely with the end of segment 1 and beginning of segment 2 of the garnet growth simulation of Harris et al. (2007).

DETERMINATION OF P–T PATHS

Thermodynamic modelling to determine P–T paths was undertaken in the model system Na$_2$O-K$_2$O-CaO-MgO-FeO-MnO-Al$_2$O$_3$-SiO$_2$-H$_2$O. Excess H$_2$O was added, and all Fe was assumed to be Fe$^{2+}$. In this study, a modified version of the procedure used in Harris et al. (2007) was used to calculate P–T paths for two new samples, LHRR10D and LHRR10I, the primary difference being the way in which the initial conditions were estimated. The initial conditions were determined using the programs Theria and Domino (de Capitani & Petrakakis, 2010; Figs 7 & 8), whereas a complex iterative procedure was used in Harris et al. (2007). See Appendix S3 for a detailed explanation of the methods used in the present study. Mineral abbreviations follow Whitney & Evans (2010).

The P–T paths were calculated using the Gibbs’ method based on Duhem’s theorem (e.g. Spear, 1995). Inputs for the calculation include the initial conditions corresponding to the beginning of garnet growth (the initial mineral assemblage, mineral modes and compositions, and the P–T of garnet nucleation), and values for the changes in two monitor parameters that occurred during garnet growth.
The $P$–$T$ paths for samples THAL4E and THAL6B were previously calculated and reported in Harris et al. (2007). The $P$–$T$ paths were calculated using the program GIBBS (version dated 16 February 2010; Spear et al., 1991). Major element profiles for garnet were simulated from the core outward assuming fractional crystallization. Changes in the mole fraction of grossular content ($\Delta X_{\text{Grs}}$) and the moles of garnet grown ($\Delta M_{\text{Grt}}$) were used as monitor parameters for garnet growth. Grossular content was used as a monitor parameter in preference to $X_{\text{Alm}}$, $X_{\text{Sps}}$ or $X_{\text{Prp}}$ because of the relative resistance of Ca

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**Fig. 4.** Trace element zoning in sample LHRR10I garnet 3. Garnet zones based on changes in REE patterns (d–f) are labelled zones 1, 2 and 3 in (a–c). Yttrium+REE-rich annulus marked by grey shaded field (zone 2). (a) Lu concentration (ppm) from core to rim; (b) Y concentration (ppm) from core to rim; (c) Grossular (Grs) content; (d) REE patterns in Zone 1; (e) REE patterns in Zone 2 (Zone 1 shown in light grey); (f) REE patterns in Zone 3 (Zones 1 & 2 shown in light grey). The growth hiatus interpreted from the major element zoning is indicated by the dashed line and coincides with the beginning of the HREE+Y annulus (zone 2).
to diffusional modification after garnet growth compared to Fe, Mn and Mg (Spear, 1995).

**P-T path for LHRR10D**

Garnet growth in sample LHRR10D was simulated from the core to a hiatus in the profile that was identified by a pronounced discontinuity in the major element profile (Fig. 3a) (e.g. Spear, 1988; Konrad-Schmolke *et al.*, 2008; Caddick *et al.*, 2010). We interpret the isochemical plot and garnet core compositional isopleths to indicate that the garnet core grew inside the assemblage quartz + chlorite + muscovite + staurolite + plagioclase (diagonal line fill in Fig. 7b).
Garnet core growth took place by the breakdown of chlorite via the approximate reaction:

$$\text{quartz} + \text{plagioclase} + \text{chlorite} + \text{muscovite} = \text{garnet} + \text{biotite} + \text{H}_2\text{O}$$  \hspace{1cm} (1)

The garnet growth simulation yielded a $P$-$T$ path consisting of a temperature increase of 37 °C and pressure increase of 1.1 kbar (Fig. 7b; Table 1), and points in the direction of the final mineral assemblage field of quartz + muscovite + biotite + staurolite + chlorite + garnet (diagonal line fill in Fig. 7d). Crossing this field with increasing temperature yielded partial garnet consumption via the approximate reaction:

$$\text{garnet} + \text{muscovite} + \text{chlorite} = \text{staurolite} + \text{biotite} + \text{H}_2\text{O}$$  \hspace{1cm} (2)

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**Fig. 6.** Trace element zoning in sample THAL6B garnet 2. Garnet zones based on changes in REE patterns (d–f) are labelled zones 1, 2 and 3 in (a–c). Yttrium+REE-rich annulus marked by grey shaded field (zone 2). (a) Lu concentration (ppm) from core to rim; (b) Y concentration (ppm) from core to rim; (c) Grossular (Grs) content; (d) REE patterns in Zone 1; (e) REE patterns in Zone 2 (Zone 1 shown in light grey); (f) REE patterns in Zone 3 (Zones 1 & 2 shown in light grey).
The garnet growth simulation is a close match to the analytical data (Fig. 3a). A resumption of garnet growth created the observed hiatus and discontinuity in the garnet profile. The conditions of growth for the post-hiatus segment are constrained by the intersection of garnet compositional isopleths (grey fields in Fig. 7d) and by the final mineral assemblage of the rock (diagonal line fill in Fig. 7d). We interpret that the peak temperature occurred inside the final mineral assemblage field and that post-hiatus garnet growth occurred when a partial reversal of the garnet consumption reaction took place during cooling.

**P–T path for LHRR10I**

The growth of garnet in sample LHRR10I was similar to LHRR10D. Both have the same initial and final assemblages, and a similar hiatus is interpreted from a discontinuity in the profile (Fig. 3b). One difference is that the pre-hiatus portion of the profile is interpreted to reflect growth in two different mineral assemblages rather than one; the central core grew in the presence of plagioclase similar to LHRR10D, while the outer core, identified as the portion outboard of the break in Ca-slope, grew in the absence of plagioclase. Growth of the outer core portion could not be simulated due to the absence of a Ca-source in the model system. The outer core portion, which incorporates some Ca, grew within the mineral assemblage quartz + chlorite + muscovite + staurolite. The models used for these minerals do not include Ca (see Appendix S3). We interpret the sharp drop in Ca through the outer core portion of the profile to reflect growth following the loss of plagioclase from the assemblage. Consequently, only the central core portion could be simulated using the Gibbs’ method.

The garnet growth simulation for the central core portion of LHRR10I yielded a P–T path consisting of a temperature increase of 12.7 °C and a pressure increase of 93 bar (Fig. 8b). The garnet growth simulation is a close match to the analytical data (Fig. 3). As the central core grew, plagioclase was fully consumed. Similar to LHRR10D, the final mineral assemblage and post-hiatus garnet isopleths constrain the post-hiatus segment to a narrow field in P–T space (diagonal line pattern, Fig. 8d). We interpret the hiatus in the same way as for LHRR10D; garnet is partially consumed as the final mineral assemblage field is crossed with increasing temperature, and then partially regrown as the garnet consumption reaction is reversed during cooling. For both LHRR10I and LHRR10D, the fact that chlorite occurs only as rims on staurolite and garnet suggests that the narrow field representing the final assemblage was completely traversed during progradation, as this would have consumed all matrix chlorite.

**LU–HF GEOCHRONOLOGY**

**Lu–Hf methods**

Garnet from three samples of the schist of Mahogany Peaks was dated using the Lu–Hf method (e.g. Scherer et al., 2000; Anczkiewicz et al., 2007; Cheng et al., 2008; Corrie et al., 2010; Wells et al., 2012): sample LHRR10I from the Rafter River Mountains and samples THAL4E and THAL6B from the Albion Mountains. Sample preparation was done using a porcelain mortar and pestle to crush and separate garnet from other minerals in the rock. For each sample, five 200–250 mg separates of relatively inclusion-free garnet were hand-picked using a binocular microscope. Whole-rock isotopic analysis was performed on the bulk rock (~250 mg/dissolution) from each sample. All samples were crushed to ~30 μm size using a diamonite® mortar and pestle, dissolved via hotplate dissolution (garnet separates) or high pressure Teflon bombs (whole-rock separates), and spiked using a mixed 176Lu–178Hf tracer. Sample-spike equilibration was achieved by hotplate equilibration for 24–48 h after primary dissolution, as outlined in Vervoort et al. (2004).

Lu and Hf were separated using cation-exchange columns as described in Cheng et al. (2008). Isotopic analyses were carried out by MC-ICP-MS (ThermoFinnigan Neptune). Hf solutions were introduced using an Aridus microconcentric desolvating nebulizer (Cetac Inc.) as dry aerosols, resulting in an enhancement of Hf signals. Hf analyses were normalized to 176Hf/176Hf = 0.282160 for the Hf standard JMC 475 (Vervoort & Blichert-Toft, 1999). Mass fractionation and isobaric interferences were corrected as outlined in Vervoort et al. (2004). All chemical separations and mass spectrometry were performed at Washington State University.

**Lu–Hf results**

Reduced Lu–Hf data for all samples are listed in Table 2, and the resulting isochrons are shown in Fig. 9. The Lu–Hf dates were calculated with Isoplot (Ludwig, 2003) and using the 176Lu decay constant of 1.867 × 10⁻¹¹ (Scherer et al., 2001; Söderlund et al., 2004). Regression calculations used a 0.5% 2σ uncertainty for 176Lu/177Hf and, for 176Hf/177Hf, the 2σ in-run uncertainty of each analysis added in quadrature with an external reproducibility of 0.01%. In the isochrons shown in Fig. 9, points shown in grey were not included in date calculations. In addition to these regressions, ‘individual garnet fraction’ dates were also calculated for each sample. These were calculated using the 176Lu/177Hf and 176Hf/177Hf for each garnet fraction combined with the corresponding whole-rock composition for that sample. The purpose of these dates is to characterize the variation in individual data points about the calculated isochron.
Points excluded from the regression calculations (generally because of high isobaric interferences on $^{176}$Hf) were not used to calculate individual garnet fraction dates.

**Sample LHRR10I**

Five garnet fractions and one whole rock were analysed from sample LHRR10I. Data from three garnet fractions and one whole rock (Fig. 9a) yield a Lu–Hf age of 150 ± 1 Ma ($2\sigma$, MSWD = 1.1). Garnet fraction G4 has a significantly older Lu–Hf date and, because of high Lu interferences, this point was not included in the age calculation. Garnet fraction G2 lies above the isochron, and thus may represent a bias with slightly older garnet cores compared to fractions G1, G3 and G5. This fraction yields an individual garnet-whole rock date of 152 ± 1 Ma, which is slightly older than, but within error of the calculated isochron. Individual garnet fraction dates for garnet fractions G1, G3 and G5 yielded ages of 149 ± 2 Ma, 150 ± 1 Ma and 149 ± 2 Ma respectively.

**Sample THAL4E**

Six garnet fractions and one whole-rock fraction were analysed from sample THAL4E (Fig. 9b); five of the garnet fractions were used to calculate a Lu–Hf isochron date of 138.7 ± 0.7 Ma ($2\sigma$, MSWD = 1.6). Garnet fraction G4 and the whole-rock fraction were excluded from the date regression calculation because of high isobaric Hf interferences. If these analyses were included in the regression the resultant Lu–Hf date would be 138.8 ± 3.4 Ma; therefore, their exclusion does not change the date determined for this sample. Garnet fraction G4 was used as a whole-rock proxy for two-point isochron ages because of the high isobaric Hf interferences with the whole-rock fraction. Two-point isochrons for garnet fractions G1, G2, G3, G5 and GC yielded ages of 140 ± 2 Ma, 141 ± 3 Ma, 140 ± 3 Ma, 144 ± 4 Ma and 138.7 ± 0.7 Ma respectively.

**Sample THAL6B**

Five garnet and one whole-rock fractions were analysed from sample THAL6B, yielding a Lu–Hf date of 132 ± 5 Ma ($2\sigma$, MSWD = 9.5) based on three garnet fractions and the whole rock (Fig. 9c). Garnet fractions G3 and G4 were excluded from the age calculation to obtain a lower MSWD value; including these analyses yields a date of 130 ± 12, which is within error of the more precise date but has a much higher MSWD (~174). The large error in the date, the high MSWD value and the high interferences on most points for this rock are most likely the result of low Hf concentrations in these garnet grains (53–87 ppb). Despite these limitations, the calculated date of 132 ± 5 Ma for this sample is considered here to have meaning in the context of its close spatial proximity to sample THAL4E and similar date. Two-point isochrons for garnet fractions G1, G2 and G5 yield ages of 131 ± 1 Ma, 132 ± 1 Ma and 133 ± 1 Ma respectively.

**DISCUSSION**

**Interpretation of P–T–t paths and trace element zoning**

In their garnet growth simulation of sample THAL6B garnet 2, Harris et al. (2007) noted that the model fit of the garnet rim was poor, particularly for the Fe profile. Harris et al. (2007) proposed open-system behaviour with respect to Fe as a possible explanation for the poor fit of the outer rim of this garnet. The trace element zoning features in garnet 2 from sample THAL6B from the Albion Mountains provide a possible alternative explanation to open-system behaviour for the problems noted for the garnet growth simulation of Harris et al. (2007). The HREE+Y-rich annulus (Fig. 6) is likely similar in origin to the HREE+Y annulus at the growth hiatus of garnet 2 from sample THAL4E. Given the shared P–T history of the two samples, similar rock bulk compositions, and their close spatial proximity (Harris et al., 2007), the increase in HREE+Y in zone 2 of sample THAL6B may also be explained by partial garnet consumption followed by regrowth. One issue with this interpretation is that the break in slope of the Ca profile in this garnet occurs after the spike in HREE+Y, which is different than the relationship between hiatuses and annuli in garnet from the other two locations.

Annuli like those seen in the HREE+Y profiles of samples from the Raft River (LHRR10I) and Albion (THAL4E) Mountains likely indicate local changes in the REE reservoir around the garnet. These changes, and the presence of hiatuses in garnet growth may be
Figure 8. Results of pseudosection modelling for sample LHRR10I. All details as in Fig. 7. The $P$–$T$ path shown in (b) is displaced $-10\, ^\circ C$ and $+150$ bar to align the end of the path with the boundary that represents the loss of plagioclase from the assemblage.
Table 1. Input values used in calculations of isochemical plots, isopleths and P–T paths, and results of P–T path calculations.

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<td>0.059</td>
<td>0.014</td>
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</tbody>
</table>

- a) Garnet core composition.
- b) Garnet composition at the hiatus.
- c) Average composition of the post-hiatus garnet segment.
- d) Pressure determined for initiation of garnet growth.
- e) Temperature determined for initiation of garnet growth.
- f) Monitor value change from the hiatus to core (hiatus minus core).
- g) Calculated changes in pressure and temperature associated with pre-hiatus (garnet core) to post-hiatus (garnet rim).
- h) Nucleation density (nuclei per 100 cm³) assumed in garnet growth simulations. Abbreviations follow Whitney & Evans (2010).

interpreted from the major element profiles (Figs 4e & 5c) and the REE patterns (Figs 4d–f & 5d–f). Based on trace and major element variations, we have defined three zones within the garnet grains in this study (Figs 4–6): zone 1 contains the garnet core; zone 2 is the HREE+Y enriched annulus, which either occurs post-hiatus (LHRR10I and THAL4E) or pre-hiatus (THAL6B); and zone 3 consists of the garnet rim post-annulus.

In zone 1, middle and heavy REEs decrease consistent with Rayleigh fractionation from the cores outward (Figs 4d, 5d & 6d). In samples LHRR10I and THAL4E, growth hiatuses interpreted from major element zoning occur at the boundary between zones 1 and 2. Within zone 2, MREEs and HREEs are enriched, resulting in the annuli observed post-hiatus (Figs 4e, 5c & 6c). The REE patterns post-annulus (zone 3; Figs 4f, 5f & 6f) are of markedly different shape than zones 1 and 2, with strong enrichment in MREE and depletion of HREE, which suggests that post-annulus garnet grew coevally with the breakdown of a MREE-enriched phase (e.g. Konrad-Schmolke et al., 2008).

Garnet grains with annuli rich in HREE+Y have been reported by numerous authors (e.g. Carlson, 2002; Yang & Rivers, 2002; Corrie & Kohn, 2008; Gierè et al., 2011). Four mechanisms have been proposed to explain Y annuli in pelitic garnet:

1. Disequilibrium partitioning during changes in kinetic parameters such as garnet growth rate may explain Y annuli. This process commonly produces distinct inclusion-rich and inclusion-free zones (e.g. Yang & Rivers, 2002), which are not apparent in the garnet in this study.

2. Infiltration of a REE-rich fluid. Textural features indicating fluid flow, such as veins and fluid inclusions may explain Y zoning, however, these are not observed in this study. Furthermore, this

Table 2. Reduced Lu–Hf data for samples LHRR10I, THAL4E and THAL6B. Points highlighted in grey were not included in age regression calculations.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Lu (ppm)</th>
<th>Hf (ppm)</th>
<th>Sample weight (g)</th>
<th>176Lu/177Hf</th>
<th>176Hf/177Hf</th>
<th>2σ (abs)</th>
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</thead>
<tbody>
<tr>
<td>LHRR10I G1</td>
<td>3.44</td>
<td>0.417</td>
<td>0.24121</td>
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<td>LHRR10I G3</td>
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<td>0.250</td>
<td>0.23622</td>
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</tr>
<tr>
<td>LHRR10I G4</td>
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<tr>
<td>LHRR10I G5</td>
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<td>LHRR10I WR</td>
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<td>THAL4E G1</td>
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<td>THAL4E G4</td>
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<td>0.091</td>
<td>0.21624</td>
<td>0.2709</td>
<td>0.282144</td>
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</table>

- a) Lu and Hf concentrations determined by isotope dilution with uncertainties estimated to be better than 0.5%.
- b) Uncertainties for 176Lu/177Hf for regressions and age calculations are estimated to be 0.5%.
- c) 176Lu/177Hf ratios were corrected for instrumental mass bias using 176Hf/177Hf = 0.7055 and normalized relative to 176Hf/177Hf = 0.282160 for JMC-475 (Vervoort & Blichert-Toft, 1999).
- d) Ages were calculated using the 176Lu decay constant value of Scheret et al. (2001) and Soderlund et al. (2004).
- e) Reported errors in 176Hf/177Hf represent within-run uncertainty expressed as 2σ, standard error. Estimated total uncertainty on individual 176Hf/177Hf measurements is estimated to be 0.01% or ~1 c.p.m. unit. These are added to the within-run uncertainties in quadrature for regressions and age calculations.

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3 Resorption of garnet during a hiatus and renewed growth may explain Y zoning. This interpretation is consistent with the results of the $P$–$T$ modelling for samples LHRR10I and THAL4E. Both rocks have growth paths that cross regions of $P$–$T$ space in which garnet was consumed and then regrown, producing the observed hiatuses and garnet rims (for instance, garnet rims in samples LHRR10I and 10D grew in the striped regions of Figs 7d & 8d).

As garnet was consumed, HREE+Y could have been enriched in the surrounding matrix due to slow matrix diffusion away from the garnet (e.g. Skora et al., 2006). When garnet regrew following resorption, the enriched area would have been overgrown, resulting in the REE patterns in zone 2 that mimic the shape of those in zone 1 but at higher concentrations (Fig. 4). Given the coincidence of HREE+Y annuli post-growth-hiatus interpreted from major element zoning, this explanation is permissive for samples LHRR10I and THAL4E. However, it would not explain the pre-hiatus annulus in sample THAL6B. Additionally, this mechanism commonly results in Mn resorption into garnet (e.g. Carlson, 2002), which is not observed.

4 Breakdown of a REE-bearing phase such as monazite, apatite, allanite or xenotime may explain Y annuli. The HREE+Y annuli observed in these rocks are most likely the result of the breakdown of xenotime based on three main lines of evidence: (i) The annuli, particularly in sample LHRR10I, are similar in shape to those reported for accessory phase breakdown (e.g. Pyle & Spear, 1999; Spear & Pyle, 2002; Yang & Rivers, 2002; Gieré et al., 2011). (ii) The REEs within the annuli (zone 2; Figs 4e, 5e & 6e) show flat HREE patterns which are enriched in MREE and HREE relative to LREE, consistent with the shape of REE patterns reported for xenotime by Spear & Pyle (2002). (iii) The Ca and Y element maps for sample LHRR10I (Fig. 2a) show thatapatite inclusions occur throughout the garnet, but xenotime occurs only in the core of the garnet (pre-annulus), which is consistent with the interpretation that the HREE+Y annulus formed by breakdown of xenotime. Only a small number of garnet grains from sample LHRR10I were mapped, so this does not exclude the possibility that xenotime occurs in other garnet rims, but in the garnet grains we have examined xenotime does not occur in the post-annulus rims.

Although it is possible that different mechanisms are responsible for the annuli in each individual rock in this study, we believe the breakdown of a REE-bearing phase (mechanism 4) is the most likely explanation for the Y annuli observed in the garnet.

**Linking trace elements and Lu–Hf geochronology**

The Lu distribution in garnet determines what part of the garnet growth history is likely being dated by...
the Lu–Hf method, whether the determined age represents the core, rim or middle. A common interpretation of Lu–Hf dates is that they are biased towards the garnet core due to preferential partitioning of Lu into the core (e.g. Lapen et al., 2003; Skora et al., 2006; Kohn, 2009). However, this interpretation cannot apply to the garnet grains in this study because of the bimodal distribution of Lu, with a large amount of the Lu being hosted close to the rim within the high HREE+Y annuli (zone 2, Figs 4–6).

To determine the significance of the Lu–Hf garnet ages with respect to the garnet growth history, we estimated the relative amount of Lu present per volume of garnet analysed from core to rim (Fig. 10). Shown for comparison is the volume relationship for a hypothetical garnet that sequestered Lu by Rayleigh fractionation from a uniform reservoir. Of all the samples, THAL6B shows a Lu distribution most similar to that predicted by Rayleigh fractionation. The Lu annulus in this sample is closer to the centre of the garnet than in the other two samples, and the magnitude of the Lu annulus spike is smaller, consistent with its similarity to the ideal Rayleigh garnet. Samples THAL4E and LHRR10I, however, show Lu distributions markedly different than the ideal Rayleigh garnet. The Lu annuli in these samples skew the distribution of Lu towards the middle/rims of the garnet. This suggests that the Lu–Hf dates determined for samples LHRR10I and THAL4E represent an overall age for garnet growth, more strongly weighted towards the rims, whereas the Lu–Hf date for sample THAL6B is representative of mostly core garnet growth. This interpretation assumes Lu is distributed similarly within all the garnet in the rock, which we know may not be the case based on the different zoning profiles in the two garnet grains analysed from sample THAL4E.

A bimodal distribution of Lu in garnet has potential implications for the interpretation of Lu–Hf garnet dates. Recent studies have successfully dated different zones of garnet growth by microdrilling to physically separate garnet cores, middles and rims (Pollington & Baxter, 2010; Dragovic et al., 2012), allowing for the determination of the duration and rate of garnet growth. In all samples dated here, each dated garnet fraction is essentially a physical mixture of garnet cores, middles and rims (zones 1, 2, 3 of Figs 4–6). This means that any given point on the isochron is influenced, to varying degrees, by all three zones of garnet. The trace element analysis above suggests that the dates are biased towards zone 2 because of the distribution of Lu in these garnet grains. Although there is not excessive scatter in the data, particularly for samples LHRR10I and THAL4E, there are some points for each sample that do not lie exactly on the same isochron as the others.

In the absence of analytical reasons for excluding points from a Lu–Hf isochron, we consider a reasonable geological explanation of points that lie above the isochron to be the result of the influence of older zone 1 cores (e.g. Kohn, 2009). Conversely, points that lie below the calculated isochron may have more influence from the garnet rims (zones 2 & 3). Thus, in natural garnet systems, assigning an isochron date is not necessarily straightforward because the scatter in the data may have geological meaning. When that scatter is smaller than the precision of the method, we cannot see the effects on the date determination. If the opposite is the case, then the scatter may be due, in part, to the duration of garnet growth.

For instance, the Lu–Hf isochron date of 150 ± 1 Ma for LHRR10I (Fig. 9a) from the Raft River Mountains includes the three youngest garnet fractions for that sample. Garnet fraction G2, which lies above the isochron, may have more influence from zone 1 of the garnet cores, represented by the peak in Lu at the centre of the garnet (Fig. 4a). The two-point isochron model date of 152 ± 1 Ma for this garnet fraction is potentially representative of a minimum date for the onset of garnet growth in this rock, as it may have more influence from older garnet cores. However, this date is not statistically different than the isochron date, which suggests that the duration of garnet growth is short with respect to the date determination.

Based on the garnet Lu–Hf ages and the analysis of what they represent in terms of the garnet growth history, it is possible to relate the ages to the determined P–T paths. For LHRR10I, the 150 ± 1 Ma

Fig. 10. Plot of volume fraction of garnet v. cumulative Lu fraction in garnet for samples LHRR10I (thick solid line), THAL4E (short dashes) and THAL6B (long dashes) based on Lu trace element zoning profiles. Shown for comparison is a curve for a hypothetical garnet that grew as a result of Rayleigh fractionation, assuming that garnet growth was linear with area (thin solid line). Upper X-axis shows normalized distance across garnet from core (left) to rim (right).
age likely represents the post-hiatus segment of garnet growth as most of the Lu is hosted in that segment (Fig. 4). This indicates that the $P$–$T$ path determined for the core (Fig. 8b), which records an episode of steep pressure increase, is slightly older than 150 ± 1 Ma. For THAL4E, the 138.7 ± 0.7 Ma age probably slightly post-dates the composite $N$-shaped path determined by Harris et al. (2007) (Fig. 11a), as the path was determined entirely from the core (post-hiatus) portions of three garnet grains, whereas most of the Lu is hosted in the post-hiatus segments (Fig. 5). For THAL6B, the 132 ± 5 Ma age likely represents the age around the end of the steep pressure increase $P$–$T$ path that was generated from the pre-hiatus segment (Fig. 11a), as the Lu is hosted mainly in the annulus just before the hiatus (Fig. 6).

Tectonic implications

In the western Raft River Mountains, a summary $P$–$T$ path involving a pressure increase of ~2 kbar and a temperature increase of ~50 °C (Fig. 11b) was interpreted from the isochemical plots and garnet growth simulations from samples LHRR10D and LHRR10I. The relatively short duration of garnet growth suggested by individual garnet fraction dates and the overall tectonic setting suggests that this pressure increase is the result of rapid tectonic burial. The previously described analysis of the distribution of Lu in garnet from LHRR10I (Fig. 10) suggests that the Lu–Hf date from this sample is skewed towards the post-hiatus or outer pre-hiatus segments, indicating that the age likely post-dates the $P$–$T$ path recorded in the central core. Therefore, the combined Lu–Hf geochronology and $P$–$T$ modelling from sample LHRR10I indicate that major crustal thickening in this portion of the hinterland of the Sevier belt occurred slightly before 150 Ma.

The composite $P$–$T$ path reported by Harris et al. (2007) based on multiple garnet grains from Albion Mountains sample THAL4E (Fig. 11a) shows a nearly isothermal pressure increase followed by a pressure decrease with some heating and then a second nearly isothermal pressure increase. Harris et al. (2007) interpreted the pressure increases to be the result of thrust burial. The previously described analysis of the distribution of Lu in garnet from THAL4E suggests that the Lu–Hf date of 138.7 ± 0.7 Ma either post-dates the recorded $P$–$T$ path or dates near the tail end of it. Thus, a major Early Cretaceous burial episode is recorded by garnet growth in the Albion Mountains.

The Late Jurassic to Early Cretaceous tectonic event documented here is the oldest Phanerozoic contractional event to have affected the metamorphic rocks in the Raft River-Albion-Grouse Creek metamorphic core complex. These rocks likely lay sufficiently far to the east of the Roberts Mountain and Golconda thrusts to have escaped tectonic burial during the Palaeozoic Antler and Sonoman orogenic events. Furthermore, Late Jurassic to Early Cretaceous contraction is the oldest of several episodes of Mesozoic to Early Cenozoic contraction (e.g. Wells et al., 2012). Therefore, we infer that the tectonic burial required to bring these supracrustal strata to the depths at which garnet growth began was also of Late Jurassic age. Thus, in addition to the 2–3 kbar (~7–11 km) of burial recorded during garnet growth, a further tectonic burial of 5–9 km is required to bring the schist of Mahogany Peaks from stratigraphic burial depths of ~10–14 km to the ~5 kbar.
metamorphic conditions at which garnet initiated growth. In summary, 12–20 km of tectonic burial is required in the Raft River–Albion–Grouse Creek core complex, west of the Wyoming salient of the fold-thrust belt, during the Late Jurassic to Early Cretaceous.

Minor Late Jurassic shortening in the hinterland has previously been recognized, including small offset thrust faults and the upgrading of cleavages in the thermal aureoles of Late Jurassic plutons (e.g. Allmendinger & Jordan, 1984; Miller et al., 1988; Miller & Allmendinger, 1991; Hudec, 1992; Smith et al., 1993). However, the unambiguous result from this study of major crustal thickening in the Sevier hinterland during the Late Jurassic to Early Cretaceous suggests that this record of early crustal thickening may be commonly obscured by the Late Cretaceous metamorphism that is pervasive in the mid-crustal rocks of the core complexes (Miller & Gans, 1989; Camilleri & Chamberlain, 1997; Lewis et al., 1999; McGrew et al., 2000; Wells et al., 2012; Hallett & Spear, 2015).

The Late Jurassic to Early Cretaceous (Tithonian to Valanginian) Lu–Hf dates reported here for crustal shortening in the Sevier hinterland fill in an important temporal gap between documented and significant Early to Middle Jurassic shortening in the western hinterland and mid- to Late Cretaceous shortening in the fold-thrust belt (e.g. Smith et al., 1993; Camilleri et al., 1997; Wyld, 2002; DeCelles, 2004). These new age constraints support a protracted Late Jurassic to early Cenozoic deformation history for the Sevier orogen rather than a two-stage history (e.g. Smith et al., 1993). We concur with previous studies (e.g. Camilleri et al., 1997; DeCelles, 2004) that the Sevier orogenic belt evolved as a retroarc orogenic wedge, with initial shortening propagating to the east through time as the wedge lengthened (e.g. Davis et al., 1983).

CONCLUSIONS

This study demonstrates that the method of combining $P$–$T$ paths determined from growth zoning in garnet with Lu–Hf garnet geochronology and in situ trace element analyses of garnet is very effective for recognizing, interpreting and dating deformation events in orogenic belts. Detailed in situ analysis of trace elements in garnet, such as HREE–Y, can provide additional insight into the reactions occurring during garnet growth and highlight both equilibrium and disequilibrium processes affecting garnet growth. This study also highlights the importance of coupling Lu–Hf geochronology with an understanding of the distribution of Lu in garnet to interpret Lu–Hf garnet dates with respect to the garnet growth history. The $P$–$T$–$t$ paths presented here from the Raft River–Albion–Grouse Creek metamorphic core complex record crustal shortening during the Late Juras-

sian to Early Cretaceous, providing some of the first direct dates of shortening in the hinterland of the Sevier orogenic belt that pre-dates development of the foreland fold-thrust belt.

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Vervoort, J.D. & Blichert-Toft, J., 1999. Evolution of the depleted mantle by isotopic dilution expressed as mole fractions \( X_{\text{Ams}} \), \( X_{\text{Sps}} \), \( X_{\text{Grs}} \) and \( X_{\text{Pre}} \) for samples LHRR10I and LHRR10D.


SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article at the publisher’s web site:

Appendix S1. Major element garnet traverse data expressed as mole fractions \( X_{\text{Ams}} \), \( X_{\text{Sps}} \), \( X_{\text{Grs}} \) and \( X_{\text{Pre}} \) for samples LHRR10I and LHRR10D.

Appendix S2. Representative acquisition parameters for trace element analysis in garnet by SHRIMP-RG.

Appendix S3. Detailed description of methods used for thermodynamic modelling of garnet growth.

Figure S1. Plot of Lu concentration v. distance across garnet 2 from sample THAL4E analysed by SHRIMP-RG.

Table S1. Mineral composition data and calculated bulk compositions for samples LHRR10I and LHRR10D.

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