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Raising the continental crust

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ABSTRACT

The changes that occur at the boundary between the Archean and Proterozoic eons are arguably the most fundamental to affect the evolution of Earth's continental crust. The principal component of Archean continental crust is Granite–Greenstone Terranes (GGTs), with granites always dominant. The greenstones consist of a lower sequence of submarine komatiites and basalts, which erupted onto a pre-existing Tonalite–Trondhjemite–Granodiorite (TTG) crust. These basaltic rocks pass upwards initially into evolved volcanic rocks, such as andesites and dacites and, subsequently, into reworked felsic pyroclastic material and immature sediments. This transition coincides with widespread emplacement of granitoids, which stabilised (cratonised) the continental crust. Proterozoic supra-crustal rocks, on the other hand, are dominated by extensive flat-lying platform sequences of mature sediments, which were deposited on stable cratonic basements, with basaltic rocks appreciably less abundant.

The siliceous TTGs cannot be produced by direct melting of the mantle, with most hypotheses for their origin requiring them to be underlain by a complimentary dense amphibole–garnet–pyroxenite root, which we suggest acted as ballast to the early continents. Ubiquitous continental pillow basalts in Archean lower greenstone sequences require the early continental crust to have been sub-marine, whereas the appearance of abundant clastic sediments, at higher stratigraphic levels, shows that it had emerged above sea level by the time of sedimentation. We hypothesise that the production of komatiites and associated basalts, the rise of the continental crust, widespread melting of the continental crust, the onset of sedimentation and subsequent cratonisation form a continuum that is the direct result of removal of the continent's dense amphibole–garnet–pyroxenite roots, triggered at a regional scale by the arrival of a mantle plume at the base of the lithosphere. Our idealised calculations suggest that the removal of 40 km of the amphibole–garnet–pyroxenite root would have raised the average level of the continental crust by ∼3 km. The emergence of the continental crust was an essential precursor to the rise of oxygen, which started some 200 Myr later.

1. Introduction

The near ubiquitous occurrence of pillow basalts in Archean greenstone sequences, which erupted onto pre-existing continental crust, suggests that the early Archean continental crust was largely below sea level (e.g. Windley, 1977; Campbell and Jarvis, 1984; Arndt, 1999; Kump and Barley, 2007; Flament et al., 2008). Towards the end of the Archean, widespread clastic sediments appeared and, subsequently, dominated the supra-crustal sequences in the early Proterozoic (e.g. Sutton, 1971; Windley, 1977; Campbell and Jarvis, 1984). This sequence of events requires the rise of the continental crust towards the end of the Archean, thus exposing it, for the first time, to continental-scale sub-aerial erosion. This is one of the most fundamental events in Earth's evolution. Without it, there would be no sediments, hydrocarbons, or habitat for land based animals, including humans. Life on Earth would be confined to the ocean and, even there, it would be devoid of animals. Oxygen, which is essential for animal life, is the product of photosynthesis, which requires several critical nutrients, including Fe and P: the principal supply of these elements to the oceans is through the erosion of continents (e.g. Falkowski, 1997; Canfield, 2005; Squire et al., 2006; Lyons et al., 2014).

The emergence of the continental crust towards the end of the Archean has previously been attributed to secular cooling of the mantle (Vlaar, 2000) or to cooling of continental crust and mantle, leading to a stronger crust and lithosphere, which ultimately is capable of supporting mountains that rise above sea level (e.g. Flament et al., 2008, 2011). An alternative suggestion, by Arndt (1999), is that Archean sea level was high due to the presence of extensive high standing oceanic ridges and plateaus. Each of these hypotheses predicts the emergence of the continental crust

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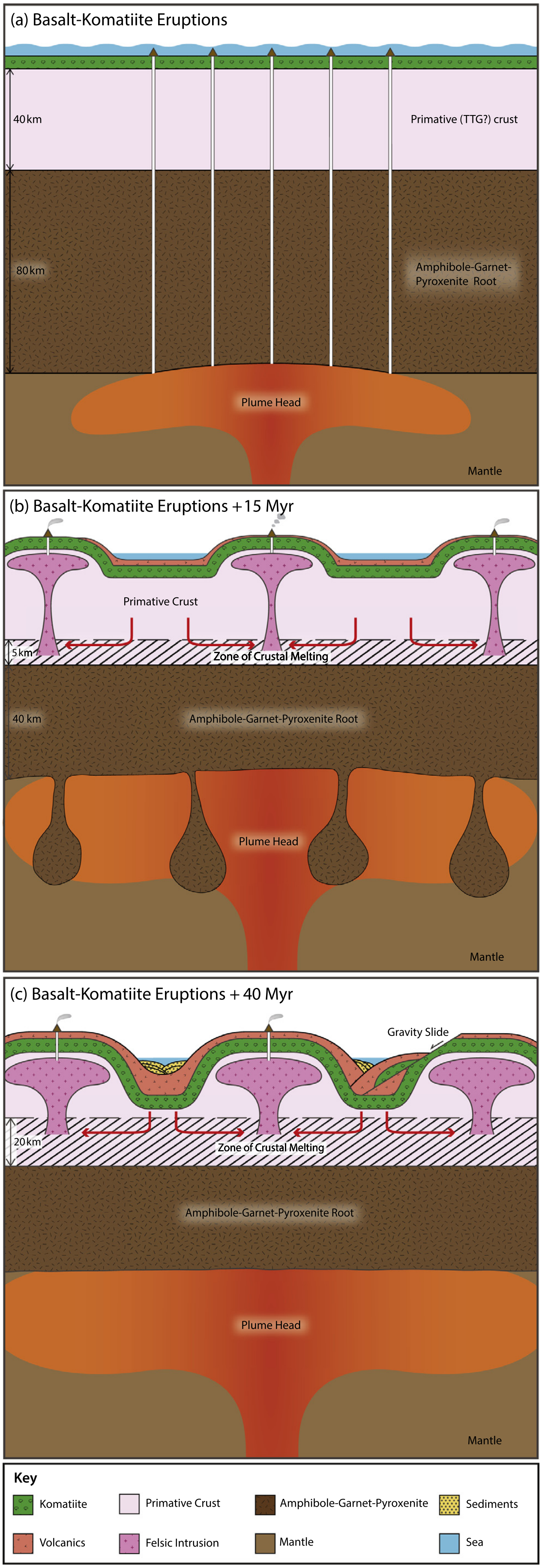

to be globally synchronous and gradational. Contrary to the predictions of these hypotheses we show here that the emergence of the continental crust was rapid, occurred at a specific time in the evolution of continents and that its timing varied from continent to continent, with by far the most important events occurring at ca. 2.65 Ga.

The andesitic (intermediate) bulk composition of Earth's preserved continental crust cannot be the simple product of mantle melting (e.g. Arculus, 1981; Rudnick, 1995). Most hypotheses for its origin require it to have been underlain by a complimentary dense amphibole–garnet–pyroxenite layer that was up to twice as thick as the preserved crust (e.g. Kay and Kay, 1985; Jagoutz and Schmidt, 2013). We will argue that these crustal 'roots' acted as ballast to the early continents, holding them below sea level, and that the rise of continents resulted from their removal back into the mantle.

The observational evidence supporting our hypothesis is summarised in the following sections. Section 2 summarises the stratigraphy of typical Archean Granite Greenstone Terranes (GGT). Section 3 describes how the geochemistry of the Archean granitoids in any given GGT varies with time, and the difference between Archean and Proterozoic granitoids, whilst Section 4 presents the evidence for the bulk of the pre-cratonisation continental crust being below sea level. In Section 5, we cover the emergence of the continental crust, which led to Proterozoic flat-lying sediments replacing deformed Archean komatiite–basalt sequences as the dominant supracrustal rocks. Finally, Section 6 presents our hypothesis, which is illustrated in Fig. 1. We argue that arrival of the mantle plumes, which gave rise to widespread komatiitic–basaltic volcanism (Campbell and Hill, 1988), triggered a sequence of events that included removal of the crustal root, extensive melting of the lower crust, regional uplift, sedimentation and cratonisation.

2. Granite Greenstone Terranes (GGTs)

2.1. The greenstones of the Kalgoorlie–Kambalda region, Yilgarn craton

We start by considering the rise of the continental crust in the well-studied Kalgoorlie–Kambalda region of the Norseman–Wiluna greenstone belt, Yilgarn craton, Western Australia (Fig. 2a). At the base of the accessible sequence is the Lunnon basalt (ca. 2.714 Ga), which is overlain, in turn, by the Kambalda Komatiites (2.705 Ga), the Devon Consols Basalts and the Paringa Basalts at ca. 2.692 Ga (Squire et al., 2010 and references therein). Thin fine-grained sedimentary layers, which are dominated by carbonaceous shales, separate the named basaltic stratigraphic units. Pillows are common in all basaltic units and this, together with the fine-grained nature of the interflow sedimentary rocks, indicates deep sub-marine deposition.

The Devon Consols and Paringa Basalts have high SiO_2, negative Nb anomalies, low ε_{Nd} and are LREE enriched, which are interpreted to be characteristics inherited from the continental

Fig. 1. Cartoon illustrating the development of a GGT: (a) a mantle plume head rises below a primitive (TTG), sub-marine continental crust, which is underlain by an amphibole–garnet–pyroxenite root. Decompression melting of the ascending plume leads to the eruption of komatiites and basalts; (b) the arrival of a plume head triggers thinning of the dense amphibole–garnet–pyroxenite root, which drips through the hot underlying plume. Heat conducted from the plume head begins to melt the base of the crust, producing felsic magma that intrudes into the upper crust to produce granitoid plutons and felsic volcanism; (c) as heat conducted from the plume reaches higher levels in the crust, the zone of crustal melting expands, which leads to the production of additional melt and melting at higher levels. Areas of upper crust that have been intruded by granite become topographic highs, whereas the greenstones become topographic lows, due to the withdrawal of granitic melt from the lower crust between the rising felsic plutons. Sedimentary material is eroded from the topographic highs and deposited in the greenstone synclines.