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Focus paper

Generation and preservation of continental crust in the Grenville Orogeny

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A B S T R A C T

Detrital zircons from modern sediments display an episodic temporal distribution of U-Pb crystallization ages forming a series of 'peaks' and 'troughs'. The peaks are interpreted to represent either periods of enhanced generation of granitic magma perhaps associated with mantle overturn and superplume events, or preferential preservation of continental crust during global collisional orogenesis. The close association of those peaks with the assembly of supercontinents implies a causal relationship between collisional orogenesis and the presence of zircon age peaks. Here these two end-member models (episodic periodicity of increased magmatism versus selective preservation during collisional orogenesis) are assessed using U-Pb, Hf, and O analysis of detrital zircons from sedimentary successions deposited during the ~1.3–1.1 Ga accretionary, ~1.1–0.9 Ga collisional, and < 0.9 Ga extensional collapse phases of the Grenville orogenic cycle in Labrador and Scotland. The pre-collisional, accretionary stage provides a baseline of continental crust present prior to orogenesis and is dominated by Archean and Paleoproterozoic age peaks associated with pre-1300 Ma Laurentian geology. Strata deposited during the Grenville Orogeny display similar Archean and Paleoproterozoic detrital populations along with a series of broad muted peaks from ~1500 to 1100 Ma. However, post-collisional sedimentary successions display a dominant age peak between 1085 and 985 Ma, similar to that observed in modern North American river sediments.

Zircons within the post-orogenic sedimentary successions have progressively lower ε_{Hf} and higher $\delta^{18}O$ values from ~1800 to ~1200 Ma whereupon they have higher ε_{Hf} and $\delta^{18}O$ within the dominant 1085–985 Ma age peak. Furthermore, the Lu-Hf isotopic profile of the Grenville-related age peak is consistent with significant assimilation and contamination by older crustal material. The timing of this dominant age peak coincides with the peak of metamorphism and magmatism associated with the Grenville Orogeny, which is a typical collisional orogenic belt. The change from broad muted age peaks in the syn-orogenic strata to a single peak in the post-orogenic sedimentary successions and in the modern river sediments implies a significant shift in provenance following continental collision. This temporal change in provenance highlights that the source(s), from which detrital zircons within syn-orogenic strata were derived, was no longer available during the later stages of the accretionary and collisional stages of the orogenic cycle. This may reflect some combination of tectonic burial, erosion, or possibly recycling into the mantle by tectonic erosion of the source(s). During continental collision, the incorporated continental crust is isolated from crustal recycling processes operative at subduction margins. This tectonic isolation combined with sedimentary recycling likely controls the presence of the isotopic signature associated with the Grenville Orogeny in the modern Mississippi and Appalachian river sediments. These results imply that zircon age peaks, which developed in conjunction with supercontinents, are the product of selective crustal preservation resulting from collisional orogenesis.

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1. Introduction

Continental crust is a key repository of Earth history, preserving the product of geological processes that have shaped the planet in deep time. This record is vulnerable to destruction through the processes of sediment subduction and subduction erosion at convergent plate margins (Scholl et al., 1980; von Huene and Scholl, 1991; Stern, 1991; Clift et al., 2009; Stern, 2011), and through lower crustal delamination (Bird, 1979; Kay and Mahlburg Kay, 1993; Houseman and Molnar, 1997; Schott and Schmeling, 1998; DeCelles et al., 2009). The locus of crustal recycling is primarily at convergent plate margins where the subducting oceanic slab carries a veneer of sediment and it tectonically erodes crustal material from the overriding plate into the mantle. Paradoxically, it is also along convergent plate margins where the vast majority of continental crust is generated. Scholl and von Huene (2009) postulated that at present the ratio of crustal formation and destruction is roughly balanced, resulting in a zero net gain of continental crustal volume. In contrast, Stern (2011) estimated the total current rate of crustal recycling to be greater than the rate at which the crust is being generated by magmatic activity, and so the present total volume of continental crust may be decreasing.

The *degree* to which the current distribution of continental crust represents the original volume generated has been considerably debated (e.g. Bowring and Housh, 1995; Hawkesworth et al., 2009, 2010; Condie et al., 2011; Cawood et al., 2013). The temporal heterogeneity of presently exposed continental crust lies at the heart of this issue. There is considerable discussion whether the “peaks” and “troughs” of continental crust formation ages (broadly represented by zircon U-Pb crystallization ages) represent periods of episodically increased generation of continental crust (Condie, 1998; Rino et al., 2004; Yin et al., 2012; Arndt and Davaille, 2013; Walzer and Hendel, 2013) or selective crustal preservation (Hawkesworth et al., 2009; Condie et al., 2011; Roberts, 2012). Furthermore, excluding the Archean (see Ernst, 2009; Cawood et al., 2013; Spencer et al., 2014a), zircon age peaks in global compilations of zircon U-Pb ages appear broadly to correspond with the timing of supercontinent formation (e.g., Condie, 1998, 2000, 2003; Hawkesworth and Kemp, 2006; Kemp et al., 2006; Campbell and Allen, 2008; Voice et al., 2011; Arndt and Davaille, 2013).

Proponents of episodes of enhanced magmatism rely on significant mantle-plume activity or mantle-overturn events (Condie, 1998; Rino et al., 2004; Komiya, 2007; Arndt and Davaille, 2013). However, the andesitic composition of the bulk continental crust (Taylor and McLennan, 1985; Rudnick and Gao, 2003) suggests that near steady-state subduction zone magmatism and the resulting volcanic arcs is the dominant contributor of new continental crust (see McCulloch and Bennett, 1994; Davidson and Arculus, 2006; Hawkesworth and Kemp, 2006; Cawood et al., 2013). Roberts (2012) proposed that the lack of zircons with depleted ε_{Hf} during supercontinent assembly reflects increased crustal recycling during these periods, which he relates to the geodynamic configuration (subduction polarity, age of colliding crust, etc.) of the assembling continental fragments (see also Murphy et al., 2003; Murphy et al., 2009; Collins et al., 2011).

The alternative viewpoint is that the peaks and troughs in the zircon age archive are artifacts of varying preservation potential during and between times of collisional orogenesis leading to the assembly of supercontinents (Hawkesworth et al., 2009; Condie et al., 2011; Roberts, 2012; Cawood et al., 2013). The simplified stages of continental collision display three stages within a generalized geodynamic “cycle” of subduction, collision, and rifting phases (Hawkesworth et al., 2009, Fig. 1). Assuming the longevity of mass balance within modern subduction zones, crustal preservation during the subduction phase is minimal despite the large volumes of crust forming from subduction zone magmatism. This is especially true for advancing subduction margins (sensu Cawood et al., 2009) where large amounts of crust are removed by sediment subduction, subduction erosion, and delamination (Clift et al., 2009; DeCelles et al., 2009; Stern, 2011). The preservation potential increases in retreating continental margins in that slab retreat is greater than the subducting plate velocity resulting in significant intra-arc and back-arc extension and generation of continental crust and in extreme examples, oceanic crust (e.g. Cawood et al., 2009). As collisional orogenesis begins and subduction zone magmatism ceases, the latter stages of subduction zone magmatism are often preserved within the foreland of the collisional orogeny (as in the Transhimalayan volcanic arc; Hodges, 2000). Additionally, magmatism produced during the continental collision is dominated by lower crustal melts forming within an over-thickened crust and compressed thermal gradients along with decompression melting during orogenic exhumation (Harris et al., 1986). A key aspect of the selective preservation model of Hawkesworth et al. (2009) is that the detrital zircons that make up an ‘age peak’ may be largely derived from the latest stage of subduction zone magmatism rather than magmatism solely associated with the collision (Fig. 1), which is a period of minimal new crust generation. Collision is followed by the collapse and eventual rifting of the continental crust and relatively minor volumes of mafic magmatism and crustal generation (Scholl and von Huene, 2009; Cawood et al., 2013). Given the above postulates, it is predicted that detrital zircons derived from a collisional orogen will exhibit a dominant age peak associated with the large-volume of latest-stage subduction related magmatism preserved during continental collision.

These first order tectonic processes and the associated ideas for the growth and loss of continental crust are often assessed using combined isotopic systems (particularly U-Pb, Hf, O) primarily linked to voluminous compilations of isotopic analyses of zircon. It is argued that zircons from large rivers that drain large areas of continental crust provide the best way to obtain an unbiased and representative sample of the continental crust therein (e.g. Iizuka, 2005; Campbell and Allen, 2008; Wang et al., 2009; Iizuka et al., 2010; Wang et al., 2011; Yin et al., 2012; Iizuka et al., 2013). However, Allegre and Rousseau (1984) and Dhuime et al. (2011) have demonstrated that continental erosion results in a distinct bias toward younger lithotectonic domains. Other workers use large global databases with tens of thousands of analyses in an attempt to

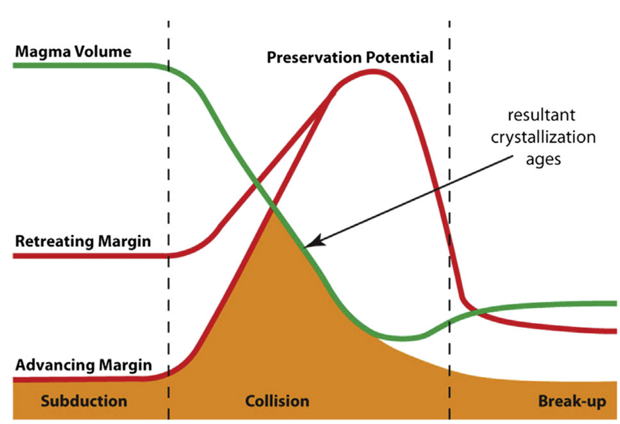

Figure 1. The volumes of magma generated (green line) and their likely preservation potential (red line) vary through the three stages associated with the convergence, assembly, and breakup of a supercontinent (after Hawkesworth et al., 2009). Peaks in igneous crystallization ages that are preserved in the rock record (shaded area) reflect the balance between the magma volumes generated during the orogenic cycle and their respective preservation potential.