The tectonic significance of (U,Th)/Pb ages of monazite inclusions in garnet from the Himalaya of central Nepal

Aaron J. Martin a,⁎, George E. Gehrels b, Peter G. DeCelles b

a Department of Geology, University of Maryland, College Park, MD, 20742, USA
b Department of Geosciences, University of Arizona, Tucson, AZ, 85721, USA

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Abstract

Textural observations, chemical zoning, and 196 in situ LA-ICP-MS 232Th/208Pb and 238U/206Pb dates of monazite inclusions in Greater Himalayan garnets demonstrate that inclusions are frequently composite grains composed of multiple generations of monazite. Cenozoic prograde and retrograde monazite are commonly intergrown, and both of these components are frequently intergrown with lower Paleozoic monazite. Because zones in most inclusions are too small to date, and because some inclusions show little zoning of Y and Th, chemical characterization alone is often insufficient to guide interpretation of the crystallization significance of Th/Pb dates. Comparison of 238U/206Pb and 232Th/208Pb dates thus is critical for interpreting the tectonic significance of dates derived from these composite inclusions. Most Cenozoic monazite crystallized between 42–29 and 22–12 Ma, and these age ranges may record prograde and retrograde metamorphism of Greater Himalayan rocks, respectively. Dates younger than ∼12 Ma are discordant, without exception. The <12 Ma dates come from the eastern side of the Annapurna Range and record limited monazite growth during retrograde metamorphism and metasomatism of these Greater Himalayan rocks. Microcracks allow communication between the interior and exterior of garnet, affecting monazite inclusions by facilitating Pb loss, dissolution, recrystallization, and intergrowth of younger monazite.

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1. Introduction

Over the past ten years, 232Th/208Pb dating of monazite has emerged as the tool of choice for constraining the timing of mid-high temperature Cenozoic metamorphism and metasomatism of Himalayan metapelitic and metapsammitic rocks (e.g. Harrison et al., 1995, 1997; Foster et al., 2000; Catlos et al., 2001, 2002b, 2004; Kohn et al., 2004). Monazite is a monoclinic light rare earth phosphate that usually incorporates high concentrations of Y and Th into its crystal structure (Catlos et al., 2002a; Harrison et al., 2002; Spear and Pyle, 2002). Monazite 232Th/208Pb dating offers several advantages over other dating methods. First, although the 232Th–208Pb system has a half-life of 14 billion years, it can be used to date even small parts of very young crystals because monazite typically contains 3–9 wt.% ThO2 (Overstreet, 1967;
Van Emden et al., 1997). This high abundance of Th allows precisely and accurately measurable quantities of radiogenic $^{208}\text{Pb}$ to accumulate in only a few million years in most grains. In contrast, UO$_2$ concentrations in monazite are normally $<0.01$ to 0.3 wt.% (Van Emden et al., 1997). This relatively low abundance makes U/Pb dating of small portions of some young monazite crystals more difficult than Th/Pb dating because insufficient radiogenic $^{206}\text{Pb}$ and $^{207}\text{Pb}$ accumulate in a few tens of M.y. to allow accurate isotopic measurements using conventional in situ techniques. Using newer high-sensitivity techniques, acquisition of precise $^{238}\text{U}/^{206}\text{Pb}$ dates for young monazites is feasible, although the common presence of excess $^{206}\text{Pb}$ derived from $^{230}\text{Th}$ incorporated during crystallization complicates interpretation of the $^{238}\text{U}/^{206}\text{Pb}$ dates of some monazite grains (Mattinson, 1973; Scharer, 1984; Parrish, 1990). Errors on $^{235}\text{U}/^{207}\text{Pb}$ dates remain prohibitively high for young monazite grains. Second, because the half-lives of the intermediate daughter products in the decay chain between $^{232}\text{Th}$ and $^{208}\text{Pb}$ are short, the system attains secular equilibrium in only $\sim30$ years (Harrison et al., 2002). Third, compared to the maximum abundance, concentrations of Th and Y commonly vary substantially within individual monazite crystals, and the mineral frequently displays conspicuous zoning of Th and Y (e.g. Zhu and O’Nions, 1999; Gibson et al., 2004; Kohn et al., 2004). Analysis of the zoning patterns of these elements often yields valuable insight into the growth history of the monazite grain. Fourth, monazite is common in Himalayan medium to high grade metapelitic and metapsammitic rocks. Finally, although metamorphic zircon could be used to constrain the timing of rocks that reached high temperatures, many medium grade Himalayan rocks likely did not experience high enough temperatures for long enough times to either grow significant quantities of metamorphic zircon or to reset the (U,Th)/Pb system in existing grains. Garnet-bearing Lesser Himalayan rocks record peak temperatures of $\sim500–650$ °C (e.g. Catlos et al., 2001; Beyssac et al., 2004; Bollinger et al., 2004; Kohn et al., 2004; Martin, 2005), but the closure temperature of most zircons is $>800$ °C (Cherniak and Watson, 2001) and abundant zircon growth in pelitic rocks metamorphosed on a typical Barrovian path commences near 700 °C with the formation of partial melt (Rubatto et al., 2001; Williams, 2001; Rubatto, 2002). Large amounts of Cenozoic metamorphic monazite grew in both medium and high temperature rocks, however.

As with any geochronometer, understanding a monazite (U,Th)/Pb date in paragenetic context is critical for understanding its tectonic significance. Matrix monazite crystals, i.e., grains that are not included in garnet, quartz, plagioclase feldspar, or some other phase, are exposed to the ambient fluids in the rock and thus are expected to lose some Pb and/or partially recrystallize even at fairly low temperatures. The closure temperature for Pb loss in monazite is $\sim500–800$ °C according to Smith and Giletti (1997), but Cherniak et al. (2004) obtain a closure temperature of $\sim900–1100$ °C, depending on cooling rate and grain size (see also McFarlane and Harrison, 2006). Probably more importantly for interpreting the tectonic significance of (U,Th)/Pb dates, dissolution, recrystallization, and intergrowth of different generations of monazite are all common and can occur at temperatures well below the closure temperature (DeWolf et al., 1993; Crowley and Ghent, 1999; Kohn et al., 2004). Indeed, monazite grows at temperatures as low as 260–400 °C during metasomatism and retrograde metamorphism (Poitrasson et al., 2000; Rasmussen et al., 2001; Townsend et al., 2001; Harlov et al., 2002; Harlov and Forster, 2003; Bollinger and Janots, 2006).

In the late 1990s, geologists began producing in situ (U,Th)/Pb dates of monazite inclusions in garnet from the Himalaya because these dates promised to yield information about the age of growth of the surrounding garnet (Harrison et al., 1997; Foster et al., 2000; Catlos et al., 2001, 2002b). Because garnet incorporates only very small amounts of Pb, and diffusion of Pb in garnet is slow, growth of garnet around a monazite grain was expected to shield the monazite crystal from both Pb loss and growth of younger monazite (DeWolf et al., 1993; Zhu et al., 1997; Foster et al., 2000). Thus, according to this early work, (U,Th)/Pb ages of monazite inclusions in garnet should represent the time at which the garnet grew around the monazite crystal, even if the rock experienced high temperatures for long times subsequent to growth of the garnet. Application of this technique in several places in eastern Asia led to numerous important and surprising results (Harrison et al., 1997; Foster et al., 2000; Hacker et al., 2000; Catlos et al., 2001, 2002b; Gilley et al., 2003; Foster et al., 2004; Catlos et al., 2004). For example, using Th/Pb ages of both monazite inclusions in garnet and matrix monazite crystals, Catlos et al. (2001, 2002b) concluded that the Main Central thrust (MCT), a major fault now exposed in the interior of the Himalayan thrust belt and thought by most workers to be inactive since the early Miocene, was active throughout the late Miocene and perhaps as recently as 3 Ma (Fig. 1). The presence of $\sim45$ Ma Th/Pb ages of monazite inclusions in garnet from the hanging wall of the MCT further led Catlos...
et al. (2002b) to conclude that these rocks attained metamorphic conditions sufficient for monazite growth during the middle Eocene, earlier than previously accepted by most Himalayan geologists.

Although the pioneering work by these groups led to some exciting conclusions, the monazite (U,Th)/Pb ages reported in Harrison et al. (1997) and Catlos et al. (2001, 2002b) raise additional unanswered questions. These authors treated most or all of the Cenozoic ages from an individual sample as a single population, which allowed them to obtain a single crystallization age for each sample by averaging multiple ages from the same sample. Single crystallization ages for each sample, in turn, allowed the authors to compare ages between samples and to place the ages in geographic context. However, many of the samples yielded a large range of Cenozoic ages, sometimes an order of magnitude larger than the errors on the ages, with multi-million year time gaps between analyses. This pattern suggests multiple age populations in many samples. More recently, Bollinger and Janots (2006) used monazite $^{208}\text{Th}/^{232}\text{Pb}$ ages and hornblende, biotite, and muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ ages from Lesser Himalayan rocks to show that many monazites grew during late Cenozoic retrograde metamorphism, not during prograde metamorphism as previously assumed by most workers. Working on rocks outside the Himalaya, several groups found that ages of monazite inclusions near cracks in their host garnet are significantly different than ages of inclusions far removed from cracks (DeWolf et al., 1993; Zhu et al., 1997; Montel et al., 2000). These workers caution that garnet only completely shields monazite from intergrowth of younger monazite if the inclusions are not intersected by cracks in the garnet. These results suggest that kinematic interpretations in the Himalaya should be reconsidered if they are based on any of the following assumptions or interpretations: 1) Garnet completely shields monazite from intergrowth of younger monazite, 2) Monazite dates represent ages of prograde or peak metamorphism, or 3) Most or all Cenozoic ages from an individual sample define a single population of ages.

In this paper we examine the tectonic significance of (U,Th)/Pb dates of monazite inclusions in garnet using a combination of textural characterization, analysis of element zoning patterns, and in situ $^{238}\text{U}/^{206}\text{Pb}$ and $^{232}\text{Th}/^{208}\text{Pb}$ isotopic dating of monazite inclusions using an inductively coupled plasma mass spectrometer equipped with a laser ablation source (LA-ICP-MS). Throughout the paper we use the term “date” to refer to a...
relatively uninterpreted radiometric time determination that might or might not have crystallization significance and the term “age” to refer to a date which we interpret to possess crystallization significance. The garnets come from Greater Himalayan metapelitic rocks collected from five transects across the Annapurna Range of central Nepal (Fig. 1). We address only Greater Himalayan garnets because we found monazite inclusions in garnets from just two Lesser Himalayan samples, both from the Nayu Ridge transect (Table ESM1). Building on the work of Foster et al. (2000, 2004), we illustrate how comparison of $^{238}$U/$^{206}$Pb and $^{232}$Th/$^{208}$Pb dates lends important insight into interpretations of the tectonic significance of monazite ages. We show that garnet crystals only partially shield monazite inclusions from Pb loss and younger monazite intergrowth; thus most monazite inclusions yield discordant $^{238}$U/$^{206}$Pb and $^{232}$Th/$^{208}$Pb dates.

2. Geologic setting

Greater Himalayan series rocks are the highest-grade rocks that are widely exposed in the Himalaya; thermobarometric estimates usually peg peak conditions at $\sim 10–14$ kbar at $\sim 700–800 \, ^\circ C$ (e.g. Ganguly et al., 2000; Stephenson et al., 2000; Daniel et al., 2003; Kohn et al., 2004; Martin, 2005). In central Nepal, geologists usually divide the Greater Himalayan series into three informal units (Fig. 2; LeFort, 1975; Searle and Godin, 2003). The structurally lowest unit, Formation I, consists of schists and gneisses produced by the metamorphism of a sedimentary succession dominated by mudstones and interbedded minor sandstones. Formation II consists of marbles and layered calc-silicates and sits structurally above Formation I (Fig. 2). Granitic rocks known as Unit III intrude near the structural top of Formation II. Formation I rocks yield detrital zircons as young as $\sim 900–590$ Ma, and Unit III yields a crystallization age of $\sim 500$ Ma, constraining the depositional age of the Greater Himalayan series protoliths to the Neoproterozoic–Cambrian (Hodges et al., 1996; DeCelles et al., 2000; Godin et al., 2001; Gehrels et al., 2003; Martin et al., 2005). Ductile thrust and normal faults internally shortened and extended Greater Himalayan rocks (Reddy et al., 1993; Hodges et al., 1996; Kohn et al., 2004; Martin, 2005).

The South Tibetan Detachment System (STDS) marks the top of the Greater Himalayan series. The STDS is a series of north-dipping normal faults that accommodated tens of kilometers of slip during the Miocene (Burg and Chen, 1984; Hodges et al., 1998; Searle et al., 2003). The STDS places less-metamorphosed Tethyan series metasedimentary rocks on more-metamorphosed Greater Himalayan series metasedimentary rocks. The Tethyan series is a thick succession of Neoproterozoic to Eocene sedimentary rocks that extend from the STDS north to the Indus–Yarlung suture zone, which marks the former subduction zone between the Indian and Eurasian plates (Fig. 1; Ratschbacher et al., 1994; Garzanti, 1999; Murphy and Yin, 2003). Numerous thrust faults cut the Tethyan rocks (Ratschbacher et al., 1994; Murphy and Yin, 2003). Lowermost Tethyan strata may be the protoliths for Greater Himalayan metasedimentary rocks LeFort, 1975; Gehrels et al., 2003; Myrow et al., 2003; Richards et al., 2005).

The MCT, the structure that bounds the base of the Greater Himalayan series, places higher-grade Greater Himalayan metasedimentary rocks on lower-grade Lesser Himalayan metasedimentary rocks (Fig. 2). In Nepal, stratigraphers divide the Lesser Himalayan series into two informal units (Upreti, 1996). The lower and thicker part of the Lesser Himalayan series, the Nawakot unit, is dominated by metamorphosed mudstones and several clean quartzite units with thicknesses of a few hundred meters (Schelling, 1992; Upreti, 1996; DeCelles et al., 2000, 2001; Dhital et al., 2002; Robinson et al., 2006). Detrital zircon U/Pb ages and the age of a granitic intrusive indicate that the basal part of the Nawakot unit was deposited between $\sim 1845$ and $1831$ Ma and that the upper part was deposited after $\sim 1500$ Ma (DeCelles et al., 2000; Gehrels et al., 2003; Martin et al., 2005).

The upper, thinner part of the Lesser Himalayan series is called the Tansen unit. Permian–Paleocene Gondwanan sedimentary rocks comprise the lower part of the Tansen unit, and the upper part consists of strata deposited in the Himalayan foreland basin between the Eocene and the Early Miocene (Sakai, 1983; Upreti, 1996; DeCelles et al., 1998a; 2004). Numerous thrust faults, most importantly the Ramgarh thrust, repeat Lesser Himalayan stratigraphy (Schelling, 1992; Srivastava and Mitra, 1996; DeCelles et al., 2001; Pearson and DeCelles, 2005; Robinson et al., 2006).

The Lesser Himalayan series was thrust southward along the Main Boundary thrust onto the Sub-Himalayan series (Fig. 2). Middle-Miocene to Quaternary foreland basin deposits, the Siwalik Group, comprise the Sub-Himalayan series (Harrison et al., 1993; Quade et al., 1995; DeCelles et al., 1998b). Several thrusts repeat parts of the Siwalik Group, and Sub-Himalayan rocks are thrust onto Quaternary and modern foreland.
basin deposits along the Main Frontal thrust (Schelling, 1992; Powers et al., 1998; Lave and Avouac, 2001).

3. Methods

Garnet grains were separated by hand from 0.5–1.0 kg of each garnet-bearing Greater or Lesser Himalayan sample from the Annapurna Range. All Greater Himalayan samples come from Formation I. Garnet grains were mounted in epoxy and polished to reveal the interiors of the grains. Monazite inclusions were identified using a scanning electron microscope equipped with an energy dispersive spectrometer.

Compositional zoning in monazite inclusions, in large areas of thin sections, and in garnet was imaged using a Cameca SX50 electron microprobe operating at an accelerating voltage of 15 or 25 kV and a Faraday cup current of 200 or 250 nA.

Monazite $^{232}$Th/$^{208}$Pb and $^{238}$U/$^{206}$Pb dates were obtained using the Micromass Isotope LA-ICP-MS at the University of Arizona. Monazite was ablated using a New Wave DUV193 Excimer laser with an emission wavelength of 193 nm operating at $\sim$50 mJ at 22 kV. The laser spot had a diameter of 10 μm and the firing rate was 4 Hz. For analyses that begin with the prefix ‘T4’ or ‘T5,’ the ablated material was carried into the
plasma source in 100% He gas; for the remaining analyses the carrier gas was 70% Ar and 30% He. The mass spectrometer was equipped with a flight tube of sufficient width that U, Th, and Pb isotopes were measured simultaneously. All measurements were made in static mode, using Faraday detectors for $^{235}$U, $^{232}$Th, $^{208}$Pb, $^{207}$Pb, and $^{206}$Pb and an ion-counting channel for $^{204}$Pb. Each analysis consisted of one 20-second integration on peaks with the laser off to measure backgrounds, twenty 1-second integrations on peaks with the laser firing, and a 30-second delay to purge the background values. Very little Hg was detected in the Ar and He gasses.

Th and U concentrations were estimated by normalization of the $^{232}$Th and $^{238}$U voltages obtained from unknown grains with the voltages obtained by ablation of NBS610 trace element glass, which was embedded in epoxy near the garnet grains. The glass was analyzed at the beginning and end of the analysis of each Greater or Lesser Himalayan sample. Analyses were corrected for common Pb content using the measured $^{204}$Pb and assuming an initial Pb composition according to Stacey and Kramers (1975) with an uncertainty of 2.0 for $^{208}$Pb/$^{204}$Pb and 1.0 for $^{206}$Pb/$^{204}$Pb. Fractionation of Pb isotopes of $\sim 5\%$ and U/Pb and Th/Pb fractionation of $\sim 20\%$ were corrected by normalization to a monazite standard with a concordant U/Pb age of 424±2 Ma (2-sigma error). The standard, from the Wissahickon Formation, Delaware, USA, was provided by J. Aleinikoff and dated using isotope dilution thermal ionization mass spectrometry (ID-TIMS) by S. Kamo. This standard was embedded in epoxy near the garnet grains and analyzed after every 3 analyses of unknown monazite. In order to assess the validity of this normalization technique, we treated $\sim 46\%$ of the standards as unknowns and compared computed $^{232}$Th/$^{208}$Pb and $^{238}$U/$^{206}$Pb ages with the ID-TIMS age (Figs. ESM1, ESM2). Although removal of standards degrades the accuracy of the mass fractionation correction, all but two of the Th/Pb analyses and all but six of the U/Pb analyses agree within error with the ID-TIMS age of the standard. Mass fractionation also increased with depth into the laser pit by up to 10%. During most analyses, signal intensity decreased after 6 to 10 s. To mitigate both effects, accepted isotopic ratios were taken as the weighted mean of the ratios from the integrations from the first 2 to 5 s within the 20-second analysis. Most analyses exhibit significant within-run complexity, probably caused by mixing of different amounts of lower Paleozoic, Cenozoic prograde, and Cenozoic retrograde monazite as the laser penetrates the monazite crystal. The resulting within-run variability in isotopic ratios and the uncertainty in selecting appropriate isotopic ratios contribute most of the error to each analysis; measurement errors and systematic errors are almost always significantly less than these uncertainties.

4. Monazite dates and Th and U concentrations

Table ESM1 provides isotopic data for 213 (U, Th)/Pb dates of monazite inclusions in garnet from the southern Annapurna Range. 17 of these dates come from an equal number of inclusions that grew in two Lesser Himalayan rocks, both from the Nayu Ridge transect. The remaining 196 dates come from 186 monazite inclusions found in garnets from Greater Himalayan rocks (multiple spots were dated in several inclusions).

4.1. Th/$^{208}$Pb dates

Fig. 3 and ESM3 show all of our Greater Himalayan monazite Th/Pb dates. There is a continuous distribution of Th/Pb dates from 505±46 Ma to 6±1 Ma. There are also several bends in the temporal trend of the dates, including a bend at $\sim 30$ Ma (Fig. 3). The most prominent bend occurs at $\sim 50$ Ma because $69\%$ of the Th/Pb dates are between $\sim 6$ and $50$ Ma whereas only $31\%$ of the dates fall between $\sim 51$ and $505$ Ma. The large percentage of inclusions that yield Cenozoic dates demonstrates that late Cenozoic metamorphism strongly overprints early Paleozoic metamorphism, although remnants of the early Paleozoic metamorphism clearly remain. Fig. 4 shows that inclusions with Th concentrations greater than $\sim 12\%$ uniformly yield Cenozoic dates, but below $\sim 12\%$ there is no correlation between Th concentration and age.

Monazite Th/Pb dates from three adjacent Greater Himalayan samples are shown in Fig. 5. Samples such as 502122 that contain garnets with many monazite inclusions show a large range of monazite dates stretching from the middle to late Cenozoic to the Mesozoic or Paleozoic (Fig. 5A, B, Table ESM1). Such a large range of dates is rarely observed for samples such as 502123 and 502124 that contain garnets with fewer monazite inclusions (Fig. 5C, D). Instead, these samples yield only a few dates scattered throughout the Cenozoic, Mesozoic, and Paleozoic.

Sample 502122 is located 150 m structurally above sample 502123, which is located 150 m structurally above sample 502124, and no major faults are known to exist between the samples. Monazite inclusions in these closely-spaced samples yield radically different Th/Pb dates, however, and the Cenozoic dates from an
individual sample clearly do not define a single population. If we wrongly treat the post-55 Ma dates from each sample as a single population and calculate weighted averages of the dates, the upper sample yields an estimate of $23 \pm 6$ Ma, the middle sample an estimate of $18 \pm 12$ Ma, and the lower sample an estimate of $30 \pm 3$ Ma (from one date). Given the very close spacing of these samples and the lack of known structures between them, it is unlikely that they experienced metamorphism at such different times. We conclude that it is incorrect to treat these ages as a single population. Examination of Table ESM1 shows that most closely-spaced samples, even those with numerous inclusions, do not yield a single population of Cenozoic Th/Pb dates. Because the Cenozoic dates from most samples do not define a single population, we cannot obtain a single crystallization age for each of these samples. It is thus difficult to compare Cenozoic dates between individual samples or to place dates from individual samples in geographic context. Instead, in the remainder of the paper we pool the Greater Himalayan ages in order to obtain useful information about the metamorphism of Greater
Himalayan rocks in general. Overall, the Th/Pb results suggest that the significance of Th/Pb dates of monazite inclusions in garnet alone as estimates of the timing of Cenozoic metamorphism is highly uncertain and requires validation using another isotopic system.

### 4.2. U/206Pb dates

Fig. 6 and ESM4 show all of the Greater Himalayan monazite $^{238}\text{U}/^{206}\text{Pb}$ dates. As for the $^{232}\text{Th}/^{208}\text{Pb}$ dates, there is a nearly continuous distribution of $^{238}\text{U}/^{206}\text{Pb}$ dates from 497±21 Ma to 7±2 Ma. There are several bends in the temporal trend of these dates, including a subtle bend at ∼25 Ma. Similar to the pattern of Th/Pb dates, the most prominent bend occurs at ∼50 Ma because 69% of the $^{238}\text{U}/^{206}\text{Pb}$ dates are between ∼7 and 50 Ma whereas only 31% of the dates fall between ∼51 and 497 Ma. The large percentage of inclusions that yield Cenozoic $^{238}\text{U}/^{206}\text{Pb}$ dates shows again that Cenozoic metamorphism strongly overprints early Paleozoic metamorphism, though vestiges of the early Paleozoic metamorphism clearly remain.

Fig. 7 shows a plot of Th/Pb date versus $^{232}\text{Th}/^{238}\text{U}$ ratio for all Greater Himalayan monazite analyses. No correlation exists between Th/Pb date and $^{232}\text{Th}/^{238}\text{U}$ for most of the analyses except that the two analyses with the highest $^{232}\text{Th}/^{238}\text{U}$ yield Cenozoic dates. However, consideration of only the concordant analyses (analyses whose Th/Pb and U/Pb dates agree within 10%) shows that the concordant lower Paleozoic monazites have a higher $^{232}\text{Th}/^{238}\text{U}$ ratio than the concordant Cenozoic monazites. The mean $^{232}\text{Th}/^{238}\text{U}$ for the four concordant lower Paleozoic monazites is 14.7 whereas the mean for the 57 concordant Cenozoic monazites is 5.9.

Fig. 7 also shows that the 10 analyses with the highest $^{232}\text{Th}/^{238}\text{U}$ come from monazites taken from the Marsyangdi Nadi transect and that 18 of the 32 analyses with $^{232}\text{Th}/^{238}\text{U}$ ratio greater than 10 come from this transect. Most of the analyses from the Marsyangdi transect with high $^{232}\text{Th}/^{238}\text{U}$ yield Cenozoic dates, though a few yield Mesozoic or Paleozoic dates. Although most of these high $^{232}\text{Th}/^{238}\text{U}$ analyses from the Marsyangdi transect are not concordant, the large number of analyses that yield high $^{232}\text{Th}/^{238}\text{U}$ suggests that either during early Paleozoic metamorphism or during Cenozoic metamorphism, or both, conditions in Greater Himalayan rocks in the Marsyangdi transect allowed growth of monazite with higher $^{232}\text{Th}/^{238}\text{U}$ than in Greater Himalayan rocks in other transects.

### 5. Textural observations and zoning patterns

#### 5.1. Monazite

Throughout our discussion of (U, Th)/Pb dates of Greater Himalayan monazite inclusions and their tectonic significance, we divide the monazites into three groups based on Th/Pb date: 505–400 Ma, 399–
56 Ma, and 55–6 Ma. We use Th/Pb dates rather than 238U/206Pb dates for these divisions for two reasons: 1) The Th/Pb dates usually have smaller or similar errors, and 2) Using Th/Pb dates alleviates any possible complications to 238U/206Pb dates caused by the presence of excess 206Pb. The upper limit for the first group, 505 Ma, is the Th/Pb date of the oldest inclusion dated, and the lower limit, 400 Ma, is near the Th/Pb date of the youngest concordant lower Paleozoic monazite. The boundary between the second and third groups, 55 Ma, is near the upper limit of estimates for the age of Cenozoic metamorphism of exposed Himalayan rocks (de Sigoyer et al., 2000; Leech et al., 2005). These estimates are based on radiometric dating of minerals in eclogite facies metamorphic rocks of the Tso Morari complex in the western Himalaya. The Tso Morari complex is bounded to the north by the Indus–Yarlung Suture Zone, and thus is located north of the traditionally-defined outcrop belt of Greater Himalayan rocks. Most of the Greater Himalayan series between the

Fig. 6. 238U/206Pb dates obtained from all 196 analyses of monazite inclusions in Greater Himalayan garnets. Error bars show total error at the 2-sigma level. The analyses are arranged with the youngest dates on the left and the oldest dates on the right. 69% of the dates fall between ~7 and 50 Ma, indicating that these rocks were strongly overprinted during Cenozoic metamorphism. With decreasing age, an increasing number of analyses come from inclusions that are intersected by obvious microcracks in their host garnet. The dates between ~400 and 46 Ma and younger than ~12 Ma are not crystallization ages; instead they are mixed dates or dates produced by significant Pb loss.

Fig. 7. Th/Pb date versus 232Th/238U ratio for all analyses of Greater Himalayan monazite. The 4 concordant lower Paleozoic monazites have a mean 232Th/238U ratio of 14.7 whereas the mean for the 57 concordant Cenozoic monazites is 5.9. The 10 analyses with the highest 232Th/238U come from monazites taken from the Marsyangdi Nadi transect. Circles show concordant analyses, squares show discordant analyses. Open squares indicate analyses from monazites from the Marsyangdi Nadi transect with 232Th/238U ratio greater than 10.
MCT and the STDS experienced metamorphism after \( \sim 40 \) Ma (Vannay and Hodges, 1996; Coleman and Hodges, 1998; Guillot et al., 1999; Godin et al., 2001; Harris et al., 2004; Kohn et al., 2004). The lower limit of the third group, 6 Ma, is the Th/Pb date of the youngest inclusion dated. The boundaries between the groups do not correspond to breaks within the series of monazite dates; a continuum of Th/Pb dates exists between 505\( \pm \)46 and 6\( \pm \)1 Ma (Fig. 3, ESM3).

Fig. ESM5A shows a backscattered electron image (BEI) of a monazite inclusion intersected by a prominent microcrack (a crack less than about 1 mm long; Engelder, 1987) in its host garnet, and Fig. ESM5B shows another inclusion that is not intersected by a microcrack in the garnet, at least in the plane of observation. 60\% of the 196 analyses of monazite inclusions in Greater Himalayan garnets from the Annapurna Range come from inclusions intersected by obvious microcracks in their host garnet. A correlation exists between the location of an inclusion relative to microcracks and the Th/Pb date of the inclusion (Fig. 8). Obvious microcracks intersect more of the inclusions that yield Cenozoic dates than those that yield older dates.

Although most monazite inclusions appear to be single grains, some inclusions are located adjacent to other inclusions (Fig. 9). If both inclusions are sufficiently large, each may be dated. In the case of analyses L15 and L16 in sample 502126, the two grains give very different Th/Pb and \(^{238}\text{U}/^{206}\text{Pb}\) dates, and neither of the dates is concordant (Fig. 9A). The shape of inclusion D5 in sample 502091 suggests that it consists of a combination of two or more monazites (Fig. 9B). Both the Th/Pb date and the \(^{238}\text{U}/^{206}\text{Pb}\) date from the center of the composite grain are intermediate between corresponding dates from the left and right sides of the grain. Only the analyses from the right and the center of the grain yield concordant dates.

Large inclusions often show prominent zoning of Y and Th that aids interpretation of \((\text{U,Th})/\text{Pb}\) dates. A jagged low Y, high Th, high Si stripe cuts across...
inclusion T4_F2 in sample 502050 (Fig. 10). This stripe also has low Ca concentrations relative to the rest of the grain, particularly the right side of the stripe. The correlations of Y, Th, Si, and Ca concentrations indicate changing importance of Th substitution vectors in monazite inside and outside the stripe. Outside the stripe, paired substitution of Ca+Th for 2 REE, the brabantite substitution, appears to dominate. The huttonite paired substitution of Th+Si for REE+P is more important inside than outside the stripe, however. Although Th/Pb and 238U/206Pb dates inside and outside the stripe are the same within error, the element zoning patterns in this inclusion indicate intergrowth of at least two different generations of Cenozoic monazite. Monazite inclusion T4_A1 in sample 502067 has at least 3 distinct sectors defined by differing Y and Th concentrations (Fig. 11). These areas also have radically different Th/Pb and 238U/206Pb dates, which demonstrate that multiple generations of monazite intergrew to form this composite inclusion. It would not be possible to reach this conclusion based on textural information alone.

Individual zones within many inclusions are too small to date without overlap with neighboring zones,
however, and some whole inclusions and parts of inclusions display little zoning of Y and Th (Fig. 12). For these monazites, only comparison of Th/Pb and U/Pb dates can help decipher which dates are likely to represent crystallization ages and which result from intergrowth of different generations of monazite. Because some analyses from apparently unzoned sectors of inclusions yield highly discordant dates (Fig. 12, right analysis), even some of these monazites are composite grains composed of several generations of monazite intergrown at the sub-micron scale.

5.2. Garnet

Because monazites are included in garnets, the growth and deformational history of the garnets can yield insight into the significance of (U, Th)/Pb dates of the included monazites. Except for extremely large grains, garnets in Greater Himalayan rocks from the Annapurna Range usually show flat major element zoning in their cores and modification of this zoning near their rims (Fig. 13, ESM6), although the scale of the modification varies depending on cooling rate (Vannay and Hodges, 1996; Catlos et al., 2001; Martin, 2005). This pattern was produced by homogenization of major element zoning during metamorphism to ∼700 °C followed by retrograde modification at the rim and diffusion of these modifications into the garnet. Thus information about growth history is not preserved in major element zoning patterns in most Greater Himalayan garnets.

Y zoning in some Greater Himalayan garnets is subdued, including garnets from sample 502067 (Fig. 13). We do not have absolute Y concentration information for these garnets, but expect low concentrations based on the conclusions of Pyle and Spear (1999) for xenotime-bearing high grade metapelitic rocks from the northeast-ern USA. The small difference in Y concentration between garnet and biotite shown in the X-ray map supports this inference because biotite generally contains less than 1 or 2 ppm Y (Bea et al., 1994; Yang et al., 1999; Yang and Rivers, 2000). Minimal addition of Y at the rim during retrograde dissolution of the garnets in this rock indicates that little Y was released during breakdown of these garnets, again suggesting relatively low Y concentrations.

Garnets in these rocks also show pervasive microcracks, including microcracks at the rims of the garnets (Fig. 13, ESM6). Some of these microcracks clearly control retrograde metamorphism and metasomatism inside the garnet. Microcracks generally cut the major element zoning patterns in garnet with no disruption of zoning.

6. Interpretations

6.1. Comparisons between all 238U/206Pb and 232Th/208Pb dates

Fig. 14 shows plots of all of the Greater Himalayan 238U/206Pb and 232Th/208Pb dates. Several trends are apparent on these plots. First, it is clear that only dates between ∼400–500 Ma and ∼12–46 Ma are concordant within 10%. Analyses between ∼47–400 Ma and younger than ∼12 Ma are discordant, without exception. All analyses that yield Th/Pb dates younger than ∼11 Ma are more than 35% discordant.

Second, 52% of the analyses yield 232Th/208Pb dates older than corresponding 238U/206Pb dates, whereas 48% yield younger 232Th/208Pb dates. Older 232Th/208Pb dates cannot result from excess 206Pb but instead must result from partial Pb loss or, more likely, from intergrowth of different generations of monazite. Excess 206Pb might explain some of the older
However, we conclude that many of the older \(^{238}\text{U}/^{206}\text{Pb}\) dates likely result from partial Pb loss or intergrowth of different generations of monazite because these same processes explain the older \(^{232}\text{Th}/^{208}\text{Pb}\) dates, commonly from monazites from the same sample or nearby samples.

Third, monazites intersected by obvious microcracks are as likely to yield concordant ages as monazites not intersected by obvious microcracks. 61% of the 61 concordant ages come from monazite crystals intersected by obvious microcracks and 59% of the 135 discordant dates come from this type of monazite. Further, the mean and the median discordance of analyses from monazites intersected by obvious microcracks are nearly identical to the mean and median discordance of analyses from monazites not intersected by obvious microcracks. The median discordance for grains intersected by obvious microcracks is 22% whereas the median discordance for grains not intersected by obvious microcracks is 21%, and the mean discordance for both types of grains is 47%. There are two alternative, though not mutually exclusive, interpretations for the similarity of these numbers. First, it is possible that some younger monazite intergrew with older grains prior to inclusion in garnet, thus introducing discordance prior to garnet growth. Second, it is also possible that microcracks control the discordance of most inclusions, though the microcracks may not be obvious in a particular section through a host garnet. Microcracks likely intersect many apparently non-intersected inclusions out of the plane of the section. Additionally, garnets from poly-metamorphosed rocks sometimes contain healed microcracks, and it is possible that some of the inclusions were intersected by microcracks that subsequently annealed, rendering them very difficult to identify (e.g. Le Bayon et al., 2006). We prefer the second interpretation because the correspondence between the Th/Pb date of an inclusion and the presence of an obvious microcrack indicates that microcracks exerted some control on growth of most Cenozoic monazite grains (Fig. 8).

Fourth, 86% of the 56 analyses that yield Th/Pb dates between 47 and 399 Ma have a Th/Pb date that is older than the corresponding \(^{238}\text{U}/^{206}\text{Pb}\) date. This pattern probably results from mixing during laser ablation of different generations of monazite that have different \(^{232}\text{Th}/^{238}\text{U}\) ratios. If lower Paleozoic monazite usually has a higher \(^{232}\text{Th}/^{238}\text{U}\) ratio than Cenozoic monazite (Fig. 7), then a Th/Pb date older than the corresponding \(^{238}\text{U}/^{206}\text{Pb}\) date should result from mixture of the two generations of monazite. The few analyses that yield older \(^{238}\text{U}/^{206}\text{Pb}\) dates probably result from uncommon mixture of lower \(^{232}\text{Th}/^{238}\text{U}\) lower Paleozoic monazite with higher \(^{232}\text{Th}/^{238}\text{U}\) Cenozoic monazite during laser ablation.

Fig. 13. BEI of, and X-ray maps of Mn and Y in, garnet from sample 502067 from the Modi Khola transect. Microcracks continue to the rim of the garnet, and some microcracks clearly control retrograde metamorphism inside the garnet. There is no change in density of microcracks between the rim and core of the garnet. Y zoning is subdued and Y concentrations appear to be low in this garnet, consistent with growth continuing to high temperatures. Minimal addition of Y at the rim during retrograde dissolution of this garnet indicates that little Y was released during breakdown of the garnet, in contrast to Mn. High Mn at the right-center of the garnet results from exchange with an inclusion of chlorite+biotite. Ap—apatite, bt—biotite, chl—chlorite, grt—garnet, ky—kyanite, mnz—monazite, ms—muscovite, q—quartz, rt—rutile.
6.2. Interpretations based on age groups

6.2.1. 505–400 Ma dates

Several lines of evidence, including early Paleozoic monazite ages, indicate that Greater Himalayan rocks experienced metamorphism accompanied by monazite growth at ∼500 Ma (Stocklin and Bhattarai, 1977; Stocklin, 1980; Garzanti et al., 1986; Hodges et al., 1996; Argles et al., 1999; Marquer et al., 2000; Godin et al., 2001; Viskupic and Hodges, 2001; Catlos et al., 2002b; Gehrels et al., 2003; 2006; Myrow et al., 2006). Accordingly, we interpret the 505–400 Ma dates from the Annapurna Range samples to represent monazite growth at this time. The strongest data that support this interpretation are the 4 analyses that yield concordant ages within this age range. The $505 \pm 46$ and $474 \pm 29$ concordant ages might record prograde metamorphism whereas the $422 \pm 18$ and $403 \pm 74$ concordant ages might record retrograde metamorphism of Greater Himalayan rocks. Fig. 4 shows that 505–400 Ma monazite generally has low to medium Th concentrations; the mean Th concentration from the four concordant analyses that yield ages in this range is 3.1%. None of the nine inclusions that yielded Th/Pb ages between 505 and 400 Ma was large enough to allow dating of a second spot within the inclusion, precluding direct comparison of Th and Y concentrations of lower Paleozoic and Cenozoic monazite within...
a single inclusion. However, X-ray maps of monazites that yielded Th/Pb dates between 399 and 56 Ma suggest that Y and Th concentrations in 505–400 Ma monazites are low relative to many Cenozoic grains. For example, in Fig. 11, the sector of the inclusion that yields a Th/Pb date of 318±40 Ma has low Y and Th concentrations relative to the parts that yield Cenozoic dates. Because the 318 Ma date is not a crystallization age but instead results from mixture of 505–400 Ma monazite with Cenozoic monazite (see next section), Y and Th concentrations in the 505–400 Ma monazite must be low in order to maintain relatively low concentrations after mixture with the high Y, high Th Cenozoic monazite.

6.2.2. 399–56 Ma dates

The continuous distribution of dates between 505±46 and 6±1 Ma shown in Figs. 3, 6, ESM3, and ESM4, with no date unrepresented between 505 and 6 Ma, strongly suggests that the Th/Pb dates between 399 and 56 Ma are not crystallization ages but instead result from intergrowth of middle or upper Cenozoic monazite with pre-existing lower Paleozoic monazite and/or loss of Pb from lower Paleozoic monazite. The recognition that none of these analyses that yield dates between 399 and 56 Ma is concordant lends compelling support to this interpretation. Textural information and the distribution of major elements in these monazite inclusions also substantiate this interpretation, because some grains show clear evidence for intergrowth of Paleozoic and Cenozoic monazite (Fig. 11). Although inclusions L15 and L16 in sample 502126 are separated by ~1 μm in the view shown in Fig. 9A, they might coalesce into one grain out of the plane of observation. In this case, an analysis of the grain would yield mixed, and thus meaningless, Th/Pb and U/Pb dates. Coalescence of grains and mixing of ages explains the texture of, and dates from, inclusion D5 in sample 502091 (Fig. 9B). The discordant date in the upper left of the composite grain is not a crystallization age; instead it results from intergrowth of younger monazite with older monazite. It is likely that many inclusions are composed of monazite intergrown in this way or on a finer scale, because large grains that show no textural evidence for intergrowth often show chemical evidence for such intergrowth (Figs. 10 and 11). In most grains, however, zones are too small to date or the grain shows neither textural nor chemical evidence for intergrowth, leaving comparison of Th/Pb and U/Pb dates the only available method for discriminating between dates that likely represent crystallization ages and those that do not (Fig. 12). This explanation for the 399–56 Ma dates is more likely than one that calls for growth of monazite at this time, because metamorphism of this age is unknown for Greater Himalayan rocks or any rocks exposed in the Himalaya. The increased incidence of obvious microcracks that intersect the inclusions that yield dates in this range suggests that microcracks allow communication between the interior and exterior of garnets. That is, microcracks permit mass exchange between a monazite inclusion and the exterior of its host garnet, resulting in Pb loss from and/or new monazite intergrowth with the inclusion. The recognition that microcracks control retrograde metamorphism in the interior of garnet supports this interpretation (Fig. 13).

6.2.3. 55–6 Ma dates

There are at least six possible explanations for the 55–6 Ma monazite dates: 1) Pb loss from monazite that crystallized at ~500 Ma. 2) Intergrowth of mid-upper Cenozoic monazite with ~500 Ma monazite, resulting in a mixed date upon laser ablation. 3) Monazite growth and inclusion in garnet during Cenozoic prograde metamorphism with no older or younger monazite component. 4) Monazite growth within garnet during Cenozoic retrograde metamorphism and metasomatism with no older monazite component. 5) Monazite growth during Cenozoic prograde metamorphism followed by intergrowth of Cenozoic retrograde monazite, resulting in a mixed date. 6) Any other combination of two or more of these possibilities. Only dates from monazites that grew as described in explanations 3 and 4 are crystallization ages, the remainder are mixed dates or result from Pb loss. In the following paragraphs we explore each of the first five explanations.

The continuous distribution of dates shown in Figs. 3, 6, ESM3, and ESM4 suggests that some of the 55–6 Ma dates likely result from Pb loss from and/or mid-late Cenozoic intergrowth with lower Paleozoic monazite crystals (explanations 1 and 2). The patterns of concordance of these dates substantiate this interpretation. None of the analyses that yield Th/Pb dates between ~46 and 55 Ma is concordant, so we infer that these analyses do not represent crystallization ages. Likewise, we interpret the discordant analyses that yield Th/Pb dates between ~46 and 6 Ma to not represent crystallization ages. We further discuss the dates between 12 and 6 Ma below. Some of the discordant dates between ~46 and 6 Ma very likely were produced by extensive mixing of middle or upper Cenozoic monazite with lower Paleozoic monazite during laser ablation of intergrown lower Paleozoic and upper Cenozoic monazite crystals. For example, if the monazite grains shown in Figs. 9 and 11 were slightly
smaller, the observed dates would commingle and produce a date that is a mixture of these dates. Further, it is likely that the discordant dates obtained for the grains shown in these figures are actually mixed Paleozoic and Cenozoic ages produced by intergrowth of monazite on a scale too small to detect except by testing for concordance.

Some of the inclusions that yield concordant mid-late Cenozoic ages may consist of monazite that crystallized only at this time, thus these grains might contain no component of lower Paleozoic monazite (explanations 3, 4, and 5). Monazite probably crystallized during mid-Cenozoic prograde metamorphism, and then garnet may have grown around and completely included the newly-formed monazite crystal (explanation 3). Monazite may grow during prograde metamorphism due to the breakdown of a combination of allanite, garnet, muscovite, biotite, ThSiO₄, thorianite, apatite, and/or other phosphate minerals. These elements, dissolved in an aqueous fluid, probably entered garnet through microcracks and precipitated as young monazite intergrowths with monazite inclusions already in garnet or as entirely new crystals. Whitney and Dilek (1998) propose a similar mechanism to explain the growth of major minerals such as biotite and sillimanite inside garnet. Although the importance of aqueous fluids for monazite crystallization previously has received little attention in the Himalaya (Bollinger and Janots, 2006), crystallization of monazite assisted by aqueous fluids has been inferred in numerous other places (e.g. DeWolf et al., 1993; Hawkins and Bowring, 1997; Crowley and Ghent, 1999; Poitrasson et al., 2000; Rasmussen et al., 2001; Townsend et al., 2001).

It is also likely that Cenozoic retrograde monazite grew on older Cenozoic prograde monazite, resulting in an intergrown monazite grain (explanation 5). Most of the Th/Pb dates between ∼12 and 6 Ma probably result from such intergrowth, although small contributions from lower Paleozoic monazite are possible. Analyses from Greater Himalayan monazite inclusions that yield dates younger than ∼12 Ma are discordant, without exception, and all analyses that yield dates younger than ∼11 Ma are more than 35% discordant. The lone monazite grain that yields a concordant age of 12±2 Ma comes from rocks from the Marsyangdi transect; in other transects the youngest concordant ages are ∼13 or 14 Ma. Thus growth of monazite inclusions large

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Fig. 15. BEI of, and X-ray map of P in, part of sample 502069 from the Modi Khola transect. Intensities on the P map inverted so that light areas indicate low concentrations and dark areas high concentrations. Both mica foliation planes and cracks and microcracks controlled the movement of P in this Greater Himalayan rock. P likely moved through the rock dissolved in an aqueous fluid. Arrows on the P map indicate cracks with moderate P concentrations. Large patches of high P concentrations are apatite crystals.
enough to yield concordant ages ended at $\sim 14$–$12$ Ma. However, the presence of inclusions from the Marsyangdi and Nayu Ridge transects that yield extremely discordant dates between 12 and 6 Ma indicates that limited monazite growth or Pb loss continued in Greater Himalayan rocks on the eastern side of the Annapurna Range until at least 6 Ma, and probably later. Limited monazite growth or Pb loss both suggest processes active at relatively low temperatures or over short time intervals. Because diffusion of Pb in monazite is slow below $\sim 700 \, ^\circ C$, limited monazite growth is a more likely explanation for the 12–6 Ma dates than limited Pb loss (Smith and Giletti, 1997; Cherniak et al., 2004; McFarlane and Harrison, 2006). These considerations lead us to conclude that all of the Th/Pb dates younger than $\sim 12$ Ma record limited monazite growth during retrograde metamorphism at temperatures low enough to grow only small quantities of monazite.

Published $^{40}$Ar/$^{39}$Ar ages of muscovite from rocks collected directly above the MCT in the Marsyangdi valley support this interpretation. Edwards (1995) obtained a muscovite $^{40}$Ar/$^{39}$Ar age of $6.2 \pm 0.2$ Ma from Greater Himalayan rocks very near our sample 502091, and thus at a similar structural position to our samples 402086, 402088, 402089, 402091B, and 402092B (Fig. 2). The structurally lowest of these samples, 402092B, yielded two very discordant monazite Th/Pb dates that overlap this $^{40}$Ar/$^{39}$Ar age within error: $8 \pm 4$ and $9 \pm 3$ Ma. The similarity to the muscovite $^{40}$Ar/$^{39}$Ar age suggests that these Th/Pb dates record limited intergrowth of monazite at temperatures below the muscovite closure temperature of $\sim 350 \, ^\circ C$ (Purdy and Jager, 1976; Jager, 1979) after $8$–$9$ Ma rather than crystallization of monazite and subsequent inclusion by garnet at temperatures above $500 \, ^\circ C$ at $8$–$9$ Ma.

Fig. 4 shows that Th concentrations of spots that yielded Cenozoic dates range from less than 1 wt.% to more than 28 wt.%. However, all of the analyses with Th concentrations greater than $\sim 12\%$ yielded Cenozoic dates. The mean Th concentration of the monazites that yielded concordant Cenozoic ages is $8.1\%$, significantly higher than the Th concentration of the monazites with concordant early Paleozoic ages. X-ray maps of monazite inclusions that preserve large remnants of lower Paleozoic monazite intergrown with Cenozoic monazite also show that the Cenozoic monazite in these obviously composite grains usually has higher concentrations of Th and Y than the lower Paleozoic monazite (Fig. 11). Although different generations of Cenozoic prograde and retrograde monazite probably have different concentrations of Y and Th (c.f. Kohn et al., 2004), the presence of intergrowths of lower Paleozoic monazite obscures these patterns in the inclusions in garnet. Matrix monazite is more likely to display clearer zoning patterns of Y and Th produced by episodes of monazite growth during Cenozoic prograde and retrograde metamorphism because the preservation potential during later metamorphism of lower Paleozoic monazite in the matrix is much less than its preservation potential as inclusions in garnet (Catlos et al., 2001, 2002b, 2004; Kohn et al., 2004).

The recognition that microcracks intersect the inclusions that yield 69% of the dates from 6–55 Ma strongly suggests that microcracks play an important role in the genesis of many of these dates. Some monazite inclusions are not intersected by obvious microcracks in the host garnet, however. Microcracks could intersect these inclusions out of the plane of observation. A 3-dimensional tomographic image of the garnet prior to sectioning would be required to assess this possibility. It is also possible that healed microcracks intersect many inclusions, but it is difficult to recognize healed microcracks in garnet, particularly in grain mount (Le Bayon et al., 2006). Either possibility would allow Pb loss from and/or younger monazite intergrowth with an inclusion.

### 7. Implications for geochronology and tectonics

#### 7.1. Tectonic implications of the monazite age data

The concordant $\sim 500$–400 Ma monazite inclusions record metamorphism of Greater Himalayan rocks at this time, supporting previous interpretations (Stocklin and Bhattarai, 1977; Stocklin, 1980; Garzanti et al., 1986; Hodges et al., 1996; Argles et al., 1999; Marquer et al., 2000; Godin et al., 2001; Viskupic and Hodges, 2001; Catlos et al., 2002b; Gehrels et al., 2003, 2006; Myrow et al., 2006; Cawood et al., 2007). Our work is the first to document concordant lower Paleozoic monazite in Greater Himalayan Formation I rocks. We speculate that the $\sim 505$–475 ages record prograde metamorphism whereas the $\sim 425$–405 ages record retrograde metamorphism of Greater Himalayan rocks. Only 9 of 196 monazite analyses yielded Th/Pb dates within 20% of 500 Ma, however, which indicates that Pb loss and/or monazite intergrowth during Cenozoic metamorphism strongly affected lower Paleozoic monazite (Figs. 3, 6, 8, ESM3, ESM4).

A relative probability plot of all 57 concordant Cenozoic ages draws attention to the temporal patterns of Cenozoic metamorphism of the Greater Himalayan rocks of the Annapurna Range (Fig. 16). Most of the ages fall into two groups, 42–29 Ma and 22–12 Ma, with very few ages between 29 and 22 Ma and only one
age older than 42 Ma. We suggest that the older age group represents monazite growth during prograde metamorphism and that the younger age group records monazite growth during retrograde metamorphism. If this interpretation is correct, we expect differences in the chemical compositions of the two generations of monazite because different reactions produced the monazites (c.f. Kohn et al., 2004). There is a small but systematic difference in Th concentrations: the 42–29 Ma concordant monazites have a mean Th concentration of 6.4 wt.% and the 22–12 Ma concordant monazites have a mean Th concentration of 10.4 wt.% (Fig. 17). The younger group also has a much greater range of concentrations. Unfortunately, we have X-ray maps of only a few inclusions composed of both 42–29 Ma and 22–12 Ma monazite. One of these inclusions comes from sample 502067 from the Modi Khola transect (Fig. 11). The Y concentration of the 31±4 Ma sector of this composite grain is much higher than the Y concentration of the 19±5 Ma sector, whereas the Th concentration of the 31 Ma part is somewhat lower than the Th concentration of the 19 Ma part (see also Table ESM1). Interaction with the relatively low Y garnets in sample 502067 (Fig. 13) might explain the relative Y concentrations of these two parts of the inclusion. If garnets growing in this rock sequestered relatively little Y, then enough Y might be available to grow relatively high Y monazite during prograde metamorphism at ~31 Ma. In contrast, garnet breakdown during retrograde metamorphism released relatively little Y (Fig. 13), making little Y available to monazite growing at ~19 Ma. The difference in Th concentrations between the two generations of monazite is more difficult to explain, but might result from different reactions involving high Th minerals such as ThSiO₄, thorianite, older generations of monazite, or perhaps apatite during prograde and retrograde metamorphism.

Burial of the Greater Himalayan series by thrust sheets...
composed of Tethyan rocks likely caused prograde metamorphism of the Greater Himalayan rocks between 42 and 29 Ma, a conclusion broadly consistent with results from the western Himalaya (Vance and Harris, 1999; Foster et al., 2000; Wiesmayr and Grasemann, 2002). Exhumation caused by slip on the STDS, MCT, Ramgarh thrust, and other nearby faults probably drove retrograde metamorphism of the Greater Himalayan series between 22 and 12 Ma, although continuous activity on each of these faults throughout this time period is unlikely.

Although the oldest concordant Cenozoic monazite has a Th/Pb age of 46±1 Ma, all but one of the concordant Cenozoic analyses yield Th/Pb ages of 42 Ma or younger. Indeed, ages between ~37 and 29 Ma dominate the largest peak on the relative probability plot. We conclude that Cenozoic monazite growth in some Greater Himalayan rocks in the Annapurna Range might have begun by 46 Ma, but abundant monazite growth in most Greater Himalayan rocks began at ~42 or even 37 Ma.

de Sigoyer et al. (2000) and Leech et al. (2005) show that Cenozoic prograde metamorphism of the Tso Morari complex in the western Himalaya to medium or higher grades was ongoing at ~55 Ma. Parrish et al. (2006) demonstrate that rocks in a similar structural position in the Kaghan Valley of northern Pakistan reached temperatures of 720–770 °C and pressures of >27.5 kbar at 46.4 Ma. These rocks from directly south of the Indus–Yarlung suture thus reached temperatures conducive to monazite growth (perhaps 300 to 400 °C) about 5 to 15 M.y. before Greater Himalayan rocks of the Annapurna Range reached similar temperatures. This temporal difference in the age of Cenozoic heating probably results from a spatial difference in the positions of the near-suture and Annapurna rocks prior to collision. The age data indicate that the Tso Morari and Kaghan rocks were located outboard of (farther north than) the Annapurna Greater Himalayan rocks prior to collision of India and Asia, and thus subduction and metamorphism of the Tso Morari and Kaghan rocks began before subduction and metamorphism of these Greater Himalayan rocks.

The termination of growth of large monazite inclusions in Greater Himalayan garnets at ~12–14 Ma may record the cooling of Greater Himalayan rocks through some critical temperature range above which large crystals can grow and below which they cannot. This critical temperature range could control either the reactions that break down minerals that contain the chemical constituents of monazite or the reactions that produce monazite from these constituents, or both. The discordant dates younger than ~12 Ma from the Marsyangdi and Nayu Ridge transects demonstrate that conditions on the eastern side of the Annapurna Range remained conducive to limited monazite growth until at least 6 Ma, especially near the MCT. As discussed in the Interpretations section, we consider partial Pb loss from older grains an unlikely explanation for these young dates because Pb diffusion in monazite is so slow at low temperatures that significant resetting of ages by Pb loss is unlikely (Smith and Giletti, 1997; Cherniak et al., 2004; McFarlane and Harrison, 2006). Because the young dates result from mixing of very young monazite with ≥12 Ma monazite, it is likely that growth of small quantities of monazite continued after 6 Ma for an unknown length of time. Monazite growth may have continued during cooling to temperatures as low as 260–400 °C (Poitrasson et al., 2000; Rasmussen et al., 2001; Townsend et al., 2001; Harlov et al., 2002; Harlov and Forster, 2003; Bollinger and Janots, 2006). The eastern side of the Annapurna Range may have remained warm enough for monazite growth later than the central and western parts of the range, or other conditions in the eastern part of the range might have allowed limited monazite growth to continue at lower temperatures than in other parts of the range. For example, the dependence of monazite stability on Th/U ratio is unknown. Higher Th/U ratios, such as those found in monazite inclusions from the Marsyangdi transect, might allow monazite growth at lower temperatures than necessary for monazite growth with lower Th/U ratios.

7.2. Using monazite for geochronology

The utility of monazite inclusions in garnet from Greater Himalayan rocks for geochronology depends on which monazite growth episode is of interest. Inclusions in garnet are the only monazite crystals that remain intact from the early Paleozoic metamorphism of Greater Himalayan rocks; matrix monazite grains partially or completely recrystallized during Cenozoic metamorphism (Catlos et al., 2001, 2002b; Gehrels et al., 2003; Catlos et al., 2004; Kohn et al., 2004; Gehrels et al., 2006). Consequently, investigations of early Paleozoic metamorphism of Greater Himalayan rocks using monazite should focus on inclusions in garnet. The presence of remnants of lower Paleozoic monazite crystals complicates the use of monazite inclusions for studying the details of Cenozoic metamorphism of Greater Himalayan rocks, however. Because microcracks allow communication between the interior and the exterior of a grain, garnet only partially shields monazite from Pb loss and/or intergrowth of new
monazite. Microcracks are ubiquitous, so many inclusions are complex intergrowths of combinations of lower Paleozoic monazite, Cenozoic prograde monazite, and Cenozoic retrograde monazite. Mixed dates from such intergrown monazites usually have no tectonic significance because they are not crystallization ages. The multiple generations of monazite intergrown throughout single composite inclusions complicate interpretations of element zoning patterns and (U, Th)/Pb dates, making interpretation of the details of Cenozoic metamorphism more difficult.

It may sometimes be easier to interpret the growth history of matrix monazite crystals (e.g. Kohn et al., 2004). Because the preservation potential during later high grade metamorphism of lower Paleozoic matrix grains is less than the preservation potential of lower Paleozoic crystals included in garnet, interpretations of (U, Th)/Pb dates, element zoning patterns, and textural relationships of matrix monazite need not necessarily involve lower Paleozoic monazite, only Cenozoic monazite. Interpretation of (U, Th)/Pb dates of matrix monazite is thus often simpler than interpretation of dates of monazite inclusions because there are fewer likely explanations of matrix monazite dates. However, because garnet still partially shields inclusions from Pb loss and intergrowth of new monazite, inclusions in garnet contain the records of the earliest Cenozoic metamorphism of Greater Himalayan rocks. Later Cenozoic metamorphism overprinted much of the early-formed Cenozoic monazite that remained in the matrix.

7.3. Implications for previous studies

Our new data, combined with previous studies of low temperature growth of monazite, shed additional light on the data and conclusions of previous workers who used in situ (U, Th)/Pb methods to date monazite inclusions in Greater Himalayan garnets. Four points seem most relevant. First, the discovery of inclusions that demonstrably consist of intergrowths of different generations of monazite indicates that the assumption that garnet shields inclusions from recrystallization and intergrowth of younger monazite is likely invalid for many inclusions. Instead, microcracks probably allow communication between the interior and the exterior of garnet. Most monazite inclusions yield discordant \( ^{238} \text{U}/^{206} \text{Pb} \) and \( ^{232} \text{Th}/^{208} \text{Pb} \) dates, and these dates are not crystallization ages. Discordant dates should not be combined with concordant ages to draw conclusions about thrust belt kinematics. Accordingly, conclusions based on the assumption that all dates are crystallization ages or on the assumption of complete shielding by garnet are dubious. Second, several authors make clear that monazite can grow at temperatures as low as 260–400 °C, especially during metasomatism (Poitrasson et al., 2000; Rasmussen et al., 2001; Harlov et al., 2002; Harlov and Forster, 2003; Bollinger and Janots, 2006). Since Greater Himalayan rocks experienced retrograde metamorphism and metasomatism during cooling from \( \sim 700 °C \) (e.g. Ganguly et al., 2000; Stephenson et al., 2000; Daniel et al., 2003; Kohn et al., 2004; Martin, 2005), it is likely that significant monazite growth occurred on the retrograde path. For example, all of the dates younger than \( \sim 12 Ma \) record limited monazite growth during retrograde metamorphism. Therefore, conclusions based on the assumption that most or all monazite growth occurred during prograde metamorphism are also suspect (c.f. Bollinger and Janots, 2006). Third, because Cenozoic prograde and retrograde metamorphism produced multiple generations of monazite in Greater Himalayan rocks, it is usually inappropriate to treat most or all Cenozoic dates as a single population. Finally, because matrix monazites are completely unshielded from recrystallization mediated by aqueous fluids in the rock, whereas inclusions in garnet are partially shielded, interpretations of the significance of ages from the two types of monazite should not necessarily proceed in the same manner. It is not obvious that ages from the two types of monazite can be compared directly or grouped a priori, without justification.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.chemgeo.2007.05.003.
References


Phosphates: Geochemical, Geobiological, and Materials Importance.


