Age trends in garnet-hosted monazite inclusions from upper amphibolite facies schist in the northern Grouse Creek Mountains, Utah

Thomas D. Hoisch a,*, Michael L. Wells b, Marty Grove c

a Department of Geology, Box 4099, Northern Arizona University, Flagstaff, AZ 86011, USA
b Department of Geoscience, University of Nevada Las Vegas, Las Vegas, NV 89154-4010, USA
c Department of Earth and Space Sciences and Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024, USA

Received 27 March 2008; accepted in revised form 13 August 2008

Abstract

We performed in situ Th–Pb dating of monazite in upper amphibolite facies pelitic schist from the Grouse Creek Mountains in northwest Utah. Sixty-six ages from inclusions in four garnet grains range from 37 to 72 Ma and decrease with radial distance from garnet cores. The age range of 30 matrix monazite grains overlaps and extends to younger ages than inclusions (25–58 Ma). The monazite grains are not intersected by cracks in the garnets, through which dissolution, reprecipitation or Pb loss might occur, and are generally too small (<20 μm) to allow for more than one age determination on any one grain. Processes that might explain inclusion ages that decrease with radial distance from garnet cores include: (1) Pb diffusion in monazite, (2) dissolution and reprecipitation of monazite, and (3) co-crystallization of monazite and garnet. After consideration of these possibilities, it is concluded that the co-crystallization of monazite and garnet is the most plausible, with monazite neoblasts deriving REEs from the breakdown of muscovite. Garnet ages derived by regression of the inclusion ages and assuming a constant rate of volume increase during garnet growth yield model ages with a maximum difference between core and rim of 22 m.y.

1. INTRODUCTION

U–Th–Pb age dating of monazite, a light rare earth element (LREE)-bearing phosphate, has become one of the primary tools for constraining the timing of moderate to high-grade metamorphism (e.g., Harrison et al., 2002); however, a number of interpretative difficulties persist. Monazite’s effectiveness as a geochronometer stems from its high retentivity for radiogenic Pb, and high Th and U concentrations coupled with low levels of common Pb (Harrison et al., 2002). Interpretation of its thermochronometric properties is hampered by conflicting experimental Pb diffusion studies and uncertainty regarding how well high-temperature properties can be extrapolated to lower temperature geologic conditions (e.g., Smith and Gilleti, 1997; Cherniak et al., 2004). In addition, monazite can be susceptible to dissolution and reprecipitation (e.g., Ayers et al., 1999; Townsend et al., 2001; Martin et al., 2007) and fluids may enhance the rate of Pb diffusion (e.g., Poitrasson et al., 1996). Mitigating against these difficulties, however, is the well-documented ability of garnet to shield monazite inclusions against Pb loss or dissolution (DeWolf et al., 1993; Poitrasson et al., 1996; Zhu et al., 1997a; Braun et al., 1998; Foster et al., 2000; Montel et al., 2000; Simpson et al., 2000; Stern and Berman, 2000; Terry et al., 2000).

Monazite is nearly ubiquitous in amphibolite-facies metapelites and understanding its petrogenesis is important to correctly interpret its geochronological significance. Monazite growth in pelitic schist normally occurs near the staurolite or Al2SiO5 isograds (e.g., Kingsbury et al., 1993; Ferry, 2000; Wing et al., 2003; Kohn and Malloy,
The garnet schists studied here are from the schist of Stevens Springs in Basin Creek canyon in the northern Grouse Creek Mountains, and are part of a sequence of alternating quartzite and psammitic, pelitic, and amphibolitic schists of Proterozoic age that unconformably overlie Archean basement (for a more complete description of the stratigraphy, see Compton, 1972; Wells, 1997; Wells et al., 1998; Hoisch et al., 2002). Prior studies in the Raft River–Albion–Grouse Creek core complex have unraveled a history of alternating shortening and extension during continued growth of the Sevier orogen (Wells, 1997; Hoisch et al., 2002). P–T paths from the schist of Stevens Spring in Basin Creek canyon detail an “N” shaped pressure–temperature path with the following sequence: isothermal burial, exhumation and heating, and renewed burial (Hoisch et al., 2002). The garnets with monazite inclusions analyzed in this study record the second period of burial (Hoisch et al., 2002). The metamorphic rocks of Basin Creek canyon lie within the Cenozoic extensional Middle Mountain shear zone, and below detachment faults, responsible for their most recent exhumation (Wells et al., 2000).

3. SAMPLE DESCRIPTION AND CONDITIONS OF METAMORPHISM

We analyzed monazite inclusions in five garnet crystals collected at the LH1 outcrop. Two of the garnet crystals are from rock sample LH1A; one is designated “lg” (large garnet) and the other “sg” (small garnet). LH1A-lg is subidioblastic with a diameter of ~5.4 mm; a portion of the grain was inadvertently truncated during sectioning, resulting in preservation of only about 60% of the original grain on the sample mount (Fig. 2). LH1A-sg is a heavily corroded grain with a long dimension of 3.6 mm (Fig. 2). Sample LH1A is cut from the same billet as the polished section analyzed by Hoisch et al. (2002) to determine a P–T path. Sample LH1A contains quartz (18%), staurolite (20%), muscovite (30%), biotite (10%), plagioclase (An3–7) (10%), garnet (5%), sillimanite (7%) and the accessory phases ilmenite, tourmaline, monazite, and zircon. Garnet growth took place via the reaction Quartz + Muscovite + Staurolite = Biotite + Garnet + Sillimanite + Albite + H2O (Table 1). Numerical simulations of the growth of two garnet grains using the Gibbs method based on Duhem’s theorem yielded rim-minus-core changes of +35 °C and +0.9 kbar, with growth beginning at ~600 °C (garnet-biotite thermometry) at an assumed pressure of 3.7 kbar (Hoisch et al., 2002). Because the albic compositions of the plagioclase (An4–7) and the Ca-poor compositions of the garnet (Xg < 0.049) yield unacceptably large propagated uncertainties for GASP geobarometry (Todd, 1998), the occurrence of sillimanite provides the most reliable pressure constraint (~3–5 kbar).

The three other garnet grains analyzed in this study were selected from eight that were collected at the base of a meter-high overhang at the LH1 outcrop, where they had weathered from the roof and fallen. Selection of three garnet grains (gm1e, gm1b, and gm3h) was made after mounting all eight in epoxy, cutting into polished sections, and then examining using back-scattered electron (BSE) images
Fig. 1. Location of the field area, geologic map of the Basin Creek area of the northern Grouse Creek Mountains (modified from Hoisch et al., 2002), and location of sample site LH1. Thick barbed line in top left inset shows leading edge of the Sevier thrust belt. Abbreviations: RR–AL–GC (Raft River–Albion–Grouse Creek ranges), Agc (Archaean Green Creek complex), Pe (Precambrian Elba quartzite), Pcb (Precambrian quartzite of Clark’s Basin), Pss (Precambrian schist of Steven’s Spring), Op (Ordovician Pogonip Group), Oe (Ordovician Eureka Quartzite), Ofh (Ordovician Fish Haven Dolomite), PPo (Pennsylvanian–Permian Oquirrh Formation), Pls (Permian limestone and sandstone), Tv (Tertiary Vipont granite), and Ts (Tertiary sedimentary rocks).

to identify those with the largest populations of monazite inclusions coupled with minimal fractures.

The schist of Stevens Springs in Basin Creek canyon exhibit well-defined shear bands that define a top-to-the-northwest transport direction parallel to a well-developed stretching lineation defined by elongate mica, quartz and strain shadows around garnets. Shear bands and strain shadows consist of quartz, muscovite, biotite, and sillimanite. Shear surfaces wrap around garnets (Fig. 2). Plagioclase with sillimanite inclusions grew inside pull-aparts (Fig. 2); because both are products of the garnet growth reaction, it is inferred that shearing initiated during the later stage of garnet growth. The shear fabric is associated with early Tertiary extension along the Middle Mountain shear zone (Saltzer and Hodges, 1988; Wells et al., 1997a). Garnet grains are generally large (~0.5–1.5 cm in diameter) and corroded. Inclusion trails of garnet are generally oblique to the matrix shear fabric and preserve an early fabric (Fig. 2). Matrix staurolite grains are generally idiomorphic to subidiomorphic; they overgrow the shear fabric and are variably rotated within it, which suggests growth during shearing and after garnet growth (Fig. 2). Staurolite is not stable in pelitic schist above the garnet-forming reaction (e.g., Spear and Cheney, 1989), so the matrix staurolite is interpreted to be retrograde. The observed corrosion of garnet within this assemblage (e.g., garnet LH1A-sg, Fig. 2) is an expected consequence of staurolite growing by retrograde reversal of the garnet growth reaction. The garnet grains analyzed that yielded paths of increasing pressures (Hoisch et al., 2002) are likely missing the portions of the rim that grew during extension due to retrograde corrosion.

The Middle Mountain shear zone in Basin Creek canyon experienced two periods of extensional shearing, the first in Middle to Late Eocene time and the second in Late Oligocene to early Miocene (Wells et al., 1997a; Wells et al., 2004). At deeper structural levels in the Archean orthogneiss, extensive subgrain-rotation recrystallization of K-feldspar, fast grain-boundary migration and dominant prism (a) slip in quartz suggest peak deformation temperatures >500 °C (FitzGerald and Stünitz, 1993; Stipp et al., 2002). Garnet grains exhibit striated surfaces and slightly lozenge-shape forms that are consistent with modification by combined shearing and retrograde garnet consumption.

4. METHODS

4.1. Sample characterization

We employed back-scattered electron (BSE) imaging and energy dispersive (EDS) X-ray analysis to identify monazite included in garnet and in matrix. High resolution BSE mosaics of the materials analyzed are shown in Electronic annexes EA-1–EA-4. On the BSE images, zircon,
Table 1

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Using garnet rim$^a$</th>
<th>Using garnet core$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muscovite$^c$</td>
<td>−0.2100</td>
<td>−0.8190</td>
</tr>
<tr>
<td>Biotite$^c$</td>
<td>0.1491</td>
<td>0.4881</td>
</tr>
<tr>
<td>Staurolite$^d$</td>
<td>−0.8682</td>
<td>−0.9984</td>
</tr>
<tr>
<td>Garnet$^e$</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>Sillimanite$^f$</td>
<td>7.1053</td>
<td>8.788</td>
</tr>
<tr>
<td>Plagioclase$^g$</td>
<td>0.0462</td>
<td>0.1848</td>
</tr>
<tr>
<td>Ilmenite$^h$</td>
<td>0.1069</td>
<td>0.1735</td>
</tr>
<tr>
<td>Quartz$^h$</td>
<td>−3.479</td>
<td>−3.634</td>
</tr>
<tr>
<td>H$_2$O$^h$</td>
<td>1.409</td>
<td>1.977</td>
</tr>
</tbody>
</table>

$^a$ Residuals: SiO$_2$ = 0.000, Al$_2$O$_3$ = 0.000, TiO$_2$ = 0.0144, FeO = −0.0144, MnO = 0.1549, MgO = 0.02764, CaO = 0.03160, Na$_2$O = −0.0013, K$_2$O = −0.0285, H$_2$O = 0.0194.

$^b$ Residuals: SiO$_2$ = 0.000, Al$_2$O$_3$ = 0.000, TiO$_2$ = −0.0861, FeO = −0.0861, MnO = 0.3755, MgO = 0.1706, CaO = 0.0619, Na$_2$O = −0.0017, K$_2$O = −0.1755, H$_2$O = 0.1181.

$^c$ Mineral composition from Hoisch et al. (2002).

$^d$ Staurolite composition determined by electron microprobe and normalized to 48 oxygens after assuming 3.06H in the formula (Holdaway et al., 1986): K$_{0.000}$Ca$_{0.003}$Mg$_{0.479}$Fe$_{3.210}$Mn$_{0.011}$Ti$_{0.118}$Al$_{1.300}$Si$_{5.474}$O$_{13.048}$OH$_{0.06}$.

$^e$ Rim composition is from Hoisch et al. (2002). Core composition determined by electron microprobe and normalized to 12 oxygens: MgO$_{0.283}$Fe$_{2.279}$Mn$_{0.385}$Ca$_{0.053}$Al$_{2.002}$Si$_{2.998}$O$_{12}$.

$^f$ Assumed to be stoichiometric Al$_2$SiO$_5$.

$^g$ Assumed to be stoichiometric FeTiO$_3$.

$^h$ Assumed to be stoichiometric SiO$_2$.

monazite and ilmenite appear much brighter than garnet due to their much higher average atomic numbers. We performed EDS analysis to distinguish monazite from zircon and ilmenite. In addition, the major element chemistry of a subset of the dated monazite grains in sample LH1A was determined using the Cameca MBX at Northern Arizona University (Electronic annex EA-5). Run conditions were a 20 nA beam current and a spot size of 1 µm. To perform analyses on the ion microprobe, selected areas were extracted from the polished slides using either a diamond wafering saw or diamond drill core and potted in epoxy together with pre-polished grains of monazite standard 554 (Harrison et al., 1999).

4.2. Th–Pb analysis

Monazite Th–Pb analyses were performed using the Cameca ims 1270 ion microprobe at UCLA. Dating of monazite was carried out during two sessions, heretofore referred to as the first and second runs. In the first run, 43 garnet-hosted monazite inclusions were analyzed from three garnet grains (gm1b, gm1e and gm3h). In the second run, monazite grains were analyzed in sample LH1A, 27 inclusions in the two garnets (“sg” and “lg”) and 30 from the matrix. Analytical procedures used for the Th–Pb monazite analysis have been previously reported (Harrison et al., 1995; Harrison et al., 1999; Kohn and Malloy, 2004). The propagation of internal errors was performed as described in Appendix A.

The principal advantage of the Th–Pb method over the U–Pb system is that Th concentrations in monazite are typically very high. In the current study, they ranged from 2.5 to 8.4 weight percent based upon electron microprobe analysis (after converting weight percents in Table EA-5 to elemental percents). High Th concentration results in better precision and higher levels of radiogenic $^{206}$Pb$^*$ relative to that obtainable in U–Pb analysis for monazites of equivalent age. As described below, use of the Th–Pb decay scheme was particularly important to this study because of the challenging analytical conditions we encountered when attempting to analyze small inclusions. Moreover, given the analytical protocols we employed, the low ($~130$ ppm) concentration of U in standard monazite 554 (45.3 ± 1.4 Ma, 2σ error; Harrison et al., 1999) did not permit us to adequately standardize the data to calculate U–Pb ages. Under more favorable circumstances, however, simultaneous exploitation of both systems can be highly advantageous (e.g., Stern and Berman, 2000; Martin et al., 2007).

There are four factors that could have potentially impacted the reliability of our analyses: charging, matrix effects, poor radiogenic yield, and unresolved interferences at $^{207}$Pb. The least serious of these relates to charging. Differences in charge build up at different analysis sites were compensated by measuring the energy distribution during the pre-sputtering interval prior to each analysis and applying the voltage offset determined from this procedure to the accelerating potential used to perform the analysis. Generally, the variation in this offset was less than 5 volts. Potentially more serious are matrix effects in monazite (i.e., changes in instrumental mass fractionation related specifically to differences in composition) that have been described in the U–Th–Pb analysis of monazite (Stern and Sanborn, 1998). The influence of matrix effects on monazite Th–Pb analysis remains poorly understood, but likely introduces some amount of additional error. Results of standard intercomparison studies at UCLA indicate that matrix effects are capable of producing errors in ion microprobe Th–Pb ages of up to ±10% relative to standard 554. The diameter of the primary ion beam employed in this study was ~15 µm. We were unable to focus the beam to a smaller diameter without sacrificing most of the primary beam intensity. Because many of the monazite grains analyzed in this study were smaller than 15 µm (see Electronic annexes EA-6 and EA-7), we employed alternative procedures to avoid analyzing the host mineral sputtered along the margins of monazite grains. Because we operate the instrument in ion microscope mode, we were able to crop the secondary beam to reduce the effective beam size. Ion microscope mode allows for an undistorted image of the sputter pit to be recovered at various focal points within the instrument, including the detector plane. In this mode, a mechanical aperture, referred to as the field aperture, is used to block signal derived from the periphery of the sputter pit. Using the field aperture, the beam emerging from the sputter pit was reduced to approximately a 10 µm square. Even at this reduced size, many monazite grains in the unknowns still did not entirely fill the area. Reducing the size of the field aperture impacts the stability of the Th/Pb calibration due to progressively greater difficulty in centering all ion beams (mass 204–264) within the field aperture. Hence reducing the dimensions of the aperture...
further would have overly degraded the analysis and further limited signal reaching the detector.

Our use of a 10 μm field aperture in analyzing both unknowns and standards adversely impacted our ability to constrain Pb/Th relative sensitivity factors. The scatter observed for our calibrations exceeds that reported in other studies that used standard 554 with a wider field aperture (e.g., Harrison et al., 1999; Catlos et al., 2002). During the first run, monazite standard 554 was analyzed 50 times (Fig. 3a). Treating the standard analyses as unknowns yielded an average age of 44.95 ± 3.47 Ma (1 s.d.), consistent with the average error of ±3.25 Ma (1σ) determined by averaging the internal errors calculated for each standard analysis. Standard 554 was analyzed 26 times throughout the second run (Fig. 3b). Treating the standard analyses as unknowns yielded an average age of 45.80 ± 3.80 Ma (1 s.d.), consistent with the average error of ±3.48 Ma (1σ) determined by averaging the internal errors calculated for each standard analysis. In both runs, the mean age of standard 554 was consistent within error with the known 45.3 Ma age of the standard (Harrison et al., 1995).

A third problem we encountered relates to uncertainties in the correction of measured 208Pb for common Pb. Overlap of the beam into regions outside of the area of the targeted monazite grains resulted in uncharacteristically high levels of common Pb, especially for matrix grains (Tables EA-6, EA-7, and EA-8). It appears most likely that the majority of the common Pb was derived from grain boundary regions. Possible sources for common Pb include minerals other than monazite that were within the field aperture (e.g., quartz, muscovite, biotite, and staurolite), common Pb adsorbed onto grain surfaces, and common Pb contained in epoxy along cracks. The gold coat is an unlikely source for common Pb because it is removed in the presputtering stage prior to analysis. We regarded analyses characterized by less than 50% radiogenic 208Pb (hereafter referred to as 208Pb*) as problematic and culled them from the data set.

Finally, there is a potential isobaric interference that can affect Th–Pb age determinations particularly for high Th monazite (Stern and Berman, 2000). The interference causes 208Pb to be overestimated and thus causes the Th–Pb age to be reported too young after correction for common Pb. The importance of the interference may be revealed on a plot of age versus percent 208Pb* (Fig. 4), analogous to the approach used by Stern and Berman (2000). For 208Pb* values >50%, there is essentially no correlation.

The dating of monazite grains intersected by cracks in garnet was largely avoided because these have been shown to be susceptible to partial dissolution, reprecipitation and Pb loss (e.g., DeWolf et al., 1993; Zhu et al., 1997b; Martin et al., 2007). The only exception was monazite grain LH1A-lg-2 (see Fig. EA-4).

4.3. Estimating core locations in garnets

In order to provide an independent qualitative measure of age relative to radial position within individual garnets, growth zoning was evaluated using major element maps
(Fig. 5). The maps were useful in determining the core locations on three of the four garnets (gm1e, gm1b and gm3h). For gm1e, the Ca-map displays growth zoning that provides a good basis for defining the core location. The Mn growth zoning is modified by secondary reequilibration along the corroded rim, making it less useful for ascertaining the core location. For gm1b, all four maps display growth-related zoning except along the lower left edge, which is corroded and displays secondary reequilibration. The Ca and Mg maps are preferred because the zoning close to the center is not as flat as the Mn and Fe maps. For gm3h, Ca and Mg maps display growth zoning and provide a good basis for estimating the core location. Similar to gm1e, Mn zoning is modified by secondary reequilibration along the corroded rim, which makes it less useful for ascertaining the core location. Interior cracks also display secondary reequilibration.

For garnet LH1A-lg, none of the maps (Ca, Mg, and Mn) provide a basis for defining the core (Fig. 5). All three display retrograde reequilibration around a cluster of quartz inclusions in the interior that obscure the zoning near the core. The core location of LH1A-lg was inferred from the idioblastic shape to be the point with the most consistent radius to the rim (Fig. 5). Garnets gm1e, gm1b, and gm3h are too corroded to permit this approach. On garnet LH1A-sg, all four maps display a zoning pattern that conforms to the heavily embayed rim and large quartz inclusion; no vestige of growth zoning is preserved. Because neither the morphology nor chemical zoning of LH1A-sg provide a basis for determining the core location, it was not determined.

### 4.4. Monazite grain characteristics

Most of the monazite grains we analyzed exhibited smooth ovoid to slightly pear-shaped or dumbbell-shaped grain outlines with long dimensions of 9–28 μm and short dimensions of 6–20 μm (Tables EA-6 and EA-7). Chemically distinct domains potentially of different ages are commonly observed in BSE images and maps of Y and Th concentrations (e.g., Spear and Pyle, 2002; Gibson et al., 2004). However, it has been shown that chemically distinct domains are not always of different ages (e.g., Williams et al., 1999). In this study, BSE images and Y and Th maps were generated on four monazite grains from garnet gm1e (Fig. 6). Three of the four grains exhibit noticeable variations in BSE grey level as well as heterogeneity in Y and Th; however, distinct domains are not apparent. The grains are too small for different areas within single grains to be dated, so the question of whether single grains possess multiple age domains is not resolved.

### 5. TH–PB AGES OF MONAZITE

Thorium–lead ages of the 72 garnet-hosted monazite inclusions range from 72.2 ± 3.7 to 34.7 ± 4.2 Ma (±1σ; Electronic annexes EA-6 and EA-8), and average 52.3 Ma (weighted by the inverse squares of the internal errors) with an MSWD of 6.9. The high MSWD value indicates that the age variation greatly exceeds that of a single homogeneous population that is defined by internal errors (e.g., Wendt and Carl, 1991). The inclusion ages are represented on a histogram in Fig. 7, which displays a unimodal negatively skewed probability density distribution with a peak at about 56 Ma. There are no indications in the age distribution of multiple distinct age populations. Rather, the data appear to represent a continuous range of ages.

A histogram of the 30 matrix monazite ages from LH1A displays an apparently bimodal probability density distribution (Fig. 7). Ages range from 58.4 ± 7.5 to 25.2 ± 2.1 Ma and average 36.2 Ma (weighted by the in-
verse squares of the internal errors) with an MSWD value of 9.1. Matrix grains consist of inclusions in plagioclase rims, staurolite, and grains in shear bands (Table EA-7). The ages of three inclusions in staurolite range from 35.0 ± 2.9 to 44.6 ± 2.6 Ma (1σ), three in plagioclase range from 46.5 ± 3.2 to 47.0 ± 3.9 Ma, and 27 in shear bands range from 25.2 ± 2.1 to 58.4 ± 7.5 Ma. Monazite in shear bands and monazite inclusions in staurolite show broad age ranges that overlap the age range of garnet-hosted inclusions at the high end and extend to ages below garnet-hosted inclusions at the low end. The age range for plagioclase-hosted inclusions is narrow and is encompassed by the range for garnet inclusions.

Within each garnet, ages generally decrease with distance from the core, as shown in plots of age versus radial distance cubed (Fig. 8). A plot of garnet moles produced versus temperature in the growth simulation of garnet from LH1A (Hoisch et al., 2002) shows that the garnet grew at a nearly constant rate of increasing moles when a constant rate of temperature increase is assumed (Fig. 9). Analogously, the value of radius cubed ($r^3$) also increases at a nearly constant rate. Thus, if garnet grew with a constant rate of volume increase, ages plotted versus $r^3$ should fall along a straight line. In the discussion that follows, a constant rate of volume increase is assumed for the purposes of exploring the age trends, recognizing that some conclusions drawn from the regressions are sensitive to this assumption.

In all four cases, the regressions show decreasing ages with increasing $r^3$ (Fig. 8). If the ages were randomly distributed throughout the garnet grains, the regressions should yield either a horizontal line or a gently sloping line that would have an equal chance of sloping toward increasing or decreasing values of $r^3$. Because there are 16 possible arrangements of slopes, the chances that all four would accidentally slope in one direction, as observed, is 6.25% (=0.54). By this argument, there is a 94% chance that the ages are not randomly distributed within the garnet grains, but reflect trends of decreasing ages toward the rims. Different assumptions concerning the rate of garnet growth (e.g., plotting ages versus $r$ rather than $r^3$) yield the same conclusion. Nevertheless, three of the four regressions yielded
MSWD values >2, indicating that the scatter of data about the regressions is much larger than can be explained by the internal errors calculated for each age determination (Fig. 8). Similarly high MSWD values are also calculated when ages are plotted versus \( r \), indicating that the high values are not sensitive to assumptions regarding garnet growth rate. For the plots of age versus \( r^3 \), the additional error added in quadrature to the internal error required to lower the MSWD value to the expected value of 1.0 is calculated to be ±4.20 Ma (gm1e), ±3.92 Ma (gm1b), and ±5.85 Ma (LH1-lg). The source of this additional uncertainty is unknown.

Subject to the correctness of the underlying assumptions, the regressions may be interpreted to represent the core-to-rim ages of the garnet hosts. Calculated \( y \)-intercepts represent the core ages and range from 56.89 ± 5.64 to 64.37 ± 4.95 Ma (95% confidence level). The model core ages overlap at the 95% confidence level, consistent with the initiation of garnet growth at approximately the same time. Although the model core ages are fairly consistent, the model rim ages are not, which is expected due to the fact that the garnets are variably resorbed. The maximum difference between core and rim model ages within a single garnet is ~22 m.y., where the rim age is calculated at the radius.
corresponding to the location of the analyzed monazite inclusion most distant from the core (LH1A-lg and gm1e, Fig. 8).

To show what the hypothesized age distribution should look like, a Monte Carlo simulation was run. In the simulation, a sphere is divided into 100 increments of equal radius. The age of the core and rim are specified and the age of the center of each increment is calculated assuming growth of the sphere at a constant rate of volume increase. The number of age determinations contained in each increment is calculated based on the relative volume of each increment and an assumed total of 10,000 determinations. A Monte Carlo simulation is run for each increment assuming a normal distribution defined by an assumed age uncertainty. The results are then grouped into five larger increments of equal radius so that the age distribution may be represented on a histogram. The calculated age distribution for two cases is shown in Fig. 10, one assuming age uncertainties equal to ±3.48 Ma (the average internal errors calculated for the standards in the second run), and one assuming ±5.23 Ma, which represents an additional ±3.90 Ma uncertainty added in quadrature. Both cases yield unimodal negatively skewed distributions, similar to the observed probability density distribution of inclusion ages (Fig. 7). The skewness results from the assumption of a constant rate of volume increase combined with analysis on a 2-d section. On a 2-d section, the area encompassed by a given radius is proportionally larger than the volume. For instance, the area of a 2-d section encompassed by a radius of 0.5r is 0.25 of the total area, but only 0.125 of the total volume.

Different underlying assumptions of garnet growth systematics lead to different extrapolated core and rim ages. Regressions that assume a constant radial growth rate lead to significantly higher extrapolated core ages than regressions that assume a constant rate of volume increase, which underscores the influence of the assumptions made regarding garnet growth systematics on the interpretation of ages. In the discussion that follows, we examine possible mechanisms that could result in monazite inclusion ages decreasing radially outward in a garnet host.

6. DISCUSSION

6.1. Hypotheses to explain age trends in monazite inclusions

There are several processes that might explain inclusion ages that decrease radially outward in the host: (1) time and temperature-dependent diffusion of radiogenic Pb in monazite, (2) fluid-mediated recrystallization of monazite grains, and (3) mineral reactions that might co-crystallize monazite and garnet. The role that each of these might have played is discussed below. An additional consideration in the interpretation of age trends is the possibility that individual monazite grains comprise mixtures of multiple age domains. Age trends among the garnet-hosted inclusions could be the product of systematic variation in the proportion of different age domains, with older domains dominating in the garnet cores, decreasing in proportion outward toward the rims. It is, however, difficult to conceive of a process that could produce this result. If, prior to occlusion by garnet, monazite grains in the matrix comprised mixtures of multiple age domains, the variations in proportions that would exist among them would not be systematic with respect to growing garnet nuclei. This process is rejected as a viable explanation and will not be considered further.

Fig. 10. Monte Carlo simulations of inclusion age distributions that assume continuously decreasing ages from 60 Ma in the core to 38 Ma at the rim. The different grey levels distinguish ages from five increments of equal radius, with white representing the core increment. See text for details of the simulations. (a) An age uncertainty of ±5.23 (1σ) is assumed. (b) An age uncertainty of ±3.90 (1σ) is assumed.
Relevant to the consideration of these possibilities is the chemistry of the monazite grains, in particular Y and Th (Table EA-5). Yttrium has been shown in a number of studies to be indicative of the timing of monazite growth relative to garnet (e.g., Pyle and Spear, 1999). Because Y is sequestered by garnet, monazite grains that grew prior to garnet tend to contain higher concentrations of Y relative to those that grew after garnet. In this study, Y concentrations do not vary systematically with radial distance from the garnet core, nor is there a systematic difference between matrix and inclusion monazite grains. Similar to Y, Th concentrations determined for grains in this study also do not vary systematically, which suggests that both Y and Th concentrations were controlled by the availability of these elements in the microdomains surrounding each monazite grain during growth. In addition, neither Y nor Th varies systematically with age. Consequently, Y and Th reveal little about the possible causes of the observed age trends. There is, however, a crude correlation between U/Th, determined by the ion probe, and the calculated age (Fig. 11). Lower values of U/Th correspond to younger ages. One possible explanation is a tendency of Th to fractionate preferentially into monazite compared to U. This would progressively deplete each microdomain in Th relative to U, causing younger monazite grains nucleating within the microdomains to possess larger values of U/Th.

6.1.1. Pb diffusion

Pb diffusivity in monazite has been investigated experimentally (Smith and Gilleti, 1997; Cherniak et al., 2004; Gardés et al., 2006, 2007). Smith and Gilleti (1997) imply that Pb diffusion is sufficiently rapid at 600 °C, the temperature at which garnets in this study began growth (Hoisch et al., 2002), to maintain isotopic equilibrium between small monazite grains and the matrix. For example, a monazite grain of 6 μm radius would be expected to retain only 0.23% of its Pb after 10 m.y. at 600 °C. Smith and Gilleti’s results are highly compatible with electron probe-determined U–Th–Pb age gradients measured by Suzuki et al. (1994) across 1.7 Ga detrital monazite grains that underwent upper amphibolite facies metamorphism at ~100 Ma. If the Pb diffusivities predicted by down temperature extrapolation of the Smith and Gilleti (1997) Arrhenius data are correct, then Pb diffusion provides a viable explanation for the observed age trends in our samples. Specifically, monazite grains would maintain isotopic equilibrium with the matrix until occluded by garnet, which would armor them against further Pb loss. Th–Pb ages of garnet-hosted monazite inclusions would record the timing of occlusion and thus date garnet growth, assuming that garnet shields the inclusions from further Pb loss. Matrix monazite grains would continue to lose radiogenic Pb until the rocks cooled below the closure temperature for Pb diffusion.

There is a significant body of data, however, that argues against appreciable Pb diffusion in monazite during amphibolite facies metamorphism. Experimental Pb diffusivities determined by Cherniak et al. (2004) and Gardés et al. (2006, 2007) are consistent with the reported preservation of precursor monazite ages in granitic rocks (Copeland et al., 1988; Kingsbury et al., 1993; Harrison et al., 1995) and through overprinting granulite facies metamorphism (Parrish, 1990; Spear and Parrish, 1996; Bingen and van Breeemen, 1998; Braun et al., 1998; Montel et al., 2000; Rubatto et al., 2001; Bosch et al., 2002). Sluggish rates of Pb diffusion also are suggested by the preservation of sharp compositional boundaries for Pb and for trace and REE elements within individual monazite grains from high-grade metamorphic rocks (DeWolf et al., 1993; Montel et al., 1996; Zhu et al., 1997a; Braun et al., 1998; Cocherie et al., 1998; Crowley and Ghent, 1999; Zhu and O’Nions, 1999a; McFarlane and Harrison, 2006).

Finally, there are a number of factors that suggest that rapid rates of Pb diffusion do not adequately explain some aspects of the dataset in the present study. If Pb diffusion according to Smith and Gilleti (1997) was the controlling factor in producing the observed age trends, then larger grains should be more retentive of Pb and record older ages than smaller grains occluded at the same radial distance (at the same time) in a given garnet. Inspection of LH1A-lg inclusions data (Table EA-6) shows that this is not the case. In addition, several of the smaller grains in shear bands (e.g., mx-10, mx-18, and mx-25, see Table EA-7) preserve ages significantly older than many larger inclusions in garnet LH1A-lg (see Table EA-6), which is contradictory to rapid Pb diffusion.

It is clear that all of the observations in previous studies that pertain to the question of Pb diffusion in monazite cannot be resolved with a single set of Arrhenius parameters. One possible resolution is to accept the Arrhenius parameters determined by Cherniak et al. (2004) and the similar results of Gardés et al. (2006, 2007) and to regard deviations as resulting from fluid-mediated diffusion and/or recrystallization. Braun et al. (1998) attributed young ages along a crack within a large older monazite grain to Pb diffusion activated by fluids. Similarly, Poitrasson et al. (1996) found
zones containing common Pb up to 40 μm wide within monazite grains, and attributed them to low temperature (200 ± 30 °C in one sample and 284 ± 16 °C in a second sample) hydrothermal activity.

6.1.2. Dissolution and reprecipitation of monazite

The observed age trends in this study might possibly be explained as resulting entirely from rapid dissolution and reprecipitation operating in the rocks prior to and during garnet growth. This would have an effect similar to exceeding the closure temperature for Pb diffusion, that is, grains would maintain isotopic equilibrium with the matrix through continual recycling and undergo closure when occluded by garnet. Shielded from further recrystallization, the Th–Pb ages of inclusions would reflect the timing of garnet growth. Grains remaining in the matrix would continue to recrystallize and reset isotopically as long as dissolution and reprecipitation remained active, and as long as the garnet host remains intact around each inclusion. When cracks in a garnet intersect a monazite inclusion, partial dissolution, reprecipitation and Pb loss may occur in situ (DeWolf et al., 1993; Zhu et al., 1997b; Montel et al., 2000; Martin et al., 2007); however, only one of the monazite inclusions analyzed in this study was observed to be intersected by cracks.

A number of studies have documented secondary or retrograde monazite growth associated with dissolution and reprecipitation (DeWolf et al., 1993; Fitzsimons et al., 1997; Terry et al., 2000; Bosch et al., 2002; Martin et al., 2007). Features such as patchy zoning, internal veining, and overgrowths have been interpreted as evidence of dissolution and reprecipitation in monazite (e.g., Bingen and van Breemen, 1998; Ayers et al., 1999; Hawkins and Bowring, 1999; Townsend et al., 2001; Bosch et al., 2002; Pyle and Spear, 2003). Within single garnet grains in granulite facies rocks, DeWolf et al. (1993) and Zhu et al. (1997b) obtained younger ages from monazite inclusions that were located near fractures in the garnet hosts, suggesting that Pb loss resulted from fluid interaction. Martin et al. (2007), by comparing Th–Pb with U–Pb ages in upper amphibolite facies rocks, in combination with chemical and textural characterization of monazite, found that Pb loss and dissolution/reprecipitation of monazite intersected by cracks in garnet was common, leading to discordant ages, commonly of no geological significance. The relationships they documented also occurred in monazite not intersected by visible cracks, suggesting the presence of microcracks or three-dimensional geometries not apparent with conventional optical techniques. Nevertheless, studies documenting fluid-assisted dissolution/precipitation and Pb loss in garnet-hosted monazite inclusions have not found correlations between the ages of inclusions intersected by garnet cracks with radial distance from the garnet cores, as found in this study.

Several factors argue against in situ dissolution and reprecipitation of monazite inclusions via cracks in the garnet grains of the present study. Of all the monazite grains dated, only one is visibly intersected by a crack, LHIA-lg-2; however, the age obtained for this grain is not anomalous with respect its location within garnet LHIA-lg. In addition, the generally low crack density of the garnet grains that host the analyzed inclusions (Figs. EA-1–EA-4) combined with the very small size of the inclusions makes it unlikely that inclusions were intersected by cracks above or below the plane of the polished surface. Retrograde fluid-mediated chemical reequilibration of major elements in garnet was observed along some cracks in gm3h and along the margins of quartz inclusions in LHIA-lg (Figs. 5, EA-3 and EA-5); however, ages obtained from monazite grains within the reequilibrated zones (e.g., gm3h-8, LHIA-lg-6 and LHIA-lg-9) did not yield anomalous ages, suggesting that retrograde diffusion of major element cations in garnet was not accompanied by alteration of the monazite inclusions.

Fluid-mediated recrystallization, however, is a reasonable explanation for matrix monazite ages that are younger than inclusions in garnet. Matrix grains, unshielded by their hosts, may have been reset to varying degrees by fluids emanating from the 28.3 ± 0.7 Ma Vipont intrusion (Compton et al., 1977; Wells et al., 1997b; Strickland et al., 2007), a granitic sill complex that increases in volume to the north (Fig. 1). In the Basin Creek canyon area, sills of Vipont granite are rare, whereas 9 km to the north abundant lit-par-lit injections, with lesser dikes, in metamorphic country rock grade downward into a sheet-like pluton of thickness greater than 200 m. Ages of 29.6 ± 0.3 Ma on monazite from the Archean basement (Strickland et al., 2007) may reflect mobilization (dissolution and reprecipitation) of monazite or Pb diffusion activated by fluids emanating from the Vipont granite. If these processes affected sample site LH1, it could explain the younger ages obtained from matrix monazite grains.

6.1.3. Co-crystallization of monazite and garnet

Monazite grains growing synchronously with garnet provide a possible mechanism for explaining the age trends (DeWolf et al., 1993; Foster et al., 2000; Harrison et al., 2002). Most monazite growth reactions that have been proposed for pelitic schist involve a REE-rich reactant phase, such as xenotime or allanite (e.g., Smith and Barreiro, 1990; Kingsbury et al., 1993; Catlos et al., 2002; Pyle and Spear, 2003; Wing et al., 2003), but most of these do not involve the production of garnet. It has also been proposed that monazite may grow in pelitic schist in the absence of a REE-rich reactant by deriving REEs and P from the breakdown of major phases where they are held in trace abundances (Franz et al., 1996; Kohn and Malloy, 2004).

Rocks in the present study lack REE-rich precursors as inclusions or as relics in the matrix; however, whether they existed at grades below the monazite-producing reaction horizon does not crop out at a lower metamorphic grade. In both this study and the study of Kohn and Malloy (2004), REEs may have been derived from the breakdown of muscovite, but the source of P is uncertain due to the lack of observed apatite. In pelitic schist, muscovite may host REE concentrations more than 100 times average chondrite values (Grauch, 1989). Both garnet and plagioclase may host trace quantities of P (Kohn and Malloy, 2004), but neither could supply P for monazite growth during the staurolite breakdown reaction (this study) because
both are products of this reaction. The participation of apatite, which may have completely reacted out, or some other P source, cannot be ruled out.

Because garnet and albite are both products of the garnet growth reaction, it may explain why monazite ages obtained from plagioclase rims record ages similar to garnet inclusions (Tables EA-6 and EA-7). Two of the three ages obtained from inclusions in staurolite are younger than any inclusion in garnet or plagioclase, which is consistent with the retrograde (younger) crystallization of staurolite. The broad range of ages found in the matrix may stem from the combined effects of monazite growth in the matrix coinciding with garnet growth, followed by the release of some grains into the matrix from garnet and plagioclase during retrograde porphyroblast consumption and shearing, and variable resetting due to dissolution and reprecipitation or fluid-activated Pb diffusion associated with the ~28 Ma Vipont intrusion. No monazite ages are as young as the 22 Ma 40Ar/39Ar muscovite cooling ages in the area (Wells et al., 1997b), indicating that resetting of monazite occurred while temperatures were higher than ~350 °C. This mechanism also provides an explanation for a few anomalously old inclusion ages obtained from monazite grains located near garnet rims (e.g., gm1e-8, LH1A-lg-20, LH1A-lg-27). If monazite grains were nucleating in the matrix at the same time as they were nucleating along garnet rims, some older matrix grains would likely become occluded during garnet growth. This is one possible source of the scatter in the regressions.

6.2. Controls on synchronous crystallization of monazite and garnet in pelitic schist

Of the three possibilities explored for producing age trends among monazite inclusions in garnet, co-crystallization with garnet seems the most plausible. At present, it can only be speculated as to why monazite was not introduced until reaching the staurolite-breakdown reaction in the upper amphibolite facies, considering that the initial crystallization of monazite typically takes place in pelitic schist at lower metamorphic grades (e.g., Kingsbury et al., 1993; Franz et al., 1996; Spear and Pyle, 2002; Wing et al., 2003; Kohn and Malloy, 2004). The answer may lie in the absence of a REE-rich precursor, such as xenotime or allanite, and initially low trace abundances of REEs in the major phases. Kohn and Malloy (2004) concluded that monazite in the rocks they studied derived REEs from the breakdown of muscovite and P from the breakdown of garnet during the lower amphibolite facies reaction

\[ \text{garnet} + \text{chlorite} + \text{muscovite} = \text{staurolite} + \text{biotite} + H_2O \]  

(1)

Using AFM projections and an appropriate assumed bulk composition (e.g., Spear, 1993), Reaction (1) can be inferred to have taken place in rocks in the current study along the prograde path, followed in sequence by the discontinuous reactions

\[ \text{staurolite} + \text{chlorite} + \text{muscovite} = \text{garnet} + \text{biotite} + H_2O \]  

(2)

and

\[ \text{staurolite} + \text{muscovite} + \text{quartz} = \text{garnet} + \text{biotite} + \text{silimanite} + H_2O \]  

(3)

Reaction (1) implies that an earlier generation of garnet existed in the rock along the prograde path, however, because no early garnets are preserved, it can be assumed that they were entirely consumed by the reaction. Unlike the rocks studied by Kohn and Malloy (2004), there is no evidence of monazite crystallizing by Reaction (1), which suggests that the primary control for producing monazite in pelitic schist in the absence of a REE precursor may not be a specific reaction, but other factors (e.g., Franz et al., 1996). If REE concentrations in muscovite increase through progressive muscovite-breakdown reactions, monazite might crystallize when a saturation limit is reached, assuming available P. The rocks in the present study experienced two additional muscovite-breakdown reactions (Reactions (2) and (3)) beyond those in the study of Kohn and Malloy (2004). The attainment of a saturation limit would depend in part on the initial concentrations of REE in muscovite.

Differences in the attainment of a REE saturation limit for muscovite might explain why monazite was introduced by Reaction (1) in the study of Kohn and Malloy (2004) and Reaction (3) in the present study.

The process might also involve the development of a REE-enriched “boundary layer” along the margins of growing garnets, analogous to that described for the crystallization of igneous phenocrysts (Bacon, 1989). If muscovite is breaking down adjacent to growing garnets, and REEs released from them diffuse too slowly to migrate away from garnet rims, the concentration of REEs might exceed thresholds for stabilizing monazite. This could result in monazite nucleating along the rims of growing garnets.

ACKNOWLEDGEMENTS

This paper was greatly improved by reviews and comments from Y. Amelin, J. Ayers, J. Baldwin, E.L. Miller, M.R. Reid, R. Stern, and I. Williams. We thank C. Coath for revising his program ZIPS to propagate errors associated with dispersion in the standard runs, and for clarifying the methods used to propagate errors. C. Harris and E. Kelly assisted with ion probe data collection and preparation of reflected light imagery, and T. Bailey prepared the BSE images of the garnet separates. We thank K. Becker at RPI for producing the garnet element maps and J. Witte for assisting with preparation of the BSE image for LH1A and microprobe analysis at NAU. This work was funded by NSF Grants EAR-9805076 and EAR-0061048 to T.D.H. and EAR-9805007 to M.L.W. The ion microprobe facility at UCLA is partly supported by a grant from the Instrumentation and Facilities Program, National Science Foundation. Acquisition of the SEM at Northern Arizona University used to generate the monazite BSE images and maps of Y and Th was supported by NSF Grant EAR-0421452.

APPENDIX A. METHOD OF ERROR PROPAGATION IN AGE DETERMINATIONS

Data reduction and error estimation for age determinations were carried out using the program ZIPS v. 3.0.2 writ-
ten by C. Coath. For each sample, the error in the $^{208}\text{Pb}/^{232}\text{Th}$ ratio was determined by addition in quadrature of the external reproducibility of the standards and the internal error calculated from the 15 “cycles” of analysis comprising each sample analysis. The error in the $^{208}\text{Pb}/^{232}\text{Th}$ ratio is propagated to the reported error in the ages. It should be noted that the error associated with the regression that determines the “relative sensitivity factor,” describing the relative fractionation of Pb versus Th (Harrison et al., 1995), is not considered, as this is generally quite small and imparts a systematic error to the age calculation, with all ages being affected similarly. This source of errors is reduced as the number of standard runs is increased.

APPENDIX B. SUPPLEMENTARY DATA

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gca.2008.08.012.

REFERENCES


Age trends in garnet-hosted monazite inclusions


