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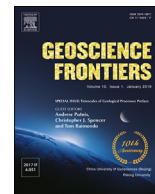


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Research Paper

Rates of generation and growth of the continental crust

Chris Hawkesworth^{a,*}, Peter A. Cawood^b, Bruno Dhuime^{a,c}^a School of Earth Sciences, University of Bristol, Wills Memorial Building, Queen's Road, Bristol BS8 1RJ, UK^b School of Earth, Atmosphere and Environment, Monash University, Melbourne, VIC 3800, Australia^c CNRS-UMR 5243, Géosciences Montpellier, Université de Montpellier, France

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ABSTRACT

Models for when and how the continental crust was formed are constrained by estimates in the rates of crustal growth. The record of events preserved in the continental crust is heterogeneous in time with distinctive peaks and troughs of ages for igneous crystallisation, metamorphism, continental margins and mineralisation. For the most part these are global signatures, and the peaks of ages tend to be associated with periods of increased reworking of pre-existing crust, reflected in the Hf isotope ratios of zircons and their elevated oxygen isotope ratios. Increased crustal reworking is attributed to periods of crustal thickening associated with compressional tectonics and the development of supercontinents. Magma types similar to those from recent within-plate and subduction related settings appear to have been generated in different areas at broadly similar times before ~3.0 Ga. It can be difficult to put the results of such detailed case studies into a more global context, but one approach is to consider when plate tectonics became the dominant mechanism involved in the generation of juvenile continental crust. The development of crustal growth models for the continental crust are discussed, and a number of models based on different data sets indicate that 65%–70% of the present volume of the continental crust was generated by 3 Ga. Such estimates may represent minimum values, but since ~3 Ga there has been a reduction in the rates of growth of the continental crust. This reduction is linked to an increase in the rates at which continental crust is recycled back into the mantle, and not to a reduction in the rates at which continental crust was generated. Plate tectonics results in both the generation of new crust and its destruction along destructive plate margins. Thus, the reduction in the rate of continental crustal growth at ~3 Ga is taken to reflect the period in which plate tectonics became the dominant mechanism by which new continental crust was generated.

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1. Introduction

Rates of change are key constraints in the development of physically realistic models for natural processes. The geological record provides evidence of processes that range from the extremely slow to the cataclysmic, from the diffusion of ions at rates of a millimetre per million years to near instantaneous earthquakes and catastrophic volcanic eruptions. We evaluate how the rates of growth of the continental crust can be constrained for different periods of Earth history, and how those in turn inform

models for the generation and the evolution of the continental crust.

In evaluating the geological record and the distribution of rocks generated in different settings, and of different crystallisation ages, it is helpful to consider both the rates at which magmas are generated, and the chances of their preservation (Gurnis and Davies, 1986; Hawkesworth et al., 2009). Magmas are generated at different rates in different tectonic settings, as illustrated by the estimates for volcanic output rates in Fig. 1 (White et al., 2006). However, magmas are generated continuously in some settings, on the timescales considered, and episodically in others. Magmas in oceanic hotspots are erupted continuously for the period of activity of a specific hot spot at rates at least one order of magnitude greater than those in other tectonic settings. The rates of eruption of continental flood basalt provinces are an order of magnitude greater than those in oceanic hotspots, but in contrast they are relatively

* Corresponding author.

E-mail addresses: c.j.hawkesworth@bristol.ac.uk (C. Hawkesworth), peter.cawood@monash.edu (P.A. Cawood), bruno.dhuime@gm.univ-montp2.fr (B. Dhuime).

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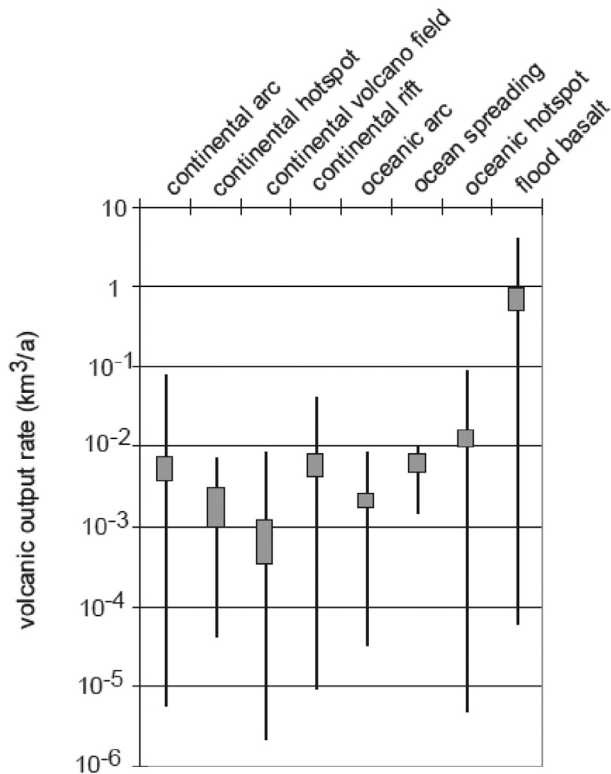


Figure 1. Estimated variations in the volcanic output rates for volcanic magmas erupted in different tectonic settings (White et al., 2006). The ratio of intrusive to volcanic rocks is typically taken to be 5:1.

short-lived. Thus, peaks of crystallisation ages in the geological record have been linked to the emplacement of mantle plumes, as inferred for the generation of continental flood basalts. Yet the composition of the continental crust is dominated by magma compositions associated with subduction (Taylor, 1967; Rudnick and Gao, 2003), rather than intra-plate magmatism.

High magma volumes are generated above subduction zones, but at these settings continental crust is destroyed by erosion, subduction, and in some areas density foundering, at rates similar to, or greater than, those at which new crust is generated (Scholl and von Huene, 2007, 2009; Clift et al., 2009; Stern, 2011). Thus, in the context of preservation, crust is destroyed along subduction zones at rates similar to, or perhaps even greater than those at which it is generated. In contrast, subduction-related rocks generated during the later stages of ocean closing, and in post orogenic magmatism, are more likely to be preserved over longer periods in the geological record (Hawkesworth et al., 2009; Cawood et al., 2013).

Another issue in understanding rates of continental growth is the extent to which the distribution of crystallization ages is a reasonable reflection of changes in the relative volumes of magma generated. Tang et al. (2017) addressed this in a study of the Central Asian Orogenic Belt in NW China, and the results from the Tianshan segment are reproduced in Fig. 2. The presently exposed areas of rocks of different ages, grouped in 20 Ma time intervals, are taken to be proxies for the volumes of magma of different ages. Encouragingly the variations in the exposed areas of rocks of different ages matches with the distribution of detrital zircon crystallisation ages, suggesting that, at least in this case, age distributions broadly reflect changes in magma volumes.

A striking feature of the continental crust is that the events recorded are heterogeneous in time with distinctive peaks and

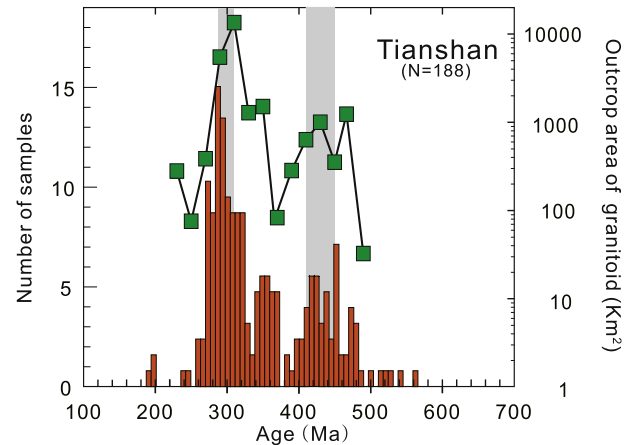


Figure 2. Comparison of the outcrop area of granitoid rocks and the distribution of crystallization ages, in the Tianshan segments of the Central Asian Orogenic Belt, from Tang et al. (2017).

troughs of ages for igneous crystallisation, metamorphism, continental margins and mineralisation, at least since 2.7 Ga (Fig. 2; e.g., Gastil, 1960; Stockwell, 1961; Brown, 2007; Bradley, 2008, 2011; Cawood et al., 2013; Cawood and Hawkesworth, 2015; Hawkesworth et al., 2016, 2017). While regionally it can be demonstrated that peaks of crystallisation ages are a reasonable proxy for periods of increased magmatism (Fig. 2), for the most part the peaks and troughs of ages are global signatures. This is unexpected in the context of plate tectonic models in which new continental crust is continuously created and destroyed. An initial question is therefore, whether such peaks of ages reflect primary or secondary processes. If they are primary, and the peaks of crystallisation ages reflect periods of enhanced crust generation, they are most readily attributed to the emplacement of mantle plumes (Albarède, 1998; Condie, 1998; Rino et al., 2004; Arndt and Davaille, 2013; Condie et al., 2015; Parman, 2015). Yet, the distribution of age peaks is similar on different continents today, and so the peaks of ages are global in distribution, which implies that the inferred plume activity was also global. Moreover, the ages of peaks in the zircon record are similar to those for passive margins and periods of crustal metamorphism, and these remain difficult to link to the emplacement of mantle plumes (cf., Cawood and Hawkesworth, 2014).

The alternative interpretation, to which we subscribe, is that the peaks and troughs of ages largely reflect the variable preservation potential of rocks generated in different tectonic settings, rather than fundamental pulses of magmatic activity, and it appears that the peaks of ages are linked to the timing of supercontinent assembly (Hawkesworth et al., 2009). There is much discussion over how well established the older supercontinents may be, but independent of that discussion the peaks of ages are typically linked to the crystallisation of zircons with relatively large contributions from pre-existing continental crust (Belousova et al., 2010; Dhuime et al., 2012; Spencer et al., 2014; Roberts and Spencer, 2015). These are attributed to periods of crustal thickening and reworking associated with compressional tectonics, and since continental collision is associated with enhanced preservation the peaks of crystallisation ages are not thought to reflect periodic changes in the rates of crust generation.

2. Geological record

There has been much discussion over the geological evidence for the onset of plate tectonics, and the extent to which juvenile

continental crust was generated in subduction-related or within plate settings in the Archaean and early Proterozoic. Juvenile crust is used here to denote new continental crust recently derived from the mantle. Stern (2005) argued that direct geologic evidence for when the modern episode of subduction tectonics began should focus on the first appearance of ophiolitic graveyards, blueschist facies metamorphic rocks, and ultrahigh-pressure metamorphic terranes. The ages for these vary, but Stern (2005) concluded that modern episode of subduction tectonics began in the Neoproterozoic. Brown (2006) and Brown and Johnson (2018) documented that the ‘cold’ high pressure assemblages, which appear to reflect plate tectonics as it has been active in the recent geological past, only became widespread from ~700 Ma. Such conclusions are increasingly accepted, and the question then becomes whether other forms of plate tectonics were in operation earlier, and how they may best be recognised. The oldest accepted evidence for high pressure metamorphism ascribed to plate subduction is presently ~2.2–1.8 Ga (Ganne et al., 2012; Weller and St-Onge, 2017), and the oldest widely accepted Cu porphyry related to an upper plate supra-subduction zone setting is also about the same age (Macey et al., 2017).

There have been a number of predominantly geochemical approaches seeking to evaluate the tectonic settings in which Archaean magmatic rocks were generated. Some rely on the recognition of boninitic magmas (Cameron et al., 1980; Polat and Kerrich, 2004; Smithies et al., 2004), and in some cases stratigraphic associations (Turner et al., 2014), also found in more recent subduction related settings. Others rely on distinctive relatively immobile trace elements and ratios such as Th/Nb which are elevated in subduction related magmas reflecting their distinctive negative anomalies in Nb and Ta. It is increasingly clear that while the separation of subduction related magmas and those generated in constructive margin and within plate settings is marked in recent examples, there is more of a continuum in Th/Nb ratios in Archaean rocks (Moyen and Laurent, 2018). Thus, there has been some caution in assigning individual geochemical signatures to tectonic setting in Archaean rocks (Pearce, 2008). Nonetheless there are

differences in for example Th/Nb between different Archaean suites. These are illustrated in Fig. 4, not because they should be relied on in isolation, but because they provide a way to illustrate the conclusions of the different studies cited in terms of the tectonic settings in which different Archaean suites were generated.

Elevated Th/Nb ratios are a feature of subduction-related magmas (e.g., Pearce, 2008), and Fig. 4 illustrates the mean Th/Nb ratios of suites of Archaean predominantly mafic rocks that are thought not to have been modified significantly by crustal contamination (Smithies et al., 2004, 2005; Shimizu et al., 2005; O’Neil et al., 2007; Jenner et al., 2009, 2013; Puchtel et al., 2013; de Joux et al., 2014). At face value this plot indicates that in the period 3.8–2.7 Ga suites of subduction-related and non-subduction-related magmas were generated at similar times in different locations. It remains difficult to put the results of such detailed case studies into a more global context. Keller and Schoene (2018) used a weighted global data base of basaltic rocks to conclude that there was no long-term change in the global proportion of arc versus non-arc basaltic magmatism at any time preserved in the rock record. Another approach is to investigate when plate tectonics became the dominant mechanism involved in the generation of juvenile continental crust based on changes in the rates of crustal growth.

3. Crustal growth models

When and how the continental crust was generated, and how the volume of the continental crust has changed with time, are fundamental questions that also impinge on the evolution of the upper mantle, and changes in the composition of ocean water and atmosphere. Models of crustal growth are typically depicted on plots of crustal volume versus geological age (Fig. 5), and they can usefully be considered in three groups. The first is based on the distribution of rocks of different ages presently preserved on the Earth’s surface (Goodwin, 1996), or, in the case of Hurley and Rand (1969), on the distribution of basement rocks of different ages. The second group of curves is based on the present day distribution of

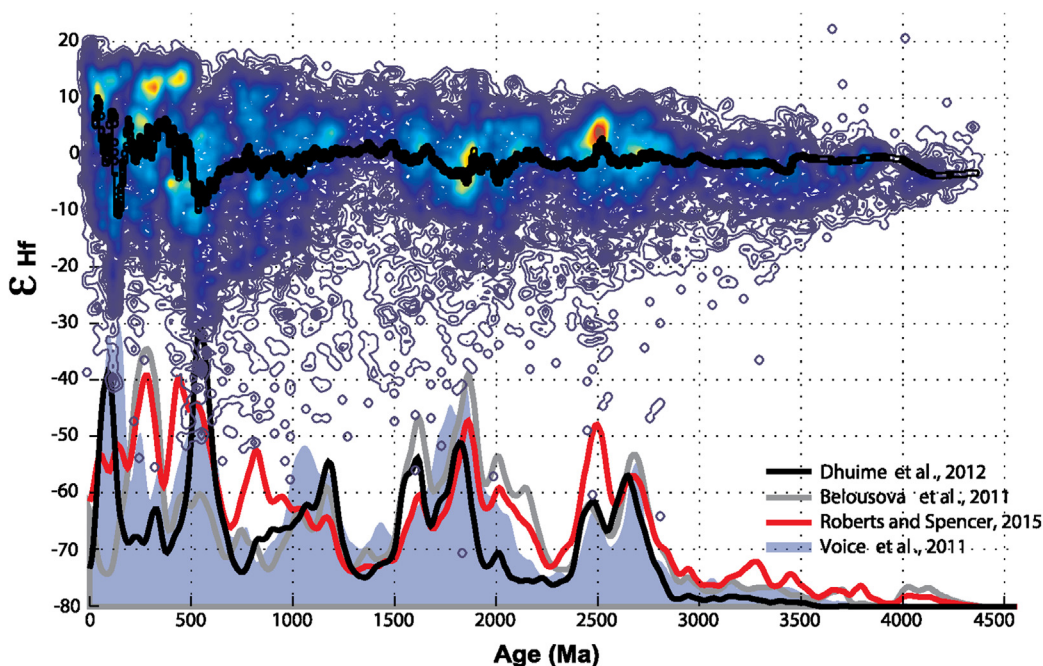


Figure 3. Zircon age distribution on a plot of initial Hf isotope values versus crystallisation age, plotted together with histogram of the same data. From Roberts and Spencer (2015) and included data from Belousova et al. (2010), Dhuime et al. (2012), and Voice et al. (2011).

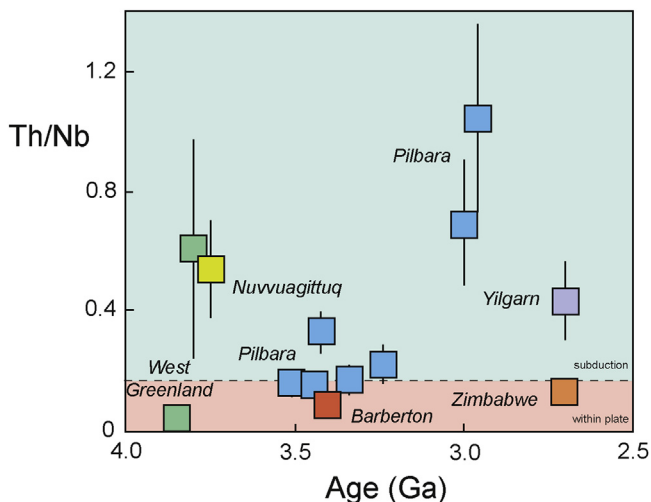


Figure 4. Mean Th/Nb ratios of suites of Archaean predominantly mafic rocks which are thought not to have been modified significantly by crustal contamination. The green field is for elevated Th/Nb ratios, which are attributed to subduction-related processes, and the orange field is for within plate magmas. Data from: Barley et al. (1998), Smithies et al. (2004, 2005), Shimizu et al. (2005), O’Neil et al. (2007), Jenner et al. (2009, 2013), Puchtel et al. (2013) and de Joux et al. (2014). The colours in the small squares reflect the different locations plotted.

rocks with different model ages, i.e. estimates of when their precursor crustal source rocks were derived from the mantle (Allègre and Rousseau, 1984; Condie and Aster, 2010). However it remains unlikely that the proportion of rocks with Archaean to (for instance) Phanerozoic model ages at the present day is a reliable indication of the relative volumes of crust that were present in the Archaean. Thus, the third group of crustal growth curves develop arguments to constrain the volumes of crust that were present at different times in Earth history, even if they are no longer preserved at the present day. Some are based on models in which large volumes of continental crust were generated early in Earth history, when the Earth was hotter (Armstrong, 1981), and others, for

example, on Ar isotopes in hydrothermal quartz as a proxy for the atmospheric $^{40}\text{Ar}/^{36}\text{Ar}$ (Pujol et al., 2013), and trace element ratios of mafic basaltic rocks (Campbell, 2003). Recently crustal growth curves have been developed on the basis of the variations in Hf isotopes in zircons whose crystallisation ages are known (Belousova et al., 2010; Dhuime et al., 2012; Iizuka et al., 2017), and these are considered in the next section.

3.1. The derivation of crustal growth models from variations in Hf isotope ratios

There are now 100s of 1000s of high quality analyses of Hf and U–Pb isotope ratios in zircon, in some cases supplemented by O isotope analyses. Many of the zircons analysed are detrital grains in continental sedimentary rocks, and they are thought to have sampled relatively large areas of the exposed continental crust. A compilation of Hf isotope data in zircons (Fig. 3) highlights: (a) how relatively few zircons have elevated Hf isotope ratios close to the composition of juvenile continental crust, and most zircons crystallised from magmas that were in significant part derived from pre-existing crust; and, (b) the distribution of the ages of zircons is heterogeneous, with periods in which there are large numbers of zircon analyses, and periods with many fewer zircon ages, as also illustrated by the histogram of zircon ages in Fig. 3 (Roberts and Spencer, 2015).

Belousova et al. (2010) developed an approach to estimate crustal volumes from the variations of Hf isotope ratios in zircon and evaluated the proportions of juvenile and reworked crust at different times, i.e. in zircons of similar ages. Thus, for each individual time slice the number of zircons with those crystallisation ages are compared with the number of zircons which have model Hf ages that fall in the same time slice. The proportion of juvenile crust X_{juv} is therefore given by:

$$X_{\text{juv}} = N_{\text{model age}} / (N_{\text{U-Pb age}} - N_{\text{model age}})$$

For any given time slice $N_{\text{U-Pb age}}$ is the number of zircons with those crystallisation ages, and $N_{\text{model age}}$ is the number of zircons

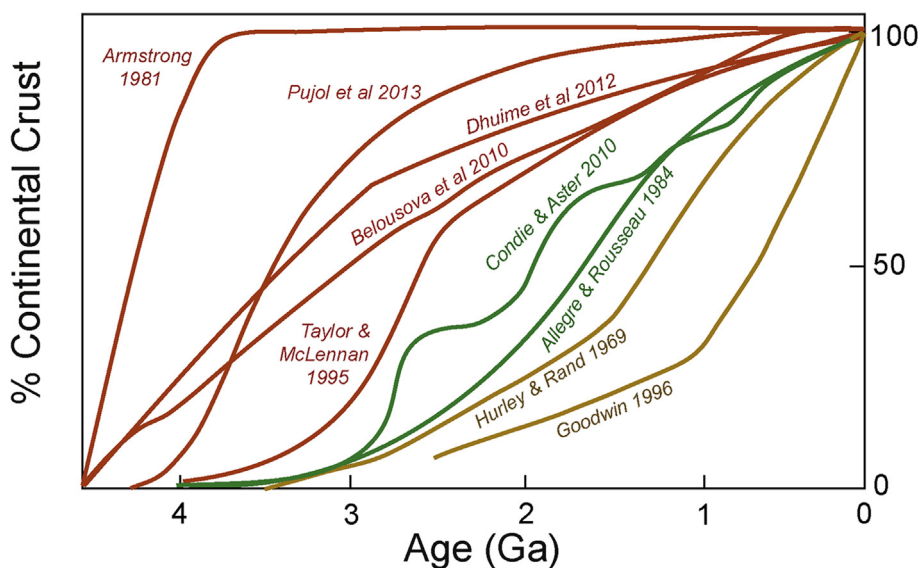


Figure 5. Selected crustal growth models. Those in brown are based on the distribution of rocks (Goodwin, 1996), or basement rocks (Hurley and Rand, 1969) of different ages presently preserved on the Earth’s surface. The curves in green are based on the assumption that the present day distribution of rocks with different model ages reflects the relative volumes of crust that were present at different times in Earth history (Allègre and Rousseau, 1984; Condie and Aster, 2010). The curves seek to constrain the volumes of crust that were present at different times in Earth history, even if they are no longer preserved at the present day (Armstrong, 1981; Pujol et al., 2013).

with model Hf ages in the same time slice as the crystallisation ages (Belousova et al., 2010). Dhuime et al. (2012) extended this approach by incorporating O isotopes to identify the proportion of zircons of different ages that had elevated $\delta^{18}\text{O}$ values. These are thought to contain a contribution of sedimentary material in the magma from which the zircon crystallised. Sediments typically contain material from different source regions, and so they tend to have hybrid model ages. As it is difficult to identify the different source materials involved, the zircons with elevated $\delta^{18}\text{O}$ values were omitted from the estimates of the proportions of juvenile crust, and how that varied with time. As a consequence the Dhuime et al. (2012) crustal growth curve has ~15% more crust at say 3 Ga than the curve of Belousova et al. (2010).

In many ways the key step in the construction of continental growth curves from zircon data is how the variations in Hf isotope ratios, and hence in the estimated proportions of juvenile crust, are converted to crustal volumes (see also discussion by Payne et al., 2016). The approach starts with the present volume of the continental crust, plotted as 100% in Fig. 5, and the cumulative volume of crust is calculated back from the present day to a selected start date in say 100-million-year time intervals based on the proportion of new crust in each time slice. One limitation is that it builds a cumulative volume of the crust through time with the current volume being the maximum possible. Hence the estimated volumes can never be greater in the past than it is at the present day (cf., Fyfe, 1978), but this is simply a restriction of this approach. Second, it remains difficult to evaluate the extent to which the calculated volume of continental crust at say 2 Ga is robustly determined by evaluating the proportions of new and reworked crust in different time slices back from the present day volumes (Payne et al., 2016). Nonetheless, the calculated volumes of crust in the geological past depend on the Hf (and Nd) isotope records, and they are not based on the proportions of crust of different ages now preserved in the geological record. The difference between for example, the Hf isotope based crustal growth curve, and the Condie and Aster (2010) curve for the proportions of rocks with different model

ages at the present time, can therefore be taken as an indication of the minimum volumes of continental crust that have been destroyed through recycling back into the mantle (Hawkesworth et al., 2013).

Continental sediments have been widely used to sample the continental crust, and this has been very successful in the determination of relatively immobile element abundances in the bulk continental crust (Taylor and McLennan, 1985; McLennan, 2001). However the radiogenic isotope ratios of sediments depend on the proportions of rocks of different ages in their source area, and that can be difficult to unpick. Erosion rates increase with topographic relief, and so most sediments are derived from relatively high relief areas. Few Archaean terrains are presently caught up in high relief areas, and so old segments of crust are under-represented in recent sediments. Hawkesworth et al. (2017, Fig. 4) pointed out that the average model Nd age of rocks from areas with >100 m topographic relief was ~1 Ga, whereas the best estimate of the model Nd age of the bulk continental crust is nearer 1.8 Ga (Chauvel et al., 2014).

The bias involved in using the Nd isotope ratios of sediments to estimate the evolution of the continental crust, was initially discussed by Allègre and Rousseau (1984), and also by Dhuime et al. (2011), Garrels and Mackenzie (1971), Goldstein and Jacobsen (1988), Jacobsen (1988), Kramers (2002), and Kramers and Tolstikhin (1997). However, the resultant crustal growth curves are still based on the present day variations of crust with different model ages, albeit corrected for any bias inherent in sampling the crust through sediments. Dhuime et al. (2017) explored how Nd isotope ratios of sediments might also be used to constrain the relative volumes of crust at different times in Earth history. Using modest values (i.e. typically 2–6) for the erosion parameter K (Allègre and Rousseau, 1984), but critically the same approach developed for Hf isotope ratios in zircon described above, Dhuime et al. (2017) concluded that very similar crustal growth curves can be obtained for Hf isotope ratios in zircons and Nd isotope ratios in sediments (Fig. 6).

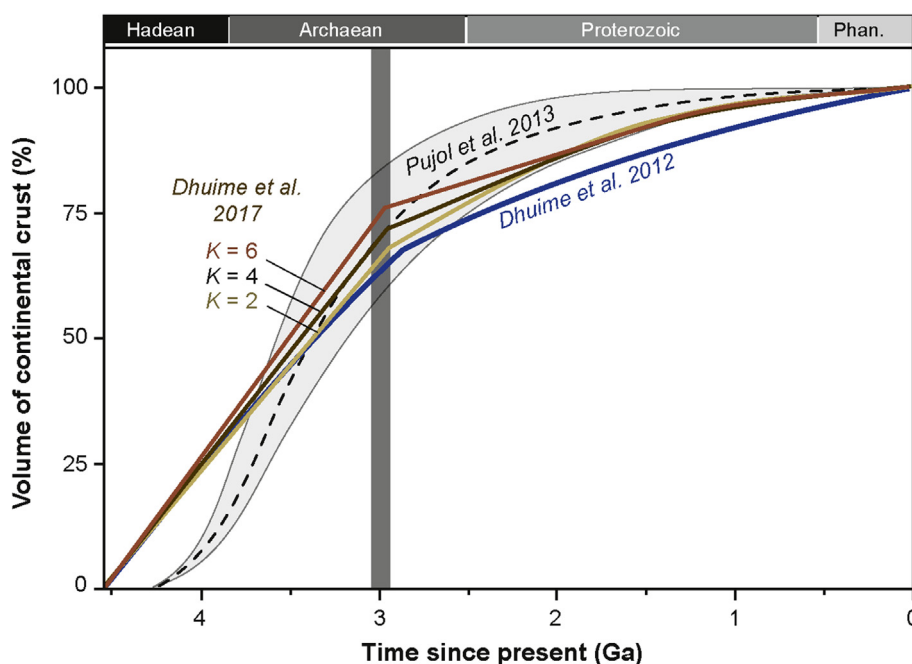


Figure 6. A comparison of crustal growth models based on Hf isotope ratios in zircons, from Dhuime et al. (2012), Nd isotope ratios in continental sediments modelled in the same way as Hf isotope variations in zircons, and with K values of 6, 4 and 2 (Dhuime et al., 2017), and for atmospheric $^{40}\text{Ar}/^{36}\text{Ar}$ (Pujol et al., 2013). K is a dimensionless erosion parameter that relates the proportions of younger to older source rocks in the sediment, to the proportions of younger to older source rocks present in the crust from which the sediment derived (Allègre and Rousseau, 1984).

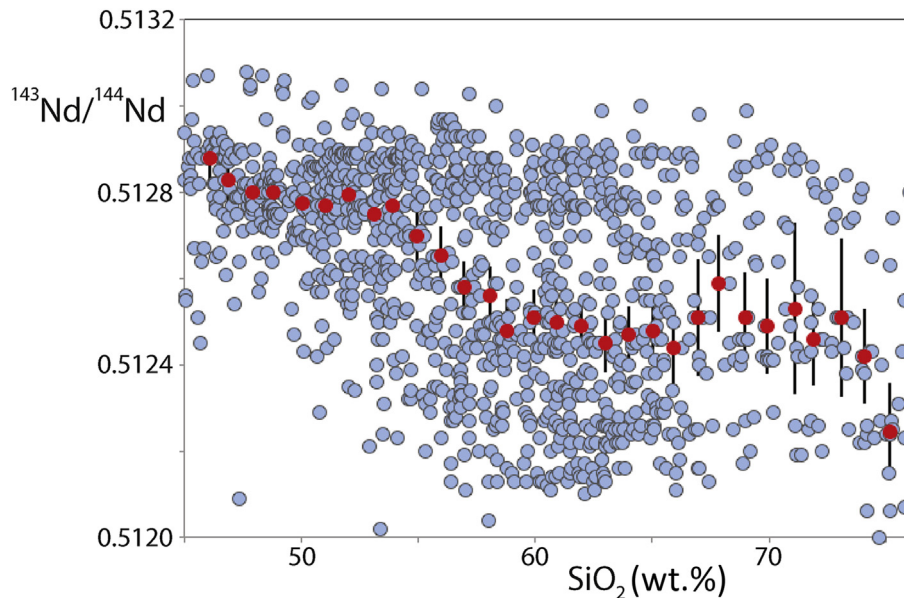


Figure 7. A plot of present day Nd isotope ratios and silica contents (in wt.%) for 1200 igneous rocks from the Andes, taken from the GEOROC data base (<http://georoc.mpch-mainz.gwdg.de/georoc/>). The red dots are the running median calculated at 1 wt.% SiO_2 intervals (with associated 2 s.e. error bars).

A major concern over the use of zircons to construct crustal growth curves is that most zircons crystallise from relatively felsic magmas, and so they may not be representative of the bulk continental crust (Hawkesworth et al., 2016; Lee et al., 2016; Keller et al., 2017). Given how crustal growth curves are calculated that implies that the proportion of new and reworked crust estimated from zircon differs from those preserved in other archives. In many settings higher silica magmas may contain relatively more reworked crust than those with lower silica contents, as illustrated in a plot of present day $^{143}\text{Nd}/^{144}\text{Nd}$ versus SiO_2 for 1200 Tertiary and younger whole rock samples from the Andes in Fig. 7. The running median indicates that there are two plateaus with the median Nd isotope ratio for rocks with $\text{SiO}_2 = 46\text{--}54$ wt.% being 0.51280, whereas for rocks with more than 59 wt.% SiO_2 it is lower at 0.51249. Assuming that most zircons crystallise from magmas with more than 60 wt.% SiO_2 , the implication is that they will have a greater contribution from pre-existing crust than magmas with lower SiO_2 contents. As such they contain relatively less new crust and so the crustal volumes estimated from zircons could reasonably be regarded as a minimum. An alternative argument is that the estimated composition of the bulk crust is ~ 61 wt.% SiO_2 , and that such magmas crystallise zircon and the zircon record is therefore a reasonable record for bulk rock compositions.

3.2. Significance of estimated rates of crustal growth, pre- and with plate tectonics

The crustal growth curves built on the detrital zircon and the fine-grained sediment records independently suggest that the continental crust has been generated continuously, and at least 65% of the present volume of continental crust was established by 3 Ga (Fig. 6). It follows that there is a marked decrease in the crustal growth rate, i.e. the volume of juvenile crust generated in the mantle minus the volume of material recycled back into the mantle, at ~ 3 Ga. The period from >4 Ga to ~ 3 Ga is characterised by relatively high net rates of continental growth ($\sim 2.9\text{--}3.4$ km^3/a), and these are similar to the rates at which new crust is generated (and destroyed) along destructive plate margins at the present time (e.g., Scholl and von Huene, 2007, 2009; Cawood et al., 2013). Since

~ 3 Ga the net growth rates have been much lower ($0.6\text{--}0.9$ km^3/a , Fig. 6), and this is attributed to higher rates of destruction of continental crust.

In the recent geological past, $\sim 24 \times 10^6$ km^3 magma is generated per million years, with $\sim 80\%$ of the volume generated at MOR, $\sim 20\%$ above subduction zones, and only 0.5% generated in intra-plate settings in both the oceans and the continents combined (Mjelde et al., 2010; Jicha and Jagoutz, 2015). If 70% of the present volume of the continental crust was generated by 3 Ga, commencing at say 4 Ga, the rate of crustal growth over that period involved the addition of ~ 5 km^3/a . This a minimum estimate of the volume of continental crust generated, i.e. it assumes that no crust was destroyed between 4 and 3 Ga, but it is a very small amount in the context of the volumes of magma likely to have been generated in a hotter Earth in the Archaean. Perhaps the rates of crustal recycling were very much higher in the Archaean (Chowdhury et al., 2017), and/or most magma was generated in the oceans, i.e. in areas not preserved as continental crust.

4. Geological implications

The reduction in crustal growth rate at ~ 3 Ga (Fig. 6), is marked by a number of changes recorded in the geological record, suggesting a change in the processes of generation and/or preservation of the crust. They are taken to reflect the development of plate tectonics as the dominant process of crust generation. Shirey and Richardson (2011) compiled isotopic and bulk chemical data of silicate and sulfide inclusions in diamond. They observed that before 3.2 Ga, the inclusions were peridotitic in composition, whereas after 3.0 Ga, eclogitic inclusions became prevalent. They linked the development of eclogitic inclusions to the subduction of mafic material, and hence to the onset of plate tectonics. Dhuime et al. (2015) evaluated the average composition of new continental crust using the initial Sr isotope ratios and model Nd ages of $\sim 13,000$ whole rock samples to estimate the Rb/Sr ratios, and hence the silica content of new continental crust. In recent magmatic rocks, Rb/Sr ratios also increase with crustal thickness, and so the calculated Rb/Sr ratios of new crust of different ages can be linked to the changes in the thickness of the crust, at least at the

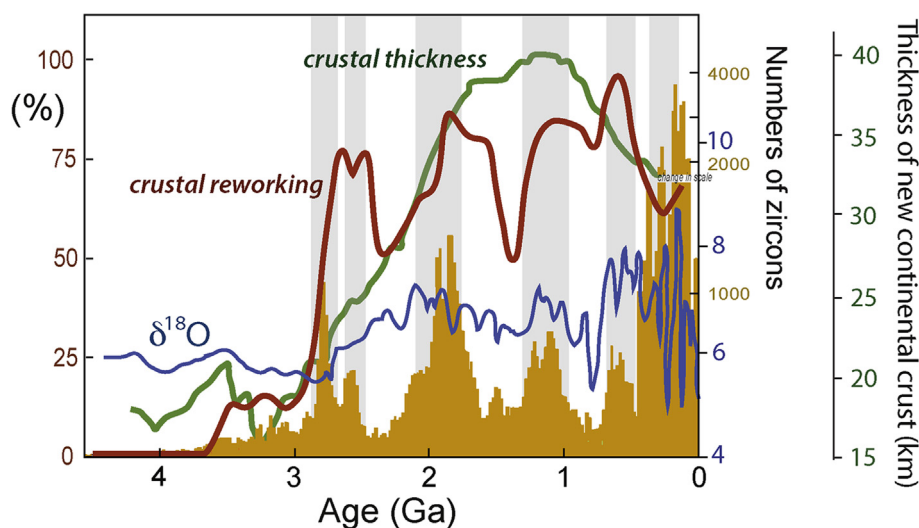


Figure 8. A summary of some of the changes that appear to mark the end of the Archaean. These include the development of supercontinents/supercratons, marked by vertical grey bars (Hoffman, 1996; Zhao et al., 2002; Bleeker, 2003; Cawood et al., 2013; Evans, 2013), the increase in the degree of crustal reworking as indicated by Hf isotope ratios in zircon (Belousova et al., 2010; Dhuime et al., 2012), the development of significant peaks in the age distribution of zircons (Campbell and Allen, 2008; Voice et al., 2011), a shift in the composition of juvenile crust from mafic to more intermediate compositions accompanied by an inferred increase in crustal thickness (Dhuime et al., 2015), and the step-up in the $\delta^{18}\text{O}$ values in zircons (Valley et al., 2005; Spencer et al., 2014).

sites of crust generation (Fig. 8). New continental crust generated before 3 Ga has on average low Rb/Sr, and it is mafic, dense, and relatively thin (<20 km). New continental crust formed after 3 Ga gradually became more intermediate in composition, buoyant and thicker, and hence more like the calc-alkaline andesitic crust that dominates the continental record today. Increasing crustal thickness after 3 Ga is accompanied by increasing rates of crustal reworking (Fig. 8), and increasing input of sediment to the ocean.

There has been much discussion over the strength of the continental lithosphere in the Archaean, and how that might be constrained from the geological record. Melt depletion events in mantle rocks may now be dated using the Re–Os decay scheme (Walker et al., 1989). Re-depletion model ages T_{RD} provide minimum ages for depletion even if, in practice, not all the Re may have been removed during melt extraction. Mantle xenoliths from cratonic areas tend to have T_{RD} ages with a peak at 2.8 Ga, and relatively few have T_{RD} ages older than 3 Ga (Pearson and Wittig, 2013). Thus, there appears to be little evidence for significant mantle lithosphere preserved from before 3 Ga, even in Archaean terranes where the crust may be older than that.

A number of features of the crustal record are summarised in Fig. 8. The $\delta^{18}\text{O}$ values of zircons are relatively low in the Archaean, and they only increase significantly at ~ 2.5 Ga (Valley et al., 2005; Spencer et al., 2014). This has been attributed to changing crustal compositions related to increasing levels of emergent crust and chemical weathering (Payne et al., 2015), but given that high-grade metamorphic terrains (Brown, 2007, 2014), and significant volumes of S-type granites (Laurent et al., 2014), only appear near the end of the Archaean, it may also reflect a change in tectonic processes (Shirey and Richardson, 2011; Cawood et al., 2013; Spencer et al., 2014; Hawkesworth et al., 2017; Satkoski et al., 2017; Smit and Mezger, 2017). The degree of crustal reworking estimated from Hf isotope variations in zircon also increases markedly at the end of the Archaean (Fig. 8).

Thus, a number of strands of evidence indicate that the continental lithosphere was not strong enough to support crustal thickening (Rey and Coltice, 2008), and hence facilitate crustal reworking and high grade metamorphism, until the late Archaean. It is inferred that this is the time when the lithosphere became

strong enough to support high-relief crust; it would be when significant volumes of continental crust started to become emergent and available for erosion and weathering, thus impacting on the composition of the atmosphere (Kramers, 2002; Campbell and Allen, 2008; Kump, 2008; Lee et al., 2016) and the oceans (Veizer et al., 1999; Shields and Veizer, 2002; Shields, 2007). The reduction in the rate of continental growth at ~ 3 Ga is therefore taken to indicate a global change in the way bulk crust was generated and preserved, and this change is linked to the development of subduction-driven plate tectonics as the dominant mechanism by which new continental crust was generated. The peaks of zircon crystallization ages appear to link up with periods of increased crustal reworking, which we link to collisional tectonics and crustal thickening (Hawkesworth et al., 2009; Cawood et al., 2013). These appear to be global scale changes, and there is a tantalising link between the periods of increasing crustal reworking and the suggested ages of supercontinents (Fig. 8).

5. Summary

Models for the generation and evolution of the continental crust are constrained by the rates of crustal growth. However, the geological record is heterogeneous in both space and time with distinctive peaks and troughs of ages for the emplacement of igneous rocks, metamorphism, continental margins and mineralisation. There is increasing evidence that magma types similar to those from recent within-plate and subduction-related settings were generated in different areas at broadly similar times in the period 3.9–2.7 Ga (Fig. 4). Yet, it can be difficult to put the results of detailed case studies carried out in different locations into a more global context. One approach is to evaluate when plate tectonics became the dominant mechanism associated with the generation of continental crust, rather than just when it started.

Less than 10% of the presently preserved rock record formed in the Archaean, and yet the end of the Archaean appears to be marked by a number of changes which, as far as we can tell, appear to be global features (Fig. 7). These include the development of supercontinents (Hoffman, 1996; Zhao et al., 2002), an increase in the degree of crustal reworking as indicated by Hf isotope ratios in

zircon (Belousova et al., 2010; Dhuime et al., 2012), the step-up in the $\delta^{18}\text{O}$ values in zircons (Valley et al., 2005; Spencer et al., 2014), the development of S-type granites (Laurent et al., 2014), and a shift in the composition of both juvenile and upper crust from mafic to more intermediate compositions accompanied by an inferred increase in crustal thickness (Dhuime et al., 2015; Tang et al., 2016).

A number of recent models based, for example, on Hf isotopes in zircons (Belousova et al., 2010; Dhuime et al., 2012), Nd isotopes in continental sediments (Dhuime et al., 2017), and Ar isotopes (Pujol et al., 2013) indicate that by 3 Ga the volume of continental crust was 65%–70% of its present day volume (Fig. 6). This marked a period of reduction in the rates of growth of the continental crust. There is little evidence that this reflects a reduction in the rates at which new crust was generated, and so it is interpreted as the time when the rates of destruction of continental crust increased. The low rates of crustal growth since ~ 3 Ga (0.6 – 0.9 km³/a) are therefore taken to reflect when plate tectonics became the dominant mechanism by which new continental crust was generated.

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