There were no large volumes of felsic continental crust in the early Earth

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ABSTRACT
New model growth curves for the continental crust based upon Hf-isotopes in zircon suggest that large volumes of felsic continental crust were present in the Hadean and early Archaean. These models sit uncomfortably with estimates of the volume of ancient crust preserved today and imply that the large volumes of crust that were created early in Earth history are now lost. However, this paper argues that there is no evidence from modern mantle geochemistry that very large volumes of early continental crust have been recycled into the mantle. In contrast significant volumes of Archaean crust may have been reworked into younger crust, although there is no evidence that this process took place in the early Archaean and Hadean.

Geological evidence from the detrital zircon record does not show evidence for large volumes of very early felsic crust, rather, geochemical proxies for Eo-Archaean and Hadean crust strongly suggest that the earliest crusts on Earth, some of which may have been subaerial, were mafic. A lack of very early felsic crust on Earth calls for a re-evaluation of current crustal growth curves and geodynamic models for the start of plate tectonics, the role of supercontinents in early continent formation and the role of the subcontinental lithosphere in continent preservation. The earliest felsic rocks on Earth may have taken the form of oceanic plagiogranites or ocean-island potassic granites as found in the modern.

INTRODUCTION

The time at which the first continental crust formed and the rate at which it has subsequently grown have been the subject of scientific debate for several decades. However in recent years with the advent of precise Hf isotope measurements in the mineral zircon new data have been presented which suggest that large volumes of continental crust were present very early in Earth history. Two lines of evidence have been used. Firstly Harrison et al. (2005) proposed, on the basis of extreme Hf-isotope mantle depletion in the Hadean, that this was an indicator that large volumes of continental crust had been extracted from the mantle at this time. Secondly, a new generation of crustal growth curves have recently been proposed, based upon Hf-isotope model ages for zircon in detrital sediments. These models predict that a large proportion of the continental crust had formed very early in Earth history (Belousova et al. 2010; Dhuime et al. 2012; Roberts and Spencer, 2015). In the model of Dhuime et al. (2012) the authors calculate that as much as 65% of the present-day volume of the continental crust had formed by 3.0 Ga. Thus these findings reopen the debate initiated by Armstrong (1968, 1991) about the early creation and subsequent destruction of the continental crust.

The significance of these studies is far reaching because frequently the formation of felsic continental crust is linked to the processes of plate tectonics. So for example Harrison et al. (2005) proposed that because of the large volumes of Hadean continental crust that were required by their model, then subduction and so plate tectonics was also operating at that time. Dhuime et al. (2012) calculated a crustal growth curve with an inflection at 3.0 Ga. This they interpreted as a fundamental change in geodynamic processes, and the start of plate tectonics on a global scale at 3.0 Ga.

The purpose of this review is to challenge, on geological grounds, the view that there were large volumes of continental crust in the early Earth. This paper explores the geological evidence for the existence of such crust and seeks to understand the implications for present crust and mantle compositions if there had been large volumes of continental crust which have now been destroyed. In addition, the isotope geochemistry community have been quick to comment on the veracity of claims for large volumes of continental crust and this paper presents a summary of their critique of this problem (see for example Guitreau and Blichert-Toft, 2014; Roberts and Spencer, 2015; Vervoort and Kemp, 2016; Payne et al. 2016).

THE PROBLEM

Figure 1 shows some of the recent growth curves calculated for the continental crust based upon the study of detrital zircons. These studies have variably used U-Pb ages, Hf-isotope model ages and oxygen isotopes in their construction (Belousova et al. 2010; Dhuime et al. 2012; Roberts and Spencer, 2015). An important feature of this figure is the gap between the volumes of continental crust observed on Earth today from the compilation of Goodwin (1996) and the volumes estimated in recent growth curves. Goodwin (1996) showed that only about 5% of the present crustal volume is older than 3.0 Ga (as previously indicated by Cawood et al. 2013; Hawkesworth et al. 2013) and whilst this figure may now need to be revised upwards in the light of more recent geochronology it still indicates the huge disparity between geological observation and the predictions of recent crustal growth calculations which suggest that ca. 65% of the present crustal volume was present at this time. This disparity is described as the 'missing crust'.

The problem may be expressed in a slightly different way by examining a frequency histogram of U-Pb zircon ages through time. Figure 2 shows the data of Voice et al. (2011) whose database comprises almost 200,000 U-Pb detrital zircon ages. Plots of this type show time intervals with a high frequency of measured ages separated by time intervals where the number of measured ages is far fewer. Currently there are different interpretations of these data. Some authors argue that there is a baseline of low level crustal productivity (Figure 2a) upon which there is superimposed a number of episodes of very high crust productivity (Condie and Aster, 2010; Condie 2014; Parman, 2015). Other authors argue that there was a high level of crust production throughout geological time but that it has not all been preserved (Figure 2b). In other words there is 'missing crust'. For these authors the focus is on the time intervals for which there are fewer U-Pb zircon ages. These are thought to represent time intervals when the continental crust was destroyed and so represent periods of lack of preservation (Dhuime et al. 2012; Cawood et al. 2013; Condie 2014). However, in this model there is no simple correlation between the time of crust generation and destruction, that is, the crust which is destroyed is not of necessity that which has been newly generated (Cawood et al. 2013).

If the 'missing crust' is real there are several possible explanations:

- Firstly, ancient crust may have been *reworked*, that is, it now exists as 'younger crust' and has been reconfigured through metamorphism and partial melting. In this case of course the missing crust is not missing in an absolute sense, but rather has lost its identity.
- Secondly, ancient crust may not have been preserved and so has been *recycled*, ie by being returned to the Earth's mantle and lost from the crustal system entirely. This is the process of crustal destruction.
- A third possibility is that in the early Earth there was a subaerial basaltic crust in addition to felsic continental crust and that in the models discussed above this has been included in the total crustal volume and treated as felsic continental crust.

There is also the possibility that the calculations upon which the growth curves are predicated are inaccurate (see for example Guitreau and Blichert-Toft, 2014; Roberts and Spencer, 2015; Vervoort and Kemp, 2016; Payne et al. 2016), in which case the immediate problem of the missing crust goes away.

SOME DEFINITIONS

It is the purpose of this paper to first explore the geological and geochemical implications of large volumes of 'missing crust' in order to better constrain the processes of crustal growth. In the sections that follow a clear distinction is made between the process of *crust generation* – which is the formation of new juvenile crust from the mantle and the processes of *crustal reworking* and *crustal recycling*. This paper also explores the geological evidence for the existence of large volumes of continental crust in the early Earth and examines the robustness of the isotopic evidence used to support it. First however, the terms *continental crust*, *crustal reworking* and *crustal recycling* are clarified.

The *continental crust* under discussion in this paper and whose origin is the subject of current debate, is that composite material which makes up the mass of the continents, is separated from the mantle by the Mohorovicic discontinuity and is distinct from the basaltic materials of the ocean crust. It is 'felsic' in composition, has an average composition which is andesitic (ca 60 wt % SiO_2) and an upper layer which is granodioritic (Rudnick and Gao, 2003). It is the most common source of zircons found in the sedimentary record. Such a crust is extremely rare on those rocky planets which are our neighbours and on Earth it is a product of mantle differentiation such that it has become extremely enriched (up to 2 orders of magnitude) in some trace elements relative to the Earth's primitive mantle (Rudnick and Gao, 2003).

Crustal reworking describes processes which takes place wholly within the crust in which continental crust is re-formed by either the processes of weathering, erosion and sedimentation and/or by the processes of metamorphism, remobilisation and partial melting (see Cawood et al. 2013). Such a process is expected to significantly modify the chemical composition of the original parent material and routinely will re-set isotopic systems such that the original parentage of this segment of crust is superficially obscured. Nevertheless some geochemical traits and isotope ratios persist through the process of reworking so that the original character of the crust can often be identified. Crustal reworking may be accentuated during the process of continental collision and rates of reworking are thought to vary over geological time, perhaps synchronised with the super-continent cycle (Dhuime et al. 2012; Hawkesworth et al. 2013).

Crustal recycling describes the loss of mass from the crust to the mantle. It describes the process of crustal destruction whereby material which was once part of the continental crust is returned to the mantle. Some authors discuss the process of crustal recycling in terms of crust preservation or in this case the lack of preservation (Cawood et al. 2013). Hence crustal recycling is the opposite of crust preservation. This will most commonly happen through the process of subduction, although the delamination of lower crust into the mantle is also frequently cited as a mechanism of crustal destruction (Stern and Scholl, 2010; Cawood et al, 2013). It should be noted however, there are a number of occurrences in the literature where the term crustal recycling is used differently, hence the need for clarity in the use of these terms. For example McLennan (1988) discusses the differences between intra-crustal recycling (which in this study = reworking) and crust-mantle recycling, which is the process of crustal destruction discussed here. Other authors use the term recycling in the sedimentary sense whereby older crustal materials are deposited as a sediment later in Earth history. This application of the term is used for example in the discussion of detrital zircons whereby old zircons are recycled to appear in younger sediments (see for example Voice et al. 2011). I propose that reworking is the better term for this process.

THE FATE OF THE 'MISSING CONTINENTAL CRUST'

1. The continental crust has been reworked

As noted above crustal reworking describes those processes which take place wholly within the crust in which continental crust is modified. Reworked crust is characterised by a young crystallization age but carries an isotopic signal of a much earlier origin. This is illustrated in Figure 3 using U-Pb and Hf-isotope data for zircons. The figure shows a plot of crystallization age, as measured using U-Pb isotopes and the calculated Hf-model age (the time at which the protolith to the present rock was extracted from the depleted mantle). It is clear that for some samples the U-Pb age and the Hf model age are the same. This is juvenile crust. However, the majority of samples appear to have a model age older than the crystallization age, superficially indicating that they represent reworked older crust. It will be shown later, that the conclusion that all non-juvenile samples represented in this graph are reworked older crust is too simplistic, for there are significant uncertainties attached to the measurement and interpretation of some of the isotope ratios (see the section below on isotopic arguments). Nevertheless this graphical indication goes some way to showing that a significant amount of the present continental crust may be reworked.

An example of crustal reworking from the UK comes from the Palaeogene granites of NW Scotland where mafic magmas, associated with the opening of the north Atlantic Ocean have intruded and melted Proterozoic and Archaean middle and lower crust. In this case felsic melts about 60 Ma in age contain a significant volume of reworked older Proterozoic sedimentary rocks (1000-1200 Ma) and Archaean tonalitic gneisses (ca 2800 Ma). This was established for granites on the Island of Skye using the Pb and Sr isotopic systems (Moorbath and Bell, 1965; Dickin, 1981). A particularly striking example is that of the Coire Uaigneich granophyre ring-dyke (Fig. 4a) which was intruded adjacent to the southern margin of the Cullin gabbros on Skye. This small 59 Ma-old granitoid body was shown to have a quartz-rich composition and an initial Sr-isotope ratio indicative of melted meso-Proterozoic sandstone (Brown 1963, Dickin and Exley, 1981). This relationship is also apparent in the field. Outcrops of meso-Proterozoic sandstone adjacent to the Cullins gabbroic intrusion show networks of veins indicative of partial melting (Fig. 4b) and in other places there are areas within the granophyre itself which are rich in quartz-rich xenoliths, characteristic of the local meso-Proterozoic sandstone (Figs. 4 c and d). These observations lend strong support to the hypothesis that this particular granitoid is in part, melted meso-Proterozoic sandstone. The heat source required to melt the crust in this region is the nearby Cullins gabbro magma chamber.

Although the Coire Uaigneich granophyre seems a relatively straightforward example of the melting of meso-Proterozoic crust to form a ca 60 Ma granitoid there is an inbuilt complexity even here. This is because the meso-Proterozoic sandstone is itself derived from a variety of forms of older crust including neo-Archaean Lewisian gneisses and mid-Proterozoic crust (Lancaster 2011).

Other examples of crustal reworking may be less specific but are indicated by the presence of inherited zircon grains in younger granitoids. This is seen in the felsic gneisses of many Archaean cratons. For example, the Zimbabwe Craton comprises an old nucleus of felsic gneisses about 3.5 Ga old (the Tokwe segment) surrounded by younger granitic gneisses 2.7-2.9 Ga old. However, some of the younger gneisses contain older inherited zircons indicating that at least in part the 3.5 Ga Tokwe segment was reworked during the formation of the 2.9 Ga and 2.7 Ga crust (Rollinson and Whitehouse, 2011). In detail this process may comprise multiple stages as indicated in the study by Laurent and Zeh (2015) of the Pietersburg block of the Kaapvaal Craton in South Africa.

How much crustal reworking has taken place, in other words what volume of ancient crust now masquarades as younger crust, and the extent to which reworking rates have changed with time are critical questions. An attempt at answering these questions at a global scale has been made by Belousova et al. (2010), Dhuime et al. (2012) and Roberts and Spencer (2015). Dhuime et al. (2012) and Roberts and Spencer, (2015) used measured oxygen isotope ratios in zircons to estimate the proportion of crust that might have been reworked at any one time and thereby estimate reworking rates through time, although, as will be discussed below, there are concerns about the robustness of this approach.

An alternative approach to setting limits on the scale of crustal reworking is to use estimates of juvenile crustal production over Earth history such as that of Condie and Aster (2010). This growth curve (Figure 5) is based upon the extant geological record and so assumes that the crustal volumes estimated are still present in the crust. When compared with the crustal preservation curve of Goodwin (1996) this curve suggests that large proportions of late Archaean and Proterozoic crustal production were subsequently reworked (Hawkesworth et al. 2013).

It has also been suggested that a deeper understanding of the scale of crustal reworking might be on a regional, rather than global scale. For example, in the case of the study of detrital zircons, there are so many uncertainties as to their provenance and geological history that regional studies will be more productive. In these more localised studies the geology is better known and so zircon crystallization ages and model ages can be better understood (Vervoort and Kemp, 2016). For example in the Archaean of Zimbabwe old inherited zircon cores and old model ages give an indication that there was more older crust of the Tokwe segment present than had been previously estimated, although in this example the true volume of older crust is not known (Rollinson and Whitehouse, 2011). Of course ultimately a global picture is what we want to obtain, but this will better come through first understanding processes at a regional level.

2. The continental crust has been recycled and returned to the mantle.

Crustal recycling is crustal destruction whereby material which was once part of the continental crust is returned to the mantle, most commonly through subduction. The fate of recycled crust in the form of sediment during subduction is complex as is illustrated in Figure 6 but there are strong indications that not much of present-day sediment is returned to the mantle. Some becomes part of an accretionary prism in the forearc, other sediment is either accreted onto the underside of the arc crust or is returned to the crust in a melt (Scholl and von Huene, 2009; Kelemen and Behn, 2016). Studies such as that of Plank (2005) showed a close link between the Th/La of subducted sediment and associated arc lavas in a given subduction zone providing strong evidence for sediment subduction. However, this study also demonstrated that not all sediment is subducted and some is recycled and returned to the crust in arc lavas. More recently it has become clear that some of the felsic rocks found in the mantle section of ophiolites represent melted subducted sediments, now preserved in the overlying mantle wedge (Rollinson 2015). Thus, whilst there is strong evidence from seismic tomography for the deep recycling of large volumes of mafic oceanic crust, it is argued here that there is less evidence for the return of significant volumes of sediment into the deep mantle.

The most powerful evidence of crustal recycling is where felsic crustal material is returned to the surface from the deep mantle. Perhaps the most unusual example of this is the recent discovery of a range of crustal minerals including quartz, zircon and corundum contained within chromitites currently located within the mantle sequence of ophiolites (Liou et al. 2014; Robinson et al. 2015). Mineral chemical arguments based upon associated high pressure phases suggest that these minerals may have been excavated from the top of the mantle transition zone (Rollinson, 2016). The only way of knowing how ancient this crustal material is through the U-Pb age of the zircons and whilst there are currently only a few measured ages not many are older than 2.0 Ga (Robinson et al. 2015). There is also growing evidence from diamond inclusions and the stable isotope geochemistry of diamonds for the subduction of crustal materials into the upper mantle (Burnham et al. 2015).

It has long been argued that the unusual trace element and isotopic chemistry of ocean island basalts requires a sedimentary component in the mantle source. Hofmann and White (1982) proposed that this may be a consequence of deeply subducted sediment. This hypothesis was tested in detail by Porter and White (2009) using mass balance calculations and data from eight different intra-oceanic arcs. They calculated the composition of the residual subducting slab (sediment + oceanic crust) after it had contributed to melt production in the arc and in each case estimated the proportion of trace elements which survived the 'subduction zone filter'. They showed that there is a net flux into the mantle and that 'almost all of the Nb, Ta, intermediate and heavy REE and most of the light REE' survive into the deep mantle. In addition average survival rates into the deep mantle for other trace elements were Th and Pb – 73%, K - 74%, U - 79%, Rb and Sr – 80% and Ba – 82%. In addition, using their measured parent-daughter elemental ratios, they modelled the Pb, Nd and Sr isotopic evolution of ocean crust with sediment subducted 1.8 Ga ago and showed that the present composition is close to that of the ocean island basalt mantle source region EMII (Porter and White, 2009). Experimental support for this approach comes from the studies by Rapp et al. (2008) and Wu et al. (2009) who showed that continental crust can be subducted to at least transition zone depths. Rapp et al. (2008) showed that at 23 GPa (ca 700 km depth) subducted sediment contains the phase K-hollandite, a high pressure form of sanidine, which has the capacity to store incompatible elements such as Rb, Ba, Sr, K, Pb, La, Ce and Th and may be the principal source of these trace elements in a deep mantle reservoir (Rapp et al. 2008). However, it is noted that not all enriched mantle reservoirs can be accounted for by means of sediment subduction (Porter and White, 2009).

More recently Stracke (2012) has shown from a study of radiogenic isotope ratios in oceanic basalts that the EM component of ocean island basalts represents input from a crustal source. In detail the variability between the different isotopic compositions displayed by ocean island basalts may be accounted for by the variable contribution of upper and lower continental crust (Willbold and Stracke, 2006). However, in these calculations the volume of subducted upper continental crust is small and has only a small influence on overall mantle heterogeneity. In contrast Stracke (2012) argues that there is geochemical evidence for the subduction of substantial volumes of lower continental crust, although this is mafic in composition and so not pertinent to the question of the recycling of felsic crust.

How much recycling ?

Whilst the evidence for the recycling of crustal material into the deep mantle cannot be in doubt, the extent to which this process has operated throughout Earth history is much debated. Recent studies have used a mass balance approach to assess the extent of crustal recycling in volcanic arcs (Scholl and von Huene, 2009). They computed the loss of sediment through the processes of sediment subduction and subduction erosion along the length of accreting and non-accreting/erosive margins in oceanic arcs and in continental subduction zones and found that the global volume recycled annually was ca. 3.0-3.2 km^3 (Scholl and von Huene, 2009; Clift et al. 2009). Of this 1.65 km^3/yr is attributed to subducted sediment and 1.33 km^3/yr to subduction erosion. More recently higher values have been proposed (Jagoutz and Schmidt, 2013; Jicha and Jagoutz, 2015) to account for those mafic and ultramafic rocks which are returned to the mantle in subduction zones by the process of lower crustal delamination. However, lower crustal delamination is not relevant to this discussion because it is a part of the process of the genesis of felsic crust in an arc environment, not its destruction.

The calculated volumes of subducted sediment are high and problematical, for if current rates of crustal destruction are typical of the last 3.0 Ga of Earth history then a volume equivalent to the entire present day continental crust would have been subducted making up about 1% of the whole mantle (Scholl and Von Huene, 2009). However, the work of Parman (2015), discussed more fully below, suggests that crustal evolution is ‘fundamentally punctuated’ (see for example Figure 2), implying that rates of crustal growth have varied over geological time and that the ‘snapshot’ of the present may not be representative of Earth history as whole.

The calculated volume of recycled sediment also conflicts strongly with the findings of Stracke (2012) who on the basis of the range of radiogenic isotope ratios in ocean island basalts concluded that the volume of subducted sediment is small. He found the strongest signal for subducted sediment in the ocean island basalts of Samoa where there is evidence for an up to 6% upper crustal contribution, although he points out that all the enriched basalts of this type ‘could ... be related to a single subduction event’. From this evidence he concludes that the ‘recycling of the upper continental crust .... is inferred to be only a minor process’ (Stracke, 2012). Thus, evidence from the geochemistry of ocean island basalts conflicts with mass balance calculations for the volume of subducted sediment and suggests that current estimates of the volume of subducted sediment are too high. Further work needs to be carried out on reassessing the volumes of subducted sediment and evaluating the extent to which they are either reworked to become part of the arc magma flux or are truly subducted and recycled into the mantle.

3. Early crust looked different

As discussed above, the continental crust under discussion in this paper is the ‘felsic’ material which has an average composition which is andesitic (ca. 60 wt % SiO_2) and which makes up the mass of the present continents. Taylor and McLennan (2009) classify planetary crusts into three: Primary crusts are formed by the process of initial planetary differentiation early in the life of the planet, Secondary crusts are the product of partial melting of a silicate mantle and so form over a longer time scale, as do Tertiary crusts which are formed by melting of secondary crusts. There is no evidence that a terrestrial Primary crust is preserved today. However, in the early Earth frequent volcanic resurfacing would have given rise to a basaltic secondary crust (Marchi et al., 2014), which may in places have been subaerially exposed, but this would have been different from a felsic continental crust. Keeping a clear distinction between ‘any type of juvenile crust’ and ‘modern type felsic continental crust’ is very important in any discussion of the emergence and growth of the continental crust.

Thus Dhuime et al. (2015) use $^{87}Sr/^{86}Sr$ initial ratios in volcanic and plutonic igneous rocks, largely assumed to be from reworked older crust, to back-calculate the Rb/Sr ratio of their juvenile protolith. They show that before 3.0 Ga Rb/Sr ratios were low, typical of mafic melts with ca 50% SiO_2, whereas after 3.0 Ga Rb/Sr ratios progressively rise to be more typical of felsic melts (maximum 58% SiO_2). Thus they conclude that until about 3.0 Ga the Earth’s crust was predominantly mafic and that a fundamental change took place at 3.0 Ga whereby modern felsic continental crust was formed after this time.

Similarly, Tang et al. (2016) use Ni/Co and Cr/Zn ratios in terrigenous sediments to estimate the MgO content of their crustal source. They show that, using this proxy, the MgO content of the crustal source decreases from >11- 4 wt % through the Archaean and indicates that a ‘mafic continental crust’, common in the meso-Archaean was gradually replaced by a ‘felsic continental crust’ in the neo-Archaean. The result of Tang et al. (2016) is important and consistent with observations on 3.7-3.8 Ga pelitic sediments from Isua in west Greenland, perhaps the oldest well preserved pelitic rocks in the world, which are very immature, have mafic compositions and imply a mafic source with very little felsic input (Bolhar, 2005).

However, the terminology of Tang et al. (2016) is not helpful as it obscures the meaning of the term ‘continental crust’. Thus in the context of the growth of the felsic continental crust it is important that a clear distinction is maintained between felsic continental crust (a Tertiary crust in the nomenclature of Taylor and McLennan (2009)) and other crusts such as subaerially exposed basaltic crusts which are Secondary crusts, produced by mantle melting in the nomenclature of Taylor and McLennan (2009). The work of Dhuime et al. (2015) and Tang et al. (2016) indicate that the Earth’s earliest crust was predominantly mafic, some of which was exposed subaerially.

THERE IS NO GEOLOGICAL EVIDENCE FOR LARGE VOLUMES OF VERY EARLY CONTINENTAL CRUST

Studies of detrital zircons in ancient and modern sedimentary rocks have failed to show substantial numbers of very ancient zircons. For example Iizuka et al. (2010) show that in modern river sediments from four continents there is no record of grains older than ca 3.3 Ga.

In all other Archaean sedimentary rocks, apart from the very ancient zircons (>4.3 Ga) found in the mid-Archaean Jack Hills, there is a striking lack of very ancient zircons.

In the Archaean of Australia for example Kemp et al. (2015) have shown that in the northern part of the Pilbara Craton there is an area of 60,000 km^2 of mid-Archaean rocks with ages between 3.0-3.5 Ga within which detrital and xenocrystic zircon crystallization ages do not exceed 3.8 Ga. They also show that Hf-isotopes in the detrital zircons indicate that many of these rocks were extracted from the mantle between 3.6-3.7 Ga. In a similar study Valley et al. (2015) showed that detrital zircons in the 3.4 Ga Strelly Pool formation in the Pilbara Craton showed a very narrow range of U-Pb ages (3510 +/- 44 Ma) and no evidence for crust older than 3.8 Ga. Taken together these studies show that the Pilbara Craton was formed from juvenile material and not built upon a substantially older basement, highlighting the absence of evidence for Hadean crust in this region (Kemp et al. 2015).

Similarly in South Africa, in the Barberton Greenstone Belt, the 3.22 Ga quartz arenites of the Moodies Group contain zircon populations with U-Pb age peaks at 3.26, 3.46 and 3.53 Ga and the 3.26 Ga greywackes of the Fig Tree Group contain zircon populations with peaks at 3.3, 3.46 and 3.52 Ga with one grain as old as 3.65 Ga (Zeh et al. 2013). The older zircons are thought to be locally derived from granitoids south of Barberton, although the oldest grains may be from the Swaziland ancient gneiss complex in the southeast (Zeh et al. 2013). These data further support the view that there was no very ancient crust in this region.

In West Greenland there is felsic crust as old as 3.8 Ga and yet U-Pb ages of detrital zircons in the 3.7-3.8 Ga Isua Greenstone belt are only as old as 3.94 Ga and these are extremely rare (Nutman et al. 2009). Further emphasising the scarcity of evidence for significant volumes of very ancient crust in the geological record.

Parman (2015) has made the same point in a slightly different way. Using the very large detrital zircon U-Pb data-base of Voice et al. (2011) he made frequency plots of U-Pb ages from detrital zircons by continent over 500 Ma time intervals as a function of the time at which the zircons were incorporated into their host sediments. He made a number of important observations

- there are major U-Pb age peaks indicative of crustal growth at 1.2, 1.9 and 2.7 Ga and these persist through time on plots for individual continental masses such that they appear strongly in sediments immediately after their formation but persist (less prominently) in younger sediments;
- there is an apparent lack of crustal production at 2.3 and 1.5 Ga as indicated by troughs in zircon frequency plots; this feature is also seen in younger sediments;
- in a given continent there is no crust older than the age of the oldest sediments;

What these data show is that when new crust is formed there is evidence of this crust in sediments which form immediately afterwards, but also that the evidence persists in younger sediments. Equally, the lack of crust-production also persists as a trough in the zircon record. This means that once new crust has formed it leaves a persistent ‘fingerprint’ in the sedimentary record. The absence of a very early age peak in the zircon record strongly suggests that very little ancient crust ever existed.

However, it important to note that the connection between the zircon record in sedimentary rocks and their source rocks is not straightforward but depends upon the proportions of the different source rocks in the catchment and the extent to which those different source rocks were preferentially eroded. This variable was defined by Allègre and Rousseau (1984) as the erosion factor *K*. Allègre and Rousseau (1984) suggested that *K* is ~2-3 for large areas of continental crust, indicating the degree of preferential erosion between younger and older crust is small, although studies by Dhuime et al. (2011) and Cawood et al. (2013) propose much higher values of ~4-15. Clearly the extent to which the sedimentary record represents original crustal volumes has a profound impact on the shape of crustal growth curves. For example if *K*=2, the value estimated by many workers (see Cawood et al. 2013) then <40% of the crustal volume was generated by the end of the Archaean, whereas if *K*=10-15 (values proposed by Cawood et al. (2013) for areas of high relief and active erosion) then 65-75% of the continental crust was generated by the end of the Archaean.

ISOTOPIC ARGUMENTS FOR THE EXISTENCE OF LARGE VOLUMES OF EARLY CONTINENTAL CRUST MUST BE RE-EVALUATED

Much of the evidence for a large volume of early continental crust is based upon Hf-isotope model ages and ε_{Hf} values calculated for the mineral zircon. A number of authors have recently reviewed this approach and showed that assumptions are made which cannot always be justified (Guitreau and Blichert-Toft, 2014; Roberts and Spencer, 2015; Vervoort and Kemp, 2016; Payne et al. 2016). For example model age calculations carry three assumptions. These are: 1. that the measured U-Pb age of the zircon represents the true crystallization age, 2. an assumption about the composition (specifically the Lu/Hf ratio) of the parental magma from which the zircon crystallised, and 3. assumptions about the Lu-Hf ratio of the average depleted mantle source and the time at which the depleted mantle separated from the primitive mantle. Vervoort and Kemp (2016) show that there are uncertainties in each of these assumptions. For example, the true crystallization age of the zircon may not always be accurately known because of problems of Pb-loss after crystallization. Further, in the case of detrital zircons the composition of the protolith cannot always be known and so its Lu/Hf ratio cannot be accurately known. Finally there is disagreement over the shape of the depleted mantle curve for Hf and the time at which it became distinct from a chondritic mantle (Vervoort et al. 2015; Hiess and Bennett, 2016). Further complications arise when the protolith is not simply derived from a mantle source but is a mixture of old crust and a melt from the depleted mantle, in which case hybrid ages are produced (Roberts and Spencer, 2015).

A further problem arises in older analyses where Hf-isotopes and U-Pb isotopes are not measured on exactly the same part of the zircon grain. This can give rise to a 'mixed analysis'. Kemp et al. (2010) showed that this approach leads to the calculation of spurious ε_{Hf} values, which in the case of Harrison et al. (2005) is thought to have produced calculated

ε_{Hf} values which were too high, and led to a wrong inference about mantle depletion in the Hadean.

In an attempt to correct for some of these problems some authors have screened their data using oxygen isotopes in zircon. This is an effective way of identifying zircons from reworked crust. Thus, the crustal growth curve of Dhuime et al. (2012) is obtained from a detrital zircon dataset, for which the protolith cannot easily be identified, but which has been screened using oxygen isotopes to remove reworked zircons. This approach rightly assumes that the measured $\delta^{18}O$ is indicative of the magmatic source and allows the identification of those zircons from reworked crust. However, more recent studies have argued that this is not an effective screening process (Roberts and Spencer, 2015; Payne et al., 2016).

This current discussion therefore raises the question of how much these uncertainties matter. It is clear than in some instances the uncertainties discussed above may be compounded to give model ages which are artefacts and calculated ε_{Hf} values which are meaningless. However, there is a divergence of view about the extent to which this uncertainty clouds our overall understanding crustal evolution growth curves. Here I would argue that the uncertainties associated with accurately isotopically characterising detrital zircons are substantial. I point to two lines of evidence. Firstly, as illustrated in Figure 3, the majority of detrital zircons examined are not juvenile and so the task of truely characterising them is significant. Secondly, it can be seen that different groups using different data sets obtain different results. For example this is evident in the crustal growth curves calculated by Belousova et al. (2010), Dhuime et al. (2012) and Roberts and Spencer (2015) (Figure 1). Each group has used a different data set and filtered it in a slightly different way and obtained a different result, suggesting that in some or maybe all instances some inappropriate data have made their way through the filtering process.

DISCUSSION AND CONCLUSIONS

This paper argues that there were no large volumes of continental crust on Earth during the early Archaean and the Hadean. Specifically, there is no evidence in the detrital zircon archive of large numbers of zircons with early Archaean and Hadean ages. Secondly, there are only small volumes of mantle melts which carry a subducted sediment signal, indicating that sediment subduction has never been a major process. If these arguments are valid then there are a number of consequences for the processes of crust generation in the early Earth:

Indications of the start of plate tectonics from crustal growth curves cannot be supported

Dhuime et al. (2012) proposed a crustal growth curve based upon Hf-isotope model ages and oxygen isotopes which shows an inflexion at ca 3.0 Ga indicating that prior to 3.0 Ga crustal growth rates were high, whereas after 3.0 they were reduced. This was interpreted to indicate a change in geodynamic processes on a global scale at 3.0 Ga, with the possible advent of a mechanism for crustal destruction after 3.0 Ga through crustal reworking and recycling via subduction. Whilst this is an attractive idea, because there are other indicators for a change in global geodynamic processes at 3.0 Ga (see for example Cawood et al 2006; Shirey and

Richardson, 2011; Condie 2016), it cannot be substantiated. Roberts and Spencer (2015) sought to replicate this work, using the same reworking correction but with a larger data set than used by Dhuime et al. (2012). Their results show a similar shaped growth curve to that of Dhuime (Fig. 1), but importantly, without an inflection at 3.0 Ga – implying that the 3.0 Ga inflexion is a product of the data set used and the way in which the data are filtered.

Links with the supercontinent cycle are over-stated

Cawood et al. (2013) argue that understanding the supercontinent cycle is critical in our understanding of the preservation of zircons during crustal growth. There is a well known cyclicity in the preservation of zircons (Figure 2), with U-Pb age peaks on histograms coinciding with the time of supercontinent formation. Cawood et al. (2013) show that the highest potential for zircon preservation is in the collisional phase of the supercontinent cycle, when new crust is created (and also reworked) but not easily destroyed, but it should be noted that this process may introduce a preservation bias into the data.

A more fundamental question is how far back in time can we be sure of supercontinents and related processes? There is some indication that some modern patterns of metamorphism can be traced back to the late Archaean (Cawood et al. 2013; Brown 2014), although evidences of Archaean supercontinents are weak. Evans (2013) showed that whilst there is reasonable evidence for the existence of the Nuna supercontinent at 1.7-2.0 Ga, 'it is not yet known whether Nuna was preceded by an earlier continental assemblage large enough to be classified as a supercontinent'. Hence, although there are proposals for the existence of late Archaean 'supercontinents' – Superia, Sclavia, Vaalbara, Zimgarn (Evans, 2013) – there is no consensus, nor any certainty of their size. For this reason mechanisms for crustal growth and zircon preservational bias based on supercontinents formation cannot be safely extrapolated into the Archaean.

The role of the sub-continental lithospheric mantle (SCLM) in the process of crust preservation has been misunderstood

It has been proposed that the SCLM plays a key role in the preservation of felsic continental crust (Cawood et al. 2013). It is thought that prior to the emergence of the SCLM at about 3.0 Ga newly formed crust was destroyed, but when the SCLM formed it provided a protective thermal insulation to newly formed crust so that the felsic crust survived. However, it has been proposed that crust formation and the creation of the SCLM is a coupled process (Rollinson, 2010). In this case crust preservation is not an independent process linked to the formation of the SCLM. Rather, Archaean felsic crust is preserved *because* felsic crust and the SCLM form together as part of a single set of processes and so are preserved together.

Thus several authors have sought to explain the different amounts of felsic crust preserved over Earth history through a balance between crust production and crust destruction related to the creation of the SCLM. For example Parman (2015) proposed that

in the very early Earth - crust-destruction >> production (no SCLM),
from 3.0-1.0 Ga - crust-production > destruction (SCLM present), and that
since 1.0 Ga - production = destruction (SCLM present).

The model presented in this study is much simpler, for in the very early Earth virtually no felsic crust was produced and there was no SCLM. Of course, if there were other mechanisms of crust production in the early Earth, in addition to but different from the coupled model described by Rollinson (2010), then this crust may have not been preserved, leading to a non-representative record of early crust production.

Crustal growth curves

A major conclusion of this review is that the most reliable growth curve for juvenile continental crust has to be one that uses a combination of U-Pb zircon crystallization ages, rock-Nd and zircon-Hf isotope data as a measure of the juvenile character of the crust coupled with rock volume data from geological maps. Currently probably the best example of such a growth curve is that of Condie and Aster (2010), based upon data from 40,000 samples. It shows that at 3.0 Ga there was as little as 5% of the present felsic crustal volume on Earth, but that during the late Archaean there was a major episode of crustal growth such that by 2.5 Ga the felsic crust had grown to almost 35% of its present crustal volume (Fig. 7). This feature of rapid crustal growth in the late Archaean is also seen in the juvenile zircon sub-set of the Roberts and Spencer (2015) data-set (not shown). It is also supported by the work of Tang et al. (2016) on the transition from high MgO mafic crust to low MgO felsic crust in the late Archaean. The Condie and Aster (2010) curve also shows that during the Proterozoic crustal growth was substantial but at a lower rate than in the Archaean. However, it was shown above that much of this crust has subsequently been reworked (Fig. 7).

More difficult to quantify, is the start of crustal recycling. In part this process is related to the volume of extant crust, but also to the operation of subduction. The few data we have on the commencement of crustal recycling are from the likely age of the source of sediment-contaminated ocean-island basalts, a subject fraught with uncertainty, but could indicate that there was crustal recycling in the palaeo-Proterozoic (Stracke et al., 2012). However as argued here, it is likely that the relative volume of this recycled felsic continental crust is small (Fig. 7).

The nature of the earliest crust

As has already been discussed above there are number of lines of evidence that suggest that the earliest crust on Earth, in the Hadean and the early Archaean before 3.0 Ga, was mafic in composition. The recent geochemical studies of Dhuime et al. (2015) and Tang et al. (2016) support this view as do older geological studies at Isua in west Greenland, the largest area of Eo-Archaean crust (Polat et al. 2002). In addition evidence from the Lu-Hf ratio in the parent to the Hadean Jack Hills zircons is also strongly indicative of a mafic protolith (Kemp et al. 2010), a view which is consistent with lunar and planetary analogues for the volcanic resurfacing of the early Earth (Marchi et al. 2014).

For this reason the oldest felsic rocks on Earth must have been produced from this mafic crust. Modern analogues can be found in the genesis of the small volume oceanic plagiogranites (Rollinson 2008, 2009; Nebel et al. 2014) and it is plausible that the granitoids parental to the Jack Hills zircons formed in such an environment (Rollinson 2008).

Alternatively, more potassic granitoids might have been generated in a plume-type setting as proposed by Willbold et al. (2009).

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FIGURE CAPTIONS

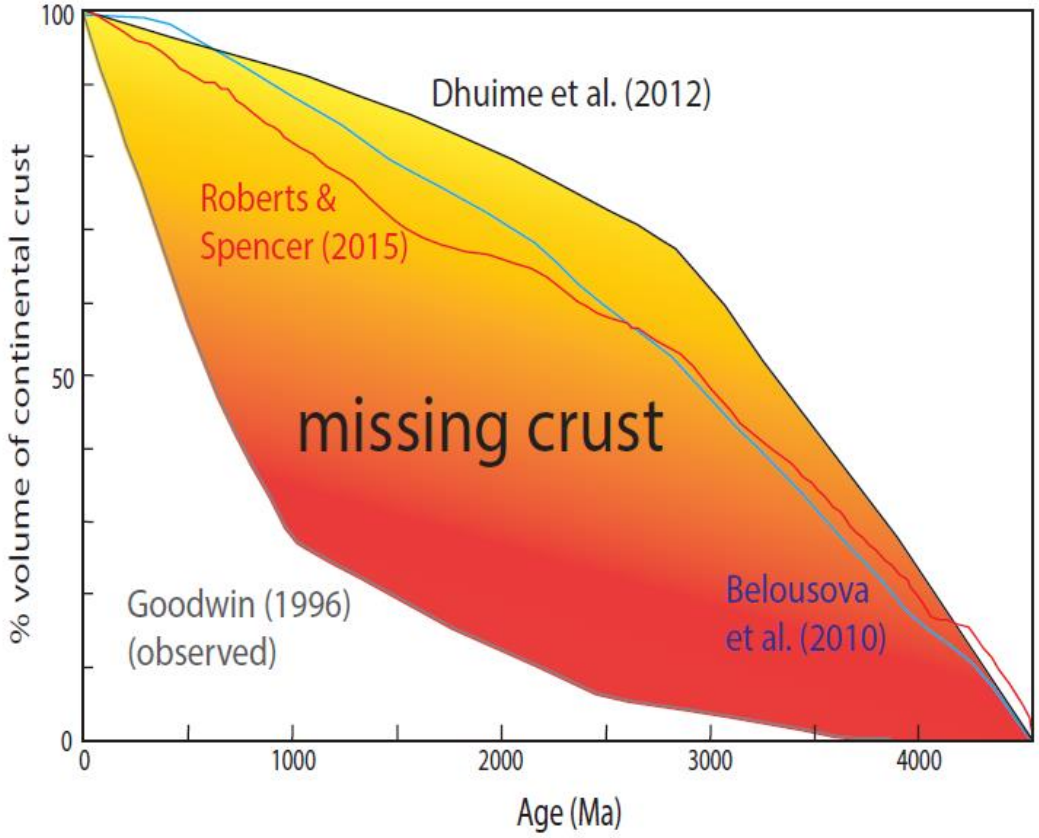

Figure 1

Figure 1. The volume of felsic continental crust predicted over geological time by the recent growth curves of Belousova et al. (2010), Dhuime et al. (2012) and Roberts and Spencer, (2015) compared with that observed today (Goodwin, 1996) and the resultant 'missing crust'.

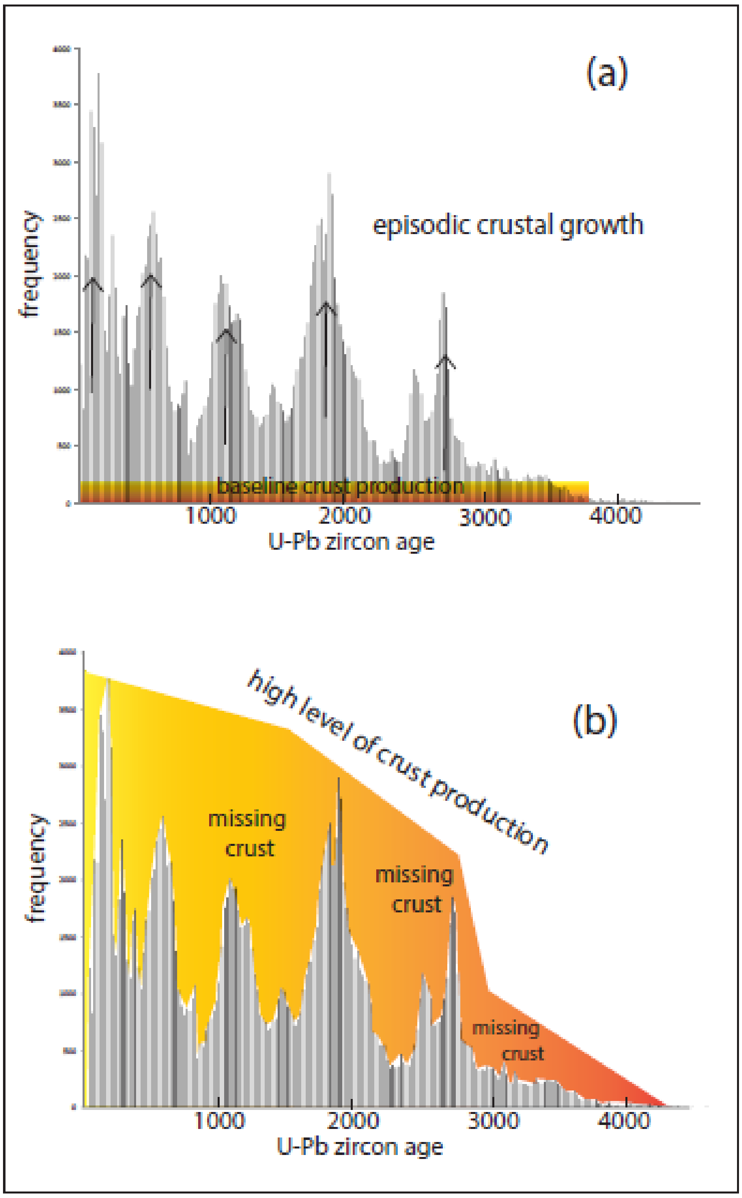

Figure 2

Figure 2. Two different interpretations of frequency histograms of U-Pb zircon ages for detrital zircons. (a) a relatively low but constant base-line of crust production with superimposed episodes of crustal growth; (b) a high level of continent crust production showing peaks of crust preserved and troughs of crust destroyed 'missing crust'. Data from Voice et al. (2011).

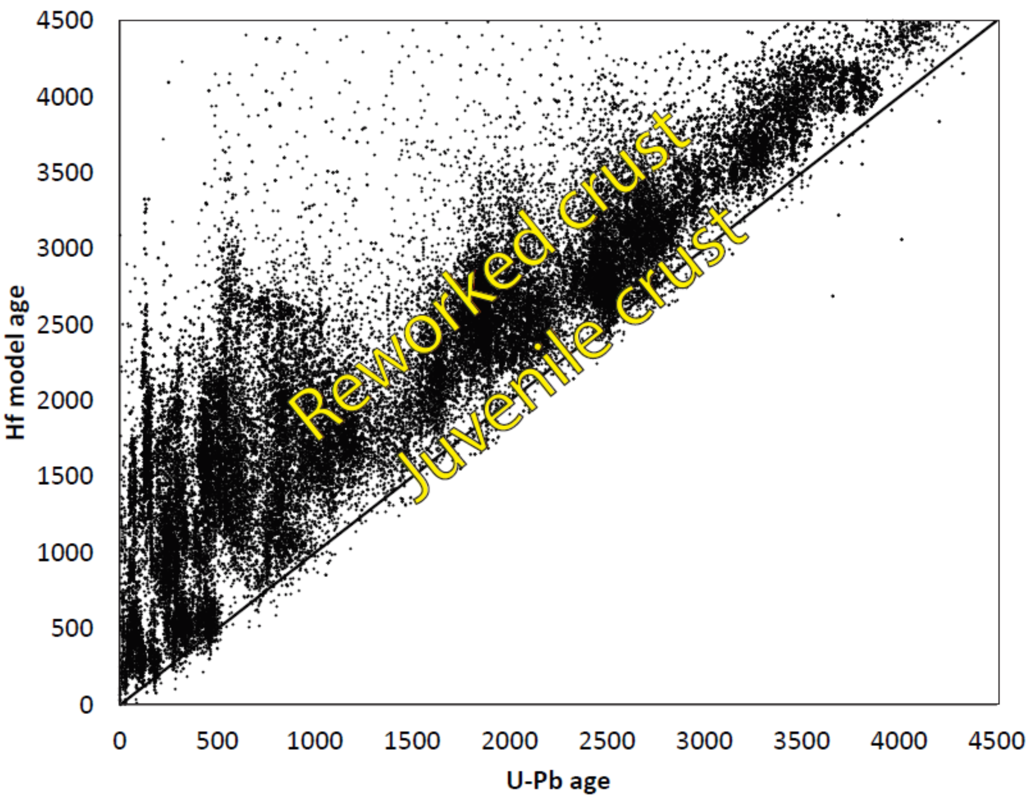

Figure 3

Figure 3. Plot of U-Pb age (the crystallization age) vs Hf-isotope depleted mantle model age (time that the parental material was extracted from the mantle) for >42,000 zircons from the database of Roberts and Spencer (2015). An initial interpretation of the data indicates that a large proportion of the continental crust is not juvenile, but is reworked.

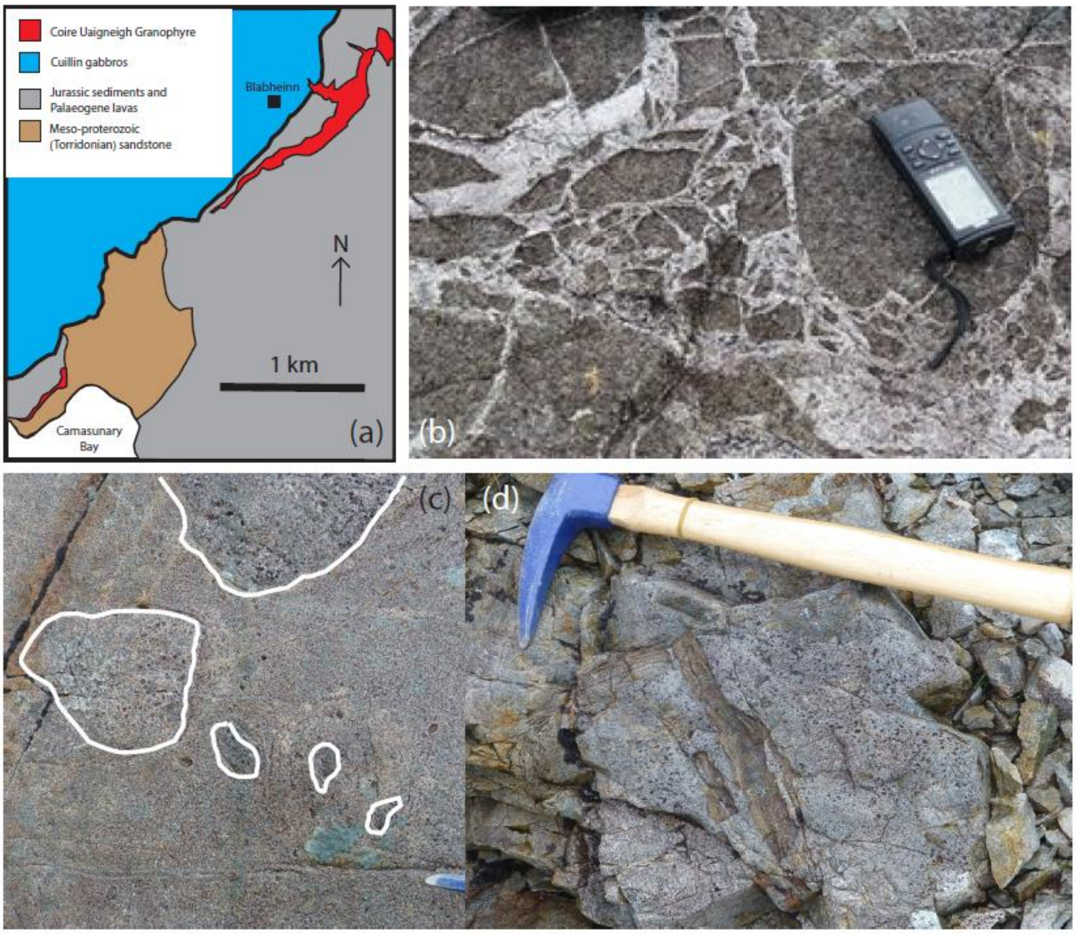

Figure 4

Figure 4. Crustal reworking on the Island of Skye, NW Scotland. (a) geological map showing the field relationships between meso-Proterozoic Torridonian sandstone, the Cullin gabbros and the Coire Uaigneich granophyres; (b) in situ partial melting of the meso-Proterozoic Torridonian sandstone; (c,d) xenoliths of meso-Proterozoic Torridonian sandstone in the Coire Uaigneich granophyre.

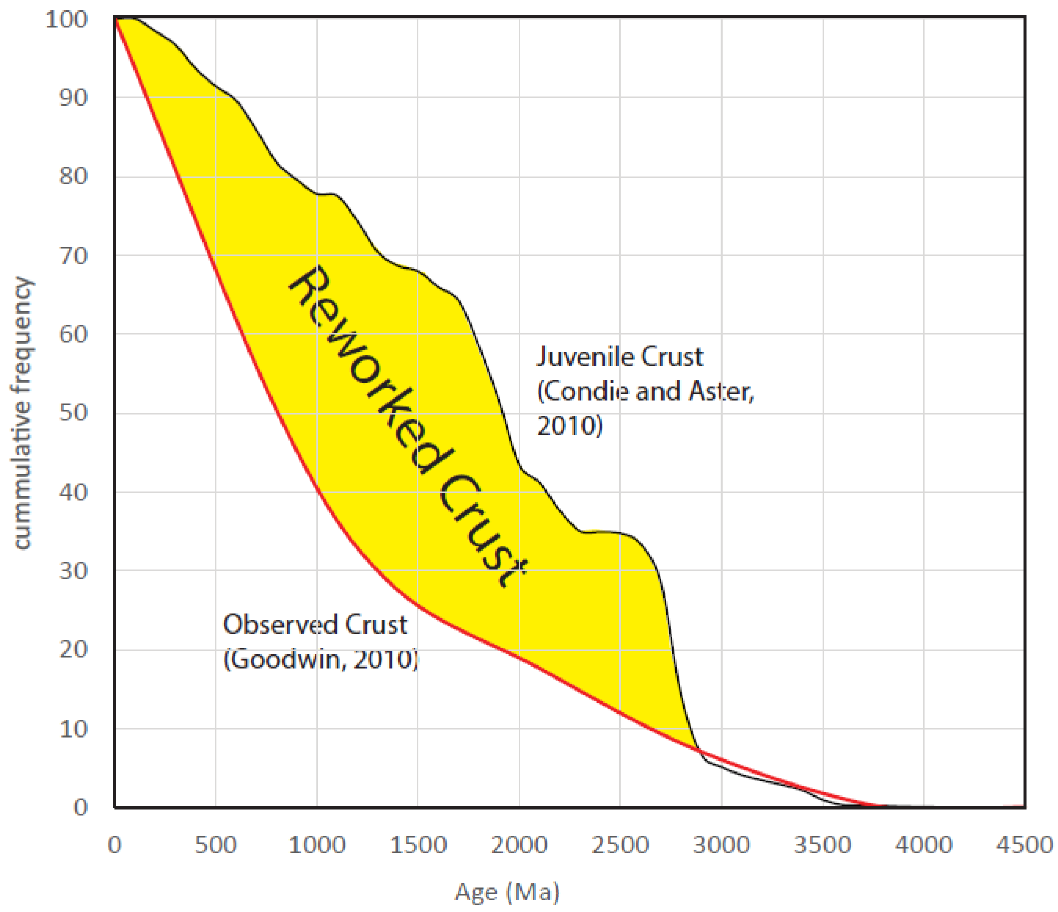

Figure 5.

Figure 5. An estimate of the volumes of reworked crust during crustal growth, based upon the difference between the volume of juvenile crust as computed by Condie and Aster (2010) and the volumes of crust observed today (Goodwin, 1996)

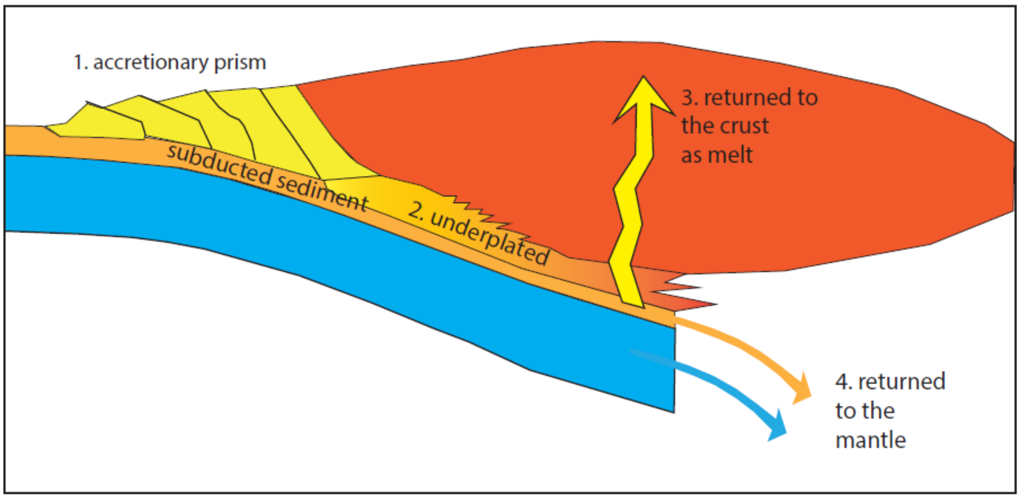

Figure 6

Figure 6. The fate of sediment during subduction showing that only a proportion of the subducted sediment will actually return to the mantle.

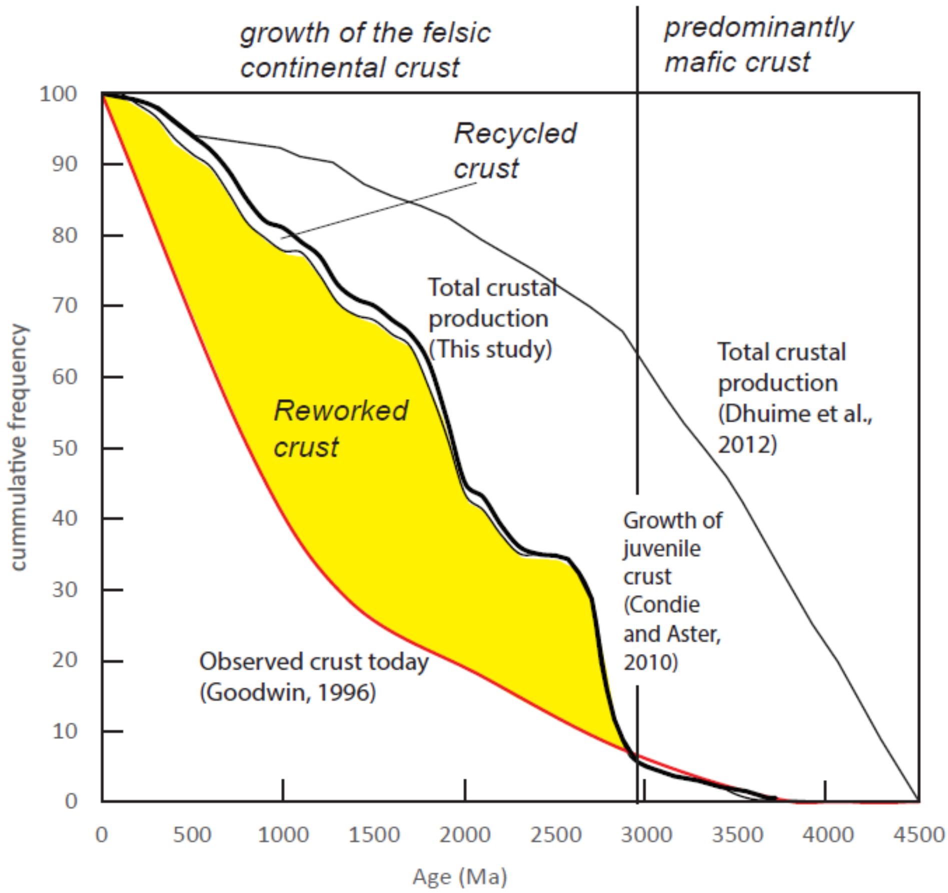

Figure 7.

Figure 7. Total crustal production over geological time. This estimate is based upon the crustal growth curve of Condie and Aster (2010) with a small additional amount of crust destroyed by crustal recycling and now returned to the mantle. The curve presented here contrasts with the crustal growth curve of Dhuime et al. (2012) which requires a very large volume of continental crust present in the early Archaean (cp Hawkesworth et al. 2014).