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Filling in the juvenile magmatic gap: Evidence for uninterrupted Paleoproterozoic plate tectonics

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ABSTRACT

Despite several decades of research on growth of the continental crust, it remains unclear whether the production of juvenile continental crust has been continuous or episodic throughout the Precambrian. Models for episodic crustal growth have gained traction recently through compilations of global U–Pb zircon age frequency distributions interpreted to delineate peaks and lulls in crustal growth through geologic time. One such apparent trough in zircon age frequency distributions between ∼2.45 and 2.22 Ga is thought to represent a pause in crustal addition, resulting from a global shutdown of magmatic and tectonic processes. The ∼2.45–2.22 Ga magmatic shutdown model envisions a causal relationship between the cessation of plate tectonics and accumulation of atmospheric oxygen over the same period. Here, we present new coupled U–Pb, Hf, and O isotope data for detrital and magmatic zircon from the western Churchill Province and Trans-Hudson orogen of Canada, covering an area of approximately 1.3 million km^2, that demonstrate significant juvenile crustal production during the ∼2.45–2.22 Ga time interval, and thereby argue against the magmatic shutdown hypothesis. Our data is corroborated by literature data showing an extensive 2.22–2.45 Ga record in both detrital and magmatic rocks on every continent, and suggests that the operation of plate tectonics continued throughout the early Paleoproterozoic, while atmospheric oxygen rose over the same time interval. We argue that uninterrupted plate tectonics between ∼2.45 and 2.22 Ga would have contributed to efficient burial of organic matter and sedimentary pyrite, and the consequent rise in atmospheric oxygen documented for this time interval.

1. Introduction

The nature and timing of continental crustal growth patterns throughout Earth's history are still under debate (e.g., Hawkesworth et al., 2010). Juvenile continental crust is the product of direct mantle melting or rapid differentiation of such material, whereas recycled crust forms from melting of pre-existing continental crustal components. One end-member model suggests that most or all juvenile continental crustal mass originated in the Archean and since then has been mostly recycled within the crust and mantle (Armstrong, 1981, 1991). Alternatively, juvenile continental crustal growth may have been progressive, either continuous (linear) or episodic through geologic time, based predominantly on the distribution of abundance peaks in magmatic and detrital U–Pb zircon ages and zircon Hf data (e.g., Condie, 1998; Hawkesworth and Kemp, 2006; Belousova et al., 2010; Dhuime et al., 2012). There is debate on the significance of the peaks in crustal age histograms (i.e., U–Pb zircon age peaks), particularly some advocate they are more representative of enhanced preservation rather than episodic crustal addition from the mantle (Hawkesworth et al., 2010). Orogenic events and periods of supercontinent assembly, in particular, represent times of the greatest growth of continental crust, by both addition (via subduction-related magmatism) and preservation by capture mechanisms such as obduction and orogeny (Scholl and von Huene, 2007; Hawkesworth et al., 2010). Accordingly, the record of U–Pb zircon age frequency distributions may broadly reflect supercontinent cycles (Hawkesworth and Kemp, 2006; Condie et al., 2011; Voice et al., 2011), favoring episodic crustal preservation

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rather than archiving episodic crustal growth (Hawkesworth et al., 2010).

Recently, the hypothesis of episodic crustal growth in the Precambrian gained support with the suggestion of early Paleoproterozoic and Mesoproterozoic episodes of plate tectonic shutdown (e.g., Silver and Behn, 2008; Condie et al., 2009), contradicting the continuity of plate tectonics over the past 180 million years that is observed in the record of seafloor spreading (Müller et al., 1997). Silver and Behn (2008) suggested that severely reduced subduction or plate tectonic 'efficiency' during intervals of 10s to 100s of millions of years in the Precambrian is one solution to cope with the 'thermal catastrophe' problem of unreasonably high upper mantle temperatures before 1 Ga. The authors do not explicitly state that plate tectonics and subduction would be entirely shut down, but their models show that reducing the subduction flux by as much as 90% between 1.5 and 1.0 Ga would resolve the 'thermal catastrophe' and also explain the apparent episodic nature of the magmatic record. O'Neill et al. (2007) suggested that Precambrian episodic tectonics were driven by a plate tectonic system operating under hotter mantle temperature conditions of the early Earth, which resulted in pulses of rapid subduction followed by 200 Myr to 1 Gyr periods of tectonic quiescence. Since the process of subduction initiation is poorly understood (e.g., Silver and Behn, 2008; Stern and Scholl, 2010), it remains unclear how subduction would be re-initiated, if subduction was to shut down completely.

The apparent paucity of zircon ages between ~2.45 and 2.22 Ga in both the detrital and magmatic records, in addition to a reduced occurrence of greenstone belts, iron formations, tonalite–trondhjemite–granodiorite (TTG) suites, and large igneous provinces (LIP) relative to the Archean record, led to a hypothesis that envisioned a ~230–250 million-year global magmatic and plate-tectonic shutdown event that drastically thwarted the production of juvenile crust (Condie et al., 2009). The hypothesized shutdown, or 'slowdown' (Eriksson and Condie, 2014), has been also implicated in allowing oxygen to accumulate in the atmosphere over the same time interval by decreasing the flux of reducing volcanic gases (Condie et al., 2009).

Given that the crustal record is inherently biased by the efficient preservation of crust during the operation of favorable tectonic processes (e.g., supercontinent assembly), finding direct geological evidence for a shutdown, or slowdown, is extremely difficult. The perspective of quantifying Precambrian plate tectonic activity similarly presents a confounding problem, considering that much of the geologic record is subducted, eroded/recycled, or reworked by metamorphism and orogenesis. However, the majority (up to 85%) of today's juvenile crustal genesis is associated with convergent plate boundary processes, whereas only 15% of juvenile crust is added at rifts, hotspots, and rifted continental margins (Stern and Scholl, 2010). Therefore, the production of juvenile (super-chondritic) crust is implicitly linked to plate tectonic activity and is most likely to be subduction related in a modern-day tectonic regime. Conversely, a reduction in juvenile crust production most simply implies reduced subduction. The result of the plate tectonic shutdown or slowdown would be an increase in the upper mantle temperature due to the stagnant lid effect, resulting primarily in anorogenic magmatism in supercontinent interiors with a geochemical signature of crustal melting (Silver and Behn, 2008). Therefore, we evaluate the shutdown hypothesis with simple two end-member alternatives. If plate tectonics and subduction were operating during the 2.45 to 2.22 Ga interval, evidence for extensive juvenile as well as non-juvenile crust production should be preserved in magmatic and sedimentary records. Alternatively, if plate tectonics and subduction were significantly slowed or not operating during the 2.45 to 2.22 Ga interval, magmatic and sedimentary records of juvenile crust production should be extremely rare, whereas recycled crust should be overwhelmingly dominant.

First, we review the record of 2.45 to 2.22 Ga magmatism in the literature and then present our own Hf and O isotope data in a subset of ~2.45 to 2.22 Ga detrital and magmatic zircon grains from the Canadian Shield. We then address the shutdown hypothesis by evaluating the presence or absence of evidence for juvenile magmatism in the 2.45 to 2.22 Ga record, and show that detrital and magmatic zircon grains of this age are more abundant than previously recognized. The record of juvenile crust production during this time interval continues to grow with further documentation, challenging the plate tectonic shutdown hypothesis.

1.1. Filling in the global magmatic gap

The global magmatic and tectonic shutdown period is bracketed by LIP events at ~2.45 and 2.22 Ga, and largely lacks LIP events or TTG emplacement (Condie et al., 2009). At the time the shutdown hypothesis was put forward, the only magmatism in the gap that was recognized was a LIP event represented by a 2365 Ma dyke swarm in India, and two granitoid suites, one on the western Rae craton, and one subduction-related, juvenile 2350 Ma granitoid suite in the Borborema Province of Brazil (Condie et al., 2009 and references therein). The time interval was not known to contain TTG suites. Detrital zircons of this age were reported from modern riverine sediments in many locations around the world, including India, Australia, Brazil, Ukraine, eastern Asia, and western Canada (Campbell and Allen, 2008; Condie et al., 2009), but neither Hf nor O data were available to evaluate the proportion of juvenile vs. recycled sources.

Recent U–Pb geochronological studies point to magmatic activity filling the gap (Fig. 1 and Table S1). Coeval ~2.37 Ga doleritic to gabbroic dykes are now recognized in both the Dharwar (India) and North Atlantic (Greenland) cratons as well as on the Tarim Block (China) and are linked to a widespread 2.37 Ga LIP event (Zhang et al., 2007; French and Heaman, 2010; Kumar et al., 2012; Nilsson et al., 2012). Similarly, a ~2.4 Ga LIP event is inferred from the ~2.42–2.41 Ga Widgiemooltha dyke swarm on the Yilgarn craton (Nemchin and Pidgeon, 1998; French et al., 2002), ~2.42 Ga Scourie dykes on the Baltic Block (Heaman and Tarney, 1989), and the ~2.4 Ga Ringvassøy mafic dyke swarm on the Fennoscandian Shield (Kullerud et al., 2006). A younger set of mafic dykes, including the ~2.295 Ga Tulisaari dolerite dyke swarm (Karelian craton; Hölttä et al., 2000) and the ~2.31 Ga Fuping complex amphibolitic dykes (+εNd values, North China craton; Liu et al., 2002) might record a less extensive LIP event at ~2.32–2.30 Ga. The ~2.257 Ga Belizário ultramafic amphibolite of the Encantadas complex, Southern Brazilian Shield (Hartmann et al., 2003), the ~2.26 Ga Chimbadzi Hill Intrusion, Zimbabwe craton (Manyeruke et al., 2004), and ~2.24 Ga norites in Antarctica (Lanyon et al., 1993) might reflect another LIP event on separate cratons.

TTG suites of this age have also now been reported, including a juvenile ~2.35 Ga Lagoa Dourada TTG suite on the São Francisco craton margin (Seixas et al., 2012), a ~2.31 Ga syntectonic TTG suite in the Côte d'Ivoire (West African craton; Gasquet et al., 2003), a ~2.37 Ga Guojiazhuang TTG gneiss of the Lüliang complex (Trans-North China orogen, Zhao et al., 2008), and a ~2.36–2.29 Ga TTG suite with +εNd values in the Borborema Province, Brazil (Dos Santos et al., 2009). Additionally, the ~2.36 Ga Três Palmeiras greenstone belt with island-arc geochemical affinities and associated ~2.34 Ga tonalite were documented in the Bacajá domain of the Central Brazil Shield (Vasquez et al., 2008; Macambira et al., 2009). Other granitoids have yielded juvenile signatures (+εHf or +εNd), including the ~2.32–2.28 Ga plutons of the Buffalo Head terrane (Villeneuve et al., 1993) and Meta Incognita microcontinent (this study), and the ~2.42 Ga Lujiagou syenogranite pluton on the southern margin of North China craton (Zhou et al., 2011).