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A whole-lithosphere view of continental growth

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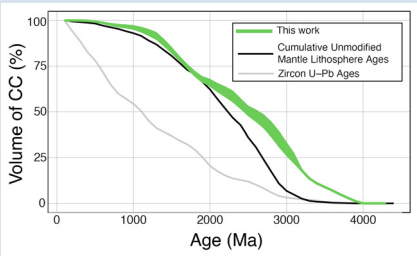
Abstract



Continental crust is a defining feature of Earth; yet, the mechanisms that control its growth remain hotly debated. Many approaches to estimating crustal growth focus solely on a single mineral—zircon, while constraints from the lithospheric mantle root remain largely neglected. Here, we critically examine the ability of zircon to accurately record the relative roles of juvenile crustal addition versus recycling, and present an alternative approach based on the geochemistry of crustal rock samples. The resulting model of continental crustal growth parallels, but pre-dates, the pattern of cratonic mantle lithosphere formation ages, indicating a distinct relationship between the continental crust and its mantle root. Our results indicate that continental crust and deep cratonic lithospheric roots grew progressively over ~2.5 Gyr of Earth history, with clear temporal links to the birth of extensive lithospheric keels and establishment of continental drainage basins.

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Introduction

Earth's intermediate to felsic composition continental crust is thicker and more buoyant than mafic oceanic crust, and represents an excellent archive of fundamental processes such as regulating the long-term carbon cycle, concentrating and hosting valuable mineral deposits, and providing unique habitats for biological development and diversification. Despite the importance of continental crust to humanity, there is little consensus on the timing of its formation and its stabilisation. Many widely used models, some of which are underpinned by zircon U–Pb and Hf isotope systematics (Belousova *et al.*, 2010; Dhuime *et al.*, 2012), emphasize the potential importance of voluminous continental growth in the Archean. These models produce a dramatic inflection point at ~3 Ga, where continental growth rate purportedly subsided and large tracts of crust were stabilised. However, there is little preserved evidence of this hypothesised voluminous ancient continental crust. Likewise, the continental lithospheric mantle—thick roots that stabilised ancient continental crust—have little extensive record prior to ~3.0 Ga (Pearson *et al.*, 2021).

Determining the relationship between the continental crust and the cratonic lithospheric mantle roots (CLMR) is critical in deciphering the growth of continental crust. In the modern Earth, deep lithospheric roots stabilise and appear to preserve extant continental crust (Lee *et al.*, 2017), so the discrepancy between preserved lithospheric mantle ages and previous crustal growth models (Fig. 1) suggests a genetic disconnect. Recent studies of the continental crust-CLMR relationship suggest that, while very ancient continental crust was formed and rapidly destroyed, the formation of lithospheric roots stabilised existing continental crust, thereby slowing the destruction, and growth rate, of continents (Hawkesworth *et al.*, 2017; Pearson *et al.*, 2021). This has been taken by some authors to indicate that continental crust and continental lithospheric mantle are related by selective preservation—and that their formation mechanisms were not related (Fig. 1). However, there are considerable uncertainties in models for continental growth rates.

Destruction of an ancient crustal record can take several forms, but is typically separated into two categories (Cawood *et al.*, 2013): 1) *Reworking*—processes that overprint the radiometric ages of the crustal record, but do not remove mass from the continents, such as partial melting and sedimentary erosion, and 2) *Recycling*—full scale removal of continental mass back into the mantle by delamination or sediment and continental subduction.

While there is isotopic evidence for some amount of continental crust recycled into the modern mantle (Jackson *et al.*, 2007), there is little evidence for vast volumes of ancient continental material residing in the mantle. For instance, volatile-element isotopic measurements typically indicate the onset of detectable crustal recycling near ~2.5 Ga (Coltice *et al.*, 2000; Parai and Mukhopadhyay, 2018; Labidi *et al.*, 2020). Thus, recycling is unlikely to be a major factor in destroying large volumes of primary continental crust before 2.5 Ga. Yet, the most ancient of crust—older than ~3.8 Ga—is restricted in its exposure at the surface of the Earth to the parts per million level. Thus, if large volumes of ancient continental crust did exist on Earth, reworking must be primarily responsible for overprinting the ancient geochronological signatures of that crust. Therefore, accurate

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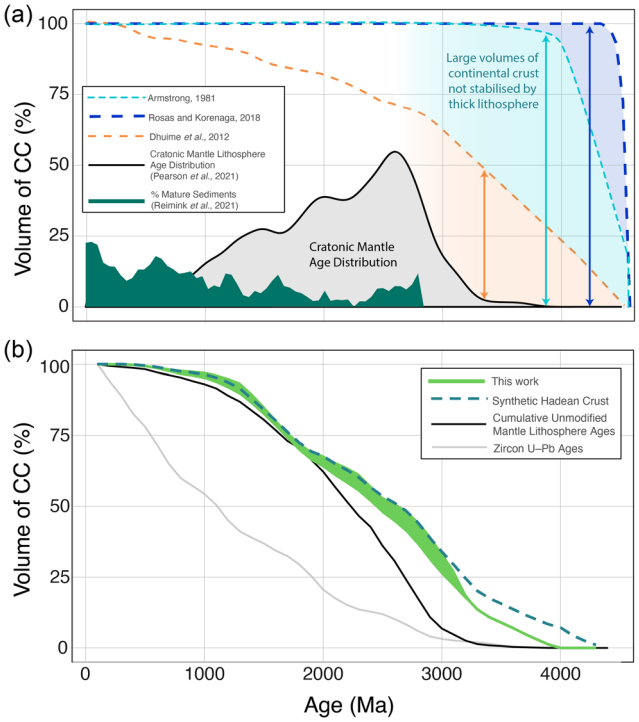

Figure 1 **(a)** Various crustal growth rate curves shown by dashed lines compared to the cratonic mantle age distribution. Vertical coloured arrows show the amount of continental recycling predicted by various estimates. The black curve shows the age distribution of unmodified cratonic mantle ages (Pearson *et al.*, 2021), while the green field shows the percentage of preserved mature sedimentary packages (Reimink *et al.*, 2021). **(b)** Shows the continental growth curve predicted in this work. The grey curve shows U–Pb ages of the preserved rock record (Puetz *et al.*, 2018). The black curve is the age distribution of unmodified cratonic mantle roots (Pearson *et al.*, 2021). The green curve is the crustal growth curve calculated here using bulk rock major element chemistry. The dashed green curve uses the same calculations as the solid green curve except for the utilisation of a synthetic Mesoarchean–Hadean rock record, to evaluate potential for sampling bias.

quantification of *reworking* is fundamentally important to model the primary formation age of continental landmasses.

Estimates of Continental Growth Rate

Recent estimates of the volumes of continental crust throughout Earth's history have relied on zircon Hf and O isotopes (Belousova *et al.*, 2010; Dhuime *et al.*, 2012; Korenaga, 2018). Hafnium isotopes in zircon can be used to both calculate the age of crust formation and the time the source material was extracted from the mantle, while oxygen isotope ratios have been used as a filter (Dhuime *et al.*, 2012). Zircon oxygen isotope ratios reflect the oxygen isotope composition of the source to the zircon-forming magmas. Oxygen isotope ratios in igneous rocks can be shifted from the unaltered mantle value by incorporation of material that has interacted with surface waters, *i.e.* sediments. Such incorporation of sedimentary rocks into the igneous system, *e.g.*, continental recycling, can generate zircon with high oxygen isotope ratios (Valley *et al.*, 2005), at least on the modern Earth.

Zircon U–Pb, Hf, and O isotope data have been combined to calculate widely used crustal growth estimates (Dhuime *et al.*, 2012) that indicate rapid crustal growth in the Archean and a

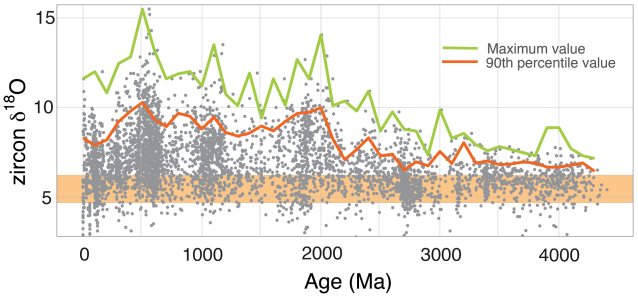

Figure 2 The distribution of zircon oxygen isotope compositions through time, highlighting the tendency of zircon oxygen isotope ratios to become progressively more extreme through time, making them a poor discriminant of continental reworking. The orange band shows a typical field for 'juvenile' zircon isotope compositions.

shift in crustal growth rate near 3.0 Ga to slower growth. Despite the popularity of this approach, drawbacks have been pointed out (Korenaga, 2018). A fundamental issue with the U–Pb/Hf/O approaches is that it is solely reliant on zircon geochemistry to accurately track continental recycling throughout geological time. While the combination of the U–Pb and Hf isotope systems may be reliable (Korenaga, 2018), the use of oxygen isotopes to track recycling is prone to uncertainty. For instance, recent studies have shown that zircon oxygen isotope ratios do not accurately identify sediment recycling in the Neoarchean (Bucholz and Spencer, 2019), a critical time period for constraining continental growth estimates. Additionally, the maximum oxygen isotope ratio of igneous zircons and shales (mature sedimentary rocks) continues to increase over time (Valley *et al.*, 2005; Bindeman *et al.*, 2018). This means that the sensitivity of the O-isotope reworking metric also changes throughout geological time (Fig. 2), making the proxy significantly less sensitive in the Archean than today. If continental reworking in the Neoarchean is under- or overestimated, it will impose a dramatic bias on any derivative continental growth curve.

To circumvent these issues, we take an approach that integrates the detrital zircon Hf isotope record—the record of the mantle extraction age of continental crust—with the bulk composition of the preserved continental rock record, to identify and correct for crustal reworking. We adopt this approach because the major element composition of igneous rocks can accurately quantify the extent of reworking of previous continental crust, whether reworking occurs via incorporation of sediments or direct melting of pre-existing continental crust (Frost and Frost, 2008; Moyen *et al.*, 2017). The major-element bulk composition approach is not inherently biased towards specific rock types. Contrary to oxygen isotope ratios, the range of major element compositions of igneous rocks is limited by the thermodynamics of partial melting: by mantle melting on one side and eutectic granite melting on the other. Thus, igneous rocks have strict limits to their composition irrespective of their age, rendering them accurate and consistent tracers of continental reworking through geological time.

Crustal Reworking

Our estimate of the reworking rate of continental crust (Fig. 3) uses input from the classic ACNK/ANK diagram of Shand, (1943), further developed to isolate source composition from fractionation and assimilation trends in magmatic rocks by Moyen *et al.* (2017). This method is explained in detail in the Supplementary Materials. In this projection, a theta value of

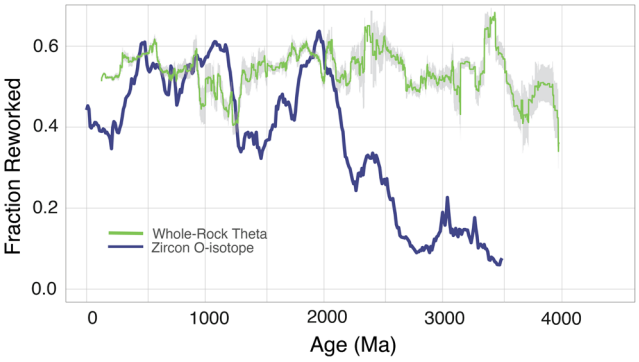

Figure 3 The fraction of rocks classified as reworked continental crust from Figure 1 using the bulk geochemistry approach adopted here (green curve with grey band showing 2SE uncertainty) compared to the reworking estimates based on zircon oxygen isotope ratios. Curves calculated in 200 Ma moving windows in 10 Ma time steps. The zircon record dramatically under-estimates reworking in the Archean.

10–30 degrees reflects crustal and peraluminous melt sources, *i.e.* a rock formed by continental reworking, whereas a theta value of less than 10 represents juvenile primitive magma with minimal crustal input (Fig. 4). An added benefit of this metric is that it classifies melts of continental crustal rocks in a similar way to melts of sedimentary rocks—useful for our purposes as both origins reflect continental reworking. This is an improvement on the commonly used aluminum saturation index, another metric used to classify whole rock geochemical data that successfully discriminates pure sediment derived melts but does not identify evolved (fractionated) compositions formed from igneous sources—a composition we must accurately identify when considering continental recycling through time.

The theta value calculation does not divide rock compositions into a binary 'reworked' or 'juvenile' category. Instead, we have employed a naïve Bayesian classifier to calculate five probabilities for each whole-rock composition, one for each class of source materials ranging from ultramafic to sedimentary. These probabilities are divided into two groups, reworked and juvenile (see Supplemental Methods for further explanation). The sum total of each reworking and juvenile probability, across all individual whole-rock measurements in any particular age bin, were then totalled to determine the reworking fraction in that age bin.

The resulting trace of crustal reworking through geological time, as viewed by the whole-rock elemental record, primarily differs from the zircon oxygen isotope record in that it is relatively constant through time. For instance, using the major element-based temporal trace in Fig. 3, the fraction of reworked crust varies by less than a factor of two (only between 0.5 and 0.3 post- 3 Ga), whereas the O-isotope based trace varies by a factor of seven, with significant swings in magnitude over short time intervals (Fig. 3).

In the Neoarchean, whole-rock data indicate significantly more reworking than the zircon oxygen isotope model. The causes of this difference are not readily apparent, but may be due to anoxic weathering conditions that adversely affect the ability of oxygen isotope ratios to accurately track continental reworking (Bucholz and Spencer, 2019). Many sedimentary rocks and their derivative melts are known from the Neoarchean period (Donaldson and de Kemp, 1998; Laurent *et al.*, 2014), indicating that continental reworking took place; yet, the existence of significant crustal reworking is not clearly captured by the zircon oxygen isotope record. The whole-rock bulk geochemical compositional record appears to be a more reliable index of crustal reworking than the zircon oxygen isotope tracer for a combination of reasons. The angular projection employed in our "reworking index", based on major elements, can identify

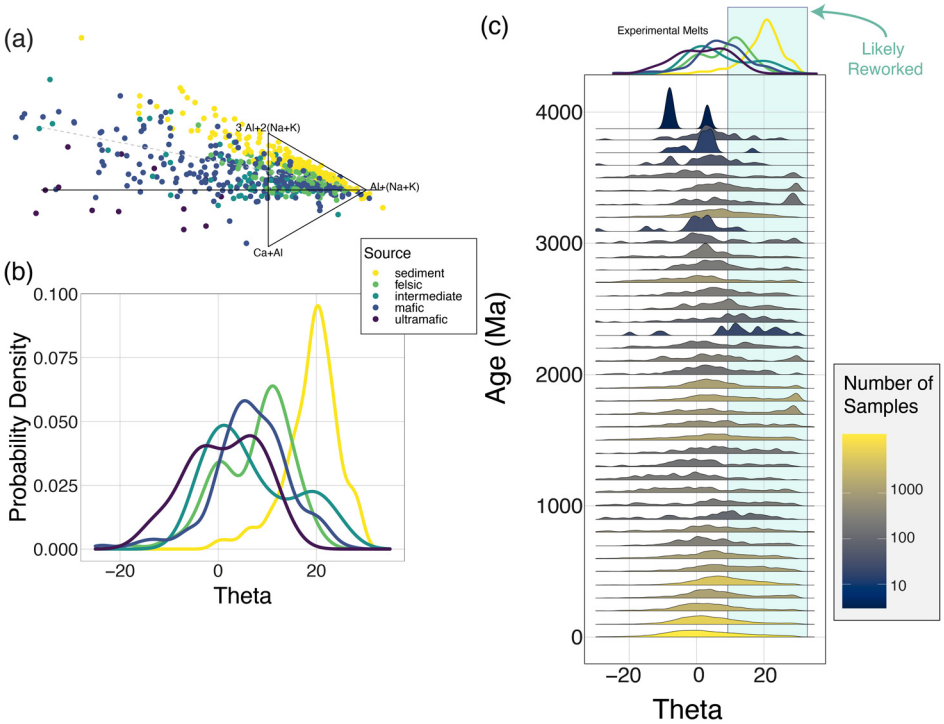

Figure 4 Reworking through time as seen through the whole-rock record. **(a)** The whole-rock geochemical data used to calculate a 'theta' value, with experimental melts shown coloured by starting composition. **(b)** Our classifier for data shown in panel b, showing the probability density for each category across a range of Theta values. **(c)** The distribution of Theta values across geological time. A probability density estimator is shown for the theta values for rocks split into 100 Ma age bins and coloured according to the number of rock samples in each age bin. Rocks that likely represent reworked crust fall into the blue field and have been present since the early Archean.

the recycling of continental igneous rocks, as well as the products of melting of sedimentary rocks—a phenomenon that zircon oxygen isotope ratios are only well-suited to detect in the post-NeoArchean rock record (Fig. 2) after large volumes of sedimentary rocks began to be deposited following continental emergence (Valley *et al.*, 2005; Reimink *et al.*, 2021).

We leverage our improved reworking metric to calculate a continental growth rate curve (Fig. 1; see supplementary methods for details) starting from a widely used crustal growth estimate based on zircon U–Pb & Hf isotopes (Dhuime *et al.*, 2012) following some refinement (Korenaga, 2018) and an updated zircon Hf dataset (Roberts and Spencer, 2015) (green curve Fig. 1b). In contrast to approaches based solely on zircon, our new bulk rock-based continental growth curve shows no slowing of continental growth at 3.0 Ga but instead indicates the onset of significant continental growth at ~3.5 Ga and reduction in crustal growth rate just before ~1.0 Ga, almost 2.0 Ga later than the zircon-based method. It has been noted that zircon Hf-isotopes have a tendency to over-estimate the mass of reworking in the source of a given rock, so the curve presented in this work (Fig. 1) likely represents a maximum crustal growth curve, as decoupling of rock mass from Hf-isotope systematics would bias the curve to artificially old ages. This over-estimation may also be a source of offset between the crust and mantle growth curves in the Mesoarchean (Fig. 1a).

The appearance of >10 % of continental crust at *ca*. 3.5 Ga coincides with a time on Earth when continental rocks were first preserved in significant volumes in the rock record. For instance, many cratonic nuclei contain rock samples that formed ~3.4–3.6 Ga (Bauer *et al.*, 2020). Thus, our calculations broadly agree with first order observations from the preserved rock record—an important test. Also, our new crustal growth curve indicates that continental growth has stagnated since ~1.1 Ga, a time on Earth marked by the appearance of preserved paired metamorphic belts (Holder *et al.*, 2019), possibly indicating the progressive evolution of plate tectonics to a modern style of colder and steeper subduction. This timing coincides with a dramatic slowing of new additions to cratonic mantle lithosphere (Pearson *et al.*, 2021), pointing to a shared lineage between stable crust and mantle lithosphere. Note that we have performed key sensitivity tests on our modelling results (preservational bias, chemical biases, *etc*) that show that our crustal growth rate curves are immune to systematic biases (Figs. S7–9).

Crustal Growth Rates

The continental growth rate reflected in global bulk rock data suggests a temporal relationship between the evolution of continental crust and the formation of deep, stable sub-continental lithospheric mantle roots that are key to defining the cratons. This relationship is very different to that previously proposed based on alternative continental growth curves (Dhuime *et al.*, 2012; Korenaga, 2018) which argue for a preservational relationship between continental crust and deep mantle roots (Hawkesworth *et al.*, 2017; Pearson *et al.*, 2021), whereby large volumes of deep mantle keels stabilised and preserved extant continental crust, whereas older, unstabilised continental crust was preferentially reworked. Instead, our bulk rock-based estimate of continental growth indicates that continental crust and deep mantle keels may have been formed in a similar time window, with the key inflection point being at ~1 Ga, a defining point for cratons (Pearson *et al.*, 2021). Continental crust begins to grow prior to the mantle lithosphere as recorded in mantle xenoliths on the modern Earth. The difference in growth rate could be due to mantle lithosphere being overprinted by younger magmatic events (Pearson *et al.*, 2002; Alard *et al.*, 2005; Liu *et al.*, 2021). This may be likely as >2.85 Ga diamond-bearing lithosphere clearly exists in several cratonic regions (Smart *et al.*, 2016; Timmerman *et al.*, 2022). Thus, we emphasise that any mechanism proposed to explain either the formation of ancient continental crust or their underlying deep mantle keels, features that collectively define the cratons (Pearson *et al.*, 2021), must account for the formation of both features at nearly the same time (Pearson *et al.*, 2007). The inflection in continental growth began near 3.5 Ga and has substantially slowed since ~1.0 Ga (Fig. 1), a feature mirrored by continental roots (Pearson *et al.*, 2021). Though felsic crust clearly cannot be derived directly from peridotite, this broad temporal link points to the possibility of mechanistic links in the formation of continental crust and the rapid docking of thick lithospheric keels beneath them, perhaps by lateral accretion and slab imbrication—a process that has been separately invoked for the production of ancient continental crust (Bauer *et al.*, 2020) and ancient lithospheric mantle (Timmerman *et al.*, 2022).

Our continental growth curve indicates that Earth's volumes of continental crust grew progressively over a 2.5 Gyr period in the middle of Earth history. There is no evidence for either large volumes of Hadean continental crust, nor signs of a decrease in crustal growth rate near 3.0 Ga, removing a key constraint used to argue for a geodynamic shift in Earth's tectonic regime near that time. Instead, our analysis indicates that most continental crust grew between 3.5 Ga and *ca*. 1.0 Ga in a relatively consistent manner (Condie *et al.*, 2018; Garçon, 2021), occurring over the same time period that cratonic mantle roots formed (Pearson *et al.*, 2021). Though the links between continental growth, craton root development, and the emergence of freeboard remain to be fully understood, our analysis suggests that they may be unrelated to a distinct change in the geodynamics of the solid Earth in the Neoarchean. Instead, our analysis places emphasis on the change in lithosphere evolution in the Mesoarchean, and may suggest that continental freeboard on Earth formed simply due to continent formation in large volumes (Reimink *et al.*, 2021). Thus, continental emergence and the rise of subaerial weathering cycles may have been caused simply by the formation and stabilisation of the continents themselves.

Data Availability

The data reduction code used to process this data set can be found in the Supplementary Information. Zircon U–Pb data shown in Figure 1 is from Puetz and Condie, (2019).

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Additional Information

Supplementary Information accompanies this letter at https://www.geochemicalperspectivesletters.org/article2324.

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