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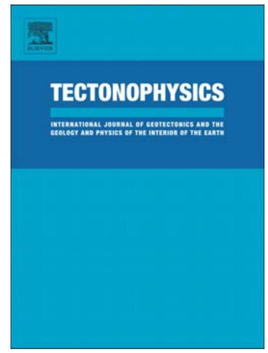

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Continental Growth and the Crustal Record

Chris Hawkesworth[1], Peter Cawood[1] and Bruno Dhuime[1,2]

[1]Department of Earth Sciences, University of St. Andrews, North Street, St. Andrews KY16 9AL, UK

[2]Department of Earth Sciences, University of Bristol, Wills Memorial Building, Queens Road, Bristol BS8 1RJ, UK

Abstract

The continental crust is the archive of Earth history. The spatial and temporal distribution of the Earth's record of rock units and events is heterogeneous with distinctive peaks and troughs in the distribution of ages of igneous crystallization, metamorphism, continental margins and mineralization. This distribution reflects 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. In contrast there are other signals, such as the Sr isotope ratios of seawater, mantle temperatures, and redox conditions on the Earth, where the records are regarded as primary because they are not sensitive to the numbers of samples of different ages that have been analysed. New models based on the U-Pb, Hf and O isotope ratios of detrital zircons suggest that at least ~60-70% of the present volume of the continental crust had been generated by 3 Ga. The growth of continental crust was a continuous rather than an episodic process, but there was a marked decrease in the rate of crustal growth at ~3 Ga. This appears to have been linked to significant crustal recycling and the onset plate tectonics. The 60-70% of the present volume of the continental crust estimated to have been present at 3 Ga, contrasts markedly with the <10% of crust of that age apparently still preserved and it requires ongoing destruction (recycling) of early formed crust and subcontinental mantle lithosphere back into the mantle through processes such as subduction and delamination.

1. Introduction

The continental crust is the record of the history of the Earth, of the processes and events that have controlled our planet's evolution. There is therefore considerable interest over the extent to which it represents a primary record that reflects the processes involved in the generation and the evolution of the continental crust, or one shaped in response to the different preservation potential of rocks generated in different settings. The oceanic record only extends back some 200 Ma whereas the rocks and minerals of the continental crust extend back to 4.4 Ga, within 150 Ma of the age of the Earth. The continental crust constitutes some 40% of the surface area of the Earth, it is andesitic in composition, 25-70 km thick, and it is less dense than the thinner (<10 km) oceanic crust of largely mafic composition, and the underlying ultramafic upper mantle. Andrija Mohorovičić linked the velocity of seismic waves to the density of the material they are moving through, and in 1910 he described what is now known as the Mohorovičić discontinuity on the basis of the acceleration of seismic waves as the base of the continental crust (Mohorovičić, 1910). The continental crust is therefore that component of the lithosphere that lies above the Mohorovičić discontinuity (Moho) and extends laterally to the break in slope in the continental shelf (Rudnick and Gao, 2003).

Early discussions of continental geology focussed on the origins and the development of different rock associations and structures. These developed within the framework of a fixist view of continental crust and ocean basins but evolved into more dynamic models with the advent of seafloor spreading and plate tectonics (e.g., Lyell, 1833; Hall, 1859; Dana, 1873; Haug, 1900; du Toit, 1937; Carey, 1958; Hess, 1962; Holmes, 1965; Wilson, 1966; Dewey and Bird, 1970). The onset of high precision dating, and the use of radiogenic isotopes to explore when different reservoirs in the Earth may have formed and the nature of their interactions, in turn allowed earth scientists to address the fundamental questions of when and how the continental crust was formed. Zircons are widely used because they yield high precision U-Pb crystallization ages, and in combination with robust Hf and O isotope compositions, the timing of the extraction of source material from the mantle can be evaluated (Patchett et al., 1982; Griffin et al., 2004; Kemp et al., 2006). The physicochemical resilience of magmatic zircons results in their preservation as detrital minerals in sediments, and hence they provide a record of the distribution of crustal material of different ages even when the primary record of this material is no longer preserved (Froude et al., 1983). The striking increase in the numbers of high precision ages has highlighted that the geological record of the continental crust is marked by peaks and troughs in the distribution of crystallisation ages (McCulloch and Bennett, 1994; Condie, 1998; Campbell and Allen, 2008; Belousova et al., 2010; Voice et al., 2011). In many ways this was unexpected, and it has provoked considerable debate over the extent to which these ages are primary or secondary signals. In this contribution we review the nature of the continental record, seek to distinguish those records that may have been influenced by biases of preservation from those that are not, and explore models for the generation and evolution of the continental crust, and their implications.

2. Features of the Geological Record

The geological record is episodic with a heterogeneous distribution, in both space and time, of rock units and events; the ages of igneous crystallization, metamorphism, continental margins, mineralization, and seawater and atmospheric proxies are distributed about a series of peaks and troughs (Fig. 1; and see also Bradley, 2011). It has long been known that the geologic record in incomplete (e.g., Hutton, 1788; Holmes, 1965; Raup, 1972), and yet there is little consistency in the interpretation of the punctuated nature of the record (Fig. 1). It is tempting to take it as a primary record of the processes that shaped the generation and subsequent magmatic evolution of the continental crust, and thus Albarède (1998) and Condie (1998; 2000, 2004) proposed that episodic patterns of crystallisation ages reflected juvenile addition to the continental crust through mantle plume activity (cf. Stein and Hofmann, 1994). More recently there have been attempts to model intermittent plate tectonics and to link bursts of igneous crystallization ages with subduction zone activity separated by longer quiescence phases of no subduction (O'Neill et al., 2007; Silver and Behn, 2008; Condie et al., 2009). It has also been argued that the observed peaks of ages reflect periods of increased magmatic activity associated with increases in the volumes of subduction-related magmas during continental break-up (Stern and Scholl, 2010).

In terms of composition, the average continental crust is that of calc-alkaline andesite with the minor and trace element signatures that are characteristic of magmas generated in subduction-related settings (Taylor, 1967; Taylor and McLennan, 1985; Rudnick, 1995; Rudnick and Gao, 2003; Davidson and Arculus, 2006). Along with evidence that plate tectonics has been active for extensive periods of Earth history (Cawood et al., 2006; Condie and Kröner, 2008; Shirey and Richardson, 2011), this strongly suggests that magmatic arcs should be the major site of continental growth (Taylor and McLennan, 1985; Davidson and Arculus, 2006). Yet global compilations of the addition and removal of continental crust along convergent plate margins highlight (a) that they are both the major sites of generation of new crust, but also of continental loss, and (b) that overall at the present day there is no net addition to the crust and possibly even a slight reduction in continental volume (Scholl and von Huene, 2007; Clift et al., 2009; Scholl and von Huene, 2009; Stern, 2011).

An alternative view is therefore that the peaks and troughs of crystallisation ages are not a primary feature, and so they should not be taken as evidence that in any global context the history of the continental crust is marked by pulses of magmatic activity. Instead the peaks and troughs of crystallisation ages reflect a biasing of the continental record, linked to the development of supercontinents (Hawkesworth et al., 2009; 2010; see also Condie et al., 2011; Cawood et al., 2013). There is increasing evidence that magmatic rocks generated in different tectonic settings have different likelihoods of being preserved over long periods in the geological record. Hawkesworth et al. (2009; 2010) outlined a model whereby the observed rock record of igneous crystallization ages is the integration of the volumes of magma generated during the three phases of the supercontinent cycle (subduction, collision and breakup), and their likely preservation potential within each of these phases (Fig. 2). Magma volumes are high in subduction settings but low during continental collision and breakup, and yet the preservation potential of rocks in convergent and breakup settings is poor, whereas the preservation potential of collisional settings is high. In this interpretation the peaks in crystallisation ages that are preserved reflect the integration of the magma volumes generated during supercontinent evolution with their preservation potential (shaded area under the curves in Fig. 2A). The resultant peak corresponds to the collisional phase of the supercontinent cycle, which typically includes the latter phases of assembly, even though the collisional phase is not a major phase of crustal generation (compare with Fig. 1). It is concluded that the supercontinent cycle tends to bias the rock record, but then in practice there are two end-member models as to how that may come about. One envisages that the preservation potential of most magmas is poor, and that significant preservation primarily occurs through continental collision and in particular at times of supercontinent assembly. The other implies that the development of super-continents in some way cleans up the record through removal and recycling of material formed during stages of extension and convergence.

Crustal reworking is accentuated by continental collision, and so one test is to evaluate the extent to which the amounts of crustal reworking increase at the times marked by peaks of crystallization ages. Dhuime et al. (2012) used the distribution of crystallization ages of zircons with Hf model ages greater than their crystallization ages as a proxy for the variations of reworked crust through time. The periods of increased crustal reworking are those of supercontinent assembly (see Fig. 6), periods that are characterized by both increased crustal reworking and preservational bias. More recently a compilation of O isotopes in zircons highlights that this record is also characterized by peaks and troughs in $\delta^{18}O$ values through time, and the periods of elevated $\delta^{18}O$ are those of supercontinent assembly (C.J. Spencer pers.comm., 2013). These links are best developed for Gondwana and Rodinia, whereas as for Nuna there is a double peak consistent with recent suggestions that the assembly of Nuna occurred during a two stage collisional process (Condie, 2013; Pisarevsky et al., 2013). The significance is that elevated $\delta^{18}O$ 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 crystallisation ages are associated with periods of crustal thickening, of continental collision and the development of supercontinents.

Finally in this section it is important to be clear about the magmatic record of rocks trapped in the crust at times of continental collision (Hawkesworth et al., 2009; Condie, 2013). As demonstrated in the Himalayas a significant volume is that of late stage subduction sequences, as in the Karakorum (e.g. (Crawford and Searle, 1993; Wu et al., 2007). Thus models in which the peaks of zircon ages are linked to continental collision and the development of supercontinents do not predict that most of the associated magmas were generated in collisional settings (see Hawkesworth et al., 2009). Rather the collisional tectonics preferentially retains the late stage subduction related and collisional magmas (which tend to be small in volume) in the crust.

3. Insights for Biased Record

One test of the suggestion that the supercontinent cycle has biased the geological record is how the estimated volumes of zircon that crystallized in magmas generated at different tectonic settings at different stages in the supercontinent cycle compare with the observed distribution of zircon crystallization ages. In principle it is possible to evaluate the numbers of zircons that crystallize in different settings each year, from the volumes of magma generated and their typical zirconium content (Cawood et al., 2013). Magmas generated in subduction zone settings crystallise less zircon per volume of magma than those in collision settings (e.g., Moecher and Samson, 2006; Dickinson, 2008). Nonetheless, given the differences in the volumes of magma generated, the numbers of zircons generated in the subduction-dominated assembly phase of the supercontinent cycle are several orders of magnitude greater than those generated in the collision phase (Fig. 3). It follows that the association of peaks of ages of zircon crystallization associated with the collision phase of the supercontinent cycle (Fig. 1) is not a primary signal, and instead it is interpreted here in terms of the bias that reflects the different preservation potential of magmas generated in different tectonic settings (Hawkesworth et al., 2009). The implication is that the observed peaks of zircon crystallization ages cannot be simply regarded as a reflection of any underlying variation in the rates of magma and of crust generation.

4. Implications of a Biased Record

Records may be biased on a range of scales and the implications of any bias will vary depending on the context. If the evolution of the continental crust is biased by the development of supercontinents, it follows, for example, that the bulk composition of the continental crust will also reflect that bias. In practice the bulk composition of the crust is dominated by magmas generated in subduction zones, and the implication is that the volumes of such magmas generated in the later stages of continental convergence, and hence preserved, are much greater than the volumes of magmas generated in collisional settings.

Discussion of primary and secondary origin for igneous crystallization ages in the continental archive also highlights the issue of the extent to which some records of Earth evolution are more likely to have been influenced by biases of preservation than others. At one level any inferred changes that depend on the distribution of geological ages, will be sensitive to the biases introduced by the supercontinent cycle. Thus components of the record which preserve a temporally-related frequency distribution, such as igneous crystallization ages (Voice et al., 2011), ages of metamorphism (Brown, 2007) and ore bodies such as gold (Goldfarb et al., 2001; Cawood and Hawkesworth, in press), and of passive margins (Bradley, 2008), are regarded as secondary signals modified by the proportion of rocks and minerals of a specific age that are preserved. However, there are other signals, for example, the Sr isotope ratios of seawater

(Shields, 2007), mantle temperatures, and redox conditions on the Earth (Foley, 2011), where the records are not sensitive to the numbers of samples of different ages that have been analysed, to any temporally-related frequency distribution. We infer that such records are essentially primary signals not modified significantly by the processes of preservation.

There is then a third group for which the effects of selective preservation are more difficult to establish, as are even the criteria to evaluate such effects. Nd isotopes in fine grained continental sediments are thought to reflect those of the exposed crust at the time of sedimentation (Hamilton et al., 1983; O'Nions et al., 1983; Taylor et al., 1983). However, they provide a biased record, both because older crust tends to be underrepresented in the composition of the bulk sediments (Allègre and Rousseau, 1984), and because the ages of crustal material preserved may be clustered around the ages of supercontinents. Similarly, the average Hf isotope ratios of magmatic zircons through time, and hence the distribution of model ages, may be biased by the ages of the material preserved. The relationships of Hf model ages and crystallisation ages of zircons are different in NW Scotland and Australia. In the former, there are marked peaks in crystallisation and model ages, with a consistent residence time of ~600 Ma (Lancaster et al., 2011). As it is argued that the peaks of crystallisation ages are the product of preferential preservation, then that presumably follows for the Hf model ages as well. In contrast, for Australia as a whole there is a continuum of model Hf ages in zircons that still retain marked peaks of crystallisation ages (Fig. 4). This has been interpreted in terms of hybridisation of Hf isotopes during erosion and sedimentation (Hawkesworth and Kemp, 2006; Hawkesworth et al., 2010), but it also presumably reflects the scale of sampling in that peaks and troughs of model ages are more likely to be preserved across relatively small areas – as in NW Scotland. On the scale of the crust, the running average for Hf isotopes in zircons appears to be complementary to that of Sr isotope ratios in seawater (Fig. 1), and that might encourage the view that the Hf isotope record in zircon is a primary signal.

5. Growth of the Continental Crust

Models for when the continental crust was generated that relied on the crustal record have often invoked periods of increased crust generation at the times of the peaks of crystallisation ages, and of supercontinental assembly (Fig. 5; Taylor and McLennan, 1985; Condie, 1998). In the context of the model presented here in which those peaks of ages reflect preferential preservation associated with supercontinent assembly, those periods would represent periods in which relatively more material was retained in the crust. In that sense they would be periods of increased crustal growth, but viewed from the mantle they would not be periods in which more continental crust was generated, just periods in which less material was returned (recycled) to the mantle.

In the 1970s and 1980s a number of models for the evolution of the continental crust were developed on the basis that the continental crust and the depleted mantle were complementary reservoirs (Jacobsen and Wasserburg, 1979; O'Nions et al., 1980; Allègre et al., 1983). This in part reflected the view that the mantle was well mixed and so representative samples of upper mantle isotope compositions were available in the isotope ratios of mantle-derived basalts. However it has been challenged in part by suggestions that the early depletion of the upper mantle may reflect the generation of other enriched reservoirs before the development of significant volumes of continental crust (Carlson and Boyet, 2008; Tolstikhin and Kramers, 2008; Caro and Bourdon, 2010).

The heterogeneous nature of the continental crust makes it difficult to obtain representative compositions at different stages in its history. In principle it can be done using Nd isotope ratios in shales, although particularly for older material it may be difficult to tie down the age of sedimentation. Sediments are analysed because they represent average compositions, and yet it is widely accepted that younger rocks tend to be sampled preferentially over older rocks (Allègre and Rousseau, 1984), and the proportions of source rocks of different ages are difficult to constrain from the Nd isotope ratio of a whole rock sample of shale. Attention has therefore shifted to the isotope record of Hf in zircons.

Detrital zircons are thought to offer a more representative record of the exposed rocks present at the time of erosion and deposition of the host sediment than is typically preserved in outcrop at the present day. Individual zircons yield high precision crystallisation ages, and the proportion of the components of different ages preserved in the zircon population of a bulk rock sediment can therefore be determined. However, most zircons crystallise from relatively evolved magmas, typically with >65% SiO_2, and so the record preserved is that of differentiated rocks in the continental crust. At present there are hundreds and thousands of zircon analyses published for both U-Pb ages and Hf isotope ratios (Belousova et al., 2010; Voice et al., 2011), and so the case can be made that they offer a newly available representative record of the changing isotope composition of the continental crust. Sediments typically represent mixtures of material from different source regions, and so the same must hold for zircons that crystallised from granites that even contain a contribution from sedimentary material. Thus the Hf isotope ratios, and the calculated model Hf ages, of these zircons will represent hybrid compositions from which it is not possible to isolate geologically useful information on the ages of their source materials. An increasingly common approach is therefore to use the O isotope ratios of zircons to identify those with a sedimentary component (Kemp et al., 2006), and then to remove these zircons from further discussion of when new crust was generated. At present however there are large numbers of zircon Hf analyses for which no O data are available, and for which it is not possible to identify those with hybrid compositions.

Belousova et al. (2010) provided the first analysis of a large number (in their case >13,000) of Hf isotope zircon measurements. They sought to evaluate the proportion of new and reworked crust by combining the numbers of zircons with selected crystallisation ages with those that have model ages in that same time slice. This increased the estimated proportions of new crust generated in any time period, but without O isotope data it was not possible to screen out those analyses that contain a sedimentary, and hence a hybrid component. Nonetheless they concluded that at least 50% of the continental crust had been generated by 3 Ga.

Given the large numbers of zircon analyses that are not accompanied by O isotope data, Dhuime et al. (2012) explored the extent to which the variations between Hf isotopes and δ^{18}O in zircons might be generalised in order to evaluate the changes in the proportions of reworked and new crustal material in zircons of different ages. In practice the use of O isotopes distinguished reworked crust that has been through a sedimentary cycle, and it is less sensitive to the reworking of igneous crust during later remelting events. The variations in O isotopes were used to determine the proportion of new crust formation ages and hybrid model ages in the analysed zircon data (~1400 analyses), and how that changed with time. The model ages >3 Ga are characterised by high degrees of new crustal material, and the proportion of new crust formation ages decreases to a trough at model ages of ~2 Ga, and then increases towards the Phanerozoic (Dhuime et al., 2012). The changing proportion of new crust formation ages in samples with different model ages was then used to recalculate the distribution of new crust formation ages from the model ages distribution of ~7000 detrital zircons for which O isotope data are not available. The distribution of new crust formation ages highlights that the generation of new continental crust was a continuous process, and that this can be established despite the peaks and troughs in the distribution of the zircon crystallisation ages (Fig. 1).

Dhuime et al (2012) then used the changes in the proportions of new and reworked crust calculated from the Hf and O isotope data (Fig. 6A inset, blue and orange histograms, respectively) to calculate a new model for the evolution of the continental crust. This model suggests that ~65% of the present-day volume of the continental crust was already established by 3 Ga ago (Fig. 6A). In some ways such figures can be difficult to test, but one way is to look again at the Nd isotope ratios of sediments and in particular at the bias introduced because younger source rocks tend to erode more readily than older source rocks. Thus the proportions of old crust are underrepresented in, for example, the Nd isotope ratios of bulk shales. This underrepresentation is expressed through an erosion factor *K* (Allègre and Rousseau, 1984), and a study of an active river system in SW Australia demonstrated that the *K* value might be as high as 15-17 (Dhuime et al., 2011). If a *K* value of 15 is used for Nd isotope ratios in Australian shales (Allègre and Rousseau, 1984) it is intriguing that this also suggests that ~65% of the present-day volume of the continental crust was already established by 3 Ga ago (Fig. 6B; Cawood et al., 2013). It is equally striking that similar figures have also been estimated more recently, from the evolution of atmospheric $^{40}Ar/^{36}Ar$ through time (Pujol et al., 2013).

In detail it is perhaps unlikely that a *K* value measured in a recent river system is representative of sedimentary systems throughout Earth history. However, relatively young material tends to get caught up in areas of high relief, and so it will be preferentially eroded, and *K* will be high. Denudation rates are higher in areas of high relief, and so it is also likely that much of the sedimentary record will be dominated by erosion in high relief terrains (Allègre and Rousseau, 1984; Gurnis and Davies, 1986). It is possible that the lithosphere was weaker in the early Archean (Rey and Coltice, 2008; Sizova et al., 2010), and that might result in less relief and lower values of *K*. Yet low values of K before say 3 Ga, do not dramatically change the aspect of the crustal growth curve (Fig. 6B). In the Allègre and Rousseau (1984) model, crust evolution is calculated in steps every 500 Ma and each calculation only involves 2 crustal segments, one old and one young. The age contrast between the two is small in the Archean, and it is only when considering time periods closer to the present day that the average age of the crust is strongly influenced by the proportions of new crust and old crust, and hence by the value of K. Thus the overall shape of the curves for the increase in the volume of continental crust through time are broadly similar irrespective of whether K is constant throughout, or it was much lower before 3 Ga (Fig. 6B). The Allègre and Rousseau (1984) model is more sensitive to uncertainties over the deposition age of 'old' sediments as that has a stronger influence on the growth curve back in time.

6. Implications for crust-mantle interactions through time

Models in which ~65% of the present-day volume of the continental crust was present by 3 Ga ago require two different stages of continental growth, with significantly different net growth rates before and after 3 Ga. During the first ~1.5 Ga of Earth's history on average ~ 3 km^3 of crust added to the continental mass each year (Fig. 6A, Stage 1). Intriguingly this is similar to the rates at which new crust is generated (and destroyed) at the present time (Scholl and von Huene, 2007, 2009). After ~3 Ga the net rates of growth of the continental crust were much lower at ~ 0.8 km^3 of new crust added each year on average (Fig. 6A, Stage 2). One interpretation is that the rates at which new crust was generated have not changed markedly over the last 4.5 Ga, and that this reduction in the average growth rate primarily reflects an increase in the rates at which continental crust is destroyed, linked perhaps to the suggested onset of subduction at ~ 3 Ga (Cawood et al., 2006; Shirey and Richardson, 2011; Dhuime et al., 2012).

The suggestion that ~65% of the crust had been generated by 3 Ga is also in sharp contrast to the observation that ~7% of the exposed present day crust is of Archean age (Goodwin, 1996). Figure 7 highlights that the difference between the Goodwin (1996) curve (A), which describes the proportions of rocks with different geological ages at the present time, and that of the Condie and Astler (2010) that describes the present day proportions of rocks with different model ages (B). This reflects the degree of crustal reworking in the present geological record. In contrast the difference between the Dhuime et al. (2012) model curve for the growth of continental crust (C) and that for the proportions of rocks with different model ages (B) reflects the volumes of crust that have been destroyed *in addition* to that routinely destroyed along contemporaneous convergent margins. Since it has been argued that subduction may not have started until ~3 Ga, the volumes of crust represented by the difference between curves C and B have presumably been destroyed since that time.

Models for the conditions under which subduction might occur in the Hadean and Archean tend to emphasis the effects of (a) the thickness of the oceanic crust, and (b) the strength of the lithosphere (e.g. Korenaga, 2013, and references therein). Davies (1992; 2006) argued that the presence of early depleted mantle would have resulted in oceanic crust thinner than modern oceanic crust (< 3 km on average), and a thinner oceanic crust would increase the viability of subduction. In contrast, van Hunen and van den Berg (2008) suggest that the lower viscosity and higher degree of melting for a hotter, fertile mantle would have resulted in a thicker oceanic crust and depleted harzburgite layer (see also Sleep and Windley, 1982; Sleep, 2007). A thicker lithosphere is likely to have inhibited the initiation of subduction, and thus a different mode of downwelling (Davies, 1992) or “sub-lithospheric” subduction (van Hunen and Moyen, 2012) might have characterized the early Earth. Sizova et al. (2010) described the changing tectonic condition on the Earth in terms of three tectonic regimes, no-subduction, pre-subduction and the modern style of subduction. The pre-subduction regime had upper-mantle temperature 175–250°C above the present, and the plates were weakened by melt percolation from the underlying sub-lithospheric mantle. Convergence results in shallow underthrusting of the oceanic plate rather than self-sustaining one-sided subduction. The models of Sizova et al. (2010) indicate that the degree of lithospheric weakening induced by emplacement of sub-lithospheric melts is the crucial parameter that controls the tectonic regime. At lower upper-mantle temperatures <175–160°C above the present, and hence lower melt fluxes, there is less melt-related weakening and stronger plates, which stabilizes the modern subduction style. The modelling is consistent with the geological evidence that the transition to the modern plate tectonic regime occurred during the Mesoarchean–Neoarchean time (ca. 3.2–2.5 Ga).

7. Concluding remarks

The continental crust is characterised by an episodic distribution of rock units and events (Fig. 1). This distribution is not regarded as a primary feature that might reflect global pulses of magmatic activity, but rather it is attributed to the different preservation potential of igneous rocks generated in different tectonic settings – those generated in some tectonic settings are more likely to be preserved than those generated in others. Advances in analytical techniques are allowing unprecedented interrogation of the continental record but many uncertainties and exciting challenges remain. These include:

- Establishing the extent to which different signals in the rock record reflect primary processes, or are sensitive to the biases introduced by tectonic processes. Whether the episodic age distribution is a generational or preservational feature (Fig. 1) is a first order example, and we conclude that those aspects of the record which preserve a temporally-related frequency distribution, such as igneous crystallization ages, ages of metamorphism, and of passive margins, are secondary signals reflecting the proportion of rocks and minerals of specific ages that are preserved. In contrast, datasets defined by the first occurrence of a phase or form (e.g., new species), or temporal changes independent of the number of data points, such are those related to seawater and atmospheric proxies (e.g., Sr isotopes in seawater, Fig. 1), are more likely to preserve primary signals.

- Integrating the signals of both mafic and more evolved rocks in studies of crust generation. Most zircons crystallise from felsic magmas and so current models of continental volumes tend to ignore contributions from more mafic lithologies. One approach is to infer the bulk composition of the crustal source regions for granitic magmas from their estimated Lu/Hf ratios (Kemp et al., 2006; Pietranik et al., 2008; Hawkesworth et al., 2010). Another may involve calculating the volumes of mafic and ultramafic crust in the continental record from analyses of U-bearing mineral phases, such as baddeleyite and zirconolite, that occur within such lithologies or their derived sediments (Bodet and Schärer, 2000; Rasmussen and Fletcher, 2004; Heaman, 2009; Voice et al., 2011). However their applicability to the problem of continental crust generation may be limited by their general paucity in igneous rocks and their lower physiochemical resilience than zircon through the rock cycle.

- Further evaluation of the effects of zircon fertility on the age distributions obtained for detrital zircon ages (Moecher and Samson, 2006; Sláma et al., 2012), and of Pb loss and how that is best established in detrital mineral populations (Leon and Deutsch, 1963; Pidgeon et al., 1966; Zeh et al., 2008; Whitehouse and Kemp, 2010).

- The differences in the processes involved in generation of the continental crust before and after ~3 Ga (Fig. 6). Basic questions include when and how did the continental crustal composition evolve from a bi-modal to a more continuous distribution with respect to silica and other elements? To what extent can the oxygen fugacity of magmas be used to distinguish those generated in subduction related and more intraplate settings that may have dominated before 3 Ga? Recent suggestions that the distribution pattern of U-Pb crystallisation ages in detrital sediments can be used to differentiate convergent, collisional and extensional basin settings (Cawood et al., 2012), may also provide a new way to constrain tectonic environment and process of generation of Archean greenstone sequences.

- Different ore deposits also have marked age distributions, for example orogenic Au in Figure 1, and it remains a high priority to resolve the extent to which these age distributions reflect when such deposits were generated, or are primarily the consequence of preservation bias. The ages of orogenic Au deposits are similar to those of supercontinent assembly, consistent with the formation of orogenic gold deposits in accretionary environments during on-going convergent plate interaction. In contrast, mineral deposit types which do not form at plate margins are less likely to show a temporal distribution that correlates with pulses of continental assembly. For example, PGE deposits related to the interaction of mantle upwelling with cratonic lithosphere (Cawood and Hawkesworth, in press).

- Destruction of the continental crust at different stages in the history of the Earth. The striking contrast in crustal volumes between the preserved exposed record and those predicted by the latest models on crustal growth (Fig. 5) require that significant volumes of continental crust have been destroyed (Armstrong, 1981). It further suggests that the rates of destruction changed over time.

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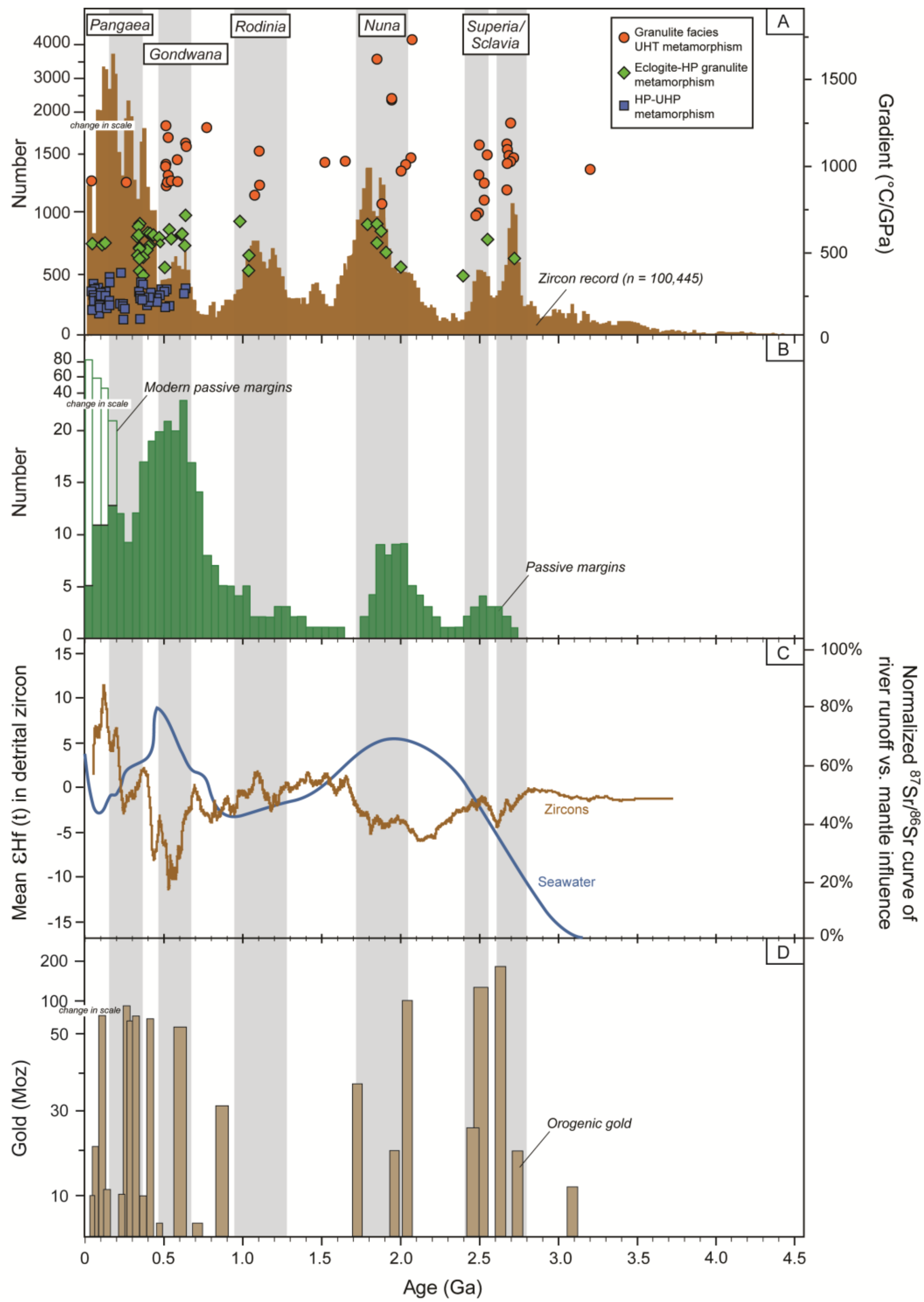

Figure 1. (a): Histogram of 100,445 zircon analyses shows several peaks in their U-Pb crystallisation ages (Voice et al., 2011) that correspond to the ages of supercontinents. Also shown is the apparent thermal gradient versus age of peak metamorphism for the three main types of granulite facies metamorphic belts (Brown, 2007). (b) Histogram of the ages of ancient and modern passive margins (Bradley, 2008); (c) Normalized seawater $^{87}Sr/^{86}Sr$ curve (Shields, 2007), and the

low $^{87}Sr/^{86}Sr$ values in the Archean may in part reflect lack of data; (d) Histogram of orogenic gold distribution (Goldfarb et al., 2001). The periods of supercontinent assembly are highlighted in grey: Superia – 2.8-2.6 Ga, Sclavia – 2.55-2.40 Ga, Nuna – 2.1-1.7 Ga, Rodinia – 1.25-0.95 Ga, Gondwana – 0.65-0.45 Ga, and Pangea – 0.35-0.15 Ga.

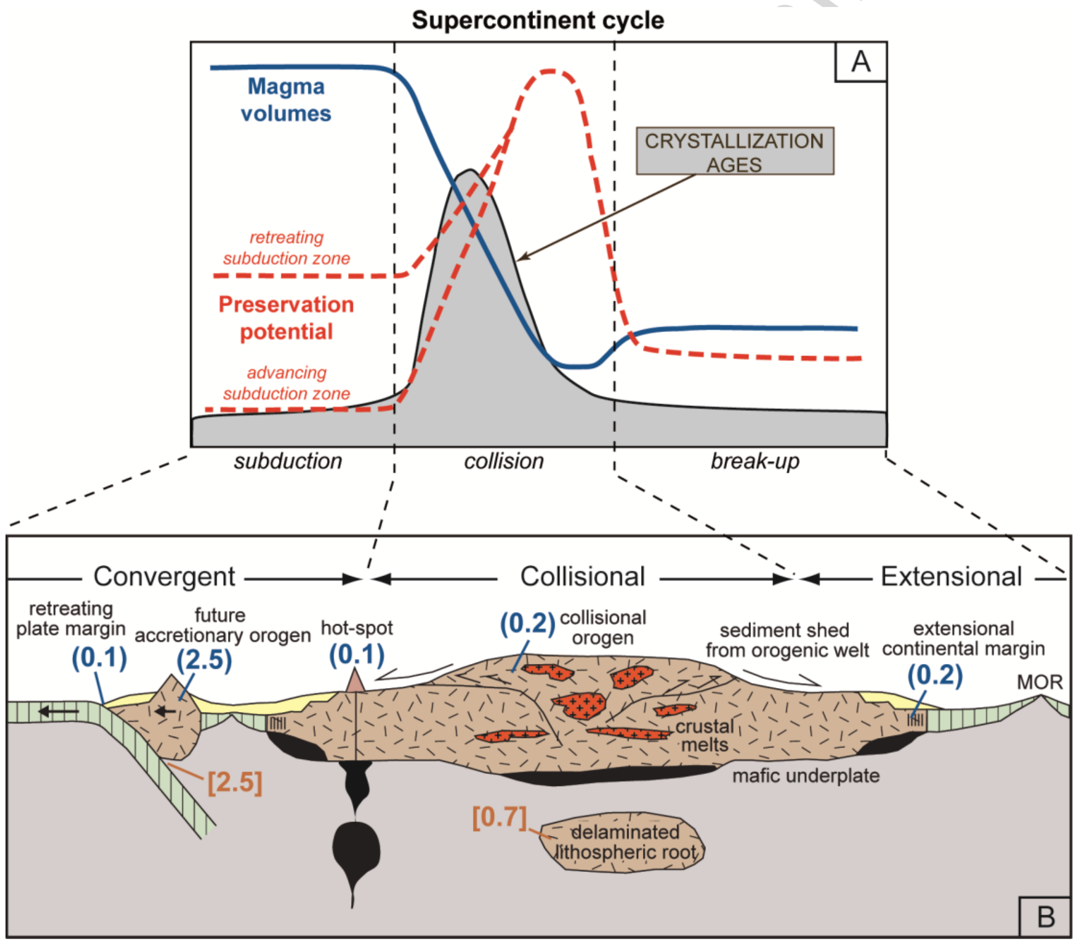

Figure 2. (a) Schematic illustration of the volumes of magma generated (blue line), and their likely preservation potential (red lines) during the stages of convergence, assembly, and break-up of a supercontinent (Hawkesworth et al., 2009; Cawood et al., 2013). In the subduction stage the preservation potential is greater at margins where the subduction zone retreats ocean ward to form extensional basins than at margins where the subduction zone advances toward the continent. Peaks in the crystallisation ages that are preserved (shaded area) are taken to reflect the balance between the magma volumes generated in the three stages and their preservation potential. (b) A schematic cross-section of convergent, collisional and extensional plate boundaries associated with supercontinent cycle showing estimated amounts (in km^3 a^{-1}) of continental

addition (numbers in parentheses above Earth surface) and removal (numbers in brackets below surface). Data from Scholl & von Huene (2007, 2009).

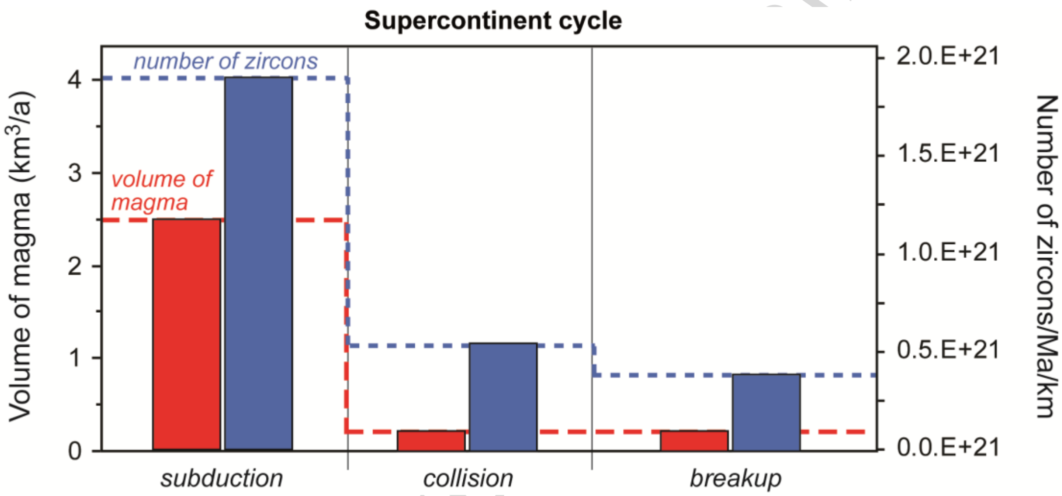

Figure 3. A summary of the volumes of magma generated (in km^3 a^{-1}) during the three stages of the supercontinent cycle (from Scholl and von Huene, 2007; 2009; see also Fig. 8) compared to estimates of number of zircons likely to crystallize from those volumes of magma in each setting (per Ma, per km; from Cawood et al., 2013). The volume of zircon generated per Ma was calculated from the average Zr content in magmas, using the relationship: Vol % zircon = 1.15 wt % Zr (Dickinson, 2008); and Zr = 150 ppm, 520 ppm and 375 ppm for subduction, collision and anorogenic magmas, respectively (Dickinson, 2008). Average zircon dimensions of 150 x 60 x 60 µm were used to convert zircon volumes into number of zircons. The number of zircons that crystallised per Ma are normalised to the total length of convergent margins (42000 km, Scholl and von Huene, 2009; Stern, 2011), to obtain zircon generation rates in Ma per km.

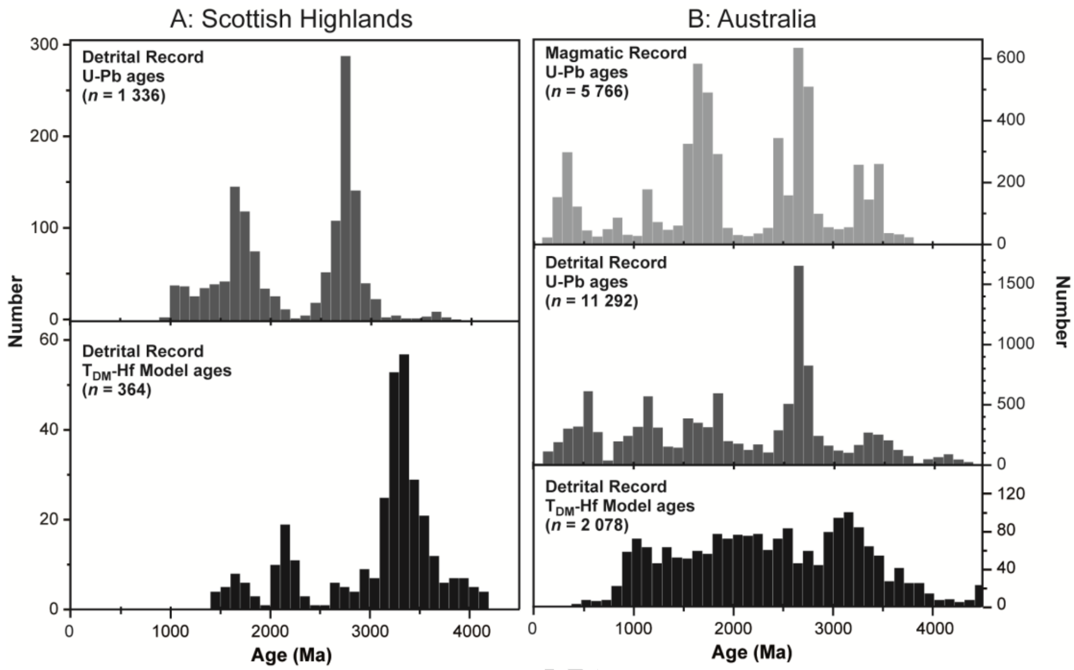

Figure 4. (a) U–Pb and Hf model age histograms for the Scottish Highlands using data from Cawood et al. (2007), Friend et al. (2003), Kinnaird et al. (2007), Kirkland et al. (2008), Rainbird et al. (2001), Whitehouse et al. (1997), and Lancaster et al. (2011). The model ages were calculated using a crustal average $^{176}Lu/^{177}Hf$ of 0.015 (Rudnick and Gao, 2003).
(b) A summary of the U–Pb crystallization and Hf model ages on zircons from Australia both in magmatic rocks and as detrital minerals (Hawkesworth et al., 2010). This contrasts the peaks of crystallization ages for the zircons from magmatic rocks and as detrital grains in sediments with the broader distribution of the Hf model ages.

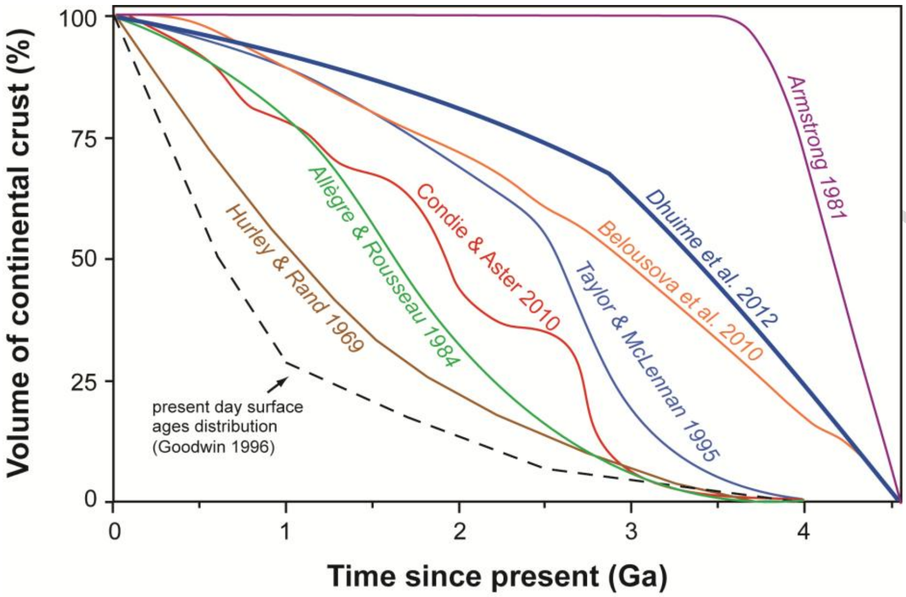

Figure 5. A summary of crustal growth models of Hurley and Rand (1969), Armstrong (1981), Allègre and Rousseau (1984), Taylor and McLennan (1985), Belousova et al. (2010), Condie and Aster (2010) and Dhuime et al. (2012) compared to the age distribution of presently preserved crust from Goodwin (1996).

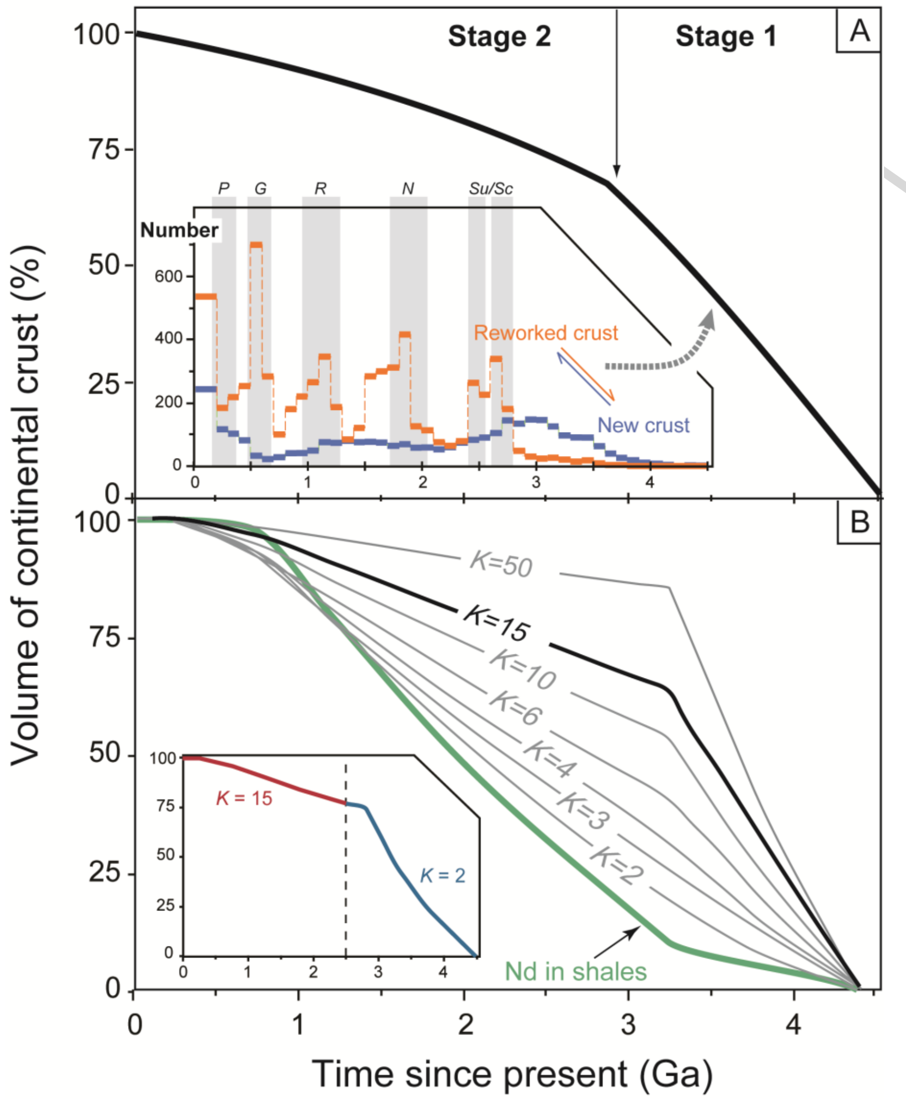

Figure 6. (a) The continental growth curve calculated on the basis of the distribution of Hf model ages in 1376 detrital and inherited zircons sampled worldwide, from which O isotope ratios are also available (from Dhuime et al., 2012, and references therein). In detail the curve is calculated from the variations in the proportions of the new crust (blue histogram) and the reworked crust (orange histogram, which represents the distribution of the crystallization ages of zircons with Hf model ages greater than their crystallization ages). The periods on increased crustal reworking coincide with the periods of supercontinent formation: P – Pangea, G – Gondwana, R – Rodinia, N – Nuna and Su/Sc - Superia/Sclavia.
(b) A plot of the increase in the volume of the continental crust from 4.5 Ga to the present day calculated from the Nd isotope ratios in shales (Allègre and Rousseau, 1984) for different values of the erosion factor *K*. The main diagram assumes that *K* is constant throughout the history of the crust, and the inset

illustrates how the estimated volumes of crust change if *K* = 2 before 3 Ga, and *K* = 15 from 3 Ga to the present day.

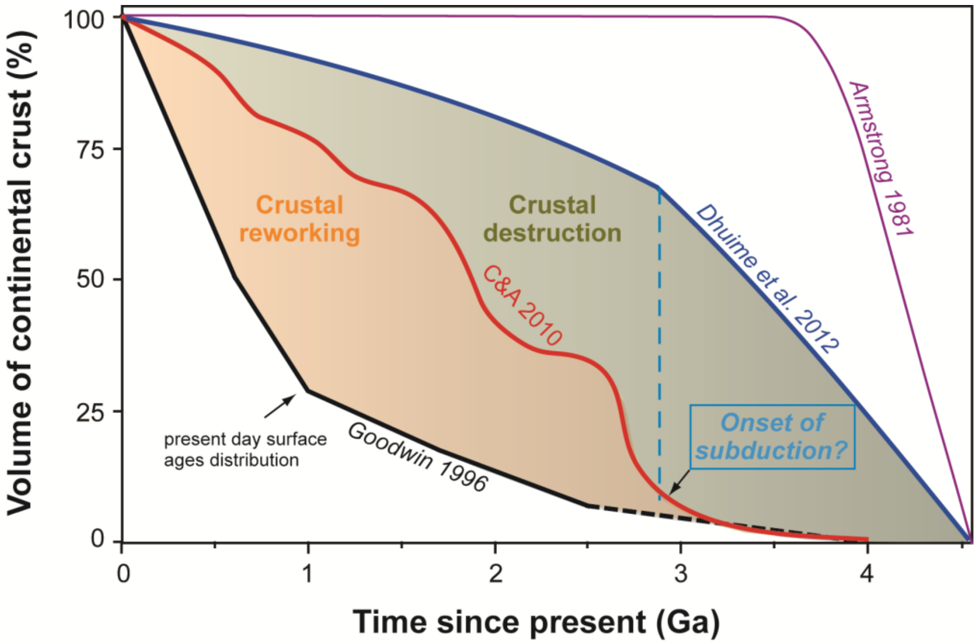

Figure 7. A schematic summary of selected curves for the growth of the continental crust. The curve of Goodwin (1996) summarises the distribution of rocks of different geological ages, and the curve of Condie and Aster (Condie and Aster, 2010) summarises the volumes of rocks with different model, or crust formation ages, both at the present day. The area between the two curves reflects the degree of crustal reworking in the present rocks of the continental crust, whereas the area between the curves for crustal growth (Dhuime et al., 2012) and Condie and Aster (2010) reflect the volumes of continental crust that were once present in the crust and have since been destroyed. The suggestion that subduction may have commenced ~3 Ga (Shirey and Richardson, 2011; Dhuime et al., 2012) would indicate that most of that crust was destroyed since that time.