Tectonics and crustal evolution

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ABSTRACT

The continental crust is the archive of Earth's history. Its rock units record events that are heterogeneous in time with distinctive peaks and troughs of ages for igneous crystallization, metamorphism, continental margins, and mineralization. This temporal distribution is argued largely to reflect the different preservation potential of rocks generated in different tectonic settings, rather than fundamental pulses of activity, and the peaks of ages are linked to the timing of supercontinent assembly. Isotopic and elemental data from zircons and whole rock crustal compositions suggest that the overall growth of continental crust (crustal addition from the mantle minus recycling of material to the mantle) has been continuous throughout Earth's history. A decrease in the rate of crustal growth ca. 3.0 Ga is related to increased recycling associated with the onset of plate tectonics.

We recognize five stages of Earth's evolution: (1) initial accretion and differentiation of the core/mantle system within the first few tens of millions of years; (2) generation of crust in a pre-plate tectonic regime in the period prior to 3.0 Ga; (3) early plate tectonics involving hot subduction with shallow slab breakoff over the period from 3.0 to 1.7 Ga; (4) Earth's middle age from 1.7 to 0.75 Ga, characterized by environmental, evolutionary, and lithospheric stability; (5) modern cold subduction, which has existed for the past 0.75 b.y. Cycles of supercontinent formation and breakup have operated during the last three stages. This evolving tectonic character has likely been controlled by secular changes in mantle temperature and how that impacts on lithospheric behavior. Crustal volumes, reflecting the interplay of crust generation and recycling, increased until Earth's middle age, and they may have decreased in the past ~1 b.y.

BACKGROUND

The geological record is incomplete—some rock types are more likely to be preserved than others, and breaks in the rock archive are marked by breaks in the depositional record in the upper crust and deformational and metamorphic events in the deeper crust. The result is an inhomogeneous distribution of ages of rock units, as strikingly seen in the peaks and troughs of U-Pb crystallization ages that appear to be a feature of the geological record (Fig. 1). This distribution of ages is unexpected in a planet whose history is thought to have been dominated by the continuous action of plate tectonics, and there is considerable debate over the causes of the peaks and troughs of ages. Much of it has focused discussion on the extent to which the generation and evolution of Earth's crust is driven by deep-seated processes, such as mantle plumes, or is primarily in response to plate tectonic processes that dominate at relatively shallow levels.

The cyclical nature of the geological record has been recognized since James Hutton noted in the eighteenth century that even the oldest rocks are made up of "materials furnished from the ruins of former continents" (Hutton, 1785). The history of the continental crust, at least since the end of the Archean, is marked by geological cycles that on different scales include those shaped by individual mountain building events, and by the cyclic development and dispersal of supercontinents in response to plate tectonics (Nance et al., 2014, and references therein). Successive cycles may have different features, reflecting in part the cooling of the earth and the changing nature of the lithosphere. In this contribution, we explore the extent to which changes in tectonic processes have shaped the geological record and the surface environments through Earth's history. Where possible these are linked to changing thermal conditions as the earth cooled.

The cooling earth influenced the depths and hence the geochemical signatures at which melt generation takes place (McKenzie, 1984; Nisbet et al., 1993) and the rheology of the crust and lithosphere (Gerya, 2014; Sizova et al., 2010). That in turn influenced tectonic processes, including the initial onset of subduction and the subsequent onset of "cold" subduction that was prevalent throughout the Phanerozoic (Brown, 2006, 2014; Stern, 2005), which shaped the surface environments on Earth. Subduction and plate tectonics resulted in the development of supercontinents and enhanced cooling that led to thickening of the lithosphere and increased crustal reworking. This, in turn, resulted in higher erosion fluxes, and changes in the Sr isotope ratios of seawater and the chemistry of the oceans (Cawood et al., 2013; Flament et al., 2013; Shields, 2007; Spencer et al., 2014). The development of the continental crust is illustrated schematically in Figure 2. Magma oceans may have persisted for 5–10 m.y. after initial accretion of the earth, and a crust, which is likely to have been mafic in composition, will have developed at a late stage in the differentiation and solidification of the magma ocean (e.g., Elkins-Tanton, 2008). The mafic crust is thought to have been thickened by continuing mafic and ultramafic magmatism until remelting and the generation of felsic magmas could occur, resulting in the bimodal silica distribution that is a feature of Archean crust (Fig. 3; Kamber, 2015; Kamber et al., 2005). The residual garnet signature (low heavy rare earth elements [HREE]) in most tonalite-trondhjemite-granodiorite (TTG) associations indicates that remelting took place at pressures >10–12 kb (Rapp and Watson, 1995). The late Archean was characterized by TTG magmatism, the remelting of intermediate to felsic crust and the generation of more potassic granites, and the stabilization of continental crust and mantle lithosphere (Carlson et al., 2005).

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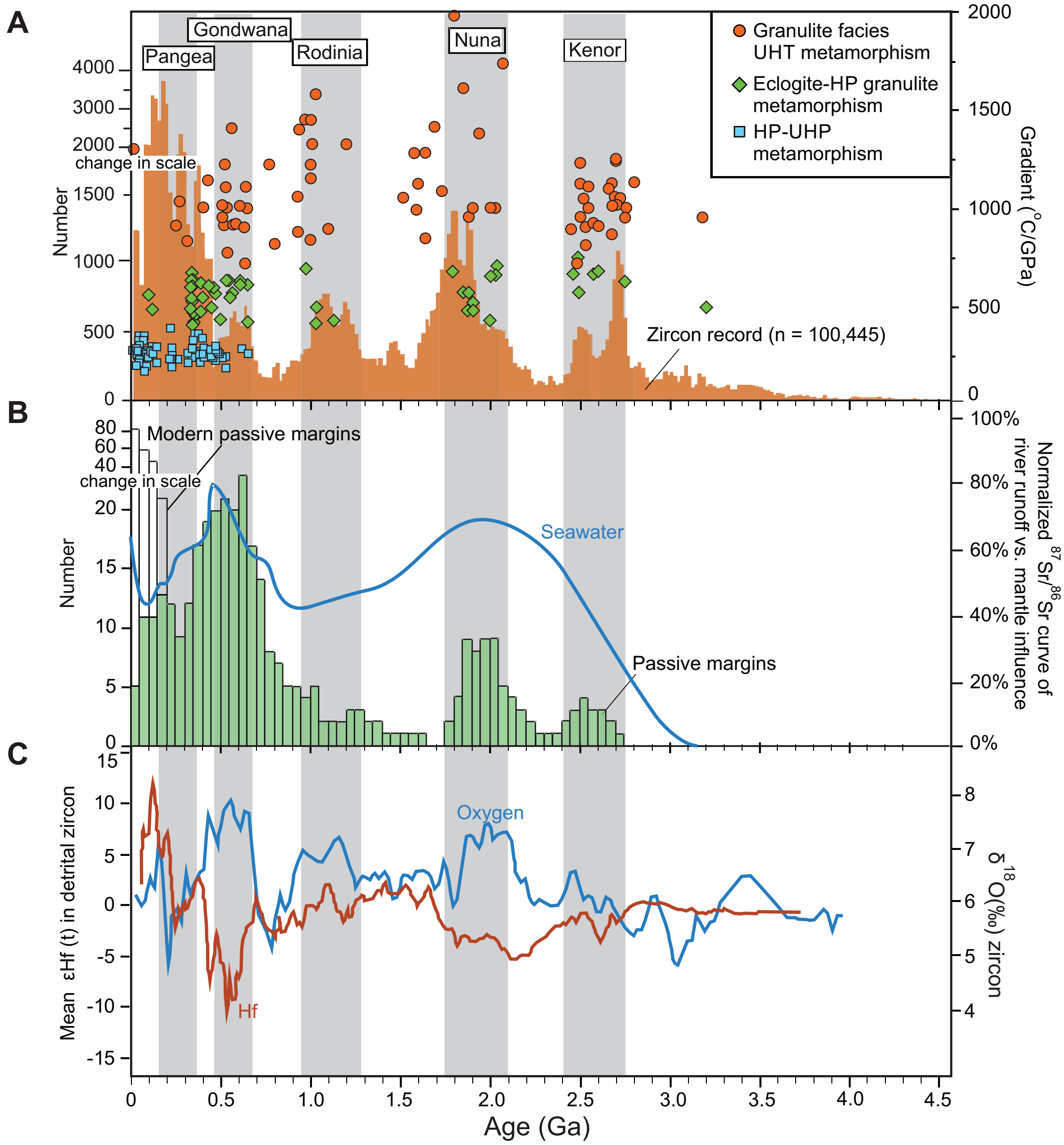

Figure 1. (A) Histogram of more than 100,000 detrital zircon analyses showing several peaks in their U-Pb crystallization ages over the course of Earth's history (Voice et al., 2011), which are very similar to the ages of supercontinents. Also shown is the apparent thermal gradient versus age of peak metamorphism for the three main types of granulite-facies metamorphic belts (Brown, 2007, 2014). UHT—ultrahigh temperature; HP—high pressure; UHP—ultrahigh pressure. (B) Histogram of the ages of ancient and modern passive margins (Bradley, 2008) and normalized seawater ^{87}Sr/^{86}Sr curve (Shields, 2007). (C) Running mean of initial εHf in ~7000 detrital zircons from recent sediments (Cawood et al., 2013) and moving average distilled from compilation of ~3300 δ^{18}O analyses of zircon versus U-Pb age (Spencer et al., 2014).

THE GEOLOGICAL RECORD

Earth's history is one of continuous activity in the generation of igneous, metamorphic, and sedimentary rocks. Yet in terms of stratigraphy, most of geological time is represented by gaps (in unconformities and disconformities) and not by the rocks themselves. Moreover, the geological record is only what remains—what is preserved. Few rocks from the oceans survive, and preservation is shaped by tectonic setting, the development of mountain belts, and erosion. Thus, while geological activity may be continuous, the distribution of different rock units is heterogeneous in both space and time; the ages of igneous crystallization, metamorphism, continental margins, and mineralization are distributed about a series of peaks and troughs (Fig. 1; and see also Bradley, 2011). The record is incomplete (e.g., Holmes, 1965; Hutton, 1788; Raup, 1972), and incomplete records tend to result in biases, not least because the preservation of the records of different environments and tectonic settings is highly variable.

The implications of bias are well established in the discussions of the fossil record (e.g., Smith and McGowan, 2007). Particular sedimentary facies dominate the rock record, and two-thirds of extant animal species have no hard parts that would lend themselves to being easily fossilized. Most fossils come from lowland and marine habitats where the conditions for fossilization and preservation are most prevalent, and although only 20% of extant

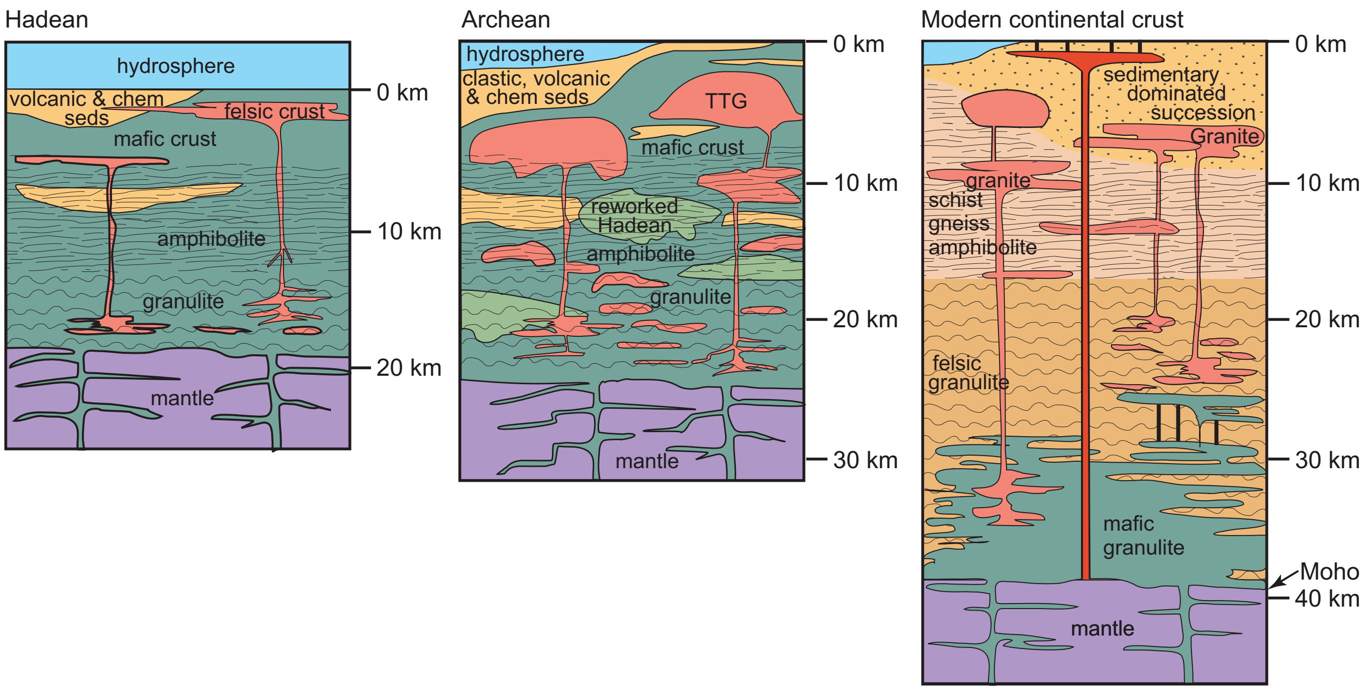

Figure 2. Schematic sections of Hadean, Archean, and modern continental crust. Hadean and Archean sections adapted from Kamber et al. (2005) and modern crust from Hawkesworth and Kemp (2006). TTG—tonalite-trondhjemite-granodiorite.

species are marine (Mora et al., 2011), marine fossils dominate the fossil record. Mineral deposits that form at or near Earth's surface (e.g., epithermal silver-gold deposits) have a lower long-term preservation potential than deeper deposits (orogenic gold; Wilkinson and Kesler, 2007).

It has similarly been argued that the peaks and troughs of crystallization ages that characterize the continental crust (Fig. 1) reflect the better preservation of igneous rocks generated in some tectonic settings compared to others. The peaks of ages are therefore thought to reflect a biasing of the continental record, apparently linked to the development of supercontinents (Cawood et al., 2013; see also Condie et al., 2011; Hawkesworth et al., 2009, 2010). The implication is that they should not be taken as prima facie evidence that in any global context the history of the continental crust is marked by pulses of magmatic activity. Rather, magmatic rocks generated in different tectonic settings have different likelihoods of being preserved over long periods. This is most marked in the contrast between the preservation of igneous rocks generated in continental and oceanic settings. However, these differences in preservation are also a feature of rocks generated in subduction and collision-related tectonic environments in the continents.

Along subduction zones, high volumes of magma are generated, but a number of studies have highlighted that the continental crust is destroyed by erosion, subduction, and in some areas delamination, at rates similar to, or greater than, those at which new crust is generated (Clift et al., 2009; Scholl and von Huene, 2007, 2009; Stern, 2011). Island arcs have higher average rates of magma generation than Andean margins, yet island arcs are more readily subducted and so they are even less likely to be preserved than continental margins (Condie and Kröner, 2013). In contrast, the volumes of magma generated in the final stages of convergence and continental collision decrease, but the chances of the resultant igneous rocks being preserved is high. Thus, ages from late stage subduction- and collision-related magmatic rocks are likely to be better preserved than those generated more generally above subduction zones, and this results in peaks of ages coincident with the ages of supercontinents. One implication is that the supercontinent cycle tends to bias the rock record (Cawood et al., 2013; Hawkesworth et al., 2009).

Crustal reworking is accentuated by continental collision, and the degree of crustal reworking has changed with time. The temporal distribution of crystallization ages of zircons with Hf model ages greater than their crystallization ages can be used as a proxy for the degree of crustal reworking, and the periods of increased crustal reworking are those of supercontinent assembly (Dhuime et al., 2012). Similarly, there are peaks and troughs in $\delta^{18}O$ values in zircons through time, and the periods of elevated $\delta^{18}O$ are also those of supercontinent assembly (Fig. 1; Dhuime et al., 2012; Roberts and Spencer, 2014; Spencer et al., 2014). Elevated $\delta^{18}O$ values indicate reworking of sedimentary material, and this is most readily achieved in sections of thickened crust in response to continental collision. Thus, this is independent evidence that the peaks of U-Pb crystallization ages are associated with periods of crustal thickening, of continental collision, and the development of supercontinents.

An alternative view is that peaks of ages reflect pulses of magmatic activity, and that as such, they might be associated with mantle plumes (Albarède, 1998; Arndt and Davaille, 2013; Condie, 1998; Parman, 2015; Rino et al., 2004). However, the composition of the continental crust appears to be dominated by minor and trace element features that are characteristic of subduction-related magmas (Rudnick and Gao, 2003), and even for the relatively young age peaks, when the rock record is better

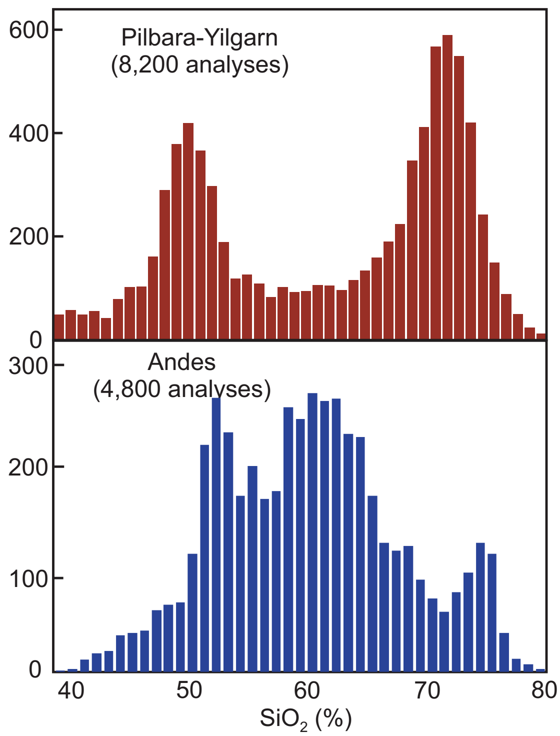

Figure 3. Whole rock SiO_2 distributions of plutonic and volcanic rocks from Archean Pilbara-Yilgarn and the Andes. Data sources from the Western Australia Geological Survey (http://geochem.dmp.wa.gov.au/geochem/) and GEOROC (http://georoc.mpch-mainz.gwdg.de/georoc/), respectively.

preserved, there is little evidence that the ages are concentrated in particular areas that might reflect plume activity. There is, for example, a peak of zircon crystallization ages associated with the Grenville at ca. 1 Ga (Fig. 1), and the Grenville is widely regarded as a collisional event (Gower and Krogh, 2002), rather than a time of unusual volumes of magma generation. We conclude that the tectonic settings in which magmas are generated, and the collisional regimes associated with the supercontinent cycle, have shaped aspects of the preserved geological record. Not all collision orogenies are marked by peaks in the ages of zircons; for example, most of the detrital zircons in rivers draining the Appalachian Mountains have ages associated with the Grenville rather than the Paleozoic (Eriksson et al., 2003). The implication is the numbers of zircons of different ages preserved in sediments depend on the depths of erosion of likely source areas, and hence presumably on the amounts of crustal thickening. Alternatively, although collision related magmas contain greater numbers of zircons than convergent plate margin magmas, the volume of such magmas is so small that this cannot explain the co-incidence of the peaks of zircon ages with the times of supercontinent assembly (Cawood et al., 2013; Hawkesworth et al., 2013).

CRUSTAL THICKNESS (AND VOLUME) THROUGH TIME

A number of different approaches have concluded that 65%–70% of the present volume of the continental crust had been formed by the late Archean (3.0–2.5 Ga; Belousova et al., 2010; Campbell, 2003; Dhuime et al., 2012; Kramers, 2002). It follows that the rates of continental growth (i.e., the rates of increase in the volume of continental crust with time) were significantly higher before 3.0 Ga than subsequently. The rates of continental growth reflect the balance between the rates of generation and destruction of continental crust, and the change at ca. 3.0 Ga has been taken to indicate that the dominant processes of crust generation changed at about that time (Dhuime et al., 2012). There is a broad consensus about the composition of the bulk/average continental crust as presently preserved (Rudnick and Gao, 2003) and how that is different for Archean terrains (e.g., Fig. 3; Taylor and McLennan, 1985). The challenge has been to obtain information on the composition of *new* continental crust, and whether that has changed with time, because that constrains the conditions under which the continental crust was generated.

Much of the geological record is of magmatic rocks derived from preexisting crustal rocks, but Sr, Nd, and Hf isotope data can be used to estimate the Rb/Sr ratios of those crustal source rocks, which we take to represent new continental crust. Crustal differentiation processes produce a range of fractionated Rb/Sr ratios, and there is therefore a strong positive correlation between Rb/Sr and the SiO_2 contents of crustal rocks and, in recent geological settings, with the thickness of the continental crust (Dhuime et al., 2015).

Dhuime et al. (2015) combined crystallization ages, Nd model ages, and initial Sr isotope ratios of igneous rocks to calculate the Rb/Sr ratios of their crustal source rocks in the period between the model ages, taken to reflect the time those crustal source rocks were derived from the mantle, and the time of generation and crystallization of the magmatic rocks analyzed. These time-integrated Rb/Sr ratios are thought to reflect those of new continental crust, because they are calculated from the time of their model Nd ages. The Rb/Sr ratios of new continental crust are highly scattered prior to 3.0 Ga, but the median is ~0.03, and it increased to a maximum value of ~0.08 from 3.0 to 1.7 Ga, before decreasing to values of ~0.065 in the past ~1 b.y. (Fig. 4A). The implication is that the SiO_2 contents of new crust increased from ~48% before 3.0 Ga to more intermediate compositions, with SiO_2 up to ~57%. This is attributed to a shift from broad-scale mantle melting and diffuse magma injection prior to 3.0 Ga to a subsequent plate tectonic regime involving subduction-related magmatism at plate boundaries (e.g., Sizova et al., 2010).

The Rb/Sr ratios of igneous rocks in modern-day Central and South America increase with crustal thickness, and so the temporal increase in the Rb/Sr ratio of new continental crust may also indicate that the thickness of the crust at the sites of crust generation increased from 20 km at 3.0 Ga to almost 40 km at ca. 1.7 Ga. The estimated thickness then decreased to nearer 30 km since ca. 1 Ga (Dhuime et al., 2015). The predominantly mafic character of Earth's crust before 3.0 Ga (see also Kemp et al., 2010; Tang et al., 2016) means that it would have had a higher density and been less buoyant than modern continental crust, resulting in a greater probability for its recycling into the mantle. Recent geodynamic modeling of Archean crust generated under higher mantle temperatures suggests that it would have been gravitationally unstable and susceptible to recycling through delamination (Johnson et al., 2013).

The curves for crustal growth rates from Belousova et al. (2010) and Dhuime et al. (2012) are based on the proportion of juvenile to reworked crust at different times. Such cumulative growth curves cannot decrease with time (Fig. 4B), and so the curve of changing crustal thickness through time offers a different

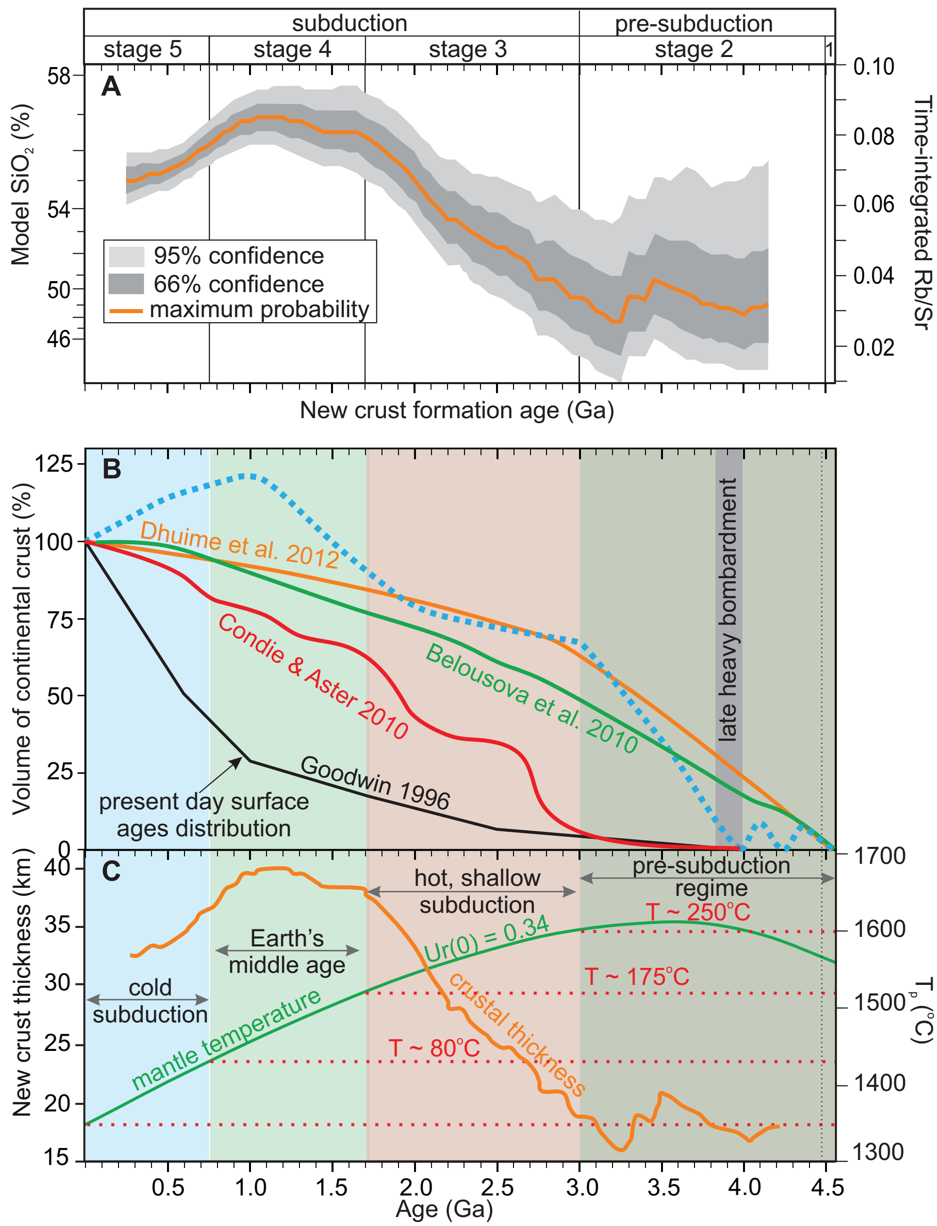

Figure 4. (A) Variation in the estimated Rb/Sr ratios, and SiO_2 contents, of new continental crust from Dhuime et al. (2015). (B) A preliminary model for the changes in volume of the continental crust (dotted blue curve) compared with the crustal growth curves of Belousova et al. (2010) and Dhuime et al. (2012), the model age distribution of Condie and Aster (2010), and the present-day surface age distribution of Goodwin (1996). The preliminary model is illustrative, and it is not unique. It assumes two types of crust generated before and after 3.0 Ga, and rates of crust generation and destruction for each. It is constrained by the volume of continental crust at the present day and 70% at 3.0 Ga, and by the present-day curve of Condie and Aster (2010). (C) Variation in the thickness of new continental crust through time (orange curve) as estimated from the Rb/Sr ratio of new continental crust (Dhuime et al., 2015), and thermal models for ambient mantle for Urey (Ur) ratio of 0.34 (Korenaga, 2013).

perspective (Fig. 4C; Dhuime et al., 2015). The high crustal growth rates before 3.0 Ga were marked by relatively thin continental crust, and at that time there is no link between estimated crustal thickness and crustal growth rates. However, by 3.0 Ga the estimated volume of crust was at least ~70% of the present-day volume, and the crustal thickness was ~50% of the present-day crustal thickness. It therefore appears that before 3.0 Ga the area of continental crust increased with crustal volume, but that since then the thickness (and volume) of the crust may have increased with little or no increase in area.

One issue is the extent to which the crustal thickness at the sites of generation of new crust can be linked to crustal volume. Our preliminary models suggest that the predominantly mafic crust generated before 3.0 Ga was largely destroyed by 2.0 Ga, and that since that time the crust predominantly consisted of post–3.0 Ga crust generated in subduction-related settings. Because the relation between Rb/Sr and crustal thickness is observed in subduction settings (Dhuime et al., 2015), it implies that crustal thickness may be a reasonable proxy for crustal volume at least over the past 2.0 b.y.

Figure 4B (dotted blue curve) illustrates such a model for the changes in crustal volumes through time. It is constrained by the present volume of the continental crust, the presence of 70% of that volume at 3.0 Ga, and the present-day distribution of crust with different model ages (Condie and Aster, 2010). It starts at the end of the heavy bombardment ca. 3.9 Ga; it assumes that the rate of crust generation was greater before 3.0 Ga than subsequently, and that the compositions of the crust generated before and after 3.0 Ga were different. Pre–3.0 Ga crust was preferentially recycled from 3.0 to 1.5 Ga following the onset of subduction at 3.0 Ga. Such models are not unique, but they indicate that changing volumes of continental crust can be modeled with two types of crust that are destroyed at different rates. The model outlined here predicts that nearly twice the present volume of the continental crust has been recycled since the end of the heavy bombardment.

The increase in thickness at the sites of crust generation from 3.0 to 1.7 Ga indicates that more of the continental crust was elevated above seawater (Flament et al., 2013), and hence susceptible to sub-aerial weathering and erosion. This increase in crustal thickness is accompanied by a steady increase in the Sr isotope ratios of seawater (Fig. 1; Shields and Veizer, 2002), implying increased continental runoff, which would increase the amounts of CO_2 draw down due to continental weathering (e.g., Kramers, 2002). Preliminary models indicate that in the mid-Proterozoic the volume of continental crust may have been up to 20% greater than at the present day, and since 1.0 Ga the crust has become thinner, and we infer that the crust decreased in volume (Fig. 4). The rates of crustal growth appear to have decreased as Earth cooled, and "cool" subduction began to dominate, which, on the basis of preserved metamorphic and other rock units, is taken to have commenced around 0.75 Ga (Brown, 2006; Cawood and Hawkesworth, 2014), such that the rates of crustal recycling were greater than the rates at which new crust was generated.

DISCUSSION

There appears to have been five stages in Earth's evolution, with the last four being recorded in the geology of the continental crust (Fig. 4). Stage 1 included the initial accretion of the Earth, core/mantle differentiation, the development of a magma ocean, and of an undifferentiated mafic crust. Most models suggest that a magma ocean may have persisted on Earth for 5–10 m.y., and continuing volcanism, along with deformation, would have progressively thickened the initial mafic crust (Kamber, 2015; Kamber et al., 2005). Once the crust was at least 15–20 km thick, remelting could take place (Fig. 2; Kamber et al., 2005), and the resultant felsic magmas represented the high silica component in the distinctive bimodal silica distribution that characterizes the Archean crust (Fig. 3). This second stage was marked by elevated mantle temperatures compared to the present day (Fig. 4C) that resulted in lithosphere weakened by the emplacement of melts (Gerya, 2014; Sizova et al., 2010). This inhibited subduction, and hence plate tectonics, and magmatism were driven by mantle upwellings that percolated the lithosphere. These might have been associated with deep-seated mantle plumes, but such models remain difficult to test, and the upwellings may have been more localized and likely originated at shallower levels, perhaps as in a heat-pipe model (Moore and Webb, 2013). In today's world, such magmatism would be regarded as intraplate; it has no association with subduction, but in a time before plates, such terminology is arguably misleading. Destruction and recycling of early crust occurred through a combination of delamination (Johnson et al., 2013) and meteorite impact, the latter continuing until the end of the late heavy bombardment ca. 3.9 Ga (Gomes et al., 2005; Marchi et al., 2014), and so perhaps we are fortunate to have the few zircon grains that have survived from the Hadean.

The onset of stage 3 is taken to be the stabilization of Archean cratons and the change in crustal growth rates ca. 3.0 Ga. It is envisaged that Earth had cooled sufficiently for "hot" subduction to take place (Sizova et al., 2010) from ca. 3.0 Ga to ca. 1.7 Ga (Fig. 4). The continental crust became thicker and more evolved, plate tectonics resulted in collisional orogenies, supercontinent cycles developed, and there was increased erosion to the oceans due to thickening and subaerial exposure of continental crust resulting in an increase in Sr isotope ratios in seawater (Fig. 1B). Models in which ~70% of the present volume of the continental crust was present at 3.0 Ga also require that large volumes of continental crust have been destroyed, presumably in the late Archean and the Proterozoic (Hawkesworth et al., 2013). However, the net growth of crust requires the rate of crust generation to exceed that of recycling (Fig. 4).

The fourth stage is from 1.7 to 0.75 Ga, referred to as the "boring billion" (Holland, 2006), and more recently as Earth's middle age (Cawood and Hawkesworth, 2014). It is marked by a paucity of preserved passive margins, an absence of significant anomalies in the paleoseawater Sr isotope record and in Hf isotopes in detrital zircon (Fig. 1), a lack of orogenic gold and volcanic-hosted massive sulfide deposits, and an absence of glacial deposits and iron formations (Cawood and Hawkesworth, 2015). It appears to have been a period of environmental, evolutionary, and lithospheric stability, which has been attributed to a relatively stable continental assemblage that was initiated during assembly of the Nuna supercontinent by ca. 1.7 Ga and continued until breakup of its closely related successor, Rodinia, ca. 0.75 Ga. It is also marked by abundant anorthosites and related rocks perhaps linked with the secular cooling of the mantle. The overlying continental lithosphere was strong enough to be thickened and to support the emplacement of large plutons into the crust, yet the underlying mantle was still warm enough to result in widespread melting of the lower thickened crust and the generation of anorthositic magmas (Ashwal, 2010).

The termination of Earth's middle age, and onset of stage 5, corresponds with Rodinia breakup at 0.75 Ga and the development of "cold" subduction. The latter is recognized by the onset of high- to ultrahigh-pressure metamorphic rocks (Brown, 2006). Falling mantle temperatures enabled deeper levels of slab breakoff in collision zones and the resultant greater depths to which continental crust was subducted prior to exhumation, allowing the development of the ultrahigh-pressure metamorphic assemblages (Brown, 2006; Sizova et al., 2014). Stage 5 is marked by a strongly episodic distribution of ages linked to the supercontinent cycles of Gondwana and Pangea (Fig. 1). Oxygen levels in both the atmosphere and deep oceans increased, phosphate and evaporate deposits became widespread, and these provided a major spurt for metazoan evolution.

The changing thermal structure of Earth resulted in changes in the properties of the lithosphere, and hence in tectonics and ultimately in surficial processes. As Earth cooled from the late Archean (Fig. 4C), the continental and oceanic lithospheres strengthened because they contained less melt and were characterized by lower temperatures. Subduction and plate tectonics caused profound changes with the onset of significant horizontal tectonics, the development of thickened mountain belts and increased erosion, a change in crustal compositions, and the recycling of continental crust back into the mantle. Secular cooling of Earth impacted lithospheric rheology, magmatic activity, and thickness, which in turn influenced surficial processes and features. Secular changes in the rheology of the lithosphere determine how it behaves in terms of global tectonics, the magmas generated, and the differential preservation of rocks generated in different settings that have shaped the geological record.

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