THE CONTINENTAL ARCHIVE: THE PRESERVATION AND GENERATION OF CONTINENTAL CRUST

P.A. Cawood[1, 2], C.J. Hawkesworth[1] and B. Dhuime[1, 3]

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

[2]School of Earth and Environment, The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia

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

ABSTRACT

Continental crust is the archive of Earth history; not just of the crust itself but of its influence on, and interactions with, the biosphere, atmosphere, hydrosphere and mantle through time. Over 4.5 billion years the continental crust has evolved to form the environment that we live in and the resources we depend on. Numerous and ever expanding data compilations, facilitated by the development of micro-analytical techniques, emphasise that the spatial and temporal distribution of the Earth's record of rock units and events is heterogeneous; for example, ages of igneous crystallization, metamorphism, continental margins, mineralization, and seawater and atmospheric proxies are distributed about a series of peaks and troughs. These peaks in rock units and events reflect biasing of the rock record in different tectonic settings, rather than fundamental pulses of activity, and are linked to the timing of supercontinent assembly and dispersal. The physio-chemical resilience of zircons and their derivation largely from felsic igneous rocks means that they are important harbingers of the crustal record. Furthermore, detrital zircons, which sample a range of source rocks, provide a more representative record than direct analysis of grains in igneous rocks. Analysis of detrital zircons suggests that ~60-70% of the present volume of the continental crust had been generated by 3 Ga. This data includes the extent to which the old crustal material is under-represented in the sedimentary record, and that there were greater volumes of continental crust in the Archean than might be inferred from the compositions of detrital zircons and sediments. Furthermore, systematic variation in Hf and O isotopes in detrital zircons of different ages reveal that the relative proportions of reworked crust, and of new crust, have changed with time. 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, that may have been linked to the onset of significant crustal recycling, probably though subduction at convergent plate margins. The Hadean and early Archean continental record is

poorly preserved and characterized by a bimodal TTG (tonalites, trondhjemites, and granodiorites) and greenstone association that differs from the younger record that can be more directly related to a plate tectonic regime. The paucity of this early record has led to competing and equivocal models invoking plate tectonic and mantle plume dominated processes. 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 requires ongoing destruction (recycling) of crust and subcontinental mantle lithosphere back into the mantle through processes such as subduction and delamination.

INTRODUCTION

The Earth has a bimodal surface elevation reflecting the contrasting chemical-mechanical properties of continental and oceanic crust. The latter is dense, gravitationally unstable and hence young, whereas continental crust is buoyant and the archive of Earth history (Fig. 1); not only of the crust itself but through the rock record of the atmosphere, hydrosphere and biosphere, and of the mantle through its interactions with the crust. Over 4.5 billion years, the continental crust has evolved to form the environment we live in and the resources we depend on. Understanding the crust and its record is fundamental to resolving questions on the origin of life, the evolution and oxygenation of our atmosphere, past climates, mass extinctions, the thermal evolution of the Earth, and the interactions between the surficial and deep Earth. Yet, when and how the continental crust was generated, the volume of continental crust through Earth history, and whether it provides a representative record, remain fundamental questions in the Earth Sciences.

Our aim in this paper is first briefly to outline the general character of the crust and to clarify the terms used, and then to explore the nature of the continental record that is available for study, to evaluate different approaches for when and how the continental crust was generated, and the relationship to the depleted mantle, and to discuss constraints on the rates of continental growth through time and the relationship to tectonic processes, especially the role of the supercontinent cycle in controlling the geological record.

Views on the evolution of the continental crust have changed dramatically as ideas on geological processes have evolved and as methods to interrogate the rock record have advanced through developments in stratigraphic analysis, petrography, paleontology, geochemistry, geochronology, geophysics and modelling. Crucially our understanding of the processes involved in the generation and the evolution of the continental crust has grown enormously through the latter part of the 20th and beginning of the 21st centuries following on from the development and acceptance of plate tectonic theory. This has focused our research on plate margins, the sites of continental crust formation and stabilization, and it has resulted in a fundamental change in the way we approach our interrogation of the Earth and its record from a descriptive documentation of units and events into unravelling the processes controlling these features. Critical to determining process is an understanding of rates of change and this has been facilitated by developments in data collection and analysis. This expansion of knowledge has been particularly important in further understanding not just the exposed surficial rock record but in gaining insight into the composition and development of the whole crust. In particular, this has led to new ideas into what shaped the record, and how representative, or unrepresentative, it may be.

SOME FACTS AND TERMINOLOGY

The total area of continental crust is 210.4 x 10^6 km^2, or some 41% of the surface area of the Earth, and the volume is 7.2 x 10^9 km^3, which constitutes some 70% Earth's crustal volume (Cogley, 1984). The crust extends vertically from the surface to the Mohorovičić discontinuity (Moho) and laterally to the break in slope in the continental shelf (Rudnick and

Gao, 2003). The Moho is defined as the jump in seismic primary-waves (P-waves) to greater than ca. 7.6 km s^{-1}. This change in seismic wave velocity is taken as a first order approximation of the boundary between mafic lower crustal rock and ultramafic mantle peridotite: the crust-mantle boundary. Petrologic studies from exposed sections of ocean floor (ophiolites) and from xenoliths in continental settings suggest that in some situations the crust-mantle boundary may differ from the Moho (Malpas, 1978; Griffin and O'Reilly, 1987).

The mean elevation of the continental crust is around 125 m (Fig. 1) and some 31% of the crustal area is below sea-level. Continental crustal thickness varies from 20-70 km, averaging around 35-40 km (Fig. 2; Mooney et al., 1998). The crust and underlying mantle constitute the lithosphere; the mechanically strong outer layer of the Earth that forms the surface plates (Barrell, 1914b, c, a; Daly, 1940; White, 1988). Heat transport in the lithosphere is conductive and the base is a rheological boundary with the isothermal convecting mantle (Sleep, 2005).

Continents include cratons, areas of stable crust, orogenic belts, and regions of continental extension, which form either intracratonic rifts or develop into zones of continental breakup and thermal subsidence (passive margins). Orogens evolve through one or more cycles of sedimentation, subsidence, and igneous activity punctuated by tectonothermal events (orogenies), involving deformation, metamorphism, and igneous activity, which result in thickening and stabilization of the lithosphere (Fig. 3A, B). Cratons are ancient orogens that have generally been undeformed and tectonically stable for long periods of time, often since the Archean, and are divisible into shields, regions of exposed crystalline igneous and metamorphic rock, and platforms, where the shield is overlain by a relatively undeformed sedimentary succession (Fig. 4).

Geologic and geophysical data show the crust is divisible into a felsic upper crust composed largely of sedimentary rock (upper few kilometers) and granite to granodiorite, a heterogeneous middle crust assemblage of ortho- and paragneiss at amphibolite facies to lower granulite facies (Fig. 3C), and a lower crust comprising granulite facies country rocks and basic intrusive rocks and/or cumulates (Rudnick and Fountain, 1995; Wedepohl, 1995; Rudnick and Gao, 2003). Thicknesses of the three crustal layers vary but the upper and middle crustal sections generally form around 30% each of a typical crustal profile with the lower crust forming the remaining 40% (Fig. 4; Rudnick and Gao, 2003; Hawkesworth and Kemp, 2006a).

The bulk composition of the crust is equivalent to andesite (Fig. 3D) and requires two stages of formation involving extraction of mafic magmas from the mantle and their differentiation through either fractional crystallization or remelting and return of the cumulate or residue to the mantle (Taylor, 1967; Taylor and McLennan, 1985; Rudnick, 1995; Rudnick and Gao, 2003; Davidson and Arculus, 2006).

Surface heat flux of Archean cratons is generally low (30-40 mW m^{-2}). Phanerozoic regions show higher heat flux values (> 60-80 mW m^{-2}), with Proterozoic regions displaying intermediate values. This variation appears to correlate with lithospheric thickness, which ranges from some 200-250 km beneath cratons to generally <100 km beneath Phanerozoic regions (Fig. 4; Pollack et al., 1993; Jaupart et al., 1998; Nyblade, 1999; Jaupart and Mareschal, 2003; McLennan et al., 2005). The absence of garnet in mantle xenoliths from Phanerozoic terranes suggest a lithospheric thickness of generally less than 60-80 km (Lee et al., 2011). McKenzie and Priestley (2008), using shear wave velocity data, have noted that areas of thick lithosphere do not underlie all cratons and also occur under platforms and regions of active deformation. They refer to these regions of continents as cores and have suggested that the thick (ca. 250 km) lithosphere beneath the plateaus in Tibet and Iran may represent regions where cratons are now being formed. The subcontinental lithospheric mantle (SCLM) of Archean cratons is composed of dehydrated, highly depleted mantle peridotite (Pollack, 1986; Boyd, 1989; Pearson et al., 1995; Boyd et al., 1997; Begg et al., 2009; Griffin et al., 2009) resulting in it being intrinsically buoyant and strong, and counteracts the destabilizing effect of their cold thermal state (Lee et al., 2011).

Crust generation involves the formation of new crust through the emplacement of new magma from the mantle and the overall area of continental crust is inversely proportional to the areas of oceanic and transitional crust on a constant radius Earth. Crust recycling is taken to be the infracrustal processes involving the return of crust to the mantle. It may occur by sediment subduction and sediment erosion at convergent plate margins, the loss of chemical solute resulting from continental erosion or hydrothermal alteration that is carried in the subducting oceanic crust, and delamination (detachment and sinking) of continental keels at collisional boundaries (Clift et al., 2009; Scholl and von Huene, 2009; Lee et al., 2011). Crustal reworking is used to mean intracrustal in origin involving the remobilization of pre-existing crust by partial melting and/or erosion and sedimentation, but all at sites within the continental crust (Hawkesworth et al., 2010). The growth of continental crust is the volume of new crust generated through time less the amount recycled to the mantle. In practice, the growth of continental crust is difficult to tie down, because radiogenic isotopes constrain only the volume of crust that has been stable for long enough for significant differences in isotope ratios to be developed from radioactive decay. However, even the generation of short-lived crust may leave a legacy in the complementary depletion of the upper mantle; depleted mantle is that mantle from which melt that becomes part of the continental crust has been extracted. The assembly of continental crust from different segments that were generated elsewhere and juxtaposed tectonically increases the volume of continental crust in the region being considered, but not the volume of continental crust overall, in the sense that the assembled fragments were already present elsewhere.

Supercontinents are assemblies of all or nearly all the Earth's continental blocks and have occurred periodically though Earth history (Nance et al., 1988; Rogers and Santosh, 2004). Superia and Sclavia are the terms proposed for end Archean cratonic aggregations (Bleeker, 2003) and Nuna, Rodinia, Gondwana and Pangea are end Paleoproterozoic, end Mesoproterozoic, end Neoproterozoic and late Paleozoic supercontinents, respectively (Hoffman, 1996). The constituent number and disposition of cratonic blocks/continents with the various supercontinents is best constrained for the younger bodies (e.g. Pangea and Gondwana) and it becomes progressively more uncertain for older assemblages (e.g. Rodinia, Nuna, Superia; Hoffman, 1991; Williams et al., 1991; Dalziel, 1997; Zhao et al., 2002; Bleeker, 2003; Veevers, 2004; Collins and Pisarevsky, 2005; Li et al., 2008; Murphy et al., 2009). Although the specific configuration of the early supercontinents is not fully resolved, the truncation of geologic trends at the edges of cratons and ancient orogens provides convincing evidence that they were components in larger continental assemblages, and this combined with data on the temporal and spatial distribution of tectonothermal events, indicates that they periodically assembled into supercontinents.

HISTORICAL PERSPECTIVE

Humanity’s development has been intimately tied to, and dependent on, the Earth and its resources, and hence it is not surprizing that most cultures developed mythologies on the Earth that often emphasised the interconnected nature of things (e.g. the Greek goddess Gaia – the personification of the Earth)(Fig. 3E). Some of the earliest recorded observations relevant to understanding the origin of the crust were by the Greeks and Romans who noted the very slow rate of change of the Earth’s surface with respect to the human timescale, and that the presence of subaerially exposed marine rocks and fossils required the vertical movement of continents with respect to sea-level. They also developed criteria that aided in the identification of rocks and minerals. The interplay of scientific ideas and religious doctrine in Europe in the 17th and 18th centuries influenced the development of geologic thought, focusing ideas on the age and origin of the crust. This lead to the concept that rocks, including igneous rocks, formed from minerals that crystallized from water, and in particular from the biblical Great Flood (or deluge, and reflected Catastrophism in Earth history). This concept was termed Neptunism and viewed the entire Earth, including the continents, as made up of sedimentary layers. It was popular as it was consistent with the literal interpretation of the Bible that the Earth was only a few thousand years old. However, observations on the contact relations of igneous rocks, which established cross cutting, intrusive relations, and the recognition of unconformities, which must encompass long periods of time, led to the alternative concept of Plutonism (also known as Vulcanism) in which the interior of the Earth was hot, with igneous rocks crystallized from magma. This in turn led to a Uniformitarianism view of the Earth in which "the present is the key to the past". The permanency of the Earth and the immensity of geologic time that the Uniformitarianism view of the Earth required was encapsulated by James Hutton’s (1788, p. 304) phrase “no vestige of a beginning,–no prospect of an end” (Fig. 3F). This powerful and emotive phrase not only emphasises the enormity of deep Earth time but provides a counterpoint to the strict biblical interpretation of the age of the Earth.

Uniformitarianism provided a framework in which to study the Earth, and researchers focused on understanding the processes that shaped and stabilized continental crust preserved in ancient mountain belts (e.g. Hutton, 1788; Lyell, 1833; Hall, 1859; Dana, 1873; Suess, 1885-1909; Haug, 1900; see discussion and references in Dott, 1974; Şengör, 1982). These early observations on the crust and its origins were based on direct field observations and were focused on Phanerozoic sequences in eastern North America and Western Europe, notably the Appalachian and Alpine orogens, with their contrasting geology influencing the ideas and theories that were proposed. Early workers on both continents acknowledged that the continental crust in these belts included a very thick accumulation of deformed sediment. North American workers considered these sequences as shallow water deposits that accumulated in asymmetric troughs at the margins between continents and ocean basins, but which also included input from an outboard source consisting of a long established basement high or borderland (Hall, 1859; Dana, 1873; Schuchert, 1910). In contrast, European workers in the Alpine Orogen regarded the sediments as being deep marine deposits that accumulated on an ophiolitic substrate in a symmetrical basin between continents (Suess, 1885-1909; Haug, 1900; Steinmann, 1906). Time integrated analysis of these orogenic belts lead researchers to speculate on the stabilization of continental crust through a tectonic cycle involving geosynclinal, orogenic and cratonic stages (Haug, 1900; Krynine, 1948; Aubouin, 1965). On a broader scale, ideas on a tectonic cycle lead to the concept of continental accretion through a succession of concentric orogenic belts (Dana, 1873; Suess, 1885-1909; Haug, 1900). This relationship was most readily observed in North America with its cratonic core and enveloping younger Appalachian and Cordilleran orogens. These ideas on the stabilization of continental crust through mountain building processes developed in a framework involving the permanency of ocean basins and fixed continents; concepts that in the 20th century were being increasingly questioned, initially by Western European and Southern Hemisphere workers (Wegener, 1924; Holmes, 1930; du Toit, 1937; Carey, 1958) who emphasised the transitory and dynamic nature of the Earth’s surface. This view of a dynamic Earth was ultimately embraced by the broader geological community and integrated into plate tectonic theory (Hess, 1962; Vine and Matthews, 1963; Wilson, 1966; Dewey and Bird, 1970). It highlighted the processes through which the continental crust was both generated and destroyed.

Chemical and isotopic data on the composition and age of the continental crust, along with geophysical data on the internal structure of the crust and lithosphere, were then integrated with evolving ideas on tectonic processes to provide further insight into the origin, and rate of growth of the crust. Early geochemical data enabled estimates of the average composition of specific rock types/tectonic units and ultimately led to estimations of the average composition of the entire crust (Clarke, 1924; Goldschmidt, 1954; Poldervaart, 1955; Taylor, 1964; Ronov and Yaroshevsky, 1969). This data set has been increasingly refined, as well as integrated with, and feedback into, tectonic models of the crust, and our understanding of the inferred interrelationship between the crust and the complementary mantle reservoir from which it is derived (Hart, 1969; Taylor and McLennan, 1985; Rudnick, 1995; Rudnick and Fountain, 1995; McLennan and Taylor, 1996; Rudnick and Gao, 2003). These studies helped to establish (i) that the overall composition of the continental crust is similar to calc-alkaline andesite, and (ii) the concept that the crust is typically derived in two stages, melting the mantle to generate mafic magma that undergoes fractional crystallisation, with or without assimilation of pre-existing crust, or crystallisation, and then re-melting to generate average crustal compositions.

Age and radiogenic isotopic data on rocks and minerals have led to a range of models on the rate of growth of the continental crust (Fig. 6). Most models indicate that the continental crust increased in volume and area through time (Hurley et al., 1962; Hurley and Rand, 1969; Fyfe, 1978; Veizer and Jansen, 1979; Armstrong, 1981; Allègre and Rousseau, 1984; Taylor and McLennan, 1985; Veizer and Jansen, 1985; Armstrong, 1991; Taylor and McLennan, 1996). These studies have tended to argue that crustal growth was continuous with early models proposing steady or increasing rates of growth through Earth history, and subsequent studies emphasising an earlier period of more rapid crustal growth, typically in the late Archaean or early Proterozoic, followed by decreasing rates of growth to the present day. The early models were often based on the geographic distribution of Rb-Sr and K-Ar isotope ages (Hurley et al., 1962; Hurley, 1968; Hurley and Rand, 1969; Goodwin, 1996) but these are biased by orogenic overprinting from events younger than the age of crust formation, and older crustal terrains tend to be less well preserved than those formed more recently. A key advance was in the development of isotope systems, in particular Nd and Hf isotopes, in which the model ages constrained when new crust was generated, for the most part unaffected by younger orogenic events (McCulloch & Wasserburg, 1978). These isotope systems have relatively long half-lives, and so the variations in Nd and Hf isotopes reflect the generation of crust that was relatively long lived. Material had to be in the crust for long enough for significant amounts of the radiogenic isotope to be generated, typically a few 100 Ma. New crust that was generated and then destroyed shortly after would not have had time to develop a radiogenic signature, and so it is in effect invisible to these isotope systems. Armstrong (1981, 1991) and Fyfe (1978) proposed an early burst of continental growth that was followed by steady-state or even decreasing crustal volumes. Armstrong (e.g. 1981) argued that constant volume was maintained by crustal recycling offsetting any additions from crustal growth. He was amongst the first to emphasise the role of recycling (contrast with Moorbath, 1975, 1977) in both understanding crustal volumes and in potentially affecting the composition of the upper mantle. However, as there is little evidence for significant volumes of Hadean and early Archaean crust from radiogenic isotope systems, it implies that much of the proposed recycled crust was too young to have developed distinctive radiogenic isotope signatures.

A second aspect is that some models of crustal growth invoke continuous growth, and others indicate that the growth of the crust was in some way episodic. The isotopic models of steady growth of continental crust (plus or minus recycling) would appear to be at odds with map patterns involving discordant datasets of discrete age provinces that are abruptly truncated at their boundaries (Gastil, 1960a, b; Dott, 1964). More recent models of continental growth tend to show pulses of enhanced growth at specific periods in Earth history (e.g. late Archean; McCulloch and Bennett, 1994; Taylor and McLennan, 1996; Condie, 1998; Rino et al., 2004). Most of the continental growth models have been based on compilations of whole rock isotopic data, in some cases of fine grained sediments that may have sampled large source areas. However, Condie (1998) used a limited suite of zircon ages of juvenile continental crust, and Rino et al (2004) developed a model based on analysis of detrital zircons of igneous origin in the modern Amazon, Mackenzie and Mississippi rivers. Rapidly expanding data bases of igneous and detrital zircon data highlight a non-continuous distribution of crystallization ages (see Fig. 7) and have led to further proposals that continental growth is episodic, corresponding with phases of the supercontinent cycle and/or to mantle plume activity (Condie, 1998; Condie, 2000, 2004; Campbell and Allen, 2008; Voice et al., 2011). But Gurnis and Davies (1986) noted that young crust is more elevated than old crust and hence more easily eroded (cf., Allègre and Rousseau, 1984) and this will lead to preferential recycling of young crust and can lead to an apparent peak in a continuous crustal growth curve at 2 – 3 Ga.

THE NATURE OF THE CONTINENTAL RECORD

The continental crust is the key archive of Earth history. It is the record of when and how the continental crust was generated, and its influence on, and interactions with, the biosphere, hydrosphere, atmosphere, and mantle through time. This discussion is intimately tied to the extent to which the rock record is representative and the methods used to extract signals from the record. It is about how best to interrogate the geological record and more recently whether it is a valid record of Earth history or is it biased by selective preservation of rocks generated in different tectonic settings. Igneous provinces are by definition restricted in space and time, and they therefore provide regional snapshots of the magmatic processes that have occurred in different tectonic settings. The same is broadly true for metamorphic provinces, and the constraints that the P-T-t paths provide on the thermal histories of different areas. In contrast, sediments contain material from their source rocks irrespective of the conditions under which those rocks were generated. The bulk compositions of detrital sediments have therefore been used to estimate the average composition of the upper crust (Taylor and McLennan, 1981, 1985; Condie, 1993; Taylor and McLennan, 1995; Rudnick and Gao, 2003), and to determine its average Nd isotope ratio and model Nd age (Taylor et al., 1983; Allègre and Rousseau, 1984; Michard et al., 1985). However, the sedimentary record is biased in terms of the different lithologies, and hence the fossil communities that are preserved (e.g. Raup, 1972, 1976; Smith and McGowan, 2007), and because younger source rocks are thought to be more accessible to erosion than older source rocks. Thus, older source rocks may be underrepresented in the bulk compositions of continental detrital sediments (Allègre and Rousseau, 1984). It is unclear whether comparable biases also occur in the igneous and metamorphic rocks of the continental crust.

Numerous and ever expanding data compilations, facilitated by the development of micro-analytical techniques, emphasise that the spatial and temporal distribution of rock units and events is heterogeneous; for example ages of igneous crystallization, metamorphism, continental margins, mineralization, and seawater and atmospheric proxies are distributed about a series of peaks and troughs. These appear, at least in part, to correspond with the cycle of supercontinent assembly and dispersal (Fig. 7).

Igneous and detrital zircon U-Pb ages and Hf isotopic data have identified peaks in ages of crystallisation (Fig. 7; Condie, 1998; Condie, 2000, 2004; Rino et al., 2004; Condie, 2005; Groves et al., 2005; Hawkesworth and Kemp, 2006b; Kemp et al., 2006; Campbell and Allen, 2008). Peaks in U-Pb crystallization ages correspond with periods of supercontinent assembly at around 2.7-2.4 Ga (Superia and Sclavia), 2.1-1.7 Ga (Nuna), 1.3-0.95 Ga (Rodinia), 0.7-0.5 Ga (Gondwana), and 0.35-0.18 Ga (Pangea). Peaks in Hf isotopes ages were recognized in early and/or regional studies but expanding data sets suggest a more continuous distribution (Belousova et al., 2010; Hawkesworth et al., 2010; Dhuime et al., 2012). The distribution of the ages of high grade metamorphic rocks is also episodic (Fig. 7). Brown (2007) categorized high-grade orogenic belts into high-, intermediate- and low-pressure high-temperature belts. He noted that the high-pressure belts were restricted to the last 600 Ma, and concluded that they reflect cold subduction as observed at present along convergent margins. Intermediate- to low-pressure high-temperature rocks are preserved dating back to the late Archean, and Kemp et al. (2007b) pointed out that their ages are grouped in clusters similar to the peaks of crust generation illustrated in Figure 7. The implication is either that periods of granulite-facies metamorphism are in some way linked to the processes of crust generation as suggested by Kemp et al. (2007b) and/or the peaks of the ages of crust generation and granulite metamorphism are themselves a function of the unevenness of the continental record.

The age pattern of ancient passive margins also reveal major peaks in the late Archean, late Paleoproterozoic and late Neoproterozoic to early Paleozoic, which correspond with times of supercontinent aggregation (Fig. 7; Bradley, 2008). The proportion of modern passive margins is somewhat different, correlating with the breakup of Pangea and the resultant increase in margin area (Bradley, 2008). Smith and McGowan (2007) noted that the Phanerozoic diversity of marine fossils is affected by the supercontinent cycle with marine rocks dominating during rifting phases of supercontinents. Bradley (2011) has recently compiled secular trends in a variety of rock units and events and noted that carbonatites (Woolley and Kjarsgaard, 2008) and greenstone-belt deformation events (Condie, 1994; Condie, 1995) also bear the imprint of Precambrian supercontinent cycles.

Mineral deposits are heterogeneously distributed in both space and time, with variations related to long term tectonic trends associated with the supercontinent cycle and changing environmental conditions such as atmosphere-hydrosphere conditions and thermal history (Meyer, 1988; Barley and Groves, 1992; Groves et al., 2005; Groves and Bierlein, 2007; Bierlein et al., 2009). For example, deposit types associated with convergent plate margins (accretionary orogens), such as orogenic gold and VMS deposits, and to a lesser extent porphyry Cu–Au–Mo and Sn–W, and epithermal Cu–Au–Ag deposits, exhibit well defined temporal patterns that broadly correlate with supercontinent assembly (Bierlein et al., 2009).

GENERATIONAL ARCHIVE OR PRESERVATIONAL BIAS

The evidence for peaks and troughs across the rock record, particularly related to igneous rock generation (Fig. 7), has been used to argue that continental crust formation has been episodic, and that in some way pulses in the formation of continental crust are linked to the development of supercontinents (e.g. Condie, 1998; Condie, 2000, 2004; Rino et al., 2004; Condie, 2005; Groves et al., 2005; Hawkesworth and Kemp, 2006b; Kemp et al., 2006; Campbell and Allen, 2008; Voice et al., 2011). Punctuated crustal growth remains difficult to explain by global changes in plate tectonic regimes, which is viewed as a continuous process (but see discussion by O'Neill et al., 2007; Korenaga, 2008; Silver and Behn, 2008a; Silver and Behn, 2008b), and so it is typically linked to mantle plume activity (Stein and Hofmann, 1993; Condie, 1998). However, the andesitic composition of continental crust along with evidence that plate tectonics has been active for much of Earth history and is a major driver for continental assembly and dispersal (Cawood et al., 2006; Shirey and Richardson, 2011), suggests magmatic arcs should be the major source of continental growth (cf. Taylor, 1967; Taylor and McLennan, 1985; McCulloch and Bennett, 1994; Rudnick, 1995; Davidson and

Arculus, 2006; Hawkesworth and Kemp, 2006b). Recently, Stern and Scholl (2009) have argued that peaks of ages reflect periods of increased magmatic activity associated with increases in the volumes of subduction-related magmas that are generated during continental break-up. The peaks of igneous crystallization ages correspond however, with the time of maximum supercontinent aggregation, not with their break-up. Also it is not known if, or why, the inferred large volumes of magmatism associated with the early phases of intra-oceanic arcs, and which for Tertiary arc systems are largely submarine, might be preserved in the rock record (Condie and Kröner, in press). Voice et al. (2011) propose from a comparison of U-Pb ages and Hf isotope model ages for ~5100 detrital zircons that the age frequency distribution of detrital grains reflects predominantly episodic crustal reworking (i.e. destruction) rather than crustal growth. Recycling of crust is indeed an important issue in evaluating growth models of continental crust (cf. Armstrong, 1981) but its role can only be evaluated after the validity of the record, and the extent to which it has been influenced by preservation processes, has been established.

Analysis of the rock record at modern convergent plate margins has established that they are not only major sites for the generation of continental crust but also of its removal and recycling back into the mantle (Fig. 8). Global compilations of sites of continental addition and removal (Scholl and von Huene, 2007; Clift et al., 2009; Scholl and von Huene, 2009; Stern, 2011) highlight that crustal growth rates in continental collision zones, sites of continental aggregation and supercontinent assembly, are low and insufficient to generate the present volume of continental crust over the history of the Earth. Although these compilations reach different conclusions on the values for addition and removal of continental crust for individual tectonic settings, reflecting the different datasets and proxies used, they reach a similar overall conclusion that, on a global scale, the processes of continental addition along destructive plate margins are counterbalanced by those of continental removal, resulting in no net growth in the current volume of continental crust.

Integration of data on the rates and sites of continental growth and removal (Fig. 8) with the observed punctuated rock record (Fig. 7) suggests that peaks in age data may not represent episodic growth but instead reflect the greater preservation potential of rocks formed in collisional belts, and that the record is therefore biased by the construction of supercontinents (Hawkesworth et al., 2009; Hawkesworth et al., 2010; Condie et al., 2011). Thus, 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. This is illustrated schematically in figure 9: magma volumes are high in subduction settings but low during continental collision and breakup (Fig. 8). In contrast, the preservation potential of rocks in convergent and breakup settings is poor, whereas the preservation potential of late stage subduction prior to collision, and collisional settings is high (Fig. 8). Peaks in crystallisation ages that are preserved (shaded area under the curves in Fig. 9) would then reflect the balance between the magma volumes generated in the three stages of supercontinent evolution and their preservation potential. As such they would be unrelated to any underlying variation in the rate of crust generation. Note that the resultant peak in figure 9 corresponds to the collisional phase of the supercontinent cycle even though this is not a major phase of crustal generation (compare with data in Figs. 7 and 8), rather than periods of subduction- and extension-related magmatism (Hawkesworth et al., 2009). In detail, 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 zircon crystallised in the former is many orders of magnitude higher than those generated during the collision stage

(Fig. 10). Thus, the greater abundance of zircons whose ages correspond with the time of supercontinent assembly (Fig. 7) is only possible due to their higher preservation potential and cannot be simply related to the volumes generated (Fig. 10). Furthermore the flux of sediment from source region to depositional basin reflects the influence and feedback between, relief, climate and tectonic setting. High runoff in zones of crustal thickening and uplift will result in rapid exhumation, erosion and high sediment flux (Koons, 1995; Clift, 2010). Basins adjacent to zones of continental collision or convergent Andean margins that receive high orographic/monsoonal rainfall feed high flux river systems. The Yellow, Amazon and Brahmaputra rivers are the top three sediment producing rivers in the world whereas rivers draining low relief arid environments have low sediment flux (Summerfield and Hulton, 1994). Thus, the high sediment flux within collision zones is likely to further accentuate the preservation, bias-induced, episodic zircon record.

Preservation bias also explains other secular trends related to the supercontinent cycle. The peaks in passive margin ages at around 2.5, 2.0 and 0.5 Ga are consistent with selective preservation. If passive margin distribution was related to when they were developed they should follow a predictable pattern related to changes in area of continental margins through time, with a minimum number of margins corresponding with the peak in supercontinent aggregation when continental margin area is reduced relative to the area of the individual constituent continents. In detail their distribution during a supercontinent cycle should be characterised by: a) a decrease in global population of passive margins during supercontinent assembly; b) few passive margins when the supercontinent is fully assembled; and c) an increase in number of passive margins during supercontinent breakup as surface area of continental margins increases (Bradley, 2008). This is not what is typically observed, and only the most recent supercontinent, Pangea and its subsequent breakup record, represented by the distribution of modern margins, appears to follow this trend. The difference in passive margin distribution associated with Pangea breakup relative to those of earlier supercontinents can be explained by the fact that the next supercontinent after Pangea has not yet formed (termed Amasia by Hoffman, 1992) and hence any preservational bias in the record will not be apparent until then. Unlike the relationship between peaks in passive margin ages that corresponds with the Superia/ Sclavia, Nuna, and Gondwana supercontinents, there is no peak associated with Rodinia. A possible explanation is that closure of the ocean related to Rodinia assembly was not bounded by active passive margins, but rather by convergent plate margins (e.g. like the current circum-Pacific “Ring of Fire”).

The time interval corresponding with the Rodinia supercontinent also lacks anomalies in the $^{87}Sr/^{86}Sr$ ratio seawater record or in the average εHf values from large zircon compilations (Fig. 7). The Sr isotope ratio is taken as a measure of the relative amount of continental versus mantle input with positive excursions, such as those corresponding with the Gondwana and Nuna supercontinents, considered indicative of uplift and erosion of continental basement during continental collision (e.g., Bartley et al., 2001). Similarly, the negative values of εHf values during these time intervals are taken to indicate greater crustal reworking associated with collision-related crustal thickening. For Rodinia time, the absence of preserved passive margins, of an evolved εHf signal and a spike in ocean water $^{87}Sr/^{86}Sr$ ratios suggests margins juxtaposed during supercontinent assembly consisted of largely juvenile material, perhaps analogous to those rimming the modern Pacific.

EROSION AND THE CONTINENTAL RECORD

The clastic sedimentary record, which samples a range of source rocks, and may provide the only record of a source that has been lost due to erosion, dismemberment or overprinting, is widely thought to provide a more representative record of the evolution of the continental crust than the present outcrop of igneous and metamorphic rocks (Taylor and

McLennan, 1995). The sedimentary record is however biased; plate margins are dominated by young rocks which are therefore more prone to erosion than older rocks. Thus the bulk compositions of sediments are biased towards the younger material in the source terrains (Allègre and Rousseau, 1984).

Erosion induced bias is expressed through the erosion factor '*K*', as defined by Allègre and Rousseau (1984). *K* contrasts the relative proportions of rocks of different ages in the catchment area with the proportion of those source rocks present in the sediments analysed (Fig. 11). This has proved difficult to measure in natural systems, and values ranging between 2 and 3 have been commonly assumed in previous studies (Garrels and Mackenzie, 1971; Allegre and Rousseau, 1988; Goldstein and Jacobsen, 1988; Jacobsen, 1988; Kramers and Tolstikhin, 1997; Kramers, 2002). These values for *K* would suggest that ~25-30% of the present volume of the continental crust had been generated by 3 Ga (Fig. 12). Dhuime et al. (2011b) developed an approach to measure *K* in a modern river system using Hf isotopes in detrital zircons and Nd isotopes in fine-grained sediments from the Frankland River in southwest Australia. They demonstrated that *K* was variable (4-17), and that it increased downstream with water volume and with topographic relief.

The running mean εHf value for zircons ranging in age from 4 Ga to 10 Ma is ~0 (e.g. Fig. 7; Belousova et al., 2010; Roberts, 2012), which indicates that there is a significant crustal component in the magmas from which those zircons crystallised. Crustal melting is in turn often associated with crustal thickening, and hence with areas of high relief. Denudation rates increase with increasing average relief (Summerfield and Hulton, 1994), and so the bias in the sedimentary record may be dominated by erosion in areas of high relief. If so, and this has yet to be tested rigorously, values of *K* = 10-15 may be more appropriate for erosion and deposition of sediments that dominate the geological record. It follows that models for the evolution of the continental crust based on analysis of sedimentary rocks should be based on the values of *K* that characterise areas of crustal thickening and hence marked topographic relief. Assuming that they are applicable back into the Archean, such values of *K* would suggest that 60-70% of the continental crust had been generated by 3 Ga (Fig. 12).

UNRAVELLING THE RECORD OF CONTINENTAL GROWTH

The last decade has seen considerable interest in the potential of zircons for studies of the generation and evolution of the continental crust. Zircons yield high precision crystallisation ages both using bulk dissolution and *in situ* techniques using the ion probe or laser ablation ICP-MS. There are hundreds of thousands of such ages (e.g. Voice et al., 2011), and they provide the backbone of the temporal framework of when different geological events took place in different regions. Zircons can also be analysed for Hf and O isotopes, and for trace elements, and they contain silicate inclusions which can be used to constrain the nature of the host magma from which they crystallised (e.g. Jennings et al., 2011).

Hafnium isotope studies of magmatic and detrital zircons are utilised to explore the petrogenesis of granitic rocks (Kemp et al., 2007a) and to unravel crustal evolution (Amelin et al., 1999; Vervoort et al., 1999; Griffin et al., 2004). Hf is concentrated in zircon (~1 w.t. %), and so zircons have very low Lu/Hf and their measured $^{176}Hf/^{177}Hf$ ratio approximates that of the host magma at its time of generation. The Hf isotope ratios are a measure of the crustal residence age, i.e. the average time since the sources of the igneous rocks from which the zircons crystallised were extracted from the mantle (the Hf 'model' age). The depleted mantle has been regarded as the complementary reservoir to the continental crust, and because the depleted mantle is thought to reside at relatively shallow levels in the Earth’s mantle it has also been regarded as the source of the basaltic magma involved in the generation of new continental crust (Jacobsen and Wasserburg, 1979; O'Nions et al., 1980; Allègre et al., 1983). Depleted mantle compositions (as measured in MORB) have therefore typically been used in model age calculations, but new continental crust is mostly generated along destructive plate margins (e.g. Taylor, 1967; Rudnick, 1995; Davidson and Arculus, 2006; Scholl and von Huene, 2007, 2009). Such magmas are more enriched isotopically than MORB since they tend to contain a contribution from recycled sediments (White and Patchett, 1984; Plank, 2005; Chauvel et al., 2008). The implication is that new crust, i.e. the magmas that cross the Moho, typically have lower Nd and Hf radiogenic isotope ratios than magmas generated from the depleted mantle (DePaolo, 1981; Dhuime et al., 2011b; Vervoort and Blichert-Toft, 1999). The weighted mean of εHf in modern island arc basaltic lavas is 13.2 ± 1.1 (Dhuime et al., 2011a), lower by ca. 3-4 ε units than the average εHf of contemporary MORB (e.g. Salters and Stracke, 2004; Workman and Hart, 2005). If model ages are calculated using the new continental crust evolution line, anchored by the present day εHf value of 13.2, they are up to 300 Ma younger than those calculated using depleted mantle compositions (Dhuime et al., 2011a).

A key aspect in developing improved models for the generation and evolution of the continental crust is in being able to interrogate the information now available in the 100s of 1000s of zircon analyses. One difficulty is that many crustally-derived magmas contain a contribution from sedimentary source rocks, and such sediments typically include material from a number of different source rocks. Thus the Hf isotope ratios and the model Hf ages of such magmas, and the zircons that crystallised from them, are likely to yield ‘mixed’ source ages that do not provide direct evidence for when new crust was generated from the mantle. It is therefore necessary to find ways to strip off the zircons that may contain a contribution from sedimentary source rocks, this is most easily done using oxygen isotopes, and then crust generation models can be constructed on the basis of the zircon record that may more faithfully record when new crust was generated.

Hf isotope analyses of zircons are increasingly combined with oxygen isotopes (i.e. $^{18}O/^{16}O$, expressed as $\delta^{18}O$ relative to the VSMOW standard). The latter are fractionated by surficial processes, and so the $\delta^{18}O$ of mantle-derived magmas (5.37 to 5.81 ‰ in fresh mid-ocean ridge basalt glass; Eiler et al., 2000) contrasts with those from rocks that have experienced a sedimentary cycle, which have generally higher $\delta^{18}O$. This is reflected in the high $\delta^{18}O$ of the crystallising zircons and it is a 'fingerprint' for a sedimentary component in granite genesis, and thus for the reworking of older crust. The *in situ* measurement of O isotope ratios from the same zircon zones analysed for Lu-Hf is therefore used to distinguish those zircons from magmas that include a sedimentary component, that might in turn have hybrid model ages. In practice there are large numbers of zircon analyses that are not accompanied by O isotope data. Thus, Dhuime et al. (2012) recently explored the extent to which the variations between Hf isotopes and $\delta^{18}O$ 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. The systematic relationship between new crust formation ages and hybrid model ages, represented by the black curve in Figure 13A, were used to recalculate the distribution of new crust formation ages (Fig. 13B, green curve) from the model ages distribution of ~7000 detrital zircon (Fig. 13B, black histogram). The shape of the green curve suggests that new crust formation of is a continuous process. A new model for the evolution of the continental crust was then established from the changes in the proportions of new and reworked crust calculated from the Hf and O isotope data (Fig. 13B, green and orange histograms, respectively). This model suggests that ~65% of the present-day volume of the continental crust was already established by 3 Ga ago (Figs. 6, 13B, inset), and it is striking that this figure of ~65% is similar to that independently estimated from Nd isotopes in sediments if K is ~15 (Fig. 12). The average growth rate of the continental crust during the first ~1.5 Ga of Earth's history is estimated to be ~ 3 km^3 of crust added to the continental mass each year (Fig. 13B, inset, 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). There was then a reduction in the net rates of growth of the continental crust at ~3 Ga and subsequently the rate of crustal growth has been ~ 0.8 km^3 of new crust added each year (Fig. 13B, inset, Stage 2). This reduction in the average growth rate may primarily reflect 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).

TECTONIC SETTINIG AND CRUSTAL RECORD

The distribution of U-Pb crystallisation ages in detrital sediments varies with respect to basin type and like the modal abundances of the clastic fill (cf. Dickinson and Suczek, 1979; Garzanti et al., 2007), varies in response to tectonic setting (Cawood et al., in press). The observed zircon record within a basinal succession represents the summation of two major variables: the presence or absence of syn-sedimentation magmatic activity and the overall spread of ages recorded. For those basins that contain igneous zircons with ages close to the time of sediment accumulation this also reflects the setting of the magmatic activity; for example forearc, trench and backarc basins at convergent plate margins. Older grains reflect the pre-history of the basin's distributive province and will likely show an episodic pattern of peaks and troughs reflecting preservational bias within the supercontinent cycle (Hawkesworth et al., 2009; Condie et al., 2011). These variables can be represented graphically by plotting the distribution of the difference between the measured crystallisation age for a detrital zircon grain and the depositional age of the succession in which it occurs (Fig. 14).

On this basis detrital zircon data can be grouped into three main tectonic settings: convergent, collisional and extensional. The detrital zircon patterns plotted in this way show a spectrum of results with overlap between the three broad basin types, particularly for increasing age of detritus with respect to depositional age (Fig. 14). There is however a significant change in the proportion of ages associated with the youngest and older magmatic events between settings. Convergent margins settings are dominated by detrital zircon ages close the depositional age of the sediment and some arc-trench basins display unimodal age spectra. Zircons from collisional basin settings contain a lower proportion of grains with crystallization ages approaching the depositional ages but still contain a significant proportion of grains with ages within 150 Ma of the host sediment. This pattern reflects the input of material from the magmatic arc that existed during ocean closure prior to collision and the variable amounts of syn-collision magmatism, along with a spectrum of older ages from cratonic blocks caught with the collision zone. Detrital zircon age patterns from extensional basins are dominated by grains that are significantly older than the depositional age of the basin. Syn-depositional magmatism in extensional settings, such as volcanic rifted margins, is largely of mafic composition with a low yield of zircon (e.g., Fig. 10).

TECTONIC CONTROLS ON CRUSTAL EVOLUTION

Present day continental crust is predominantly generated through plate tectonics at convergent plate margins (Taylor, 1967; Rudnick, 1995; Davidson and Arculus, 2006), stabilized through orogenesis (Cawood and Buchan, 2007; Cawood et al., 2009; Cawood et al., 2011), and preferentially preserved in the long term geological archive through the supercontinent cycle (Hawkesworth et al., 2009; Hawkesworth et al., 2010). Plate tectonics is a response to the thermal history of the Earth. Establishing how long plate tectonics has been the modus operandi of continental growth remains difficult to tie down, with suggestions ranging from not long after initial formation of the lithosphere in the Hadean (e.g. Sleep, 2007; Harrison et al., 2008) to the Neoproterozoic (e.g. Stern, 2005). Increasing evidence from a variety of sources including geological, paleomagnetic, geochemical, geophysical and mineralization patterns suggest that plate tectonics has been active since at least the late Archean (Cawood et al., 2006; Condie and Kröner, 2008; Rey and Coltice, 2008; Sizova et al., 2010). Extrapolating the role of plate tectonics further back into the Archean or into the Hadean is hindered by the paucity of the rock record, apart from a few regional remnants (e.g. Isua greenstone belt, Acasta Gneiss, Nuvvuagittuq greenstone belt), along with mineral fragments (detrital zircons and their inclusions) of appropriate age (e.g. Jack Hills of the Narryer Gneiss terrane).

The tectonic setting of early continental crust must also consider its complementary subcontinental lithospheric mantle which shows an episodic and coeval age distribution (Pearson, 1999; Pearson et al., 2007). The buoyancy and strength of late Archean cratonic lithosphere (Lee et al., 2011) suggests that the paucity of an earlier record may reflect secular generation and destruction processes, probably linked to thermal evolution of the mantle. Shirey and Richardson (2011) note that eclogitic mineral inclusions in diamonds, which come from the subcontinental mantle lithospheric keels, are only present after 3.0 Ga, and reflect the onset of subduction and continental collision.

A number of features have encouraged suggestions that the early continental crust may not have been generated solely in subduction related settings. These include the episodic distribution of crystallization ages, and in the ages of new crustal material, assuming that they are a primary signal, as discussed above. The Archean crust is strikingly different in that most old terrains have marked bimodal distributions in silica, as in the more mafic rocks of the greenstone belts and the common TTG (tonalites, trondhjemites, and granodiorites) association (Martin, 1993; Rollinson, 2010; Van Kranendonk, 2010). Such bimodal distributions are a feature of intraplate continental flood basalt provinces (e.g., Mahoney and Coffin, 1997), and this has led to suggestions that much of the Archean crust was generated in intraplate settings, that in many instances have been linked to mantle plumes (e.g. Smithies et al., 2005; Bédard, 2006; Bédard et al., 2012). Archean and younger crust both have marked negative Nb anomalies, and these are typically taken as a strong indication of magmas generated in subduction zone settings (Pearce, 1982; Wilson, 1989; Pearce and Peate, 1995). However, such trace element discriminants have been established for mafic rocks, and they work best in rocks that can be related reasonably directly to their mafic precursors – as in modern destructive plate margin settings (Wilson, 1989; Macdonald et al., 2000). In associations with a marked silica gap, negative Nb anomalies can have been developed during melting of the mafic source rocks, or be a feature of those source rocks, and so not be a reliable indicator of the setting in which the high silica rocks were generated. The negative Nb anomalies of the TTG, and hence the average Archaean crust, have been attributed to small amounts of residual rutile (Rollinson, 2010), and the presence of amphibole (Foley et al., 2002), during partial melting of hydrated source rocks, and so they may not require a subduction related setting. A greater challenge however, is the presence of water in the source rocks for the TTG (Rapp, 1997), and their marked positive Pb anomaly, and how these might be introduced in an intraplate setting. These equivocal geochemical signatures have resulted in subduction-related and plume related interpretations, often for similar regions/periods (e.g. compare Bédard, 2006; Wyman, 2012)

The Jack Hills zircons have received a great deal of attention, and yet it is unclear how representative they are of magmatic process in the Hadean and early Archean. Kemp et al. (2010) highlight how different the Hf isotope-crystallisation age trends were compared with the magmatic records of destructive plate margin associations. Instead they invoked an enriched mafic crust that might have formed by terrestrial magma ocean solidification, and interacted with the nascent hydrosphere at low temperatures. Foundering of such hydrated basaltic shell to deeper crustal levels would in turn result in partial melting and the generation of the TTG (Kamber et al., 2005) and crystallisation of the zircons now found in the Jack Hills sediments. Hadean and early Archean detrital zircons from Wyoming show similar features that are related to anhydrous melting of primitive mantle in plume like setting (Mueller and Wooden, 2012).

Models of the evolution of continental crust, particularly early ones, focused on processes of crustal generation. Armstrong (1991, and references therein) referred to this as the myth of crustal growth, and he was one of the first to emphasise that crustal growth depends on the balance between the rates at which new crust is generated and also destroyed by weathering, erosion and ultimately returned to the mantle. Such processes are clearly observed at the present day as plate tectonics involves the generation and recycling at convergent plate margins through arc magmatism and sediment recycling (through sediment subduction and subduction erosion; von Huene and Scholl, 1991; Scholl and von Huene, 2007, 2009; Stern, 2011), and provides a mechanism to explain the bulk chemical composition of the crust. Residual mafic material is recycled back into the mantle in most models for the generation of the relatively evolved bulk crustal compositions, and such processes have presumably been active for as long as average continental crust has been generated, ~3.5 Ga. However, it is much more difficult to establish how long crustal material has been destroyed by erosion and subduction, which in turns requires that plate tectonics was active.

The period 3 Ga to the end of the Archean is increasingly viewed as a time of marked change in the dominant global tectonic regime(s) (Figure 15). Shirey and Richardson (2011) noted the stabilisation of eclogite samples in the continental lithospheric mantle, which they attributed to the onset of subduction in ways comparable to that at the present day. The models of, for example, Taylor and McLennan (1985) and Dhuime et al. (2012)(Fig. 6) indicate a change in the average rate of continental crustal growth ~3 Ga, as do models that involve erosion factors (K) of ~15 in the interpretation of the Nd isotope ratios in shales (Fig. 12). Figure 15 illustrates the possible changes in the nature of continental crust and lithosphere that may have taken place towards the end of the Archaean in response to an evolving thermal regime (S. Foley, pers. comm., 2012). An early lithosphere consisting of a bimodal association of TTG and greenstone evolves through development of accretionary and collisional orogenic processes into a regime producing andesitic crust by at least 3.0 Ga.

In many models the volumes of continental crust inferred to have been present in the late Archaean and the Proterozoic are markedly higher than the volumes of crust of those ages preserved at the present day. The latter has been estimated by Goodwin (1996) and it is in effect the crustal growth curve of Allègre and Rousseau (1984) assuming that K=1 (Figs. 6, 12). Thus, the crustal growth curve of, for example, Dhuime et al. (2012) suggests that 65% of the present day volume of crust was present at 3 Ga, whereas the curve of Goodwin (1996) summarises the relative volumes of crust of different ages preserved at the present day and indicates that rocks generated by 3 Ga comprise just 7% of the present day volume of the crust. The striking implication is that much of the crust that was present at 3 Ga has since been destroyed, and it is tempting to link that destruction to the suggested onset of the plate tectonic regime, and hence significant recycling via subduction, at ~ 3 Ga.

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FIGURE CAPTIONS

Figure 1. Bimodal distribution of surface elevations on the Earth, relative to sea-level, emphasising the contrasting physical-chemical properties of continental and ocean crust. Adapted from Taylor and McLennan (1985, 1996).

Figure 2. Contour map of the thickness of the Earth's crust (developed from model CRUST 5.1). The contour interval is 10 km, with 45 km contour interval also shown to provide greater detail on the continents. To a first approximation, the continents and their margins are outlined by the 30 km contour. Source of figure http://earthquake.usgs.gov/research/structure/crust/index.php.

Figure 3. A: Cerro Aconcagua (6962 m) in western Argentina is the highest mountain outside Asia and the tallest in the Americas. It lies within the accretionary Andean Orogen and formed through non-collisional coupling between the downgoing Nasca oceanic plate and the continental lithosphere of the South American plate; B: Glencoul thrust on the northern side of Loch Glencoul, NW Highlands, Scotland. Silurian-age thrust faulting of Meso- and Neoarchean (Lewisian) gneiss over a footwall of Cambrian strata (Eriboll and An-t-Sron formations) that are resting unconformably on underlying Lewisian basement. C: Roadcut near Loch Laxford, NW Highlands, Scotland, showing Meso- and Neoarchean grey gneiss (Lewisian) and associated dark-grey to black biotite-rich restite layers cut by 1.85 Ga (Laxfordian) granite; D: Construction of continental crust through andesitic magmatism demonstrated by the Nevados de Payachatas volcanoes; Parinacota (Right) and Pomerape (Left) in Northern Chile. Both were constructed within the last 300 Ka, with Pomerape the older (more eroded) and Parinacota the younger, having undergone postglacial sector collapse to produce a large debris avalanche (foreground hummocks). E: The Stones of Calanais, are a Neolithic monument on the island of Lewis Scotland, composed of

Lewisian Gneiss. The stones are arranged in a central circle augmented by linear avenues leading off to the points of the compass. To the north the avenue comprises a double row of stones. At the heart of the monument is a Neolithic burial mound that was raised some time after the erection of the stones. The precise date of construction of the circle is unclear but the stones were erected about 5000 years ago. The purpose of sites like this (including Stonehenge) remains a mystery but research suggests that they comprised important central places for the local farming community and may have been aligned to prominent features of both land and sky. The stones were quarried locally and their transport and construction would have formed a focal activity at the time; F: Siccar Point, Berwickshire, NE England. Hutton's iconic angular unconformity between gently-dipping Devonian Upper Old Red Sandstone on near-vertical Silurian sandstones and shales. Source of images: A-C, Peter Cawood; D, Jon Davidson, University of Durham; E, Caroline Wickham-Jones; F, British Geological Survey digital data bank http://geoscenic.bgs.ac.uk/asset-bank/action/viewHome.

Figure 4. Schematic cross section of types of continental lithosphere emphasising the thick stable nature of Precambrian cratons. Thickness of lithosphere beneath Archean regions of the order of 200-250 km and oceanic lithosphere is up to 100 km.

Figure 5. Schematic section of the continental crust, adapted from Hawkesworth and Kemp (2006a).

Figure 6. Crustal growth models of Hurley and Rand (1969), Armstrong (1981), Allègre and Rousseau (1984), Taylor and McLennan (1985), Condie and Aster (2010) and Dhuime et al. (2012) compared to age distribution of presently preserved crust from Goodwin (1996). Sources of images: early Earth – http://www.universetoday.com/58177/earth-formation/, present day Earth – NASA.

Figure 7. A: Histogram of ca. 7000 detrital zircon analyses shows several peaks in their U-Pb crystallisation ages over the course of Earth history (Campbell and Allen, 2008), which are 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). B: Histogram of the ages of ancient and modern passive margins (Bradley, 2008). C: Normalized seawater $^{87}Sr/^{86}Sr$ curve (Shields, 2007) and running mean of initial εHf in ca. 7000 detrital zircons from recent sediments (Dhuime, Hawkesworth & Cawood, unpub. data). Low $^{87}Sr/^{86}Sr$ in Archean reflect lack of data.

Figure 8. 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 blue above Earth surface) and removal (numbers in red below surface). Data from Scholl & von Huene (2007, 2009). The volume of continental crust added through time via juvenile magma addition is approximately compensated by the return of continental and island arc crust to the mantle, implying that there is no net growth of continental crust at the present day.

Figure 9. The volumes of magma generated (blue line), and their likely preservation potential (red line) based on relations outlined in figure 7, vary through the three stages associated with the convergence, assembly and breakup of a supercontinent. Peaks in igneous crystallization ages that are preserved (shaded area) reflect the balance between the magma volumes generated in the three stages and their preservation potential, and will result in an episodic distribution of ages in the rock record.

Figure 10. Volumes of magma generated (in $km^3\ a^{-1}$) during the three stages of the supercontinent cycle (from Scholl and von Huene, 2007; see also Fig. 8; 2009) compared to estimates of number of zircons likely to crystallize for each setting (per

Ma, per km). 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), in order to obtain zircon generation rates in Ma per km.

Figure 11. Schematic representation of the 'preferential erosion' model used by Allègre and Rousseau (1984) to model the growth of the continental crust through time. $T_{sediment}$ and T_{source} are the model ages of the sediment, and their sources rocks respectively. The 'erosion factor K' is defined by K = (y/(1-y)) /(x/(1-x)).

Figure 12. Continental growth curves for the Gondwana supercontinent, calculated from the Nd isotope data for Australian shales (Allègre and Rousseau, 1984). The variation of the erosion factor K has a dramatic influence on the shape of the growth curves. If K=1 (i.e. no preferential erosion of the different lithologies producing the sediment), then 30% of the continental crust was generated by the end of the Archean, but this increases to 75% if K=15.

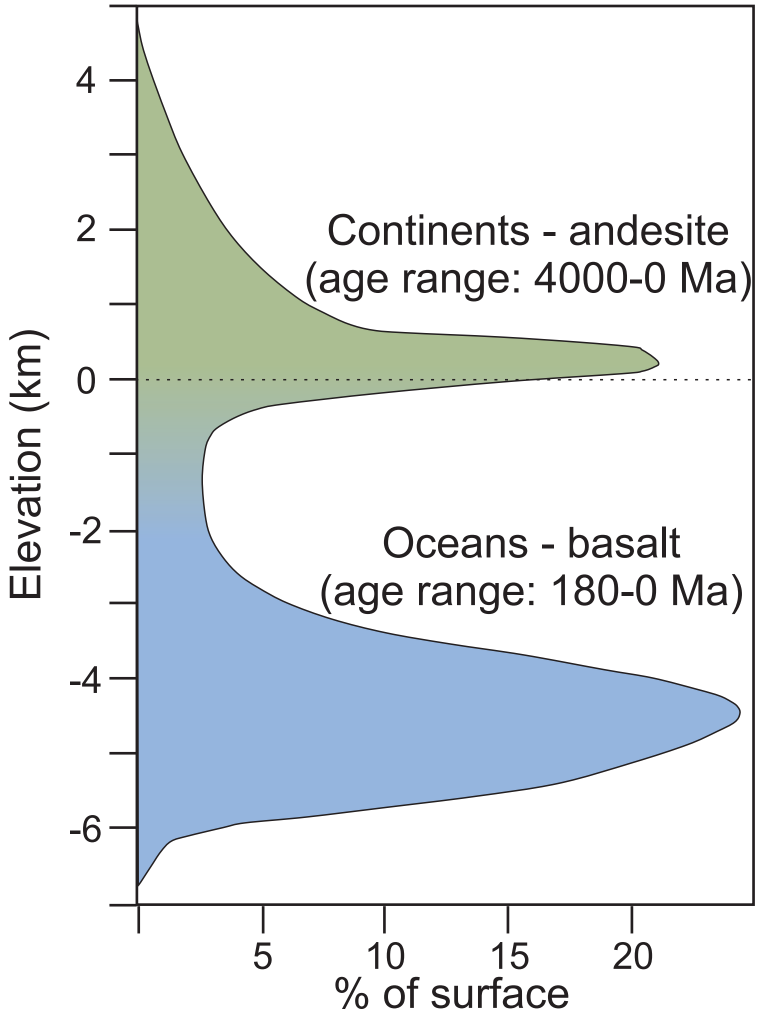
Figure 13. A: Distribution of Hf model ages in 1376 detrital and inherited zircons sampled worldwide, from which O isotopes have been measured (from Dhuime et al., 2012, and references therein). O isotopes were used by Dhuime et al (2012) to screen 'hybrid model ages' (grey bins) and model ages that represent true periods of crust generation (green bins) in the global model ages distribution. The proportion of new crust formation ages versus hybrid model ages is represented by the red dots. These dots define a systematic variation with time, represented by the black curve. B: The

systematic relationship defined by the black curve in Fig. 13A was used by Dhuime et al. to calculate the distribution of new crust formation ages (green histogram) from the distribution of model ages in ~7000 detrital zircons worldwide. From the variations in the proportions of the new crust (green 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), a continental growth curve has been calculated (blue curve, inset).

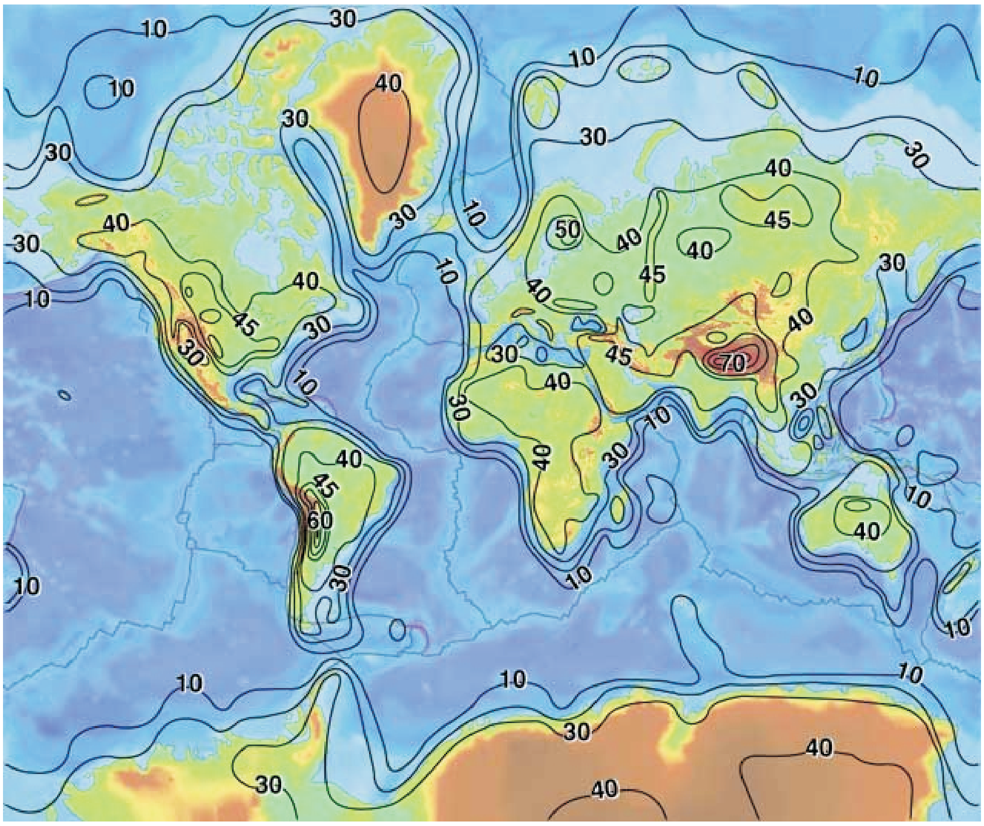
Figure 14. A: Summary plot of variation of the difference between the measured crystallisation age for a detrital zircon grain and the depositional age of the succession in which it occurs based on cumulative proportion curves, and displayed as a function of three main tectonic settings: convergent setting (A), collisional setting (B), and extensional setting (C). B: Schematic cross-section of convergent (A), collisional (B) and extensional (C) plate boundaries associated with supercontinent cycle showing simplified basinal settings for accumulation of detrital zircons.

Figure 15. Temporal evolution of lithosphere associated with thermal evolution of mantle from early Earth involving (adapted from S. Foley, pers. comm., 2012) a bimodal association of TTG and greenstone evolves through development of accretionary and collisional orogenic processes into a regime producing continental crust of andesitic composition by at least 3.0 Ga.

Cawood et al. Fig. 1

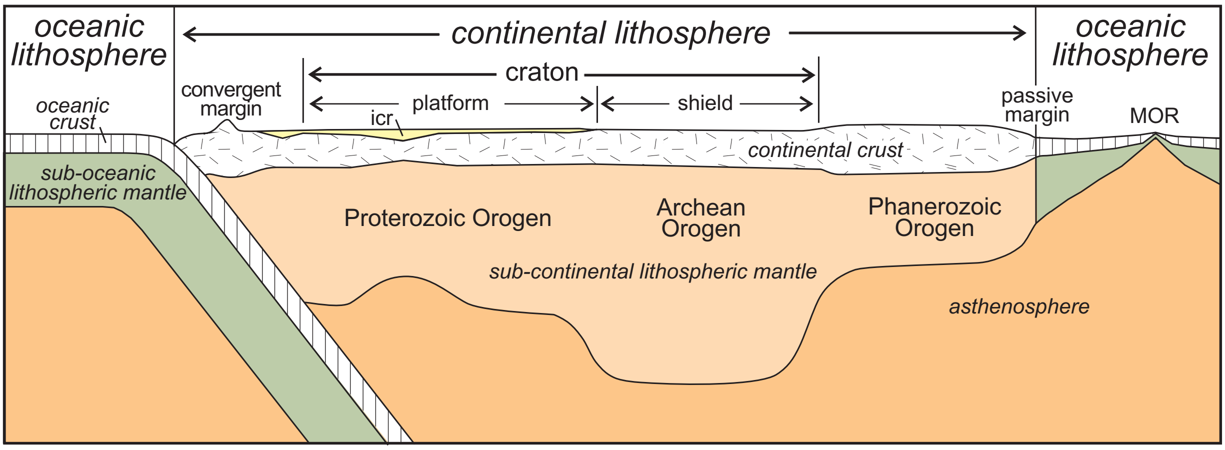


Cawood et al. Fig. 2



Cawood et al. Fig. 3

Cawood et al. Fig. 4



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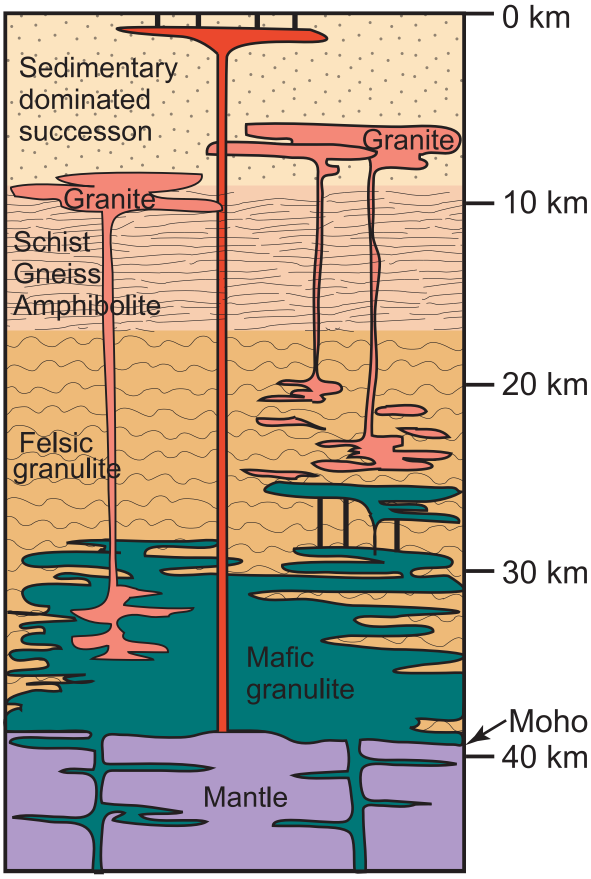

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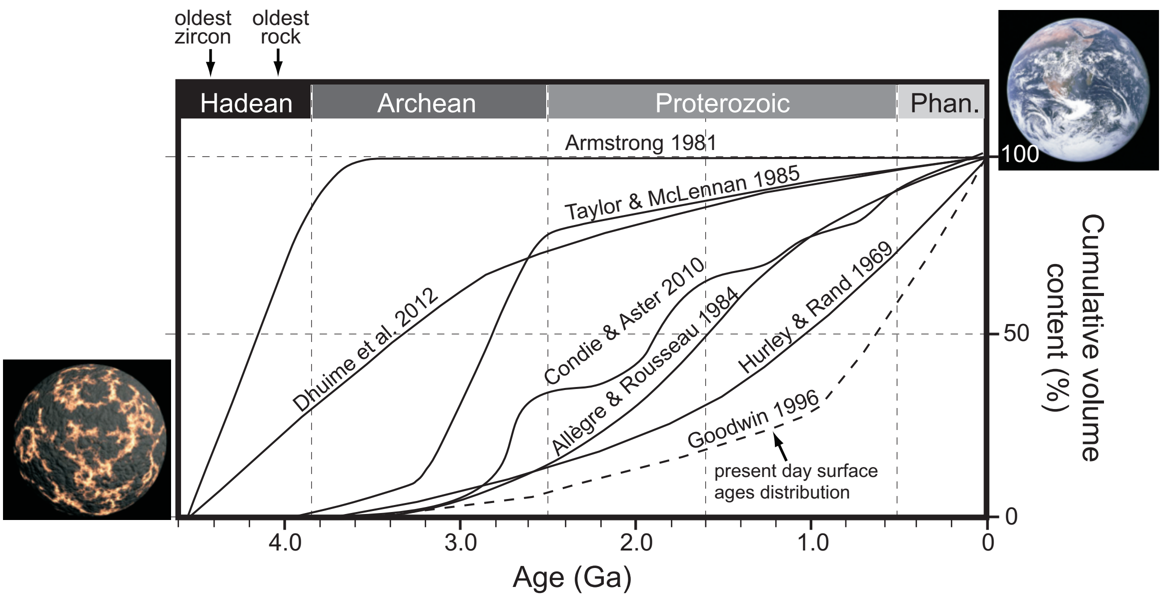

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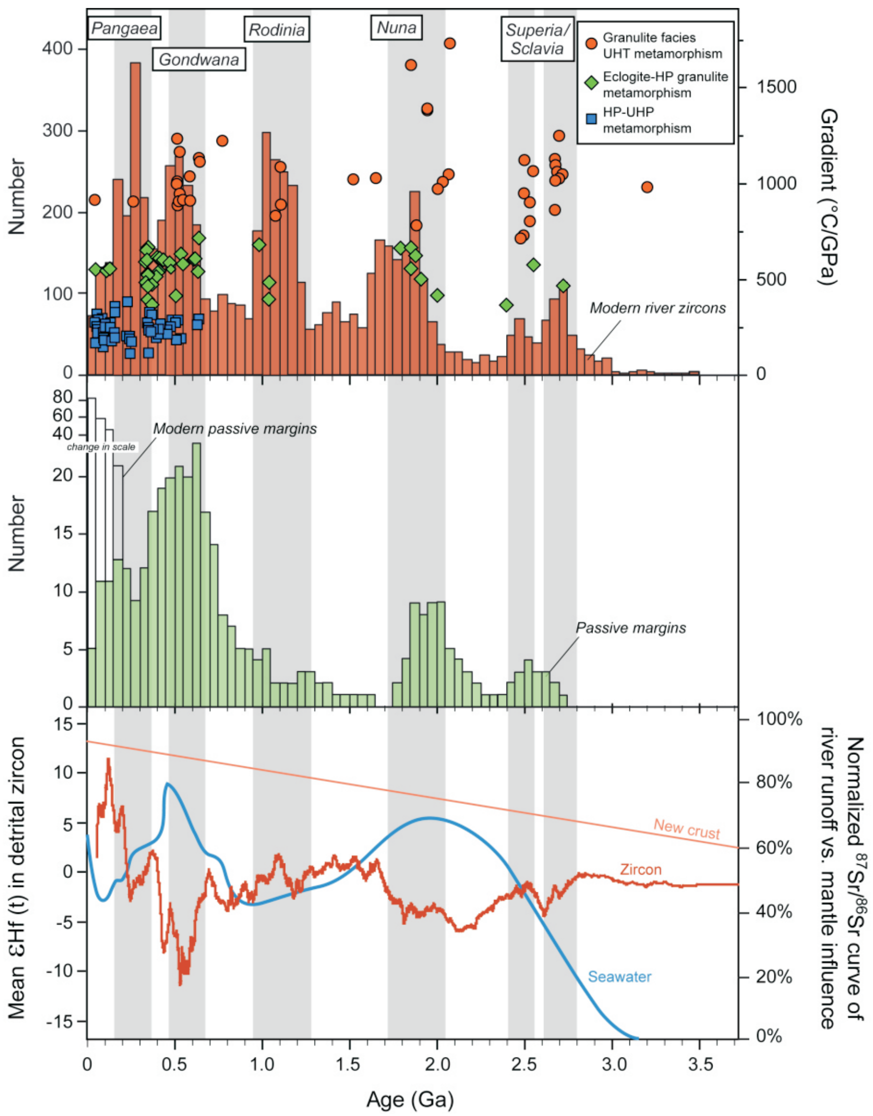

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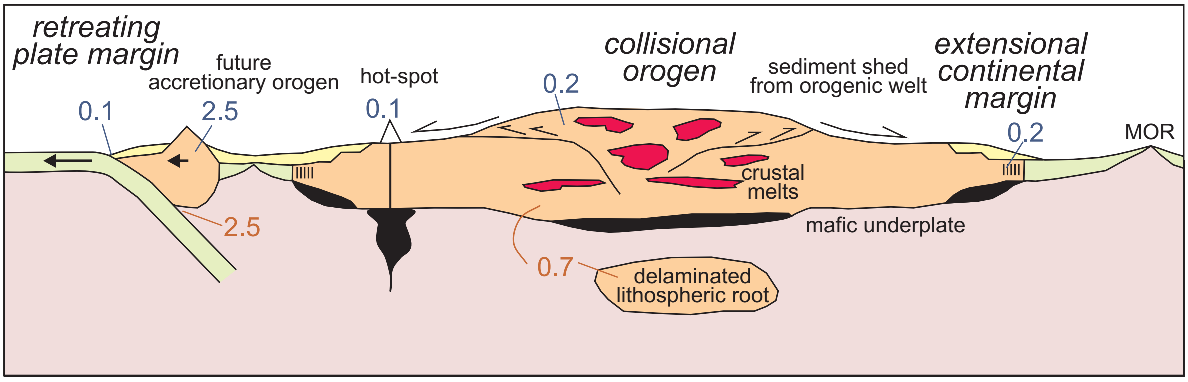

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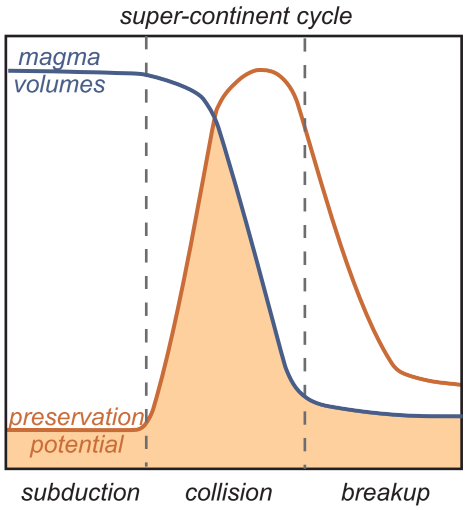

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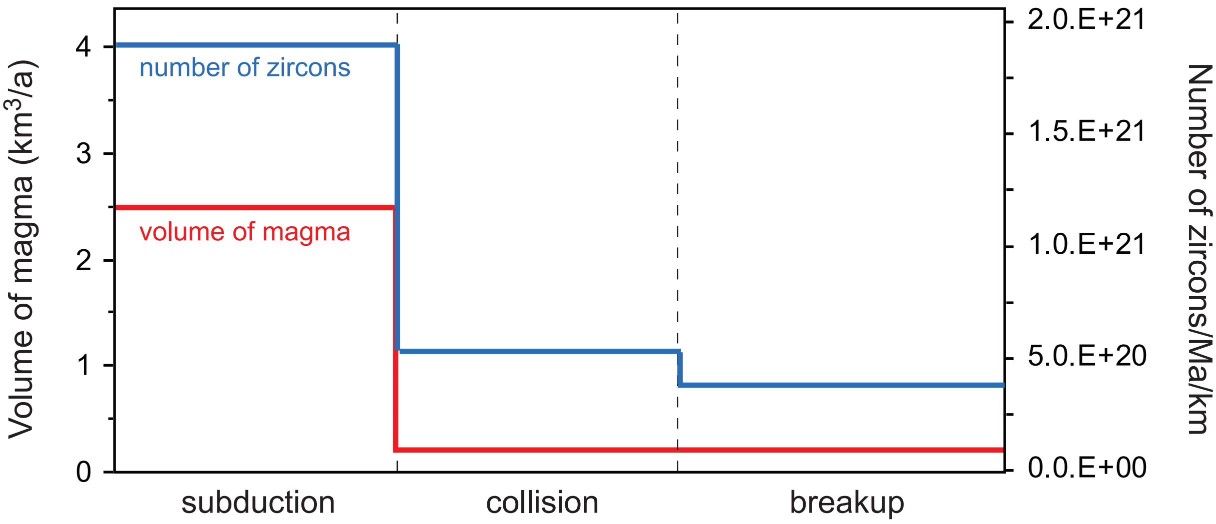

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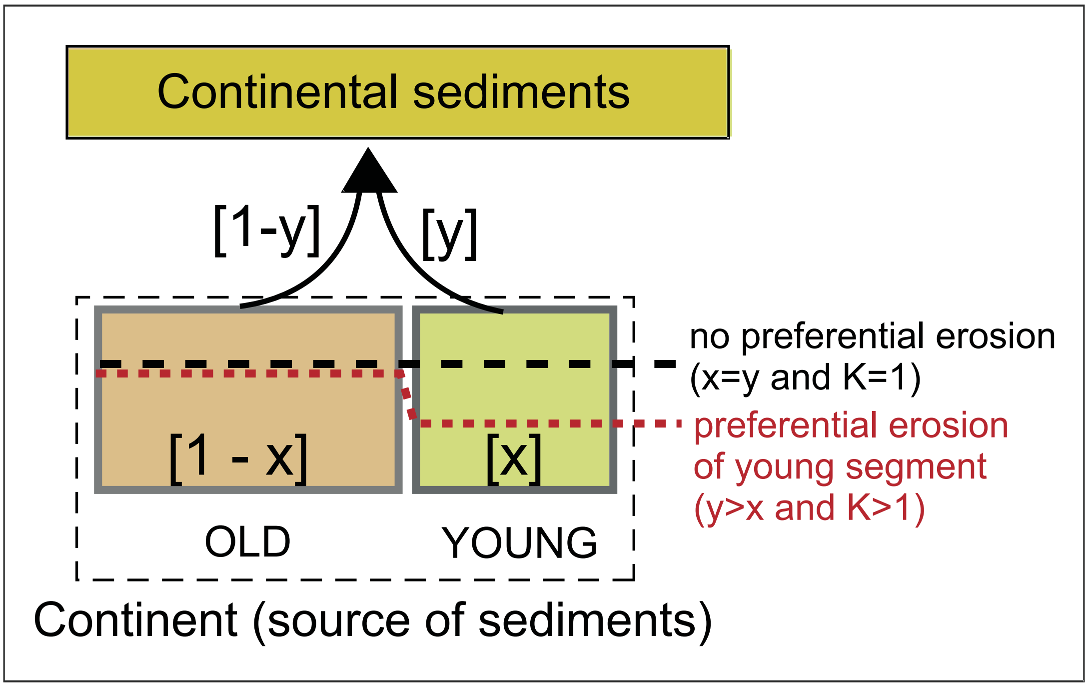

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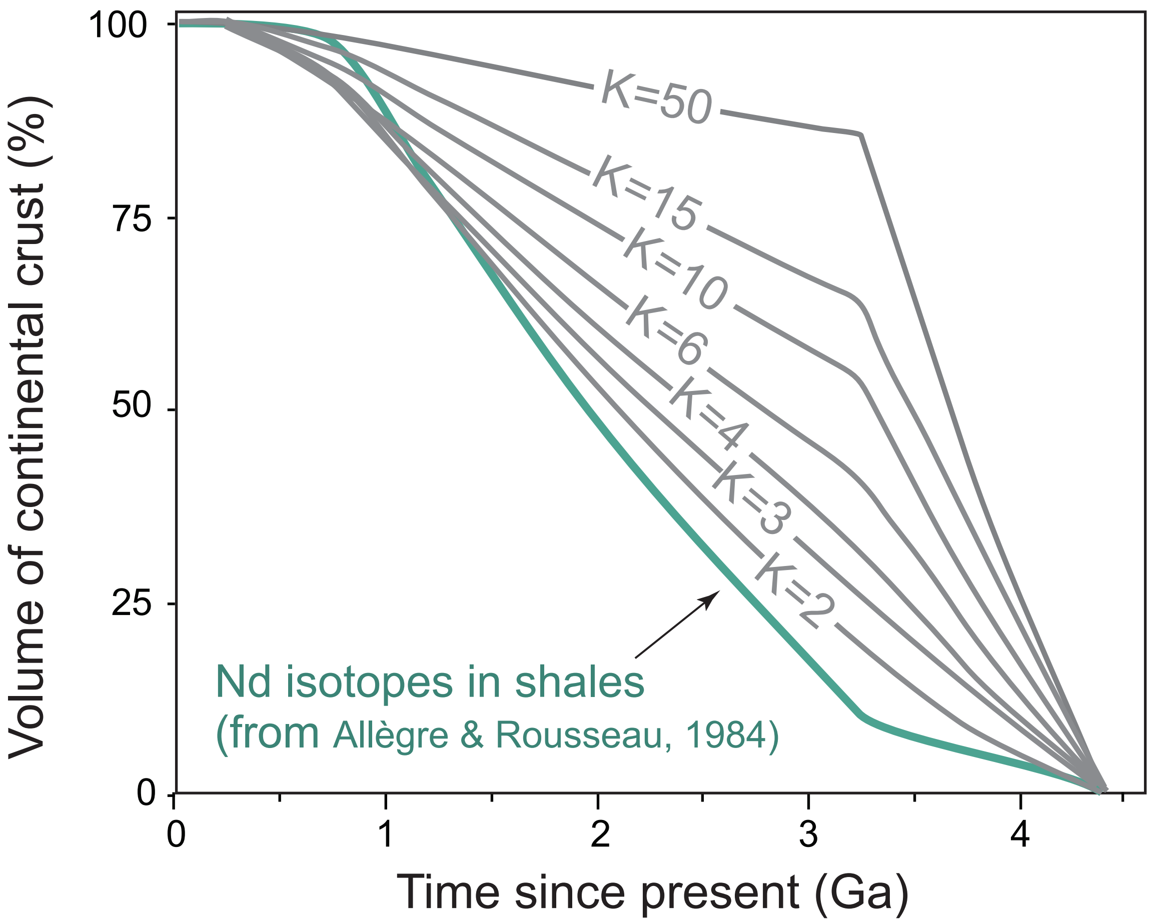

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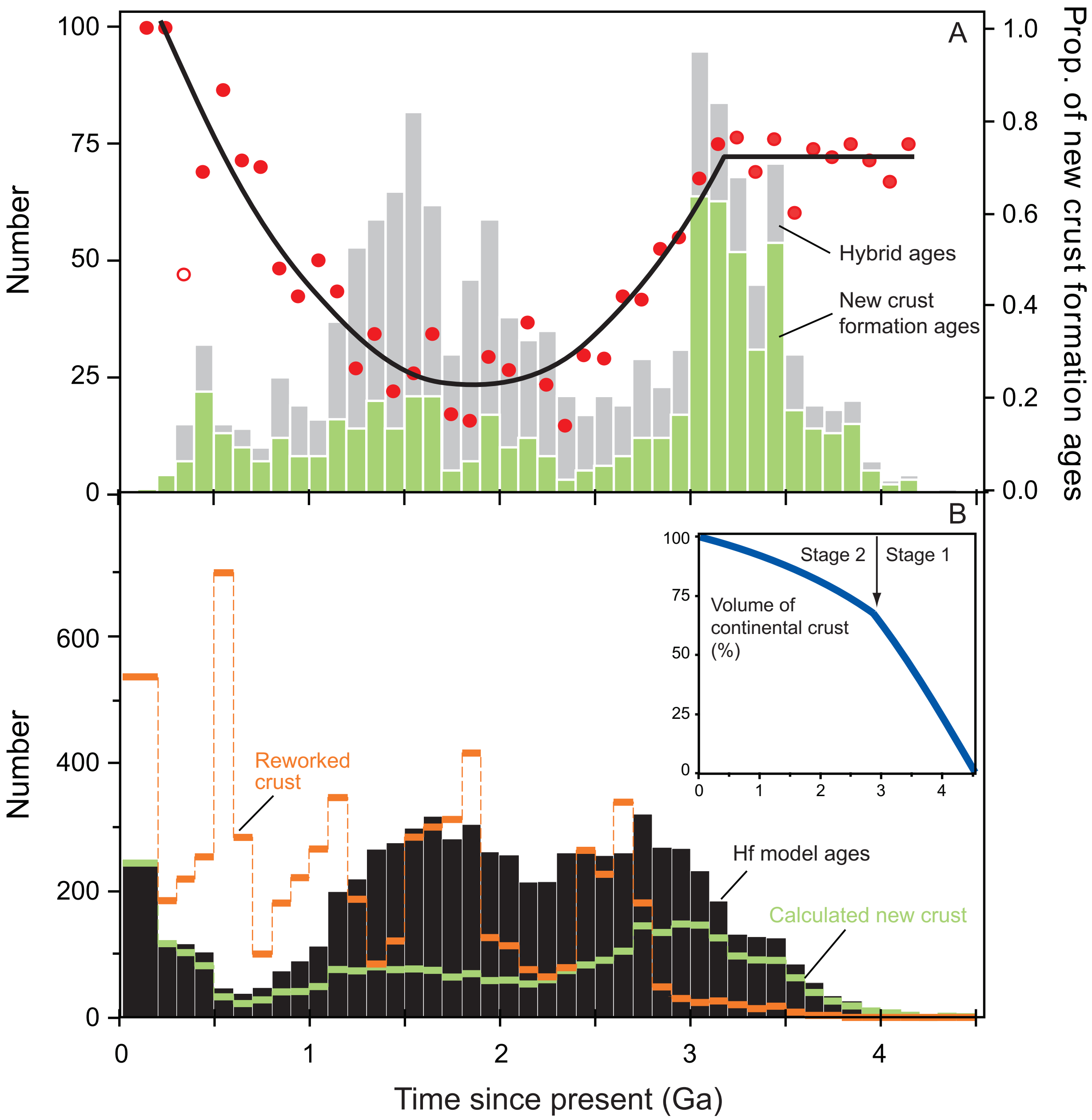

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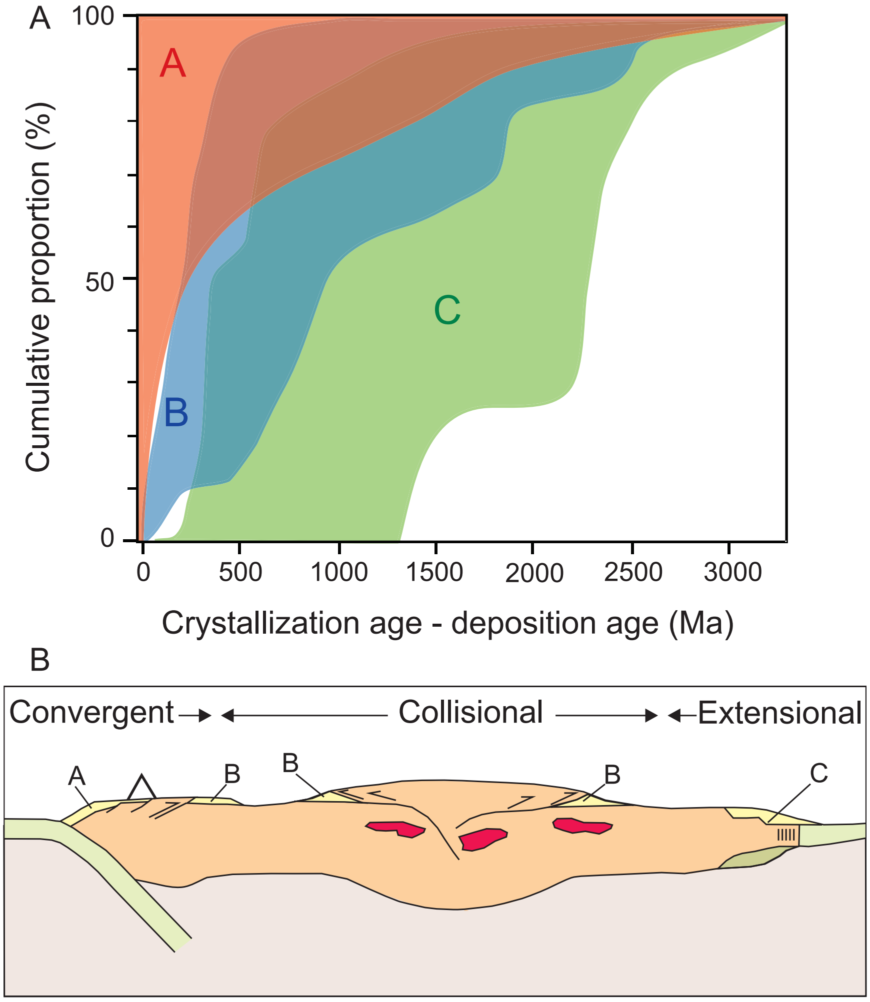

Cawood et al. Fig. 15