Zircon age peaks: Production or preservation of continental crust?

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ABSTRACT

Zircon age peaks are commonly interpreted either as crustal production peaks or as selective preservation peaks of subduction-produced crust selectively preserved during continent-continent collision. We contribute to this ongoing debate, using the Nd isotopic compositions of felsic igneous rocks and their distribution during the accretionary and collisional phases of orogens. The proportion of juvenile input into the continental crust is estimated with a mixing model using arc-like mantle and reworked continental crust end members. Orogen length and duration proxies for juvenile crustal volume show that the amount of juvenile crust produced and preserved at zircon age peaks during the accretionary phase of orogens is 3 times that preserved during the collisional phase of orogens. The fact that most juvenile crust is both produced and preserved during the accretionary phase of orogens does not require craton collisions for its preservation, thus favoring the interpretation of zircon age peaks as crustal production peaks. Most juvenile continental crust older than 600 Ma is produced and preserved before final supercontinent assembly and does not require supercontinent assembly for its preservation. Episodic destabilization of a compositionally heterogeneous layer at the base of the mantle may produce mantle plume events leading to enhanced subduction and crustal production. Our Nd isotope model for cumulative continental growth based on juvenile crust proxies for the past 2.5 b.y. suggests a step-like growth curve with rapid growth in accretionary orogens at the times of zircon age peaks.

INTRODUCTION

There is an ongoing debate about the interpretation of zircon age peaks in igneous rocks and detrital sediments (Rino et al., 2004; Arndt and Davaille, 2013; Hawkesworth et al., 2013). The conventional interpretation is that the age peaks correspond to peaks in production of new continental crust extracted from the mantle (Stein and Hofmann, 1994; Condie, 1998; Albarède, 1998). However, this interpretation has been challenged by advocates of recycling and preservation models; they propose that the peaks record periods of enhanced preservation of crust during the assembly of supercontinents (Condie and Aster, 2009, 2010; Hawkesworth et al., 2010; Voice et al., 2011). In the preservation models, juvenile crust is preferentially trapped in collisional orogens during continent-continent collisions, and the peaks do not record enhanced crustal production. Although numerous models of continental growth have been proposed, some based on Hf model ages (in some cases filtered with oxygen isotope data), none has clearly distinguished between the production and preservation interpretations (Belousova et al., 2010; Condie and Aster, 2010; Dhuime et al., 2012; Arndt and Davaille, 2013; Roberts and Spencer, 2015). In recent years, precision of isotopic ages and Hf and Nd isotopic measurements has increased, and thus the zircon age peaks can be better defined (Condie and Aster, 2010). As pointed out in earlier studies, detrital zircons probably give the best representation of global ages because large rivers sample broad continental regions, whereas zircons from outcrops of igneous rocks show significant geographic variations (Campbell and Allen, 2008; Belousova et al., 2010; Iizukaa et al., 2013). Evidence suggests that zircon age peaks at 2700, 1900, 1100, 550, and 260 Ma are global or at least very widespread, whereas peaks at 2500, 2150, 1630, and 800 Ma are more regional in extent (Fig. 1). There may or may not be a widespread peak around 100 Ma. Age valleys are more difficult to track, but those around 2300, 900, and 400 Ma may be global, and those at 1500, 1350, and 700 Ma appear to be only regional in extent.

Hawkesworth et al. (2010), Condie and Aster (2009), and Condie (2013) suggest that zircon age peaks correlate with times of craton collisions when juvenile crust produced in subduction zones is preferentially preserved. In this study, we identify and attempt to quantify the juvenile component of continental crust with whole-rock Nd isotopes from felsic igneous rocks, and depending on their geographic locations, we group them into collisional or accretionary phases of orogens. During the accretionary phase of orogens, juvenile crust is produced and at least partially preserved in the forearc, arc, or backarc regions; whereas during the collisional phase, very little juvenile crust is produced, but crust produced during the accretionary phase may be captured and selectively preserved. In this study, we identify and tally orogens by orogenic phase during each zircon age peak, and from this information, we distinguish juvenile crust produced and preserved during accretionary phases from that produced during accretionary phases but preserved during collisional phases. We also estimate the volumes of juvenile continental crust preserved during accretionary and collisional orogen phases using three proxies: number of samples, orogen length, and orogen duration.
Figure 1. Raw and filtered distributions of zircon ages from 3500 Ma to the present, with episodes of Archean supracrust assembly (green shaded area), final supercontinent assembly (pink shaded areas), and supercontinent breakup (yellow shaded areas) superimposed. (A) Raw distribution for Database 1; (B) bandpass-filtered distribution for Database 1; (C) raw distribution for modern river Database 2; (D) bandpass-filtered distribution for modern river Database 2 (Puetz et al., 2016). Database sources: Campbell and Allen (2008); van Hoang et al. (2009); Belousova et al. (2010); Yang et al. (2012); Itizuka et al. (2013); Welke (2013); Blum and Pecha (2014); Gärtnert et al. (2014); Licht et al. (2014); Yi et al. (2014). Filtering methods discussed in Puetz et al. (2016).

**METHODS**

The term *cluster sampling* refers to the collection of multiple samples from a single geographic site and is commonly used in obtaining zircon grains for U/Pb isotopic analysis. In contrast, *regional sampling* relies on single (or few) samples collected from many different sites. A detailed discussion of cluster and regional sampling is given in Puetz et al. (2016). A cluster sample is not a true random sample, and this method normally increases the uncertainty of estimates made from geological populations. Importantly, cluster sampling is valid only when each cluster serves as a small-scale representation of the total population and there is a high degree of age heterogeneity within each cluster (Lo and Watson, 1998). Because zircons obtained from a single outcrop of an igneous rock tend to have similar ages, the narrow age range makes this type of sampling inappropriate for estimating global zircon age distributions. Thus, zircon databases containing cluster samples of igneous rock from single geographic sites are likely to exaggerate some age peaks (Figs. 1A and 1B). Conversely, detrital-zircon cluster samples from either modern sediments or ancient sedimentary rocks typically show a wide age variation, making them viable for inclusion in global databases, in agreement with earlier studies of detrital-zircon ages (Campbell and Allen, 2008; Belousova et al., 2010). Moreover, Stehman and Selkowitz (2010) show that cluster sampling is especially appropriate for making geological age estimates when combined with regional sampling—an approach used here for developing an improved global zircon database (Figs. 1C and 1D) (Puetz et al., 2016).

Two U/Pb zircon databases are developed from samples obtained from previous studies, with duplicates removed. Database 1 (Figs. 1A and 1B) contains a mixture of igneous, metamorphic, and detrital sedimentary zircons from Roberts and Spencer (2015) and Voice et al. (2011). Database 2 (Figs. 1C and 1D) contains detrital zircons exclusively from modern river sands, with the exception of Antarctica zircons, which are from young sedimentary glacial deposits. All samples in Database 2 are weighted proportionally to corresponding continental surface areas, and sampling of all seven continents was accomplished by using published ages of detrital zircons (see Puetz et al., 2016). The samples are used to develop raw histograms for both databases, consisting of 30-m.y. bins (Figs. 1A and 1C). The raw time-series records are high-pass filtered using division with a 41-weight Gaussian smoother and then low-pass filtered with a 3-weight Gaussian smoother (Puetz et al., 2016). This type of bandpass filter produces smoothed and detrended time-series plots (Figs. 1B and 1D) of major peaks and valleys in zircon ages.

Published εNd(t) isotopic data from felsic igneous rocks are given in Supplemental Table 11 and plotted in Figure 2 as a function of age. Felsic igneous rocks not related to orogens, such as those from large igneous provinces (LIPs) and continental rifts, are not included in the database. Although model ages are commonly used to construct models of continental growth (Belousova et al., 2010; Dhuime et al., 2012) because of the uncertainties and ambiguities associated with model ages as summarized by Arndt and Goldstein (1987) and Roberts and Spencer (2015), we have chosen to use εNd(t) values in felsic igneous rocks to estimate the proportion of juvenile crust in mixtures of mantle-derived magma and recycled crust (Fig. 2; Supplemental Table 1 [see footnote 1]). Although depleted mantle with the composition of an ocean-ridge basalt source is commonly used as the juvenile mantle end member in εNd(t) mixing models, we use a less depleted end member that should be more representative of the mantle wedge with an assumed εNd(t) today of +8 as proposed by Dhuime et al. (2011). This choice is appropriate because our aim is to establish how the flux from the mantle source into the crust varied as a function of time, not the overall evolution of the crust-mantle system. The reworked felsic crustal end member is chosen to encompass ≥98% of the negative εNd(t) values, with a modern value of 1.12.
about –17. Using alternative modern epsilon values anywhere between –13 and –25 results in only a small difference in the mixing proportions (10%–20%). Contours of 70% and 90% mantle input are shown in Figure 2 with the latter contour falling close to the $\varepsilon_{\text{Nd}}(t) = 0$ line. Contrary to the idea that rocks with $\varepsilon_{\text{Nd}}(t)$ close to zero consist largely of recycled older crust, this calculation shows that they are mainly juvenile. Each geographic site from which $\varepsilon_{\text{Nd}}(t)$ data are available is assigned to an orogen, which is classified into an accretionary or collisional phase (Condie, 2013; Supplemental Table 2). We have a total of 47 accretionary phase orogens and 22 collisional phase orogens in our database.

Figure 3 is a flow chart of our analysis of the data. Median $\varepsilon_{\text{Nd}}(t)$ values and zircon isotopic ages of felsic igneous rocks are calculated for each sample site, which is then assigned to an orogen and to a zircon age peak or valley, the latter of which are selected from Figure 1. The proportion of juvenile crust based on sample numbers is estimated using the 90% contour as a cutoff for juvenile input (Fig. 2). We use this value as proxy #1 for volume of juvenile continental crust (column L, Supplemental Table 2 [see footnote 2]). For proxy #2, we use orogen length (column N, Supplemental Table 2 [see footnote 2]). To estimate orogen length, orogens are plotted on the modern globe and measured with a global measuring tool (Freemaptools.com), and then cumulative orogen length is calculated for each zircon age peak. Orogen durations are from Condie (2013, with updates; column P, Supplemental Table 2 [see footnote 2]) and are estimated from the onset of ocean basin closing (oldest evidence for subduction) to the termination of deformation. Again, cumulative orogen duration is calculated for each zircon age peak. Both cumulative proxies are considered to be minimal estimates. Uncertainties are shown in Supplemental Table 2 (see footnote 2) as one standard deviation of the mean for calculated values based on the range of $\varepsilon_{\text{Nd}}(t)$ for each orogen. These uncertainties are small compared to uncertainties related to representativeness of sample populations, orogen lengths, and orogen durations, all of which are difficult to estimate but are probably ≤20%.

## RESULTS

The calculated percentage of juvenile input into each orogen is based on number of samples for which $\varepsilon_{\text{Nd}}(t)$ is available and is given in Figure 4 (including both cluster and regional samples). Our flow chart in Figure 3 shows how this figure is constructed. If the number of samples is representative of the overall volume of juvenile continental crust preserved, the accretionary
phase of orogens contains greater than 80% juvenile input (with a median value of 91.3%). This estimate is similar to observations from earlier studies based on Hf isotope data (Dhuime et al., 2012). In contrast, the collisional phase of orogens, which is more variable in juvenile and reworked proportions (Fig. 4), generally contains 70%–85% juvenile input (median = 77%), with some containing <50% (e.g., Damara, Jiangnan, and Arrowsmith orogens; Supplemental Table 2 [see footnote 2]). These relationships support the results of previous studies (Condie and Aster, 2009; Hawkesworth et al., 2010) that most juvenile crust is produced during the accretionary phase of orogens and not during the collisional phase.

To estimate the distribution of juvenile continental crust in the rocks that define zircon age peaks, we have assigned each orogen to a zircon age peak or valley based on age. Using the 90% juvenile mixing contour as the lower limit of juvenile input (Fig. 2), the fraction of juvenile crust preserved in age peaks and valleys is roughly the same (50%–80%), with a suggestion that the two valleys older than 1 Ga have somewhat greater juvenile input than the peaks (Fig. 5).

The results also suggest an overall decrease in the relative proportion of juvenile crust produced with time with perhaps a steep decline after the 1100 Ma peak where a drop may occur from 70%–80% to <70%. This trend is consistent with the results from Hf isotope studies of detrital zircons (Belousova et al., 2010; Dhuime et al., 2012; Roberts and Spencer, 2015). The overall decline with time may be due to smaller volumes of magma from the mantle as mantle temperatures decrease (Condie et al., 2016) combined with an increase in the thickness and abundance of continental crust. The latter constitutes a filter that inhibits the passage of magma toward the surface and increases the amount of contamination with preexisting crust.

Because the distribution of Nd sample sites can be biased by uneven regional sampling methods, we have selected two additional proxies for the volume of juvenile continental crust produced with time: orogen length and orogen duration (Supplemental Table 2 [see footnote 2]). The length proxy for juvenile crust in accretionary
orogens exceeds that in collisional orogens by a factor ≥3 (Fig. 7). For age valleys, the production-preservation rate of juvenile crust in both proxies for both types of orogens is similar to the low values characteristic of collisional peaks. Results are not shown for the 1630 and 800 Ma peaks or for the 700 or 900 Ma valleys because of inadequate Nd isotopic data. Although the length and duration proxies have uncertainties that are difficult to quantify, both proxies of the volume of juvenile continental crust have similar age distributions. These estimates of juvenile crust proportions are greater than those of Condie (2013) reflecting our much larger and more representative Nd isotope database and more precise proxies for orogen volumes through time. The number of geographic sites with $\varepsilon_{\text{Nd}}(t)$ data increased from 50 to 69, and the number of samples increased from 1410 to 5939. The bottom line of these observations is that most of the juvenile crust is produced and preserved during the accretionary phase of orogens and thus does not require craton collisions for its preservation.

**DISCUSSION**

Our analysis of Nd isotopic data from zircon age peaks and valleys suggests that a large proportion of juvenile continental crust is both produced and preserved during the accretionary stage of orogens, thus favoring a crustal production interpretation for the zircon age peaks as previously suggested (Condie, 1998; Arndt and Davaille, 2013). Some accretionary orogens, such as the Great Proterozoic accretionary orogen (GPAO) of Laurentia (Condie, 2013), can produce and preserve juvenile crust for several hundred million years before a terminal collision, and the terminal collision only selectively preserves the past few tens of millions of years of this crust. The GPAO is subdivided into geographic components based on episodes of orogenic activity in Supplemental Table 2 (see footnote 2). For the past 200 m.y., the production and recycling rates of continental crust in the Andes have been approximately the same, and this may also apply to the circum-Pacific region for this time interval (Scholl and
von Huene, 2009). If so, there may have been little or no net growth of continental crust on Earth for the past 200 m.y. (Stern and Scholl, 2010; Stern, 2011). However, our three juvenile crust proxies (number of samples, orogen length, and orogen duration) do not seem to support this conclusion on a global scale, particularly in the Precambrian. These proxies suggest that the rate of juvenile continental crust production and preservation has been relatively constant or decreasing with decreasing age for the past 2 b.y. (Figs. 5–7). A useful comparison of the \( ^{147} \text{Nd}(t) \) of sediments and granitoids and \( ^{176} \text{Hf}(t) \) in detrital zircons as a function of age from ca. 4 Ga to the present is given in Condie and Aster (2013). In the time period from 1 to 2 Ga, \( ^{147} \text{Nd}(t) \) and \( ^{176} \text{Hf}(t) \) show remarkable agreement and exhibit relatively small amplitude changes. This suggests that both isotopic systems are dominantly sampling the same or similar types of orogens. Prior to 2 Ga, \( ^{147} \text{Nd}(t) \) is consistently more juvenile than \( ^{176} \text{Hf}(t) \), probably as a result of sampling of orogens with different ratios of juvenile to reworked crust, and perhaps also due to recycling of older zircons. Additional support for the interpretation of zircon age peaks as crustal production peaks is the preservation of both peaks and valleys in detrital sediments (Parman, 2015). The prominence of the 1900 and 1100 Ma peaks and the 2300 and 1500 Ma valleys in detrital zircons from progressively younger sediments suggests that the memory of these peaks is preserved and propagated through time.

Continent-continent collisions associated with supercontinent assembly are an important part of the preservation model for the interpretation of zircon age peaks (Fig. 1) (Hawkesworth et al., 2010). However, there is considerable uncertainty and disagreement of the timing of the supercontinent cycle prior to ca. 600 Ma. Also, during the initial stages of collision, uplift may bias the detrital-zircon input into sediments, when detritus is derived chiefly, if not exclusively, from the upper plate. Results of Li et al. (2013) and Pisarevsky et al. (2014) show that zircon age peaks generally do not correlate well with the assembly of Precambrian supercontinents (Campbell and Allen, 2008; Bradley, 2011; Evans, 2013). Peaks at 3300, 2700, and 2500 Ma occur before the assumed onset of the supercontinent cycle, and only one Archean supercraton (Superia) may have assembled in the Neoarchean (2700–2500 Ma; Evans, 2013) (Fig. 1). However, the >200 m.y. duration commonly assigned to supercontinent assembly (e.g., Hawkesworth et al., 2010) overlaps two distinct peaks—the 2700 Ma peak, which is of global extent, and the 2500 Ma peak, which dominates in China and India. Likewise, the global 1900 Ma zircon age peak coincides with early craton collisions (1900–1800 Ma) but not with the final assembly of Nuna (1700–1500 Ma; Pisarevsky et al., 2014; Pehrsson et al., 2016). Rodinia assembly may or may not correlate with the 1100 Ma peak because estimates of assembly times range from 1250 to 980 Ma (Cawood et al., 2001) to 1000–850 Ma (Condie et al., 2015a). The small 1630 Ma peak and large 530 Ma peak may correlate with the assembly of supercontinents Nuna (1700–1500 Ma) and Gondwana (650–520 Ma; Cawood and Buchan, 2007), respectively. Age valleys at 1500 and 1350 Ma occur before supercontinent (Nuna) breakup, and age valleys at 900 and 400 Ma may correlate with supercontinent assembly. Only the 700 Ma age valley may correlate with supercontinent breakup (Rodinia, 825–570 Ma; Cawood et al., 2001). Although continent-continent collisions certainly have the potential to selectively preserve juvenile crust produced both before and during the collisions (Hawkesworth 2009, 2010; Condie and Aster, 2010), most juvenile continental crust older than 600 Ma is produced and preserved before final supercontinent assembly, as documented above.

The coincidence of Re/Os model age peaks from mantle xenoliths with zircon age peaks at 2700 and 1900 Ma records the existence of mantle events corresponding in time to the proposed crustal production events (Pearson et al., 2007; Ionov et al., 2015). Episodic emplacement of LIPs and eruption of komatiite (Condie et al., 2015b) at the times of the crustal age peaks provides further evidence of a mantle origin. On this basis, we retain the model in which the peaks are triggered by global mantle plume events, as advocated by Stein and Hofmann (1994), Condie (1998), and Arndt and Davaille (2013). Refinement of the Clapeyron slope of the ringwoodite reaction at 660 km shows that slab avalanches at this seismic boundary are not likely to have triggered bursts of mantle plume generation (Katsura et al., 2003; Fei et al., 2004). Also, global plume events triggered by slab avalanches tend to work for 2D models (Machetel and Weber, 1991) but not for 3D models (Tackley, 1996). Interpreted in light of global LIP events, experimental plume models of Davaille (1999) suggest that the episodic destabilization of a compositionally heterogeneous layer at the base of the mantle could produce mantle plume clusters with a recurrence time of 100–300 m.y. Such destabilization requires heating of the bottom lower mantle either due to a higher concentration in radioactive elements and/or to heat transport from the hot core. The thermal state of the latter is modulated by the episodic resonance of lunar-solar tidal forces on a billion-year time scale (Greff-Lefftz and Legros, 1999; Andrault et al., 2016). Although this time-dependent core thermal condition might also contribute to periodic global plume events, the heterogeneous mantle model recurrence time of 100–300 m.y. agrees well with the strong periodicity of zircon age peaks and LIP events (plume generation events) of ~274 m.y. (Puetz et al., 2014; Condie et al., 2015b). These episodes of mantle plume generation operate independently of the supercontinent cycle. We emphasize that we do not advocate generation of continental crust directly for plume-derived material; instead we propose that the generation of plumes led to enhanced subduction and consequent accelerated growth of continental crust and, thus, could be responsible for global zircon age peaks (Arndt, 2013; Arndt and Davaille, 2013).

And finally, our Nd isotope model based on the length and duration proxies suggests a step-like cumulative growth curve for continental crust in the past 2.5 b.y. with rapid growth at 2.1–1.8, 1.2–1.0, and 0.65–0.35 Ga (Fig. 8). Crustal recycling rate may have increased at 1.6–1.3 and 1.0–0.7 Ga when the growth rate decreases. The 0.65–0.35 Ga period corresponds to the assembly of Pangea-Gondwana, the 1.2–1.0 Ga period to assembly of Rodinia, and the 2.1–1.8 Ga period to the beginning of the assembly of Nuna (Fig. 1) (Condie et al., 2015b). The overall continental growth pattern differs significantly from models based on HF model ages, which show most continental growth between 2 and 4 Ga and lack the step-like pattern of the Nd isotope model (Belousova et al., 2010; Dhuime et al., 2012).
CONCLUSIONS

(1) Based on Nd isotopes in felsic igneous rocks, the fraction of juvenile continental crust produced during zircon age peaks in the past 2.5 b.y. is similar to that produced during age valleys. This suggests that the mechanisms of continental growth are similar in age peaks and valleys, most probably related to subduction.

(2) Accretionary orogens are more abundant than collisional orogens during zircon age peaks.

(3) Using oxygen length and duration as volume proxies in conjunction with Nd isotopes in felsic igneous rocks, the cumulative volume of juvenile continental crust produced and preserved during zircon age peaks during the accretionary phase of orogens is 3 times that preserved during the collisional phase of orogens.

(4) The fact that most of the juvenile crust is both produced and preserved during the accretionary phase of orogens does not require craton collisions for its preservation and, thus, favors the interpretation of zircon age peaks as crustal production peaks.

(5) Our Nd isotope model for continental growth based on juvenile crust proxies suggests a step-like cumulative growth curve for continental crust in the past 2.5 b.y. with rapid growth at 2.1–1.8, 1.2–1.0, and 0.65–0.35 Ga.

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