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Review Article

Continental growth and the crustal record

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ABSTRACT

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

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1. Introduction

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

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component of the lithosphere that lies above the Mohorovičić discontinuity (Moho) and extends laterally to the break in slope in the continental shelf (Rudnick and Gao, 2003).

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

2. Features of the geological record

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

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

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

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

Finally in this section it is important to be clear about the magmatic record of rocks trapped in the crust at times of continental collision (Condie, 2013; Hawkesworth et al., 2009). As demonstrated in the