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Review Article

Episodic Earth evolution

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A B S T R A C T

U–Pb ages of zircons from Precambrian granitoids and major rivers are grouped into a series of major peaks at about 2.7, 2.5, 2.1, 1.9 and 1.1 Ga. Recently these peaks have been interpreted as times of enhanced preservation of the continental crust associated with the assembly of supercontinents. An older interpretation, which we support, is that they correspond instead to periods of accelerated crustal growth related to episodic convection of the mantle. In this paper we use fluid mechanics experiments to develop a new model of mantle convection and crustal growth. A dense layer at the base of the mantle persists until 2.7 Ga when it destabilizes and generates large domes that rise into the upper mantle. There they cause a large increase in the rate of subduction which leads to enhanced granite magmatism at convergent margins and thus to a pulse of crustal growth. The domes heat the upper mantle which partially melts at mid-ocean ridges to produce thick oceanic crust that resists subduction. The subsequent period of subdued plate motion is broken by the next generation of mantle domes. Before and after the Archean–Proterozoic period of episodic crustal growth, plate tectonics operated quasi-continuously.

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1. Introduction

In the 1960s and 1970s, when radiometric ages of Precambrian rocks were first compiled, it became clear that these ages are not uniformly distributed. Instead they are confined to a small number of short, specific time intervals (peaks), separated by longer periods (troughs) in which ages are rare or absent (Hurley, 1968; Hurley and Rand, 1969; McLellan and Taylor, 1982; Moorbath, 1977; Moorbath and Taylor, 1981; Veizer and Jansen, 1979). The favored interpretation at that time was that the continental crust, the source of most of the dated samples, grew during a small number of short, intense pulses (Nelson and DePaolo, 1985; Reymer and Schubert, 1986).

At first, when the total number of age dates was small and the samples came from only a few localities, the possibility remained that the pattern of peaks and troughs was an artifact of biased or incomplete sampling of a few localities, and that the recorded distribution was not representative of the continental crust as a whole. It was thought that as

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rocks from unsampled continents were dated, and as the precision and accuracy of dating methods improved, the peaks would disappear and the troughs would be filled. This has not happened. In the most recent compilations (Condie and Aster, 2010; Condie et al., 2009), which include the ages of crustal rocks from all continents, the peaks persist. Furthermore, the same peaks are present in the spectra of ages of detrital zircons from large rivers, which sample large parts of the continent in a relatively unbiased manner that should not favor rocks of any particular age period (Bodet and Scharer, 2000; Campbell et al., 2005; Goldstein et al., 1997; Iizuka et al., 2010; Rino et al., 2004; Wang et al., 2009).

The peaks are now interpreted in two different ways. One school relates them to episodic convection of the mantle which led to short spurts of accelerated crustal growth, separated by periods of inactivity (Condie, 1998; Moorbath and Taylor, 1981; Reymer and Schubert, 1986; Stein and Hofmann, 1994). The pulses are linked to hot "superplumes" from the deep mantle (e.g., Condie, 1998; Isley and Abbott, 1999), to return mantle flow triggered by slab avalanches (e.g., Condie, 2004; Davies, 1995; Stein and Hofmann, 1994), or to periods of accelerated plate motion and subduction (e.g., O'Neill et al., 2007). The second school correlates the peaks to periods of supercontinent assembly, a manifestation of the global plate tectonic system that itself strongly influences mantle convection (Campbell and Allen, 2008; Condie and Aster, 2010; Gurnis, 1988; Hawkesworth et al., 2009, 2010; Kemp et al., 2006; Maruyama et al., 2006). In the latter interpretation, the peaks do not correspond to pulses of true crustal growth but to periods of enhanced preservation of continental crust.

In this paper we first outline the evidence that the peaks are real and not an artifact of incomplete or biased sampling, and we discuss the "anatomy" of the major peaks. This analysis leads us to conclude that the peaks do indeed correspond to periods of accelerated crustal growth. We then use the results of analog modeling experiments to develop a model of episodic mantle convention and pulsed growth of the continental crust.

1.1. The ages of Precambrian rocks

Two main sources document the pattern of ages of rocks of the continental crust. The first is the compilations of radiometric ages of samples from outcrops of the granitic rocks that form a major part of the continental crust; the second is the ages of detrital zircons in sediments transported by modern rivers. The most reliable and complete data are U–Pb zircon ages, but valuable and complementary information comes from Sm–Nd and Lu–Hf isotopic analyses of whole rock samples and zircons, respectively. Most of this information has been compiled and interpreted by Kent Condie in various papers and books that he and his co-workers have published over the past decade (e.g., Condie, 1994a, 1998, 2004; Condie and Aster, 2010; Condie et al., 2009). We cannot improve on these compilations and are largely in agreement with his presentation of the results, which we reproduce in Figs. 1–2. However, as will become evident in later sections, our interpretation of these data is very different to his.

A key diagram is Condie and Aster's (2010) compilation of U–Pb zircon ages of orogenic granitoids and detrital zircons (Fig. 1). This diagram, and others of a similar nature, display 5–7 prominent peaks separated by intervals in which ages are far less common. The peaks are present, though not with exactly the same relative magnitude and position, in compilations of ages of both orogenic granites and detrital zircons. Condie and Aster (2010) identify five peaks, at 2700, 1870, 1000, 600 and 300 Ma. To these can be added smaller but distinct peaks at about 2500 and 2100 Ma. There is a widespread agreement on the position of the 2700 Ma peak, but the younger peaks are commonly placed at various positions within the intervals 1.9–1.8 Ga and 1.1–1.0 Ga.

The largest and most conspicuous peak, at 2.7 Ga, is unique. It is by far the largest and it registers a global event that affected rocks in all

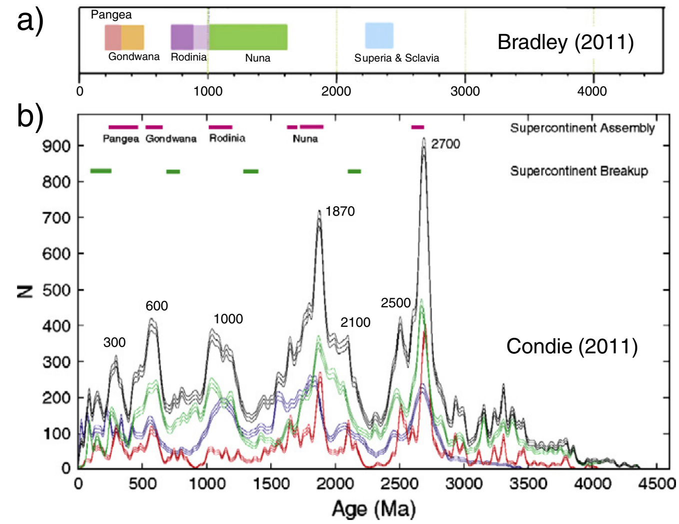

Fig. 1. (a) Distribution over the past 4.5 Ga of U/Pb zircon ages in detrital zircons (blue, black and green spectra) and orogenic granitoids (red spectrum). Shown in the upper part of the diagram are the estimated times of assembly and breakup of supercontinents (from Condie, 2011). (b) An alternative interpretation of the life-cycles of supercontinents, from Bradley (2011).

the continents (Condie, 1998; McCulloch and Wasserburg, 1978; Reymer and Schubert, 1986; Stein and Hofmann, 1994). It corresponds to the time of formation of vast swaths of "juvenile" continental crust; i.e., crust that segregated rapidly from the mantle without significant involvement of older crustal material. Examples include large granite–greenstone belts; i.e., regions of mafic–ultramafic volcanic rocks and granitoids, in the southern Superior and Hearne Provinces of Canada (Card, 1990), throughout Zimbabwe (Bickle and Nisbet, 1993), in Finland (Martin et al., 1983), and in parts of Brazil and Siberia (Puchtel et al., 1993) (Table 1). In many of these regions, the rocks appear to have been emplaced in an oceanic setting remote from older continental crust (Kimura et al., 1993); in others, the rocks erupted through older continental crust, as in Zimbabwe (Blenkinsop et al., 1993; Nisbet et al., 1993) and the eastern Yilgarn of Australia (Hill et al., 1992; Myers and Swagers, 1997). The continental flood basalts of the Fortescue (Australia) and Ventersdorp (South Africa) also erupted during this period (Nelson et al., 1992). In regions of older

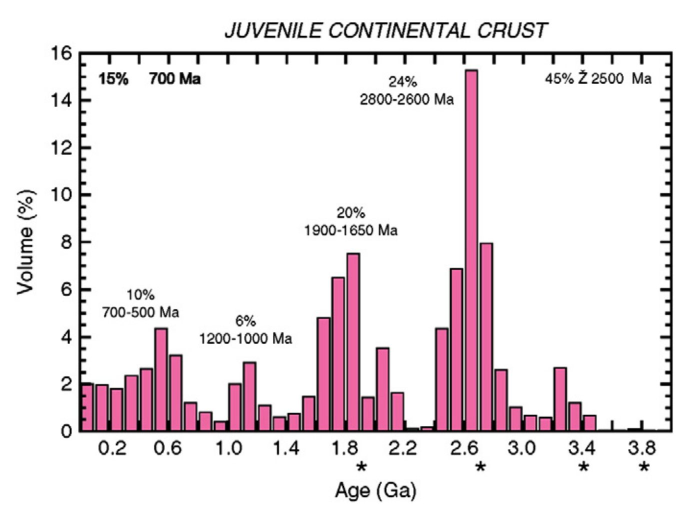

Fig. 2. Distribution of the ages of juvenile granitoids; i.e., samples whose Nd model ages are similar to the U–Pb zircon age indicating that the source material was extracted rapidly from the mantle.
From Condie (2011).