Garnet Geochronology: Timekeeper of Tectonometamorphic Processes

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Dissolved garnet solutions (orange) are loaded onto ion exchange columns to isolate elements of interest: Sm, Nd, Lu, and Hf.

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Garnet's potential as a chronometer of tectonometamorphic processes and conditions was first recognized over 30 years ago. The Sm–Nd and Lu–Hf systems have since emerged as the most effective chronometers, permitting age precision of better than ±1 My, even on tiny samples such as concentric growth zones within individual crystals. New, robust analytical methods mitigate the effects of ubiquitous mineral inclusions, improving the precision and accuracy of garnet dates. Important differences between Sm–Nd and Lu–Hf with respect to partitioning, diffusivity, contaminant phases, and isotopic analysis make these two systems powerfully complementary.

Keywords: Sm–Nd, Lu–Hf, geochronology, isochron, metamorphism, tectonics

INTRODUCTION

Given the power of garnet as a recorder of tectonometamorphic processes and conditions, geoscientists have long desired to link that information to an absolute chronology. Thus the goal of garnet geochronology is not merely to date garnet growth; rather, it is to constrain the ages, durations, and rates of specific Earth processes or conditions that can be directly linked to garnet growth via chemical, thermodynamic, or petrographic means. Garnet is especially useful because (1) the thermodynamics controlling the pressure–temperature–composition (*P–T–X*) conditions of garnet growth is well understood, (2) garnet generally records prograde—rather than retrograde—tectonometamorphic processes, (3) garnet grows in a wide range of *P–T–X* conditions spanning diverse tectonic contexts and rock types, and (4) garnet preserves chemical (i.e. *P–T–X*) and age zonation potentially spanning millions of years. Here, we review the fundamentals of garnet geochronology, including the challenges that have slowed its progress. We also illuminate key advances of the past decade and underscore the potential of garnet geochronology.

A BRIEF HISTORY OF GARNET GEOCHRONOLOGY

The origins of garnet geochronology can be traced to two papers (Van Breemen and Hawkesworth 1980; Griffin and Brueckner 1980), whose authors applied the samarium–neodymium (Sm–Nd) isotopic system to date metapelites and eclogites, respectively. These workers recognized garnet as one of the few minerals that strongly fractionates parent Sm over daughter Nd, producing a favorably high parent–daughter isotope ratio for geochronology. The 1980s witnessed further attempts to date garnet with Sm–Nd until, in 1989, the first uranium–lead (U–Pb) (Mezger et al. 1989) and rubidium–strontium (Rb–Sr) (Christensen et al. 1989) garnet dates were published. Subsequent research showed that these systems in garnet are often dominated by mineral inclusions or are too susceptible to the complexities of local mineral-scale equilibrium and to the mobility of parent and daughter elements in crustal fluids (e.g. Romer and Xiao 2004; Sousa et al. 2013). As a result, U–Pb and Rb–Sr dating in garnet were mostly abandoned, while Sm–Nd chronology remained the method of choice during the 1990s. In 1997 came the first published application of lutetium–hafnium (Lu–Hf) garnet geochronology (Duchêne et al. 1997). Garnet strongly fractionates Lu over Hf, even more than it fractionates Sm over Nd, leading to very high Lu/Hf parent–daughter ratios, especially in garnet cores. Herein we showcase recent advances in garnet preparation procedures and Nd and Hf analytical precision, and we highlight the complementarity of the Sm–Nd and Lu–Hf garnet geochronometers.

DATING GARNET WITH ISOCHRONS

Garnet is dated with the isochron method, which exploits the decay of a radioactive parent isotope (e.g. ^{176}Lu or ^{147}Sm) to a stable daughter isotope (e.g. ^{176}Hf or ^{143}Nd), as reviewed in Figure 1. The measured garnet, paired with one or more additional measurements (for example, of the surrounding rock matrix), will define a straight line called an *isochron* on a plot of D/R versus P/R (where D is the daughter isotope, R is a stable and nonradiogenic reference isotope of the daughter element, and P is the parent isotope). Isochron geochronology requires that all samples (data points) on the isochron (1) were in initial isotopic equilibrium, with identical $[D/R]_i$, at time t, and (2) have remained closed systems with respect to the parent and daughter elements ever since. Initial isotopic equilibrium may exist among minerals formed simultaneously from an isotopically homogeneous source, or it may result from diffusion among—or recrystallization of—preexisting minerals during heating or metamorphism. Violation of these requirements will scatter data points from a perfect line. To evaluate whether the observed scatter exceeds that which can be explained by the analytical uncertainties, a quantity known as the "mean square of weighted deviates" (MSWD) is generally reported with multipoint ($n > 2$) isochron data (e.g. Wendt and Carl 1991). If all observed scatter can be explained by analytical causes alone, the MSWD will be close to 1, whereas larger values indicate that significant geologic scatter exists. Values less than 0.3 imply that the analytical uncertainties have been

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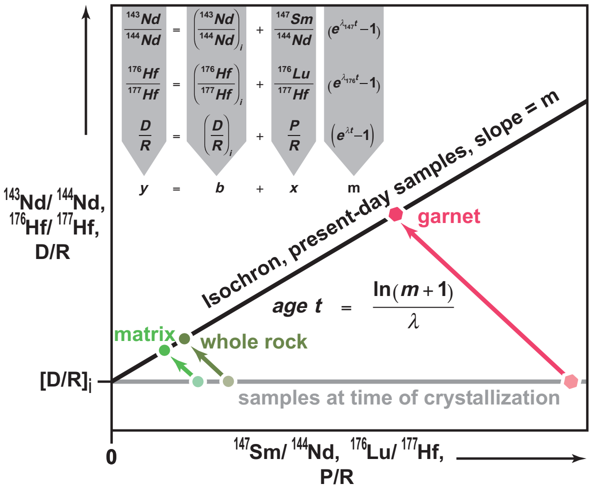

FIGURE 1 **Garnet dating with isochrons.** This isochron diagram shows axes and decay equations for Sm–Nd, Lu–Hf, and the general case. Measured present-day compositions (bold points) define a straight line—an "isochron"—whose slope (m) determines the age (*t*) of garnet growth. The decay constant (λ) is the probability of decay expressed as decays/atom/year: $\lambda_{176Lu} = 1.867 \times 10^{-11}$ y^{-1}; $\lambda_{147Sm} = 6.54 \times 10^{-12}$ y^{-1}. D = daughter isotope; P = parent isotope; R = a stable, nonradiogenic reference isotope of the daughter element.

overestimated. It follows that the use of MSWD values for testing whether the isochron assumptions have been met requires a realistic assessment of the analytical uncertainties. The use of "conservative" (i.e. high) estimates can mask the presence of initial isotopic disequilibrium, leading to underestimated age uncertainties.

Sometimes only two-point isochrons are feasible (or advisable; see below), but two points *always* define a scatter-free line, so it becomes impossible to evaluate the amount of geologic scatter and adherence to the isochron assumptions (though comparison of multiple two-point isochron ages from concentrically zoned garnet or from multiple samples in an area provide a useful statistical check). However, populating an isochron with additional data will not necessarily yield a more accurate or precise age. For example, different garnet generations in the same rock (or the same crystal!) may have grown at significantly different times (e.g. Kohn 2009; Skora et al. 2009; Pollington and Baxter 2010; Herwartz et al. 2011), or matrix minerals may have grown (or reequilibrated) before or after garnet growth. A good geochronological analogy to this is the reason one wouldn't combine amphibole, mica, and K-feldspar ^{40}Ar–^{39}Ar data into a single age; these minerals grow and become closed systems for Ar at different temperatures and times in a metamorphic rock with a prolonged tectonic history. In general, the geochronologist must take care not to populate an isochron with samples that are suspected *a priori* to have grown at significantly different times or to have never attained isotopic equilibrium.

PRECISION OF ISOTOPE RATIO MEASUREMENTS AND PRECISION OF AGES

The precision of garnet dating ultimately depends on the garnet P/R and analytical capabilities. For a given analytical uncertainty in D/R, the uncertainty of the isochron slope will generally decrease with an increasing spread in P/R among the points, with the latter being controlled by the high P/R of garnet. Element partitioning typically endows *pure* garnet with P/R > 1 (Fig. 2a; values as high as ~50 have been reported for ^{176}Lu/^{177}Hf: e.g. Lagos et al. 2007). Modern mass spectrometers achieve

Sm–Nd and Lu–Hf Primer

Sm, Nd, Lu, and Hf are normally found at the ppb to several tens of ppm level in most rocks and minerals. Notable exceptions include zircon (up to ~1 wt% Hf) and monazite (up to ~1 wt% Sm and 9 wt% Nd).

Sm and Nd are trivalent REEs with similar ionic radii:

- Sm and Nd have similar chemical behavior and are not fractionated strongly by most minerals.
- Garnet is exceptional as it strongly fractionates Sm over Nd, more than most minerals.

Radioactive parent ^{147}Sm decays via alpha emission to daughter ^{143}Nd (half-life = 106 billion years).

Lu is a trivalent REE and Hf is a tetravalent high field strength element (HFSE; high charge-to-ionic radius ratio):

- Lu and Hf have strongly differing chemical behaviors and can be strongly fractionated.
- Garnet is exceptional as it strongly fractionates Lu over Hf, more than most minerals.

Radioactive parent ^{176}Lu decays via beta emission to daughter ^{176}Hf (half-life = 37.1 billion years).

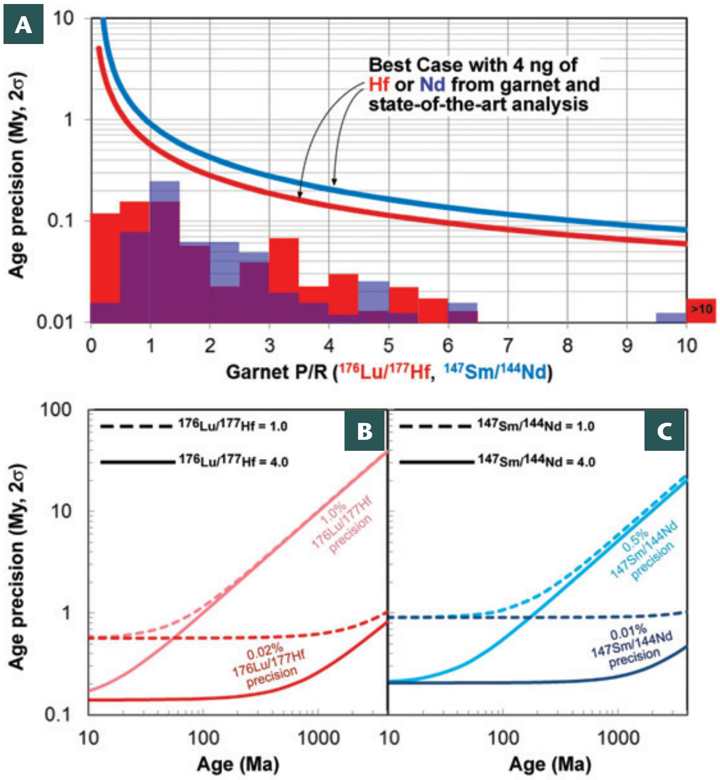

FIGURE 2 **Theoretical best-case precisions of Sm–Nd and Lu–Hf garnet dating.** Shown are two-point garnet-matrix isochron age precisions (blue = Sm–Nd, red = Lu–Hf), assuming best-case D/R analytical precisions of 10 and 35 ppm, respectively (2RSD) for 4 ng of Nd and Hf from garnet. The matrix is assumed to have ^{147}Sm/^{144}Nd = 0.12, ^{176}Lu/^{177}Hf = 0.02, and best-case D/R precisions of 2 ppm and 11 ppm (2RSD) for unlimited amounts of Nd and Hf, respectively. Actual sample complexities, the addition of points to the isochron, smaller samples, and laboratory- and instrument-specific analytical limitations can worsen precision. (**A**) Age precision versus garnet P/R. Precisions are modeled for an absolute age of 10 Ma. The histograms (linear vertical scale) indicate the range and relative frequency of ^{147}Sm/^{144}Nd (blue) and ^{176}Lu/^{176}Hf (red) values found in garnet from over a hundred samples prepared by the authors. Purple indicates overlapping histograms. (**B**) Lu–Hf and (**C**) Sm–Nd age precision versus absolute garnet age for different P/R values and analytical precisions.

D/R precisions of 10 ppm (2RSD) or better (e.g. 2 ppm; Caro et al. 2006) for hundreds of nanograms (ng) of Nd or Hf. In common practice, however, 10–40 mg samples of pure garnet yield only about 1–10 ng of Nd or Hf (or less; see below). Fortunately, recent improvements in NdO$^+$ analysis with a tantalum activator (e.g. Harvey and Baxter 2009) via thermal ionization mass spectrometry (TIMS) and Hf analysis via new-generation multicollector inductively coupled plasma mass spectrometry (MC–ICPMS) with improved cone designs and vacuum systems produce 10 ppm and 35 ppm 2RSD external precisions for 4 ng of Nd and Hf, respectively, opening the door to higher-resolution applications. Unfortunately, garnet lacks sufficient Nd or Hf for precise isotope measurements by today's microbeam methods, such as laser ablation inductively coupled plasma mass spectrometry (LA–ICPMS) or secondary ion mass spectrometry (SIMS). A large laser pit would yield only about a picogram of Hf or Nd. Figure 2a shows analytically feasible best-case precisions of two-point garnet-matrix isochron ages. When P/R is greater than ~1.0 for either Sm–Nd or Lu–Hf, better than 1.0 My precision is achievable. The analytical precision of D/R dominates the uncertainty in younger ages (Figs. 2b, c), whereas P/R uncertainties contribute more to the overall age uncertainty as isochrons steepen. Thus the advantage of higher P/R values in garnet diminishes with age as the solid and dashed curves in Figure 2b, c merge. The P/R values are derived from separate measurements of P and R concentrations by isotope dilution, and their quoted precisions are typically 0.1–1%, depending on the element pair (^{176}Lu/^{177}Hf is more challenging because Lu has only two isotopes, hindering precise isotope dilution analysis), though improvements towards 0.01% are emerging (e.g. for ^{147}Sm/^{144}Nd; Baxter and Inglis 2010).

ACCURACY OF GARNET AGES

Many natural phenomena can invalidate the isochron assumptions, compromising the accuracy of garnet dates. For example, the isotope composition of the matrix might be heterogeneous, or might evolve during protracted garnet growth creating uncertainty in the matrix composition with which garnet equilibrated (e.g. Thöni 2002; Romer and Xiao 2004; Pollington and Baxter 2010, 2011; Sousa et al. 2013). Local matrix heterogeneity should be evaluated with multiple analyses. Within the matrix, low-D/R phases such as zircon and monazite may sequester much of a rock's Hf and Nd, respectively, preventing full isotopic equilibrium between the matrix and the growing garnet (e.g. Scherer et al. 2000). Compared to other isotope systems, however, such effects on Sm–Nd and Lu–Hf are minor because only slight isotopic variation develops among low-P/R matrix minerals, with the exception of ancient inherited phases.

More insidious is the difficulty of separating garnet from its inclusions. The effects of monazite, apatite, and zircon inclusions on garnet dates are well documented (for reviews, see Scherer et al. 2000; Thöni 2002; Pollington and Baxter 2011) and vary according to the inclusions's age, P/R, and daughter-element concentration relative to those of garnet (Fig. 3a). Inclusions with very low daughter-element concentrations rarely affect garnet ages. Common low-P/R inclusions (e.g. Nd-rich monazite and Hf-rich zircon) with the *same age* as the garnet will merely pull the "garnet" down the isochron, degrading age precision but not accuracy. Inclusions having a *substantially different age* than the garnet displace "garnet" analyses along mixing vectors pointing away from the true garnet–matrix isochron, leading to loss of accuracy (Fig. 3). Such inclusions (or differently aged garnet) with higher P/R will pull "garnet" analyses along mixing vectors diverging even more sharply from the true isochron.

Even the most diligent handpicking *cannot* eliminate all inclusions, so two general strategies for minimizing their effects have evolved: (1) *dissolving inclusions* out of crushed garnet using acids (e.g. Anczkiewicz and Thirlwall 2003; Pollington and Baxter 2011) and (2) *dissolving garnet* with acids, leaving refractory inclusions intact (e.g. Lagos et al. 2007). The first method is useful for Sm–Nd because many minerals rich in rare earth elements (REEs), such as monazite, dissolve more readily than garnet, whereas the second technique is applied to Lu–Hf because Hf-rich minerals (e.g. zircon, rutile) are often more refractory than garnet. Specific parameters (e.g. acids, grain size, duration, temperature) often require tuning to recover the cleanest garnet while minimizing sample loss.

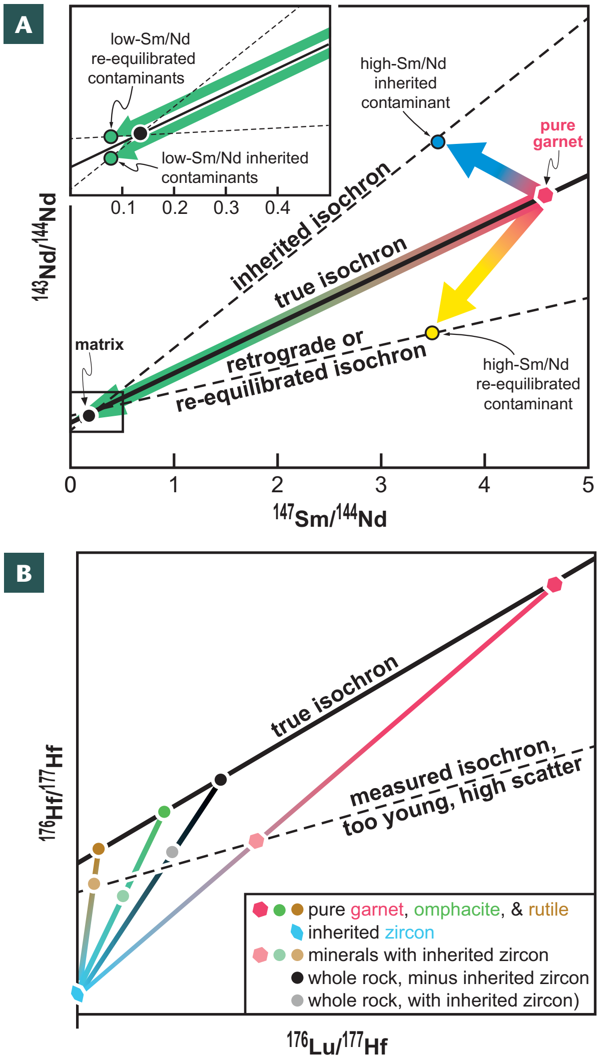

Figure 3 **The effects of included minerals on the age accuracy.** (**A**) Sm–Nd diagram showing the effects of contamination due to inclusions on measured garnet compositions (thick, colored arrows show contamination vectors). Most common inclusions have Sm/Nd near the matrix value, creating contamination along the green vectors close to the true isochron. Inclusion effects are most problematic when contaminated "garnet" has P/R < 1.0 (green vectors in inset) or if inclusions have unusually high Sm/Nd (blue or yellow vectors). Inclusions with ^{147}Sm/^{144}Nd greater than that of the matrix bias the contaminated garnet–matrix age *toward* the inclusion age; inclusions with ^{147}Sm/^{144}Nd less than that of the matrix (e.g. monazite) bias the contaminated garnet–matrix age *away* from the inclusion age. (**B**) Lu–Hf diagram showing the effects of old, inherited zircon included in minerals of an otherwise well-equilibrated eclogite; the measured compositions of those minerals are shifted downward along mixing lines (colored gradients), producing an erroneously young age and excessive scatter among samples, worsening the age precision.

How clean is clean enough? Two rules of thumb derive from our collective experience on over a hundred rocks from diverse environments. First, cleansed garnet yielding P/R > 1 is usually sufficient to eliminate significant effects from low P/D inclusions (FIG. 3A). Second, pure garnet exhibits low Nd and Hf concentrations, generally <0.5 ppm and often <0.1 ppm. Less than 10% of garnet separates prepared by the authors have >1 ppm Nd or Hf, and these exceptions seem restricted to high- to ultrahigh-temperature granulites and felsic magmatic settings. Garnet analyses with P/D < 1 and >1 ppm Nd or Hf are likely still contaminated by inclusions, the effects of which should be evaluated. Fortunately, modern cleansing methods can successfully mitigate contamination issues for Sm–Nd and Lu–Hf even in garnet that is riddled with inclusions (e.g. Anczkiewicz and Thirlwall 2003; Lagos et al. 2007; Dragovic et al. 2012).

INTERPRETATION OF "BULK" GARNET AGES

Most reported garnet ages are from bulk multigrain garnet analyses for which no attempt has been made to separate different garnet growth zones or generations. Because garnet crystals may grow slowly over millions of years, such "bulk garnet dates" fall somewhere within the garnet growth interval. Bulk dates may be precise, but this uncertainty does not define the duration of garnet growth. It is useful to ask, "What time within the total garnet growth interval does a given bulk age represent?" If mineral separation procedures do not accidentally fractionate different garnet generations (e.g. via magnetic separation; Lapen et al. 2003), the part of the growth interval represented by the bulk date can be determined from knowledge of parent isotope zonation in the garnet crystals. In the simplest case, where the parent isotope is homogeneously distributed within the garnet, the bulk date will represent a volume-averaged date for all concentric growth zones in the crystals. If, however, the parent isotope is strongly zoned from core to rim, then zones having the highest concentration of the parent isotope will make the largest contribution to the bulk date. Herein lies a crucial difference between the Lu–Hf and Sm–Nd systems: whereas Lu is often strongly zoned, sometimes with a Lu concentration 100 times higher in garnet cores than in rims, Sm tends to be relatively unzoned or shows increasing concentration towards the rim (Lapen et al. 2003; Skora et al. 2006; Cheng et al. 2008; Kohn 2009). Thus, bulk Lu–Hf garnet-growth dates are often older than bulk Sm–Nd dates from the same sample owing to such differences between Lu and Sm zonation. For garnet never heated above ~700 °C (where daughter-isotope diffusion becomes significant; see below), parent-isotope zonation is the dominant factor controlling offsets between bulk Lu–Hf and Sm–Nd ages. Furthermore, with careful analysis of Lu and Sm zoning in representative garnet crystals from a sample (e.g. via laser ablation) and some assumptions about the constancy of garnet growth rate, the observed difference between Lu–Hf and Sm–Nd dates can be modeled to constrain the *duration* of garnet growth (e.g. Lapen et al 2003; Skora et al. 2009). When multiple garnet preparations are analyzed for multipoint isochrons, a high MSWD may indicate that the preparations differ with respect to proportions of older core and younger rim material and that garnet growth was protracted or occurred in multiple events (e.g. Kohn 2009).

ZONED-GARNET GEOCHRONOLOGY: "TREE RINGS" OF CRUSTAL EVOLUTION

The previous discussion reminds us that a metamorphic garnet crystal may grow over several million years. If the concentric growth rings of a garnet can be likened to the pages of a history book, we are getting better at turning the pages a few at a time rather than reading only the title on the cover. A historian might ask, "When was the Hundred Years' War?" and hope for a better answer than "ca 1400 AD." A geologist might ask, "When did that garnet in FIGURE 4 grow?" and hope for a better answer than "25.5 ± 5.3 Ma (n = 13, MSWD = 270)," that is, the result of combining all 12 garnet analyses (from a single crystal!) with the matrix in an ill-advised multipoint isochron. In fact, the Hundred Years' War lasted from 1337 to 1453 and included periods of warfare interspersed with periods of peace, each driven by evolving sociopolitical conditions in England and France. The garnet crystal in FIGURE 4 grew over 7.5 million years, from 27.5 to 20.0 Ma, punctuated by two pulses of rapid growth related to evolving thermodynamic and tectonometamorphic conditions (e.g. Pollington and Baxter 2010). Although currently limited to relatively large single crystals (>5 mm diameter; Pollington and Baxter 2011), zoned-garnet geochronology can unveil a vast storehouse of information.

Zoned garnet... ...like tree rings!

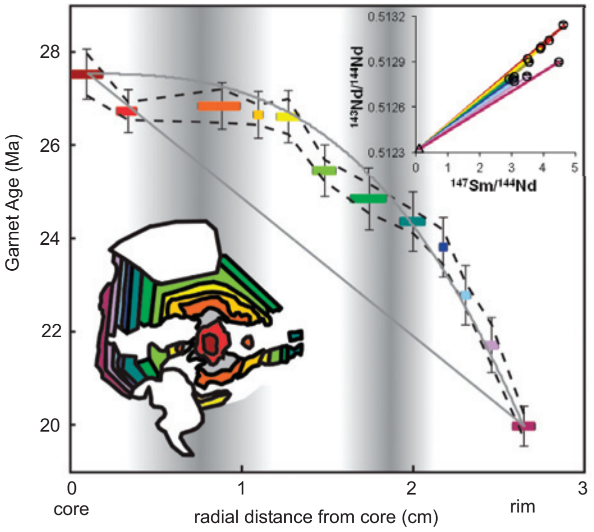

FIGURE 4 **Zoned-garnet geochronology.** (TOP, LEFT TO RIGHT: Location of chemically contoured concentric drill trenches, as pictured in the lower panel; cut tree trunk showing analogous concentric growth rings; Micromill device; concentrically zoned and microsampled garnet wafer 1 cm in diameter, in plan view and side view, shown with a diamond-encrusted drill bit used to cut annuli (multicolored) for analysis. BOTTOM: Age zonation in a 6 cm diameter garnet from Austria revealing two pulses of rapid growth (gray bars). Models of constant radial growth (straight grey line) and of constant volumetric growth (curved grey line) are shown. The inset diagram shows isochron data. DATA AND FIGURE ELEMENTS ARE FROM POLLINGTON AND BAXTER (2010, 2011).

In the late 1980s, several groups pioneered zoned-garnet geochronology (e.g. Cohen et al. 1988; Christensen et al. 1989; Vance and O'Nions 1990). Microdrill sampling (Ducea et al. 2003) provided higher spatial resolution and a means of separating concentric growth shells (rings in 2-D) defined by chemical zoning within a single garnet (Pollington and Baxter 2011). The different growth zones can be paired with the same representative matrix analysis to create an array of garnet–matrix isochrons revealing a high-resolution "tree ring" chronology of garnet growth (Fig. 4). The value of such high-resolution chronology transcends the garnet itself, as it may be directly linked to *P–T* evolution (Caddick and Kohn 2013 this issue), strain (e.g. Christensen et al. 1989), dehydration (Dragovic et al. 2012), or other related tectonic processes. Zoned-garnet geochronology can also resolve interpretive issues stemming from bulk garnet dates.

Several studies discuss preparatory and interpretive issues associated with zoned-garnet geochronology (e.g. Romer and Xiao 2004; Kohn 2009; Pollington and Baxter 2011). Comparison of "matrix" (without garnet) and "whole-rock" (including garnet) analyses can help evaluate how much garnet growth itself has fractionated the P/R in the residual matrix (generally insignificant for Sm–Nd where garnet Sm and Nd concentrations are both very low). Where open-system modification of the matrix is suspected (e.g. mobilization of REEs by fluids or anatectic melts) or when the local matrix is heterogeneous in D/R or P/R, zoned-garnet geochronology should be approached cautiously. Given that relatively uniform ^{147}Sm/^{144}Nd throughout a garnet crystal should yield equally precise ages from core to rim, the Sm–Nd system is well suited for high-resolution zoned-garnet geochronology. Depending on Nd concentration and inclusion density, a 1 cm diameter garnet crystal could yield between 3 and 11 high-precision (better than ±1 My) Sm–Nd dates from concentric growth zones (Fig. 4; Pollington and Baxter 2011).

DIFFUSIONAL RESETTING OF GARNET AGES

Many garnet crystals grow between 400 and ~700 °C (see Caddick and Kohn 2013), never reaching hotter conditions. At these temperatures (unless heating duration is extreme), primary growth ages should be well preserved in all but the tiniest grains and the outermost growth zones because diffusional modification will be insignificant (Fig. 5). For garnet subsequently heated above ~700 °C, "diffusive reopening" (Watson and Cherniak 2013) may partially reset ages. Because garnet is generally not completely reset at high temperatures before cooling, the traditional "closure temperature" concept rarely applies (Ganguly and Tirone 1999).

To illustrate how to model the extent of diffusional resetting of garnet ages, Figure 5 uses the data of Tirone et al. (2005) for Nd in garnet to address the following question: how long would a garnet need to reside at a given temperature for it to fully (i.e. >95%), or minimally (i.e. >5%), reequilibrate its Nd isotopes and reset its age? For example, a 5 mm crystal would have to be heated at 700°C for 360 My before its *bulk* age would be >95% reset, whereas a 1 mm diameter garnet would require only 14 My. The calculations in Figure 5 represent *minimum* resetting timescales because the data of Tirone et al. (2005) are the *fastest* published REE diffusivities. Changing the diffusivity (e.g. ~10× slower REE diffusivity, as reported in Carlson 2012) leads to a proportional change in the Sm–Nd-resetting timescale (e.g. ~10× longer timescale). Similarly, slower Hf^{4+} diffusivity (e.g. at least 10× slower than REE^{3+}; Kohn 2009; Bloch et al. 2010; Anczkiewicz et al. 2012; Smit et al. 2013) leads to timescales required for Lu–Hf age resetting at least an order of magnitude longer than for Sm–Nd. This is part of the reason why Lu–Hf dates tend to be older than Sm–Nd dates from granulite facies garnet. Even for crystals that have been significantly reset (e.g. Fig 5A, inset), preserved core-to-rim isotopic zonation can still prove valuable for reconstructing primary core-growth ages or thermal histories via diffusion modeling when applicable (e.g. Ganguly and Tirone 1999).

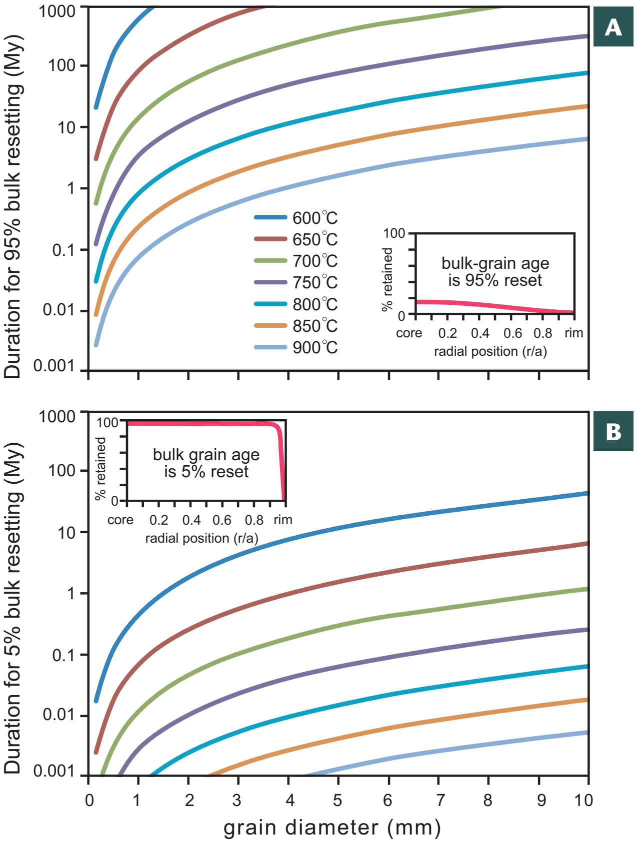

Figure 5 **Diffusional resetting as a function of grain radius, temperature, and heating duration.** The colored curves show the minimum duration of heating at specified temperatures required to reset the *bulk*-grain Sm–Nd age by (**A**) 95% or (**B**) only 5%. The inset diagrams show the intragrain radial pattern of diffusional age resetting for each case. The calculations use the fastest published REE diffusion data (Tirone et al. 2005). If slower diffusivities for the REEs (e.g. Carlson 2012) or Hf (e.g. Bloch et al. 2010) are used instead, the curves will shift proportionally higher towards longer durations for Sm–Nd and Lu–Hf, respectively.

Last, we emphasize the dominance of daughter-isotope diffusion (Nd or Hf, as described above) over parent-element diffusion (Sm or Lu) in affecting *bulk* garnet ages (Scherer et al. 2000). The isotopic compositions of Sm and Lu are essentially constant throughout the Earth, so there is nothing there for diffusion to reset. On the other hand, elemental diffusion of Sm relative to Nd or Lu relative to Hf could potentially change P/R and affect dating. This is moot for Sm and Nd whose diffusivities are similar. For Lu (relatively fast) and Hf (relatively slow), the Lu/Hf of garnet is largely controlled by equilibrium partitioning between the available matrix and the growing garnet (though kinetic factors may also play a role; Skora et al. 2006). Thus, changes in Lu/Hf due to diffusion into or out of the garnet will affect bulk garnet dates only if significant changes in (1) the relative partition coefficients of Lu and Hf or (2) the Lu/Hf of the available matrix have occurred since garnet growth. In contrast, diffusive redistribution of Lu *within* zoned garnet crystals *can* more readily affect the dates of individual growth zones.

CONCLUSIONS

Garnet crystals contain a "tree ring" chronology of tectonometamorphic processes potentially spanning millions of years. Moreover, garnet chronologies can be directly linked to specific conditions and processes relevant to the

Earth system (e.g. burial, exhumation, heating, cooling, deformation, subduction, continental collision, melting and magmatism, dehydration, fluid flow, ore mineralization). The Lu–Hf and Sm–Nd systems are powerfully complementary and may be interpreted together by the savvy geochronologist. Decay constant uncertainties and other sources of systematic error (e.g. Schoene et al. 2013) should be considered when comparing absolute Lu–Hf and Sm–Nd dates to each other or to other chronometers. Both systems require careful removal of inclusions, which is possible with modern techniques. For bulk garnet analyses, Lu–Hf dates can be older than Sm–Nd dates owing to differences in Lu and Sm zonation, and, in high-grade rocks, slower diffusion of Hf than of Nd.

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