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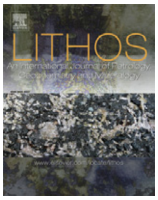

Review paper

The world turns over: Hadean–Archean crust–mantle evolution

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ABSTRACT

We integrate an updated worldwide compilation of U/Pb, Hf-isotope and trace-element data on zircon, and Re–Os model ages on sulfides and alloys in mantle-derived rocks and xenocrysts, to examine patterns of crustal evolution and crust–mantle interaction from 4.5 Ga to 2.4 Ga ago. The data suggest that during the period from 4.5 Ga to ca 3.4 Ga, Earth's crust was essentially stagnant and dominantly mafic in composition. Zircon crystallized mainly from intermediate melts, probably generated both by magmatic differentiation and by impact melting. This quiescent state was broken by pulses of juvenile magmatic activity at ca 4.2 Ga, 3.8 Ga and 3.3–3.4 Ga, which may represent mantle overturns or plume episodes. Between these pulses, there is evidence of reworking and resetting of U–Pb ages (by impact?) but no further generation of new juvenile crust. There is no evidence of plate-tectonic activity, as described for the Phanerozoic Earth, before ca 3.4 Ga, and previous modelling studies indicate that the early Earth may have been characterised by an episodic-overturn, or even stagnant-lid, regime. New thermodynamic modelling confirms that an initially hot Earth could have a stagnant lid for ca 300 Ma, and then would experience a series of massive overturns at intervals on the order of 150 Ma until the end of the EoArchean. The subcontinental lithospheric mantle (SCLM) sampled on Earth today did not exist before ca 3.5 Ga. A lull in crustal production around 3.0 Ga coincides with the rapid buildup of a highly depleted, buoyant SCLM, which peaked around 2.7–2.8 Ga; this pattern is consistent with one or more major mantle overturns. The generation of continental crust peaked later in two main pulses at ca 2.75 Ga and 2.5 Ga; the latter episode was larger and had a greater juvenile component. The age/Hf-isotope patterns of the crust generated from 3.0 to 2.4 Ga are similar to those in the internal orogens of the Gondwana supercontinent, and imply the existence of plate tectonics related to the assembly of the Kenorland (ca 2.5 Ga) supercontinent. There is a clear link in these data between the generation of the SCLM and the emergence of modern plate tectonics; we consider this link to be causal, as well as temporal. The production of both crust and SCLM declined toward a marked low point by ca 2.4 Ga. The data naturally divide the Archean into three periods: PaleoArchean (4.0–3.6 Ga), MesoArchean (3.6–3.0 Ga) and NeoArchean (3.0–2.4 Ga); we suggest that this scheme could usefully replace the current four-fold division of the Archean.

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1. Introduction

The state of the crust–mantle system during the Hadean period is still unclear; the only recognised relics of the Hadean crust are a few zircons, with ages mostly 4.1–4.3 Ga, recovered from much younger rocks (Fig. 1). However, even these traces have been the subject of several different tectonic interpretations, ranging from the modern to the cataclysmic. Large populations of zircons, in younger sediments or datable rocks, only begin to appear well into EoArchean time, from about 3.7 Ga. However, the oldest dated rocks from the subcontinental lithospheric mantle (SCLM) are only about 3.5 Ga old (Griffin et al., 2009), and it is not clear on what type of substrate these earliest crustal rocks might have rested.

The conventional subdivision of the Archean into EoArchean, PaleoArchean, MesoArchean and NeoArchean is shown in Fig. 1. The transition from the Hadean to the EoArchean is conventionally set at 4.0 Ga. Ideally such boundaries should be defined by a geologically important (or at least definable) event; in this case none have been identified, although dynamic modelling (see O'Neill et al., 2007, in press) offers some insights.

In this report we examine the zircon record (ages, Hf and O isotopes, trace elements) using a database of >6500 analyses with ages >2.0 Ga, and the Os-isotope data derived from both the in situ analysis of sulfides and Os–Ir phases in peridotite xenoliths, and whole-rock Re–Os analysis of such xenoliths. We couple our observations with dynamic modelling, to propose mechanisms for the evolution of the crust–mantle system through the Hadean and Archean periods. Finally, we also suggest a new subdivision of the earliest part of the geological time scale, based on currently recognisable patterns in the data, inferred to mark significant tectonic events from 4.5 Ga to 2.4 Ga.

2. Methods and databases

2.1. Zircon data

Data on zircon ages and Hf-isotope ratios are taken from the database described by Belousova et al. (2010), supplemented by more recently published analyses (Geng et al., 2012; Naeraa et al., 2012) and our unpublished data. This database ($n = 6699$) is built largely on detrital-zircon suites, but also includes many zircons separated from igneous rocks. All analytical data were recalculated using the same parameters. For the calculation of ε_{Hf}, we have used the chondritic values of Bouvier et al. (2008) and the decay constant (1.865×10^{-11} yr^{-1}) of Scherer et al. (2001). The Depleted Mantle (DM) curve (Fig. 1) is that defined by Griffin et al. (2000; $^{176}Lu/^{177}Hf = 0.0384$).

To examine the distribution of “juvenile” Hf-isotope ratios, we have taken all data within a band corresponding to ±0.75% around the Depleted Mantle curve (Belousova et al., 2010; Fig. 1). Such “juvenile” geochemical signatures indicate that the source rock for the zircon was derived directly from the convecting mantle, or had only a very short crustal residence time after formation from mantle-derived magma. The described procedure reduces the exaggeration of the younger peaks that would be produced by the Expanding difference through time between the Chondritic Earth ($\varepsilon_{Hf} = 0$) line and the Depleted Mantle (Fig. 1) where trace-element data are available on single zircon grains, we have classified them in terms of rock type, using a modified version of the discrimination scheme outlined by Belousova et al. (2002). Where zircons are extracted from igneous rocks, the composition of those rocks is recorded in the database.

Oxygen-isotope data can, like Hf-isotope data, allow an evaluation of the juvenile vs recycled nature of the source region of the zircon's host magma. In nearly all cases, the two isotopic systems are in agreement. O-isotope data are available for relatively few zircons in the dataset; these are discussed where relevant. Analyses of Th/U ratios have been used to exclude clearly metamorphic zircons, and thus the ages reported here are considered to reflect the timing of igneous crystallisation, except as discussed below.

2.2. Re–Os data

Re–Os data on sulfide and Os–Ir phases have been obtained by in situ LA-MC-ICPMS analysis, essentially as described by Pearson et al. (2002) and Griffin et al. (2004a, 2004b). The database includes published analyses from kimberlite-borne xenoliths in S. Africa, Siberia and the Slave Craton (Aulbach et al., 2004, 2009; Griffin et al., 2002, 2004a, 2004b, 2011, 2012; Spetsius et al., 2002) as well as new data on sulfides included in olivine xenocrysts from the Udachnaya kimberlite (Yakutia) and sulfides included in chrome-pyrope garnet xenocrysts from the Mir kimberlite (Yakutia). We have added our unpublished analyses of sulfides in xenoliths from other localities in N. America and Asia. An overview of whole-rock Re–Os analyses of mantle-derived peridotite xenoliths is given by Carlson et al. (2005).

2.3. Numerical modelling

To assess the potential behaviour of the plate-mantle system under evolving Hadean mantle conditions, we employ the visco-plastic mantle convection code *Underworld* (Moresi et al. 2007). We solve the standard convection equations for conservation of mass, momentum, and energy under the Boussinesq approximation, with varying Rayleigh number (i.e. varying basal temperatures) and internal heating. The mantle itself is a modelled as a viscoplastic fluid, with an extremely temperature-dependent viscosity that varies, using a Frank-Kamenetski approximation, from 1 at the base to 3×10^4 at the cold upper boundary (see O'Neill et al., in press, for details). Deformation in the near-surface is accommodated by plastic yield using a Byerlee criterion for yield stress (scaled so the cohesion is 1×10^5, and the depth-coefficient is 1×10^7 for a Rayleigh number of 1×10^7; see Moresi and Solomatov (1998) for details). We do not consider phase transitions or depth-dependent properties in these models. All our units are non-dimensionalised