Orogenic climax of Earth: The 1.2–1.1 Ga Grenvillian superevent

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ABSTRACT

The rate of growth of the continental crust is controversial. We present an evaluation of time-constrained analyses of oxygen isotopes in zircon grains and incompatible element (Zr, Th) concentrations in magmatic rocks to test for variations in the degree of crustal recycling through geological time. The data indicate a rise in these geochemical proxies from ca. 3.0 Ga to a statistically significant peak at 1.2–1.1 Ga during the amalgamation of supercontinent Rodinia, and a decrease thereafter. When combined with other geological and geophysical observations, the data are interpreted as a consequence of an unprecedented level of crustal recycling and sediment subduction during Rodinia assembly, arising from a "Goldilocks" (i.e., just right) combination of larger, thicker plates on a warmer Earth with more rapid continental drift relative to modern Earth. The subsequent decrease in δ^{18}O, Zr, and Th measurements is interpreted to reflect decreasing drift rates on a cooling Earth.

INTRODUCTION

The growth of Earth's continental crust over time depends on the rate of production at arcs and in oceanic plateaus versus the rate of recycling back into the mantle through subduction erosion. Current estimates suggest that these competing processes have been approximately in balance since the Neoproterozoic (Scholl and von Heune, 2009), implying that continental crust reached a maximum volume at some time in the Precambrian, when the Earth was hotter.

However, the rates of crustal growth over geological time remain controversial. Armstrong (1991) advocated for the essentially complete growth of continental crust prior to 3.5 Ga, whereas others have suggested more gradual crustal growth (e.g., Belousova et al., 2010). Furthermore, it is unknown whether crust grew in pulses associated with periods of supercontinent assembly (Stein and Hofmann, 1994; Condie, 1998), or whether the episodic record is an artifact of preservation (e.g., Hawkesworth et al., 2009). Nonetheless, recent studies indicating periods of enhanced exchange between the lower and upper mantle lend support to the episodic nature of crustal growth (Condie et al., 2001; Roberts, 2012; Van Kranendonk et al., 2012).

Incompatible trace elements (ITEs) represent another way of investigating the growth and/or recycling of crust, as they are preferentially excluded from common rock-forming minerals during fractional crystallization due to their unsuitable size and/or charge to fit within the cation sites of crystals, and are partitioned into silicate liquids during melting. This process has led to average upper continental crust highly enriched in ITEs relative to the mantle (Zr = 237 vs. 11 ppm, Th = 11 vs. 0.09 ppm). Elevated concentrations of Zr and Th above these crustal values in magmas reflect enhanced crustal recycling and the importance of preexisting continental crust in the orogenic cycle.

Oxygen isotope variations also reflect the orogenic cycle through the nature of the source material: low values ($\delta^{18}O = 5.3‰ \pm 0.3‰$) imply a mantle source, or a crustal source not exposed to surface weathering, whereas higher values (7.5‰–12‰) imply incorporation of material affected by near-surface weathering processes into magmas through subduction (Valley et al., 2005).

Naturally, these proxies will vary spatially at any one time, but global data sets should identify temporal changes in source contributions, as well as potential changes in the amount of crustal recycling, as ITEs are preferentially concentrated and oxygen isotopes elevated toward heavy values by subduction, collision-related uplift, erosion, and crustal recycling.

In this paper we investigate the changing nature of the global supercontinent cycle by analysis of a global compilation of δ^{18}O values from dated zircon grains, complemented by ITE concentrations (Zr and Th) in a global database of dated magmatic rocks (Appendices DR1 and DR2 in the GSA Data Repository[1]). The data show statistically significant peaks in oxygen isotope and ITE values at 1.2–1.1 Ga, accompanying the Grenvillian assembly of supercontinent Rodinia, and a successive decrease thereafter. We argue that the data reflect a global climax in the amount of crustal recycling arising from a "Goldilocks" (i.e., just right) combination of fast drift of larger, and possibly thicker, continental plates on a warmer Earth with more rapid continental drift compared with modern day.

METHODS AND SAMPLE MATERIALS

We present whole-rock concentrations of Zr and Th from 340 samples of magmatic rocks of a range of ages from Western Australia; the magmatic crystallization ages were determined by U-Pb analysis of zircon through secondary ionization mass spectrometry (Appendix DR1). These data are complemented by a global compilation of 2913 analyses of Zr and Th concentrations in magmatic rocks, extracted from the Petrological Database (PetDB; http://www.earthchem.org/petdb), North American Volcanic and Intrusive Rock Database (NAVDAT; http://www.navdat.org), and the Geochemistry of Rocks of the Oceans and Continents database (GEOROC; http://georoc.mpch-mainz.gwdg.de/georoc) (as queried through the Integrated Earth Data Applications EarthChem website; http://www.earthchem.org). Oxygen isotope data are compiled from 1262 dated magmatic zircon grains from previously published sources (Appendix DR2).

To analyze the data, we employ the scan statistic (Naus, 1965; Glaz et al., 2009) to retrospectively search through time for data clusters with high values, using a normal probability model (Kulldorff, 1997; Kulldorff et al., 2009) in which a temporal window of all sizes between 5 and 100 Ma is moved over the time series. The maximum value relative to the number of observations in the window is recorded over all possible time periods and compared to its distribution under the null hypothesis of a purely random process (for more detail, see the Data Repository).

RESULTS

When plotted against time, the δ^{18}O, Zr, and Th data sets show low-amplitude peaks and troughs after ca. 3.0 Ga that correlate with periods of supercontinent assembly and dispersal as determined from geological

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[1]GSA Data Repository item 2013205, Appendix DR1 (whole rock chemical parameters and SIMS U-Pb zircon crystallization age for magmatic rocks within Western Australia), and Appendix DR2 (oxygen isotope values in zircon grains from the compilation of Valley et al. [2005] with additional data from Kirkland et al. [2010] and Be'eri-Shlevina et al. [2009]), is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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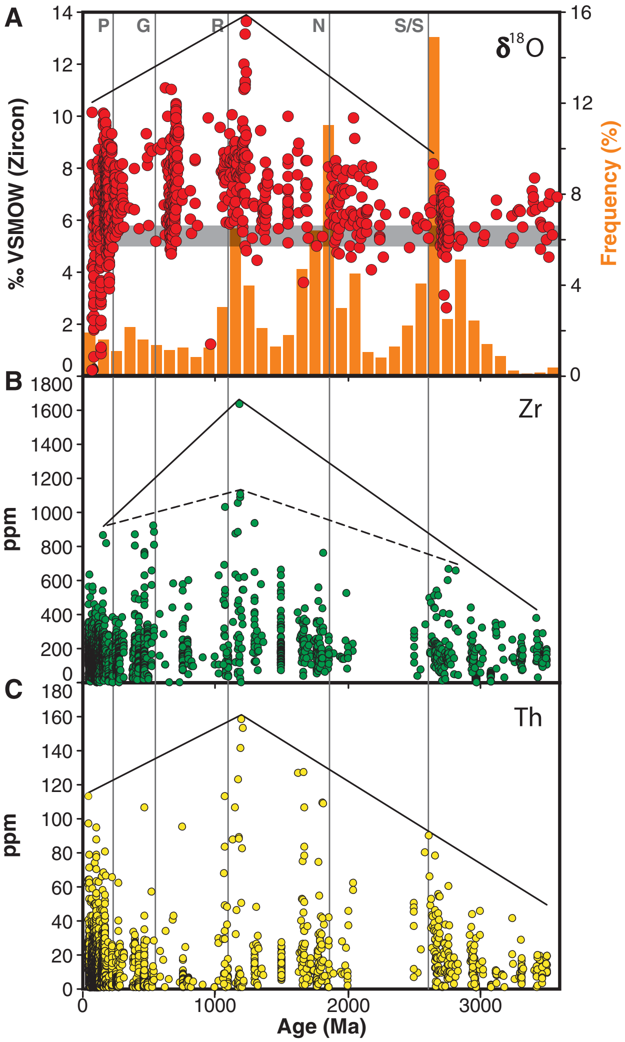

Figure 1. Evolution plots. A: δ^{18}O in zircon grains from global compilation (as detailed in Appendix DR2; see footnote 1) set against backdrop of histogram of zircon ages (from Condie, 1998). VSMOW—Vienna standard mean ocean water. B, C: Concentrations of incompatible trace elements (Zr and Th) in dated igneous rocks from global geochemical data sets (http://www.earthchem.org) augmented by dated rocks from Western Australia (Appendix DR1; and see West Australian Resource Information and Map Services Geochemistry Database Search: http://www.dmp.wa.gov.au/geochem). Supercontinents: P—Pangea; G—Gondwana; R—Rodinia; N—Nuna; S/S—Superia/Sclavia.

and isotopic data (Fig. 1). Using the scan statistic, a statistically significant ($p < 0.001$) temporal cluster of heavy oxygen and high Zr concentration is present at 1.2–1.1 Ga, during Grenvillian assembly of the supercontinent Rodinia (Table DR1 in the Data Repository). Scanning across Proterozoic Earth history (2.5–0.5 Ga) reveals a statistically significant ($p < 0.001$) temporal cluster of high Th concentration, also at 1.2–1.1 Ga.

These peaks are not only higher at 1.2–1.1 Ga than at any time during the preceding 2.5 Ga, but also higher than at any time thereafter (Fig. 1). Oxygen isotope concentrations in zircon were on average 1.84% greater than at any other time in Earth history; whole-rock Zr and Th concentrations were on average 332 ppm and 22 ppm greater than at any other time in all of Earth history, and in Proterozoic Earth history, respectively (Table DR1). The 1.2–1.1 Ga peak identified herein is also evident in Zr concentrations from the Grenville orogen of North America (to 1700–1800 ppm; Moecher and Samson, 2006).

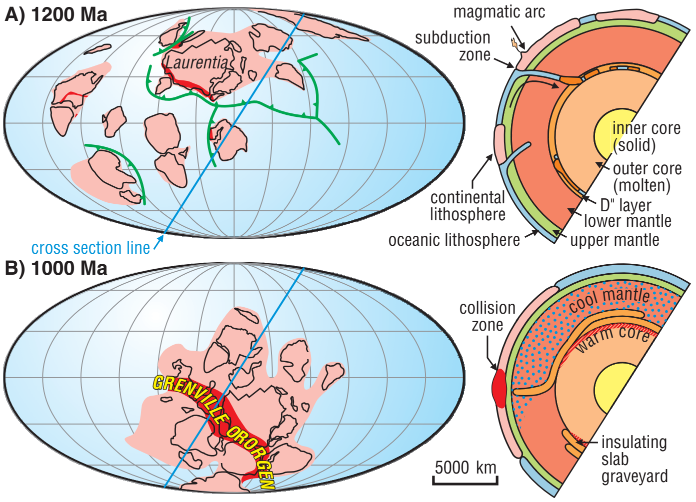

Figure 2. Schematic evolution of Grenvillian superevent. A: Leading to Rodinia assembly, showing multiple subduction zones (green lines, teeth on hanging wall) and collisions (red areas). B: Final Rodinia assembly across Grenville orogen. Widespread subduction during supercontinent assembly results in mantle cooling.

DISCUSSION

Orogenic Climax in Earth History

The 1.2–1.1 Ga peak in geochemical and isotopic signatures, identified in Western Australia, North America, and global data sets, indicates that the Grenvillian orogeny represents a unique episode in Earth evolution. Enrichment of ITEs may arise from fractionation and/or multiple episodes of remelting of crustal sources. In the case of Zr, temperature is an important control on Zr solubility and its concentration in melts (Moecher and Samson, 2006). However, these processes can only proceed so far and generally only produce maximum concentrations of 500–600 ppm Zr in A-type granites, with rare maxima of 1370 ppm (Collins et al., 1982; Whalen et al., 1987), well below the maximum values presented here and in Moecher and Samson (2006). It is significant that melting temperature is regarded as having no control on the variation of oxygen isotopes through time (Valley et al., 2005). Combined, these considerations imply a distinct orogenic control on the compositional anomalies identified here that relate to the total volume of subducted sediment and/or recycled continental crust.

Five aspects of the Grenvillian orogenic cycle are anomalous and have direct bearing on the geochemical and oxygen isotopic peaks identified here.

1. Large tectonic plates previously formed during dispersal of the supercontinent Nuna ca. 1.8 Ga were made significantly larger by addition of juvenile crust over wide areas from 1.7 to 1.3 Ga, within marginal plate settings of arcs and backarcs (e.g., southwest and southeast North America, Baltica, southwest Australia; Dickin and Higgins, 1992; Slagstad et al., 2009; Evans and Mitchell, 2011; Kirkland et al., 2011).

2. Large areas of the continental crust were also substantially thickened over the same time interval by underplating basaltic magmas that fractionated to generate voluminous, temporally unique, Mesoproterozoic anorthosite-mangerite complexes (Windley, 1995).

3. Earth's mantle was ~55 °C hotter than present (Labrosse and Jaupart, 2007; Michaut and Jaupart, 2007; Brown, 2008), as evidenced by the lack of blueschists in orogens older than the Neoproterozoic and the presence of thicker ophiolites in the Mesoproterozoic (Moores, 1993).

4. The rate of continental drift immediately prior to Grenvillian orogenesis was nearly an order of magnitude larger than at any subsequent time in Earth history (O'Neill et al., 2007; Swanson-Hysell et al., 2009).

Although primarily a function of hotter more rapidly convecting mantle, higher drift rates at this time may have been exacerbated by enhanced slab pull of thicker oceanic lithosphere (i.e., Moores, 1993).

5. Paleogeographic reconstructions and tectonic analysis reveal that the Grenville orogen was perhaps the longest and widest in Earth history (giant-supergiant orogen of Beaumont et al., 2010), spanning 25% of the globe, or a distance of ~20,000 km along strike and as wide as 800 km, including a core zone several hundred kilometers wide with large slabs of deep-crustal eclogite (Fig. 2; Eaton et al., 1995; Rivers et al., 2002; Li et al., 2008). These features indicate a vast area of crustal thickness doubling during a protracted continent-continent collision (Davidson, 2008; Hynes and Rivers, 2010). For comparison, the largest and highest orogen on modern Earth is the Alpine-Himalayan orogen, which is ~8000 km long and as much as 400 km wide.

These features demonstrate that the Grenville orogen was of unprecedented size, necessitating a powerful driving force. Whereas Beaumont et al. (2010) ascribed variations in orogenic magnitude solely to variations in temperature, data from the Himalaya orogen show that it is the product of the anomalously rapid drift of the Indian continent (18–20 cm/yr; Kumar et al., 2007), dragged on top of a large subducting plate of cold oceanic lithosphere. Thus, continental drift rate is an additional, and perhaps highly significant, factor in determining orogenic magnitude, with temperature likely to be a resultant function of rollback-generated backarc extension (Collins, 2002). Plate size and strength (rigidity) also play a significant role in orogen magnitude: small, weak (hot) plates produce small, or broad, low-grade orogens, whereas large, stiff plates produce large orogens (Tapponnier et al., 1982; Cruden et al., 2006). Combined, rapid drift rate, enhanced plate size and strength, and elevated temperature define what we refer to here as high orogenic intensity.

The long duration and large aerial extent of juvenile crust formation in arc-backarc settings immediately preceding Grenvillian orogenesis, combined with the evidence for multiple collisions during orogeny (1.3–1.0 Ga; Davidson, 2008; Hynes and Rivers, 2010), are important in understanding the peak in geochemical and isotopic anomalies recorded here (Fig. 2). Large-scale extension and rollback of the subducting plates creates juvenile crust in backarcs, whereas pulses of compression during accretion episodes consume newly generated crust (Gower and Tucker, 1994; Fisher et al., 2010). Such tectonic switching generates large volumes of ITE-enriched sediment derived from the continental hinterland and erosion of newly formed arc and backarc crust in developing mountain belts (Curray, 1994; Collins, 2002). This sediment, affected by high degrees of surficial weathering and transported into subduction zones, becomes incorporated into the magmatic system and fractionated (Chiarenzelli et al., 2010).

It is this tectonic switching, operating at the unprecedented scale of the Grenville orogen and in combination with the fast drift rate, anomalously thick and more rigid continental plates, and thicker oceanic lithosphere involved in Rodinia assembly, that we suggest was the cause for the unrivalled level of recycled orogenic crust at this time. That the scale of this process was evidently unmatched throughout the rest of Earth history suggests that this period represents a "Goldilocks" combination of large plates on a warmer, more rapidly convecting Earth (Fig. DR1).

Prelude

Secular cooling of Earth since at least the Neoarchean (Herzberg et al., 2010) has contributed to the changing style and thermal gradients of more recent orogenic belts (Brown, 2008). Such temporal changes in tectonic style are the result of large plates on cooler mantle, which have different rheological properties, styles of interaction, and insulating capacities than smaller plates on hotter mantle (Anderson, 1982; Rey and Houseman, 2006; Hynes and Rivers, 2010). Through the Archean, the combination of higher overall geothermal gradients and higher radiogenic heat production within continental crust resulted in weak, generally submergent continental plates and wide, hot orogens (Cruden et al., 2006) that were unable to produce the scale of orogeny, or associated crustal recycling as on younger Earth.

By 2.4 Ga continents had emerged (Rey and Coltice, 2008), by 2.0 Ga bona fide ophiolites appeared in the rock record (e.g., Kontinen, 1987), and the modern-style supercontinent Nuna had formed by 1.8 Ga (Reddy and Evans, 2009); all of this points to the progressive thickening and stiffening of continental lithosphere through the Paleoproterozoic. However, Nuna assembly did not produce the same degree of crustal recycling shown by Rodinia, implying either that pre-Nuna plates were not as large as, and/or weaker than, post-Nuna plates, or drift rates were slower. Given the evidence of a nearly global magmatic shutdown at 2.45–2.2 Ga (Condie et al., 2009), the latter may have been the most significant factor (Fig. DR1).

Dénouement

The decrease in geochemical and isotopic proxies of orogenic recycling after the Grenvillian superevent is here ascribed to secular decrease in mantle temperatures and resultant slower rates of continental drift and thinner oceanic lithosphere. In addition, recent estimates of tectonic erosion at subduction zones exceeding crustal growth at arcs suggest that continental plates may have actually decreased in volume since 1.0 Ga (Scholl and von Heune, 2009), thereby further contributing to reduced orogenic intensity after this period.

CONCLUSIONS

A statistically significant ($p < 0.01$) and unrivalled cluster of high values in geochemical proxies of crustal recycling (zircon $\delta^{18}O$, whole-rock Zr and Th) is found at 1.2–1.1 Ga, representing an orogenic climax in Earth history during the Grenvillian assembly of supercontinent Rodinia. We suggest that this climax reflects a "Goldilocks" combination of large plates on a warmer mantle with faster rates of continental drift. Prior to that time, plates were smaller and less rigid and thus unable to match the orogenic intensity of the Grenvillian superevent. Post-Grenvillian secular decrease in mantle heat, slower drift rates, and thinner oceanic lithosphere, coupled with an imbalance of subduction erosion over crust production, resulted in smaller continental plates and declining orogenic intensity after 1.2–1.1 Ga.

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