

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 ($1.865 \times 10^{-11} \text{ yr}^{-1}$) of Scherer et al. (2001). The Depleted Mantle (DM) curve (Fig. 1) is that defined by Griffin et al. (2000; $^{176}\text{Lu}/^{177}\text{Hf} = 0.0384$).

To examine the distribution of “juvenile” Hf-isotope ratios, we have taken all data within a band corresponding to $\pm 0.75\%$ 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 ($\varepsilon_{\text{Hf}} = 0$) 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-pyropo 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 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

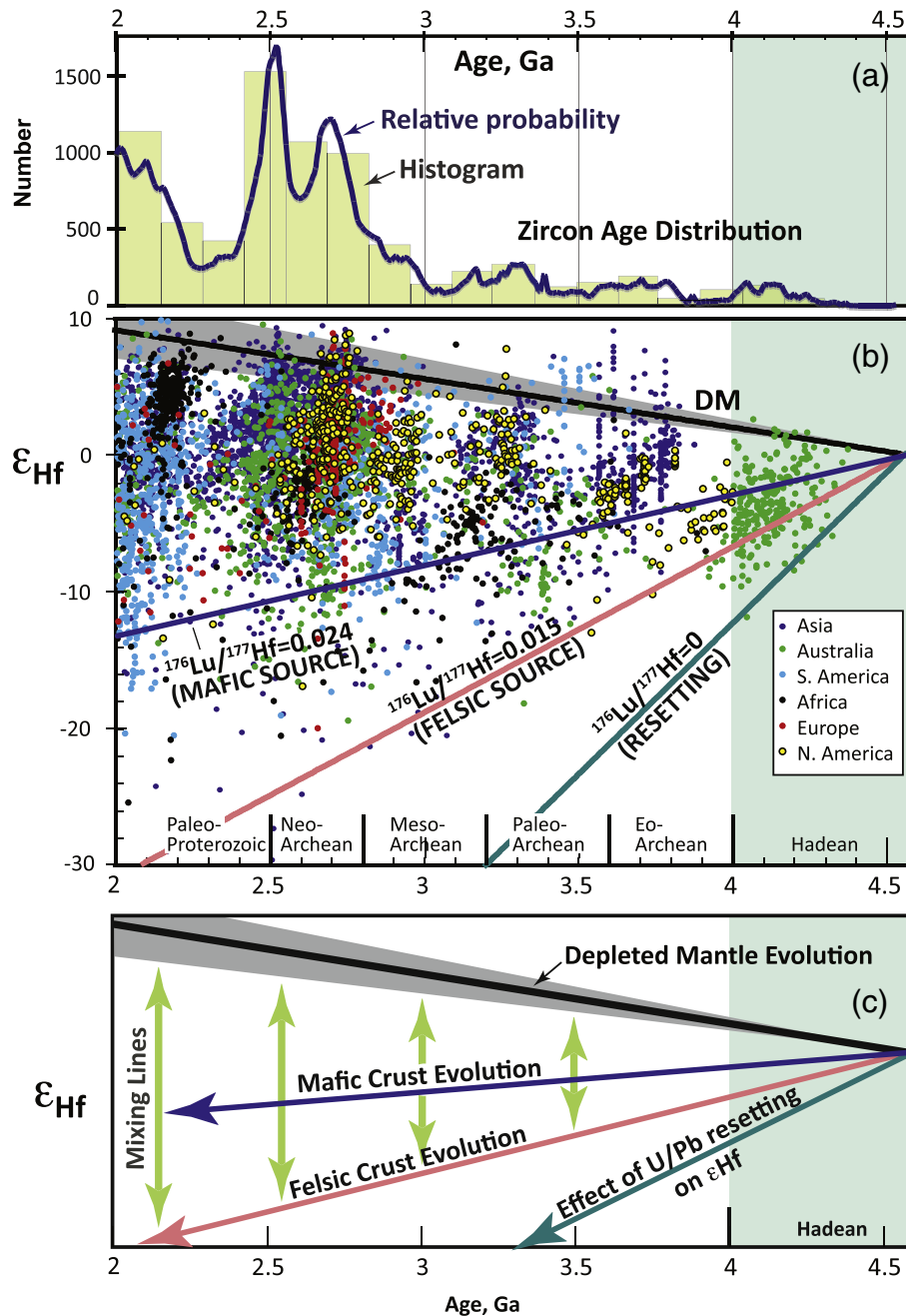


Fig. 1. ϵ_{Hf} vs age for zircons worldwide, divided by region. The database ($n = 6699$) is attached as Appendix A1; it builds on the data of Belousova et al. (2010) updated with >2000 analyses published, and/or produced in our laboratories, after 2009. The conventional subdivision of the Hadean and Archean is shown along the X axis. (a) Zircon age distribution shown as a histogram and a cumulative-probability curve. (b) Distribution of Hf-isotope data. The “juvenile band”, defined as $\pm 0.75\%$ of the ϵ_{Hf} of the Depleted Mantle line at any time, is shown as a grey envelope. Evolution lines from 4.5 Ga are shown for reservoirs corresponding to typical mafic rocks ($^{176}\text{Lu}/^{177}\text{Hf} = 0.024$), the average continental crust ($^{176}\text{Lu}/^{177}\text{Hf} = 0.015$), and zircons, approximated by $^{176}\text{Lu}/^{177}\text{Hf} = 0$. (c) shows these evolution lines and a simplified explanation (see text).

before being incorporated into the model, in the manner of Moresi and Solomatov (1998).

The initial condition for the simulation is from an equilibrated model with an internal heat generation of $Q = 8$ (non-dimensional, present day $Q \sim 1$), and a basal temperature of $T_{\text{base}} = 1.2$ (present day $T_{\text{base}} \sim 1$). The model initially is in a hot stagnant-lid regime as a result of these properties, which are meant to represent the hot Hadean mantle with contributions from high radioactive heat production, a hot core, and significant primordial heat. We then allow the internal heat generation and basal temperatures to decay through time. While short-lived radioactive isotopes, like ^{26}Al , may contribute to the thermal state of the initial model, they decay too rapidly to be incorporated into long-term evolution models, and we solely consider the decay of ^{40}K , ^{238}U , ^{235}U , and ^{232}Th . We

also adopt a simple core-evolution model based on the results of Nimmo et al. (2004). If we assume present-day temperatures at the core-mantle boundary are around $T_{\text{base}} \sim 1$, then according to Nimmo et al. (2004), at the beginning of the Hadean they would have been around $T_{\text{base}} \sim 1.2$. The temperature evolution of the core is pseudo-linear in these models, and we project this evolution forward along this trend.

3. Geochemical data

3.1. Zircon data: U–Pb ages, Hf isotopes, trace elements

The full zircon dataset ($n = 6699$), coded by geographical region, is shown in Fig. 1, and the numbers of zircons with $\epsilon_{\text{Hf}} > 0$ in each time

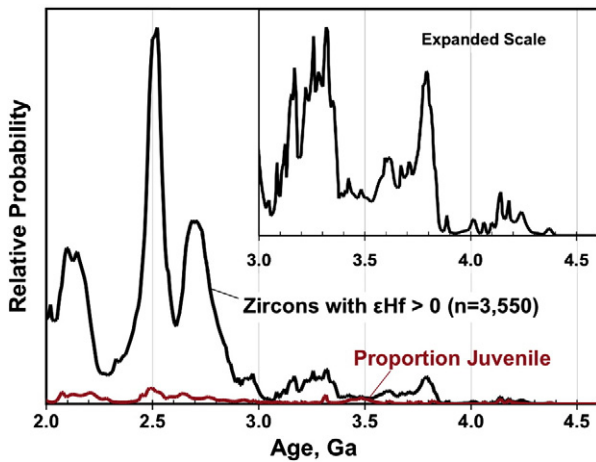


Fig. 2. Cumulate-probability curve and age histogram for all zircons with ϵ_{Hf} falling within 0.75% of the Depleted Mantle curve in Fig. 1. Inset uses an expanded scale to show detail in the oldest datasets.

slice are shown in Fig. 2. The cumulative-probability plot of Fig. 2 shows a small peak around 4.2 Ga, a larger one at ca 3.8–3.6 Ga, another at ca 3.4–3.1 Ga, and then a buildup to a major peak at 2.75 Ga, which is closely followed by a final sharp, larger peak at 2.5 Ga. We will describe the nature of each “event”, as revealed by the isotopic data, in turn; speculations on mechanisms will be deferred to the Discussion.

3.1.1. Hadean zircons

The Hadean zircon record is dominated by material from Western Australia, but has recently been supplemented by a few data from Asia and N. America (Fig. 1). The most striking aspect of this record is the relative paucity of juvenile signatures; the peak at 4.2–4.1 Ga in Fig. 2 represents ca 5% of the zircons in that age band, and none of the oldest zircons (4.45–4.25 Ga) has significantly suprachondritic Hf-isotopes. This may suggest that the Depleted Mantle model is not relevant to the earliest Earth, prior to ca 4.25 Ga, but the data are too limited for firm conclusions. The very low ϵ_{Hf} of many of the oldest zircons might suggest the reworking of older material, but this would require that the older reservoir had evolved with $\text{Lu}/\text{Hf} = 0$ since 4.55 Ga, which seems unlikely. Alternative explanations are that these zircons crystallized from magmas derived from a non-chondritic reservoir, or that their ages have been reset by later metamorphic events, which left the Hf-isotope signatures unchanged (see Discussion below).

Many of the younger Hadean zircons (Fig. 3) lie in a band extending downward from the DM line. This trend, which extends down to ages as young as 3.9 Ga, could be interpreted as the result of reworking of the juvenile material represented by the 4.2-Ga “peak”. This would require that the 4.2 Ga material was more felsic ($^{176}\text{Lu}/^{177}\text{Hf} \approx 0.01$) than the present-day mean continental crust ($^{176}\text{Lu}/^{177}\text{Hf} \approx 0.015$; Griffin et al., 2000). Grains falling in the lower part of the band would require even more felsic sources.

Cavosie et al. (2005) give trace-element data for 40 zircon grains (3.8–4.4 Ga) from Jack Hills; 75% classify as derived from intermediate rocks (<65% SiO_2). Seven dated grains (all with ages >4.1 Ga) classify as derived from mafic rocks, and three grains, all with ages <4.1 Ga, classify as derived from felsic granitoids (>70% SiO_2). Inclusions of quartz, feldspar and muscovite in the zircons have been used to suggest their derivation from intermediate to felsic rocks, although later studies (Rasmussen et al., 2011) suggest that many such inclusions are metamorphic in origin. A few zircons from N. America and Asia, with ages near 4.0 Ga, come from felsic rocks (Geng et al., 2012; Pietranik et al., 2008).

3.1.2. Early- to mid-Archean zircons

The first major peak in juvenile input occurs at 3.8 Ga, followed by a series of minor peaks to ca 3.5 Ga (Fig. 2); this is defined by data from Asia and N. America (including Greenland) with a few from Africa

(Fig. 3). While most of the zircons with ages 3.85–3.75 Ga have $\epsilon_{\text{Hf}} > 0$, consistent with derivation from a Depleted Mantle source, very few of the younger ones in this age band have $\epsilon_{\text{Hf}} > 0$ (Fig. 3). Most of the zircons with ages 3.7–3.4 Ga have low ϵ_{Hf} , lying in a band with a slope corresponding to $^{176}\text{Lu}/^{177}\text{Hf} \approx 0.01$; this suggests that their host magmas could be derived by reworking of the 3.8 Ga juvenile material. Naeraa et al. (2012) have argued that the data for a set of zircons from W. Greenland fit a shallower trend consistent with derivation from a “TTG crust” ($^{187}\text{Lu}/^{188}\text{Hf} = 0.024$) corresponding to the 3.8 Ga juvenile material from the same area. On a larger scale, the N. America dataset in Fig. 3a suggests a more felsic crust, or at least remelting of the more felsic portions. Data from other continents scatter more widely, but the mean data from each continent are consistent with those from N. America, suggesting a global process.

The next evidence of juvenile magmatic activity is the peak at 3.35–3.15 Ga (Fig. 2). This is represented by material mainly from Asia, N. America and S. America (Fig. 4a). Unlike the earlier peaks, many of the zircons with juvenile Hf-isotope signatures appear to be derived from mafic and metamorphic rocks (Fig. 4b). Many zircons from this time range fall along a trend extending to progressively lower ϵ_{Hf} , possibly corresponding to the progressive reworking of reservoirs 3.3–3.35 Ga old with $^{176}\text{Lu}/^{177}\text{Hf} \approx 0.01$. Interestingly, most of the zircons in the lower part of this band are detrital (from metasediments, no trace elements) whereas most of those with identified host magmas lie in the upper part of the band. The proportion of zircons from granitoid rocks appears to increase further in this time slice.

In this age range, there are few of the older zircons with ϵ_{Hf} near the $\text{Lu}/\text{Hf} = 0$ line. However, there is a significant population with very low ϵ_{Hf} , which may be derived from remelting of the ca 3.8 Ga population.

3.1.3. NeoArchean zircons

The NeoArchean zircon record is marked by two major, sharply defined peaks at 2.75 Ga and 2.55 Ga (Fig. 2). The buildup to the older peak is marked by minor shoulders at 2.9 Ga and 2.8 Ga; only the first may be significant. The older peak is dominated by material from N and S America, Asia and Europe; the younger peak is mainly made up of zircons from Asia and Australia. However, nearly all regions have contributed material to both age peaks. The burst of magmatic activity at 2.55 Ga marks the end of the Archean as traditionally defined; the overall abundance of zircons in the database decreases markedly from ca 2.45 Ga, and zircons with juvenile Hf isotopes disappear almost entirely, marking the start of a worldwide period of quiescence (low mantle-derived magmatic activity) that lasted for about 300 Ma (Fig. 1).

The data also appear to reflect a change in the mechanisms involved in the large-scale Neo-Archean magmatism; the whole range of ϵ_{Hf} increases in the last 0.5 Ga of the Archean (Fig. 1). The age peaks at 2.75 and 2.55 Ga are also peaks of juvenile input to the crust (Fig. 2). However, while the juvenile inputs are clearly important, the record also suggests a more intense reworking of the older crust than is seen in earlier episodes, as reflected in the large proportion of zircons with $\epsilon_{\text{Hf}} < 0$ (Fig. 5). The lowest of these are consistent with derivation of their host magmas from “mafic crust” up to 4.5 Ga in age, or younger but more felsic crust (Figs. 1, 5).

Zircons from granitoid rocks feature prominently in both of the major NeoArchean magmatic episodes, but especially in the younger one; those in the younger peak generally have higher ϵ_{Hf} .

3.2. Os-isotope data

3.2.1. Sulfides and platinum group minerals

The Os budget of mantle-derived peridotites (whether sampled as massifs or xenoliths) resides in minor phases; these are typically base-metal sulfides, but in some cases, especially where the peridotites carry lenses of chromitite (e.g. Gonzalez-Jimenez et al., 2012a; Shi et al., 2007) Platinum Group Minerals (PGMs), such as Os–Ir alloys and Platinum Group Element (PGE) sulfides may be abundant (see review by Gonzalez-Jimenez et al., 2013). The samples included in the

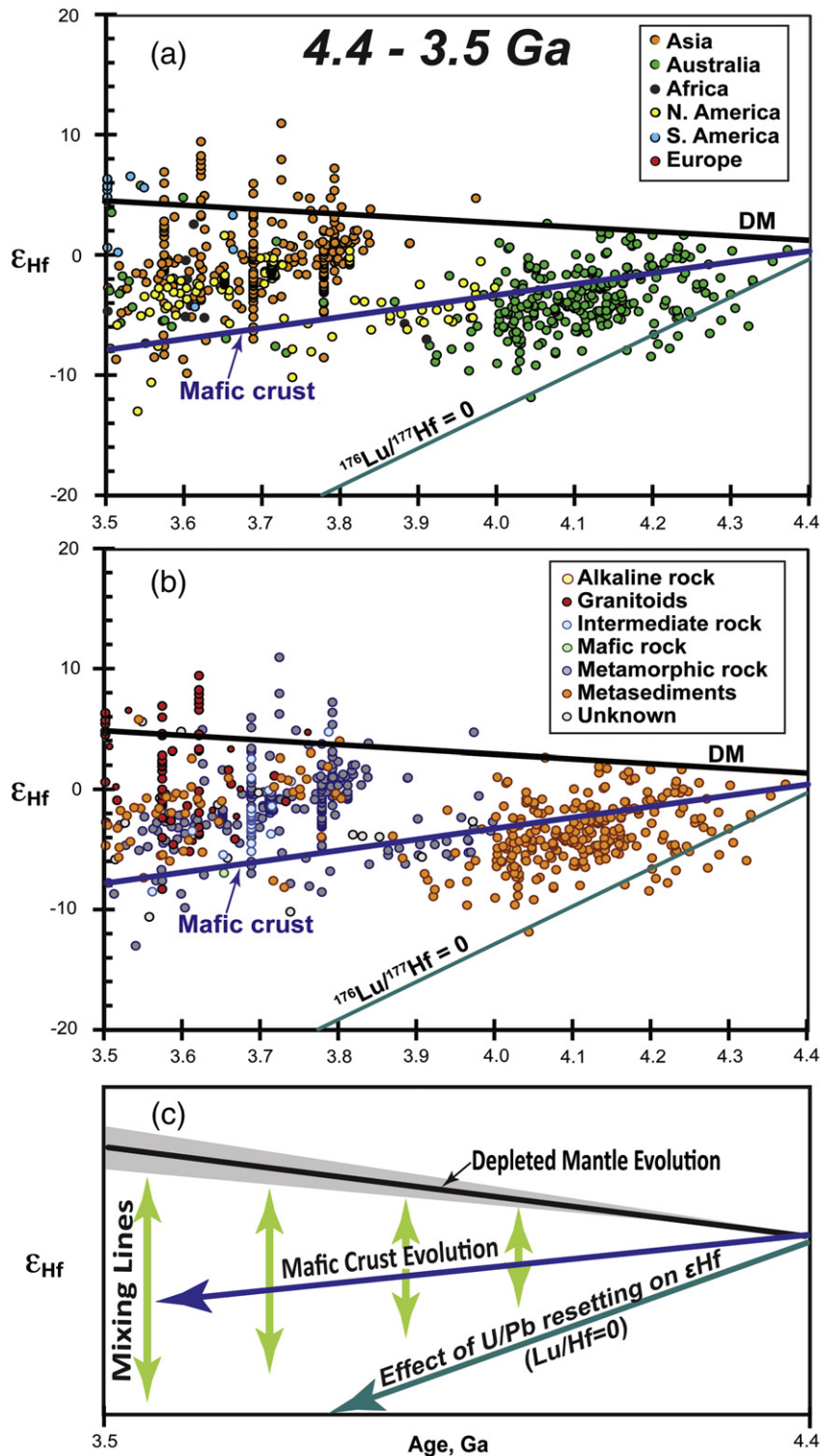


Fig. 3. ϵ_{Hf} vs age for all zircons in the age range 4.5–3.5 Ga. (a) by region; (b) by rock type, either estimated from trace-element data, or taken from the sample. The dark blue line in (b) shows the evolution of a mafic reservoirs with $^{176}\text{Lu}/^{177}\text{Hf} = 0.024$ (see text for explanation); the solid green line shows the evolution of a reservoir 4.56 Ga old, with $\text{Lu}/\text{Hf} = 0$ (i.e. ancient zircons). The “unknown” category in (b) corresponds to suites of detrital zircons with no trace-element data. (c) as from Fig. 1.

following discussion have been screened: all have very low Re/Os , and their Os -isotope values therefore are taken as recording the composition of Os in the melts or fluids that deposited them. The Re -depletion model ages (T_{RD}) calculated from individual mineral analyses can give an indication of the timing of melt depletion in their host rocks, or the timing of metasomatic activity derived from the convecting mantle (Gonzalez-Jimenez et al., 2012b; Griffin et al., 2004a, 2004b; Shi et al.,

2007). Our previous studies have shown that most peridotite xenoliths, and many massif peridotites, contain Os -bearing phases with a range of T_{RD} , reflecting a complex history of fluid-related processes (Griffin et al., 2004a, 2004b; Marchesi et al., 2010). These include both melt extraction and multiple overprinting by metasomatic fluids of different origins (O'Reilly and Griffin, 2012). While model-age peaks commonly match with events in the overlying crust, these fluid-rock interactions

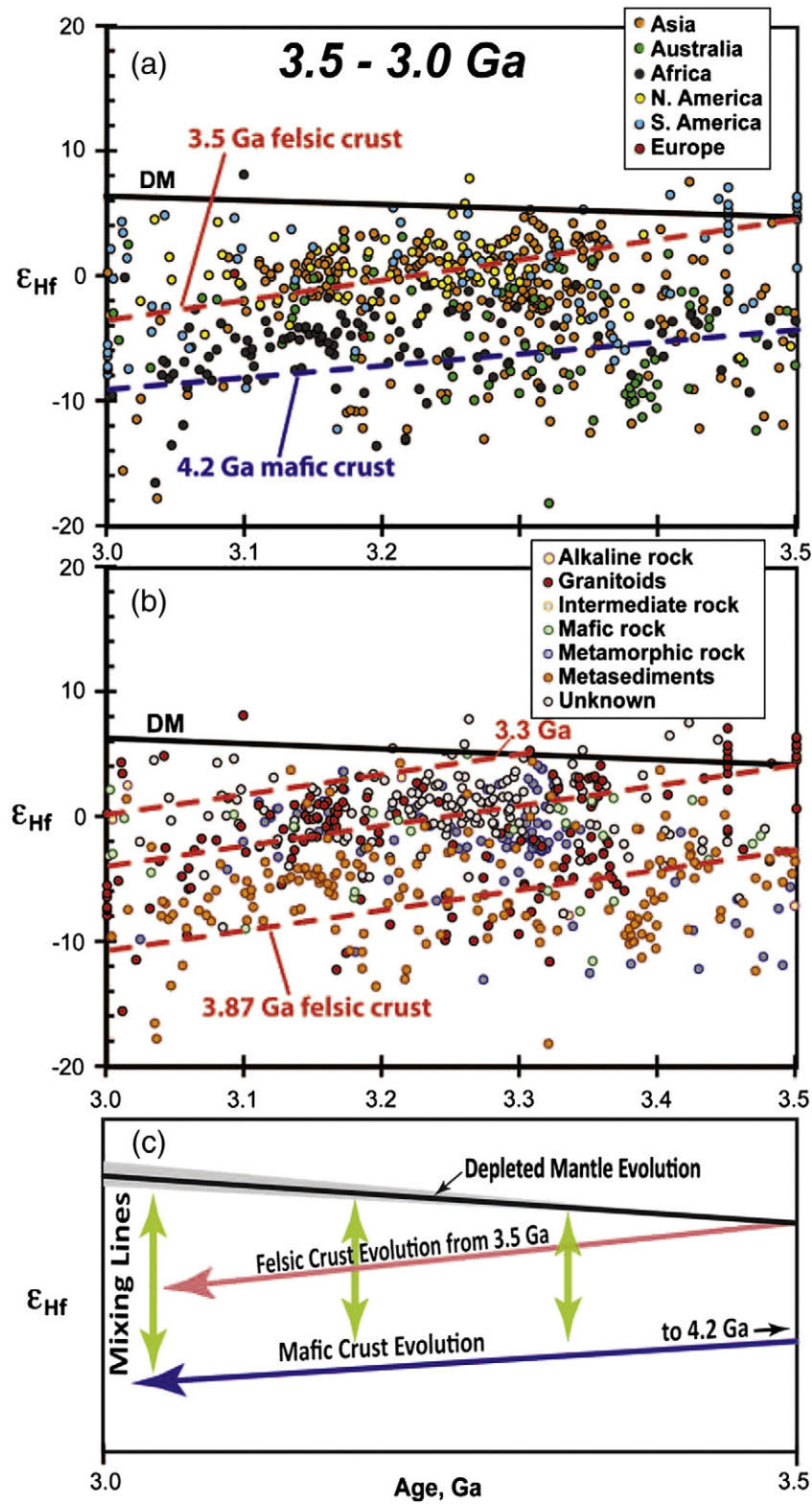


Fig. 4. ϵ_{Hf} vs age for all zircons in the age range 3.5–3.0 Ga. (a) by region; (b) by rock type, either estimated from trace-element data, or taken from the sample. The light red dashed lines in (b) show the evolution of reservoirs with $^{176}\text{Lu}/^{177}\text{Hf} = 0.01$ (see text for explanation). The “unknown” category if (b) corresponds to suites of detrital zircons with no trace-element data.

undoubtedly lead to grains of mixed origins, with model ages that do not correspond to any real event.

The full xenolith dataset is shown in Fig. 6; as noted above, it is dominated by samples from South Africa, Siberia and the Slave Craton in Canada. The most striking observation, compared with the zircon data,

is the absence of Hadean or Eo-Archean model ages; we have no evidence in the sulfide data for the existence of any SCLM for the first billion years of Earth’s history. The earliest significant peak in T_{RD} appears at 3.4–3.2 Ga, corresponding to the second major peak in T_{DM} from the zircon data (Figs. 2, 6). This is part of a buildup to the major peak in

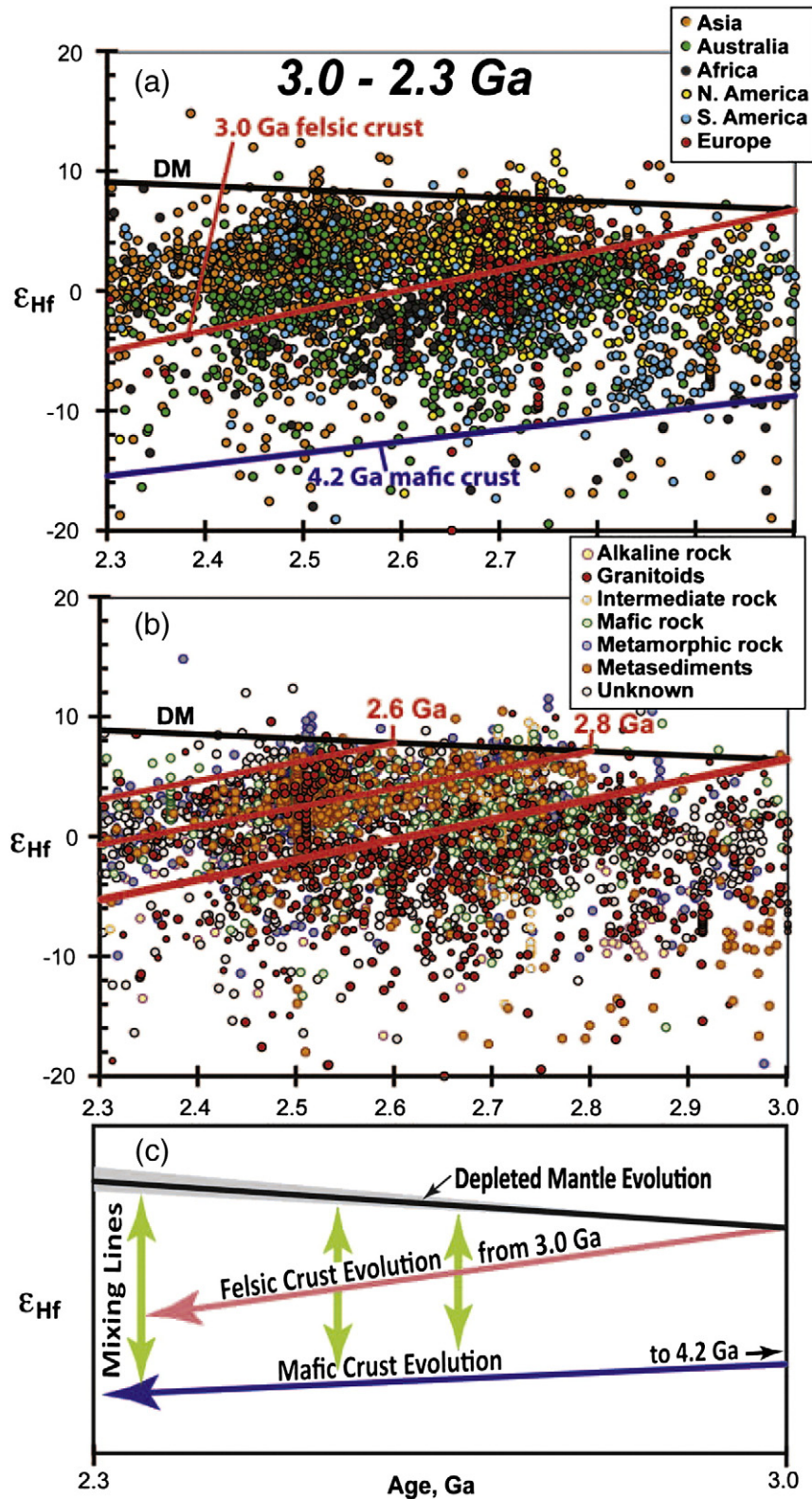


Fig. 5. ϵ_{Hf} vs age for all zircons in the age range 3.0–2.3 Ga. (a) by region; (b) by rock type, either estimated from trace-element data, or taken from the sample. The red lines show the evolution of reservoirs with $^{176}\text{Lu}/^{177}\text{Hf} = 0.01$ (see text for explanation). The “unknown” category in (b) corresponds to suites of detrital zircons with no trace-element data.

sulfide T_{RD} at ca 2.8 Ga; this peak may be mildly bimodal with sub-peaks at 2.85 Ga and 2.7 Ga, coinciding with the Neo-Archean explosion of magmatic activity shown by the zircon data. This peak drops off sharply toward younger ages, mirroring the “shutdown” in magmatic activity from ca 2.4 Ga, as shown by the zircon data.

3.2.2. Whole-rock analyses of peridotites

The T_{RD} of whole-rock samples that have experienced no metasomatism following their original melt depletion may record the timing of that depletion event. The Os-isotope compositions of any samples that have been metasomatized by (Os-bearing) melts or fluids must necessarily

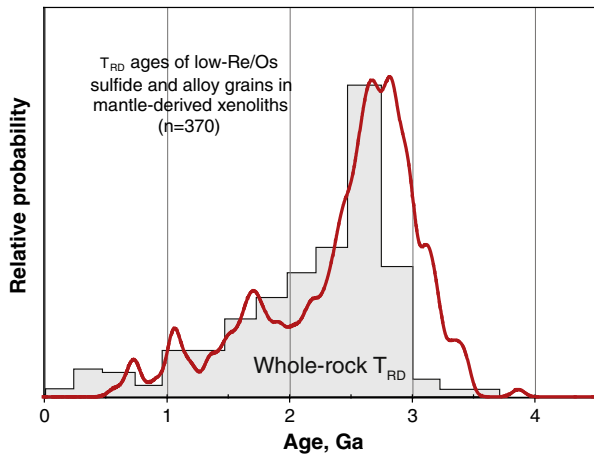


Fig. 6. Re–Os data. Red line shows relative-probability distribution of T_{RD} model ages for sulfide and alloy grains from mantle-derived xenoliths, peridotite massifs and diamonds. Grey histogram (after Carlson et al., 2005) shows distribution of whole-rock T_{RD} ages from mantle-derived peridotite xenoliths.

represent mixtures, and their T_{RD} will not be meaningful in terms of dating an event. Since all of the samples discussed here come from the subcontinental lithospheric mantle (SCLM), they provide information only on the timing of formation and modification of the SCLM, rather than the convecting mantle. A review by Carlson et al. (2005) on the geochronology of the SCLM shows only three whole-rock xenoliths (all from South Africa) that give T_{RD} ages around 3.6 Ga (Fig. 6). There is a sharp increase from 3 Ga, leading up to a pronounced peak at 2.5–2.75 Ga, mirroring the sulfide data. As with the sulfide/alloy data, there is no evidence for the existence of significant amounts of SCLM prior to 3.5 Ga. A long tail of T_{RD} ages down to ca 1 Ga probably reflects the abundance of younger sulfides in repeatedly metasomatised xenoliths (c.f. Griffin et al., 2004a, 2004b).

4. Discussion

The data presented above suggest that juvenile addition to the continental crust in the Hadean–EoArchean, as preserved in the zircon record, occurred primarily as pulses at ca 4.2 Ga, 3.8 Ga and 3.3–3.4 Ga. Between these pulses of activity, zircon appears to have crystallised primarily from intermediate melts. The zircon data suggest the surface was largely stagnant and tectonically quiescent during the interval from 4.5 Ga to 3.4 Ga, interspersed by short bursts of surface tectonic–magmatic activity. Is this pattern simply an artefact of limited sampling or preservation, or could it reflect the real behaviour of the early Earth? Before proceeding with a discussion of the data, it is useful to consider some aspects of Earth's early evolution, as revealed by dynamic modelling.

4.1. Numerical modelling of the early Earth

Previous modelling by O'Neill et al. (2007) suggested a mechanism by which plate activity itself could have been episodic in the Precambrian, without appealing to internal phase transitions or other mechanisms. This model was based on the idea that the high internal temperatures of the early Earth would have resulted in lower mantle viscosities, decreasing the coupling between the mantle and the plates. The simulations showed first a transition into an episodic overturn mode – long periods of tectonic quiescence interspersed by rapid intervals of subduction, spreading, and tectonic activity – and eventually another transition into a stagnant mode where the internal stresses are too low to generate any surface deformation. These initial models have been largely borne out by later work, including the conceptual approach of Silver and

Behn (2008) and the numerical models of van Hunen and Moyen (2012), and Gerya (2012), which focus on different aspects of the mechanism, but reach the same conclusion. They are largely consistent with more recent geological (Condie and O'Neill, 2010; Condie et al., 2009) and paleomagnetic constraints (Piper, 2013). Further complexities such as the dehydration of the depleted residuum after melt extraction have been suggested to assist (Korenaga, 2011) or hinder (Davies, 2006) Hadean tectonics, and given the lack of constraints we do not consider it further.

Here we expand these earlier models to consider the temporal evolution of the Hadean Earth, from its earliest thermal state to the end of the EoArchean, including the effects of waning radioactive decay, loss of primordial heat, and cooling of the core. We adopt the approach outlined by O'Neill et al. (in revision), expanding those models to high-aspect-ratio simulations to examine how the Earth system would adjust to cooling through time.

A representative model of Hadean to EoArchean evolution is shown in Fig. 7. The four time slices show an evolution from a hot initial state (a), characterised by a hot, thin stagnant lid and vigorous convection beneath it, through an overturn event where the initial lid is largely recycled and a large proportion of the initial heat is expelled (b, c), to another stagnant lid (d) that develops and stops the surface activity. This timeline extends from 4.55 Ga to roughly the end of Eo-Archean time at 3.5–3.6 Ga.

An important component to these models is the interaction between the evolving basal temperature and waning heat production, through time. High basal temperatures result in greater buoyancy forces – effectively a higher basal Rayleigh number. This enhances the tendency towards lid mobilisation. However, greater heat production within the mantle also tends to promote stagnation of the lid. The balance between these two forces as a planet evolves largely controls its tectonic evolution. We have adopted a simple linear core-evolution model, and an exponential decay of heat production, and the tectonic scenario in Fig. 7 is insensitive to minor perturbations in these factors (O'Neill et al., in revision).

A second critical factor is the initial condition. O'Neill et al. (in revision) noted that the initial conditions in evolutionary mantle models can fundamentally affect the apparent evolution of a model planet. They showed that for the same evolving core temperatures and heat production curves, a planet may follow widely divergent tectonic paths depending on the amount of initial (primordial) heating. Models with a “hot” initial condition ($Q \sim 8$, similar to Fig. 7) show transitions from stagnant, to episodic overturn, to a mobile-lid regime and eventually to a cold stagnant-lid regime. Models starting from a “cold” initial condition ($Q < 4$, roughly in equilibrium with radioactive heat production, without any significant primordial heat) may begin in a plate tectonic regime, and then never leave it until the internal temperatures decay to the point that the lid becomes too thick to mobilise, and the model enters a cold stagnant-lid mode. However, it is highly probable that heat generation during Earth's accretion was significant – the sum of accretional impact energy, gravitational energy from core segregation, and heat from the decay of short-lived isotopes such as ^{60}Fe and ^{26}Al was enough to raise the temperature of the entire Earth by thousands of degrees (O'Neill et al., in revision). Therefore, the initial conditions shown in Fig. 7a are probably the most relevant, and it is likely that the earliest Earth was largely stagnant.

The curve in Fig. 8b illustrates the evolution of the Nusselt number (convective heat flux) through time, for the simulation shown in Fig. 7. The initial mode of heat loss is stagnant-lid – characterised by inefficient heat loss through the conductive lid (Fig. 7a, c.f. Debaille et al., 2013). It is likely that voluminous mafic–ultramafic volcanism would be associated with such a regime with a thin, hot, stagnant lid. Eventually, ongoing convergence triggers a convective instability, and the first overturn event happens (Fig. 7b). This is associated with an enormous spike in the heat flux (Fig. 8b), as much of the trapped primordial heat and generated radioactive heat is dumped during the active-lid episode.

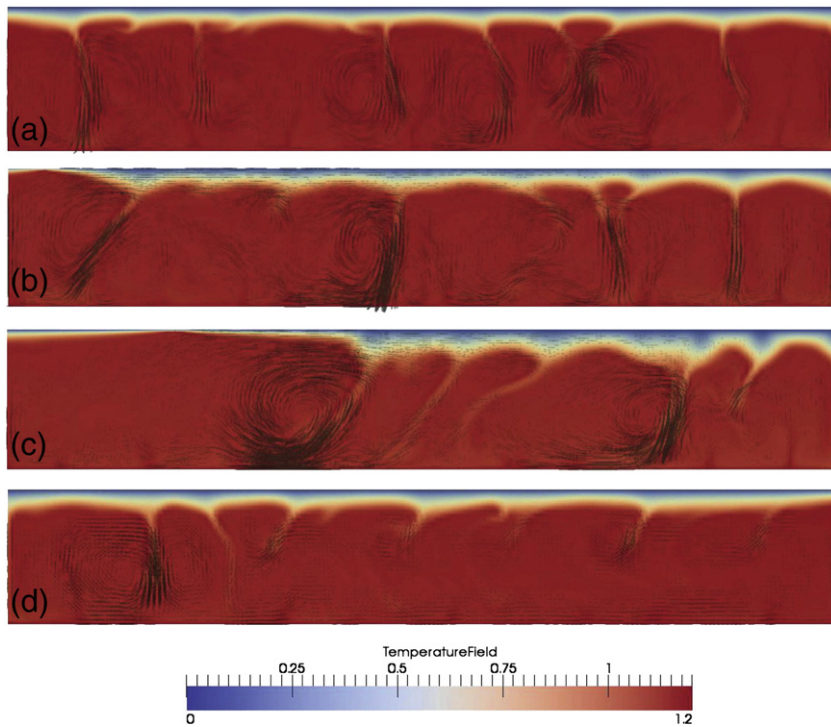


Fig. 7. Simulation of the evolution of a mantle convection model, from a hot initial condition, in a stagnant-lid regime (a), through an overturn event where the majority of the crust is recycled (b and c), and into a subsequent stagnant lid again (d). The colours in the plots reflect the temperature field, from an invariant surface temperature of 0 (290 K) to a basal core-mantle boundary temperature of 1.2, which varies as outlined in the text. Black arrows denote velocities, and their length velocity magnitude.

The episode is short – on the order of 30 Ma, though the activity probably is localised in different areas at different times, and the surface velocities are extremely high. It seems likely that most of the proto-lid would be recycled into the convecting mantle.

After this initial recycling of the proto-lid, the new lithosphere is thin, hot, and comparatively buoyant, and subduction ceases (Fig. 7d). The lid stagnates, convection re-establishes itself beneath the immobile lithosphere, and heat flux subsides to low (stagnant-lid) levels. As the convective planform evolves, convection thins some portions of the lithosphere and thickens others, until a critical imbalance is once again attained and a subduction event ensues. The second event is marginally more subdued, as a large fraction of the initial heat was lost in the first episode. However, extremely high heat fluxes are seen throughout the 900 million years of evolution covered in this model.

It should be emphasised that this model is not attempting to replicate Earth's precise evolution, but rather to provide some insights into the plausible range of dynamics of an Earth-like system, under a thermal evolution similar to Earth's during its earliest history. However, it is interesting to note that the time lag between the initialization of the model and its first overturn is ~300 Myr, and the overturn events in this example are spaced at ~150 Myr intervals. This is of the same magnitude of the recurrence rate observed in the zircon data (see below), but it should be noted this spacing is very sensitive to rheology and mantle structure, which are not explored in detail here.

4.2. Evolution of the crust–mantle system

The distribution of zircon U–Pb ages from the Archean–Hadean period is reasonably well-known. As shown in Fig. 1, the ca 6700 available analyses worldwide (Table A1) define a small peak in the late Hadean (probably over-represented due to its inherent interest), another broad low peak in the EoArchean and a third in the PaleoArchean, before a steady climb from ca 3.0 Ga to the major peaks at 2.7 and 2.5 Ga. When compared with the much smaller dataset of zircons

with juvenile Hf-isotope compositions (Fig. 2) there are two striking aspects: the low proportion of juvenile input (4.5% of all analyses; 20% have $\epsilon_{\text{Hf}} > 0$) prior to 3 Ga, and the dramatic rise in that proportion during the youngest Archean activity. These two observations in themselves underline the stark differences between Hadean/Archean and modern crust–mantle relationships, and the evolution of those processes from the Hadean through to the end of the Archean. However, there are several questions that must be asked about the nature of the zircon record, and the sort of events that it may define.

4.2.1. The Hadean Hf-isotope record – magmatic, metamorphic, or both?

There are essentially no zircons with juvenile Hf-isotope signatures before the small “bloom” at 4.2 Ga. Older zircons have very low ϵ_{Hf} ; this would commonly be interpreted as suggesting that they were generated by remelting of much older material (back to 4.5 Ga). However, many can only be modelled on the basis of a 4.54 Ga source with $\text{Lu}/\text{Hf} = 0$. The small peak of juvenile input at 4.2 Ga is followed by a large group of zircons with $\epsilon_{\text{Hf}} < 0$ extending down to ca 4.0 Ga (Fig. 3). Again, some can be modelled as produced by reworking of mafic to felsic material produced during the 4.2 Ga “event”, but some of these 4.2–4.0 Ga zircons also would require a source that retained a very low Lu/Hf since at least 4.2 Ga.

This appears unlikely; the most obvious alternative is that the U–Pb ages of many of these ancient zircons have been reset without measurable disturbance of the Hf-isotope system, leading to artificially low ϵ_{Hf} . Beyer et al. (2012) demonstrated that zircons from the Archean (>3 Ga) Almklovtdalen peridotite in western Norway give a range of U–Pb ages stretching from 396 to 2760 Ma, but all have the same Hf-isotope composition, corresponding to a T_{DM} of 3.2 Ga (similar to whole-rock Re–Os model ages); the lowest ϵ_{Hf} is –49. They interpreted this pattern as reflecting metamorphic resetting (probably through several episodes) of the primary 3.2 Ga ages, without affecting the Hf-isotope composition.

Nemchin et al. (2006) have argued that many of the Jack Hills zircons no longer retain true magmatic compositions, either elementally or isotopically, due to weathering, metamorphism or other causes. Rasmussen

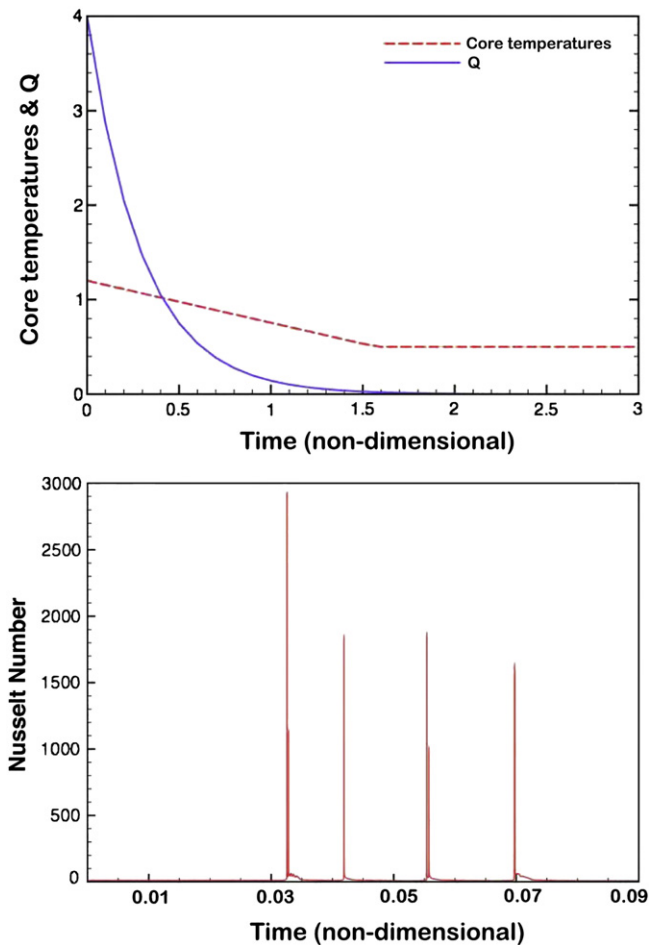


Fig. 8. Upper) The evolution of core temperatures (dashed line) and heat production Q , for the model shown in Fig. 7. Both heat production and core temperatures wane through time according to the evolution shown, affecting the thermal state of the evolving simulation. Time is non-dimensional in these simulations, and we keep our results in that format to facilitate comparison between codes — here a time interval of 0.1 is equivalent to ~1 Ga of real evolution. Lower) Evolution of Nusselt number (convective heat flow), for the model shown in Fig. 7. Four overturn events are apparent, where the lid was rapidly recycled into the mantle, resulting in the creation of new lithosphere and high resultant heat fluxes.

et al. (2010) used xenotime-monazite geochronology and Wilde (2010) used zircon geochronology, to document several episodes of deposition, volcanism and low-grade metamorphism through the Jack Hills belt. Rasmussen et al. (2011) have shown that many of the silicate (quartz + muscovite) inclusions in the ancient Jack Hills zircons are metamorphic in origin, and probably have replaced primary inclusions of apatite and feldspar. Some inclusions with such metamorphic assemblages are connected to the grain surface by microcracks, but others are not, suggesting small-scale permeation of the zircons by fluids. Monazite and xenotime in the zircons give ages of 2.6 or 0.8 Ga, and temperatures of 350–490 °C. If fluids have been able to penetrate the zircon grains to this extent, it is unlikely that the U–Pb systems would remain unaffected. Kusiak et al. (2013) have recently demonstrated that Hadean ages, as well as anomalously young ages, in some Antarctic zircons are artefacts of the redistribution of Pb within single grains, probably in response to metamorphic heating and the activity of fluids.

An obvious question is whether this process also could modify the O-isotope composition of the zircons. Ushikubo et al. (2008) documented extremely high Li contents, and highly fractionated Li isotopes, in the Hadean zircons from Jack Hills. They identified this as the signature of extreme weathering, but then argued for remelting of highly weathered material to produce the parental magmas of the zircons. However, it

must be questioned whether in fact the high Li represents a secondary effect on the zircons themselves, as documented by e.g. Gao et al. (2011).

Wilde et al. (2001) noted correlations between LREE enrichment, increased $\delta^{18}\text{O}$ and lower U–Pb age within a single grain; although this was interpreted in terms of evolving magma composition, it is also consistent with the infiltration of pre-existing zircon by crustal fluids. Cavosie et al. (2005) extended the inverse age– $\delta^{18}\text{O}$ correlation to the whole population of grains with ages of 4.4–4.2 Ga. The $\delta^{18}\text{O}$ values of grains that retain zoning progressively depart from the mantle value as apparent age decreases, and even larger dispersions of $\delta^{18}\text{O}$ occur in grains with disturbed CL patterns. However, Cavosie et al. (2006) still argued that most of the Jack Hills zircons have magmatic REE patterns, with only a small proportion showing LREE-enrichment. Although these were also grains with disturbed age patterns, the authors appeared reluctant to consider them as altered by fluid processes.

Valley et al. (2002, 2006) and Pietranik et al. (2008) summarised published O-isotope analyses of the Jack Hills zircons. A comparison of the data distributions of O-isotope and Hf-isotope data suggests that the zircon populations dominated by low ϵ_{Hf} values also show a predominance of heavy O-isotopes ($\delta^{18}\text{O} > 6$ permil). Lower values appear mainly in time-slices that contain more zircons with more juvenile Hf. However, in the dataset reported by Kemp et al. (2010) zircons with $\delta^{18}\text{O} > 6$ permil appear to be present in most time slices.

Valley et al. (2006), Pietranik et al. (2008) and Kemp et al. (2010) interpreted the high values of $\delta^{18}\text{O}$ as reflecting the subduction or burial, leading to remelting, of felsic or mafic rocks that had been altered by surface water. However, the question remains whether burial and melting were necessarily involved. Instead, the scatter of high- $\delta^{18}\text{O}$ values may represent alteration of zircons by surface (or shallow-crustal) processes, either through weathering or during the metamorphic disturbances documented by Rasmussen et al. (2011). Another question is whether the inferred high P and T represent long-term burial, or the effects of large meteorite impacts, producing felsic melts like those found at the Sudbury impact crater (e.g. Zeit and Marsh, 2006).

Many of the above studies demonstrate the confusion that can arise from a focus on ϵ_{Hf} in isolation. A more nuanced view may be gained by considering the trends in the “raw data”, i.e. the simple variation of Hf_i with time. Fig. 9a shows that the data for the Jack Hills zircons group into two populations, each with a very small range of Hf_i but a wide range (ca 300 Ma) in age. This effect also has been demonstrated in single zoned grains, in which younger rims have $^{177}\text{Hf}/^{176}\text{Hf}$ similar to that of the core (Kemp et al., 2010). Fig. 9b shows a similar trend extending horizontally from ca 3.8 Ga. Another, but less well-defined, trend may extend horizontally from ca 3.35 Ga. These trends are similar to, though less extended in terms of age, to those described by Beyer et al. (2012) in zircons from the Almklovdalen (Norway) peridotites.

We suggest that each of the trends in Fig. 9 represents a single crustal-formation event (?4.5 Ga; 4.2–4.3 Ga; 3.8–3.9 Ga; ? 3.3–3.4 Ga), and that most of the age spread in each population reflects (possibly repeated) metamorphic disturbance of the U–Pb systems. In contrast, reworking of a crustal volume with a non-zero Lu/Hf would produce a noticeable rise in the overall Hf_i through time; no such rise is obvious in either of the two populations outlined in Fig. 9a. The partial resetting of the U–Pb ages may have occurred during the Proterozoic events documented by Grange et al. (2010) and Rasmussen et al. (2011), but may also reflect the events (e.g. impact melting) that grew rims on some zircons at 3.9–3.4 Ga (Cavosie et al., 2004). Kemp et al. (2010) recognized many of these problems, and attempted to filter their U/Pb–Hf isotope data on Jack Hills zircons to account for them. They concluded that the ϵ_{Hf} -age correlation in their filtered data is consistent with the evolution of a mafic crustal reservoir; a similar trend can be seen in the larger dataset (Fig. 3b). This raises the possibility that further high-precision datasets, with multiple isotopic systems measured on the same spots of carefully selected zircons, will be able to define real crustal-evolution trends in specific areas. At present, the data shown in Fig. 9 do not require

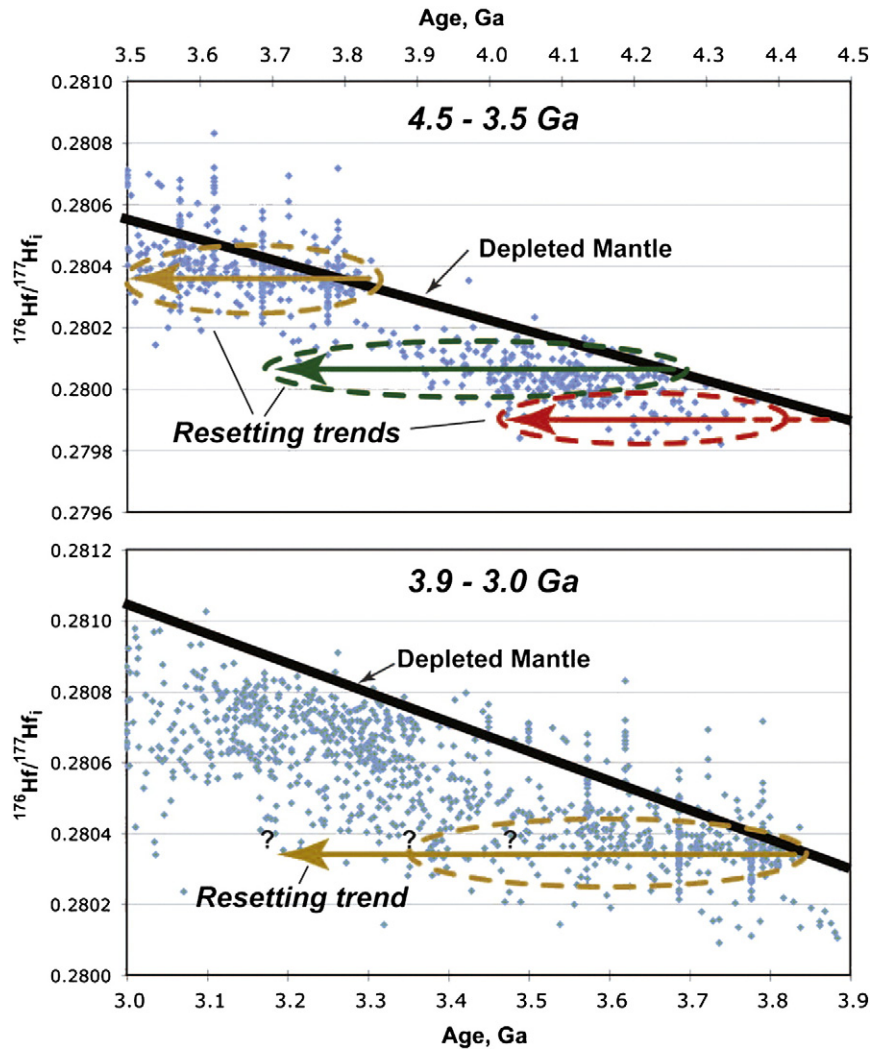


Fig. 9. Plots of U–Pb age vs $^{177}\text{Hf}/^{176}\text{Hf}$ in ancient zircons. Ovals enclose single populations of zircons with similar Hf-isotope ratios but a range in age. We suggest that each of these trends represents a single original population of zircons (ca 4.5 Ga, 4.2 Ga and 3.8 Ga), in which the ages have been reset by surficial or metamorphic processes, without modifying the Hf-isotope compositions (cf Beyer et al., 2012). More typical plate-tectonic processes appear to begin around 3.4 Ga.

real crustal reworking, in the sense of burial and remelting, to have occurred prior to ca 3.5 Ga.

4.2.2. Composition of the earliest crust

Numerous students of the Jack Hills zircons have argued that they document the presence of a felsic crust and a cool planet early in the Hadean period (Harrison et al., 2005, 2008; Pietranik et al., 2008; Valley et al., 2002, 2006). However, as noted above, some of the mineralogical evidence for this idea has been questioned. The data of Kemp et al. (2010) suggest a generally mafic composition for the Hadean crust. The trace-element data of Cavosie et al. (2006) indicate that <10% of the analysed grains came from felsic rocks, while 75% of the 40 zircons studied crystallized from intermediate ($\text{SiO}_2 < 65\%$) melts, which could represent differentiates of large mafic complexes. Another possibility is the generation of felsic melts by large-scale meteorite impact, followed by magmatic fractionation (e.g. the Sudbury complex).

A ‘‘Late Heavy Bombardment’’ around 4.0–3.8 Ga (Fig. 10a) has been widely accepted as a mechanism for supplying the upper Earth with a range of elements (such as the PGE) that are overabundant relative to the levels expected after the separation of Earth’s core (Maier et al., 2010). However, Bottke et al. (2012) have argued that the heaviest bombardment would have been earlier, during Hadean time; it would have begun tapering off by ca 4 Ga, but would have remained a

prominent feature of the surface environment down to ca 3 Ga (Fig. 10a), and would have produced large volumes of shallow, relatively felsic melts, especially during the Hadean and early Archean periods.

4.2.3. Early Archean crustal development

From the discussion above, we would argue that the existing Hadean zircon data carry no information requiring ‘‘crustal reworking’’ (other than by impact melting) and cannot be used to infer the presence of subduction or other manifestations of plate tectonics; similar conclusions have been reached by other recent studies (e.g. Kemp et al., 2010).

The same is true of the next juvenile peak at ca 3.85 Ga; in this case most of the zircons with ages from 3.8 to 3.55 Ga, and some younger ones, have been modelled as reflecting the reworking of felsic material produced around 3.85 Ga, with little other juvenile input (e.g. Pietranik et al. (2008)). However, a large proportion of the zircons with ages from 3.85 to 3.4 Ga again define a population (Fig. 9b) that has essentially constant Hf_i over that range of ages, rather than the rising Hf_i expected of an extended crustal-reworking process. Zircons from the 3.4 to 3.6 Ga age range, which represent the ‘‘tail’’ of the population, mostly have $\delta^{18}\text{O} > 6$ (Valley et al., 2002). This pattern also is perhaps best interpreted as the crustal modification of a single population of juvenile zircons, rather than reworking of large crustal volumes through burial and melting.

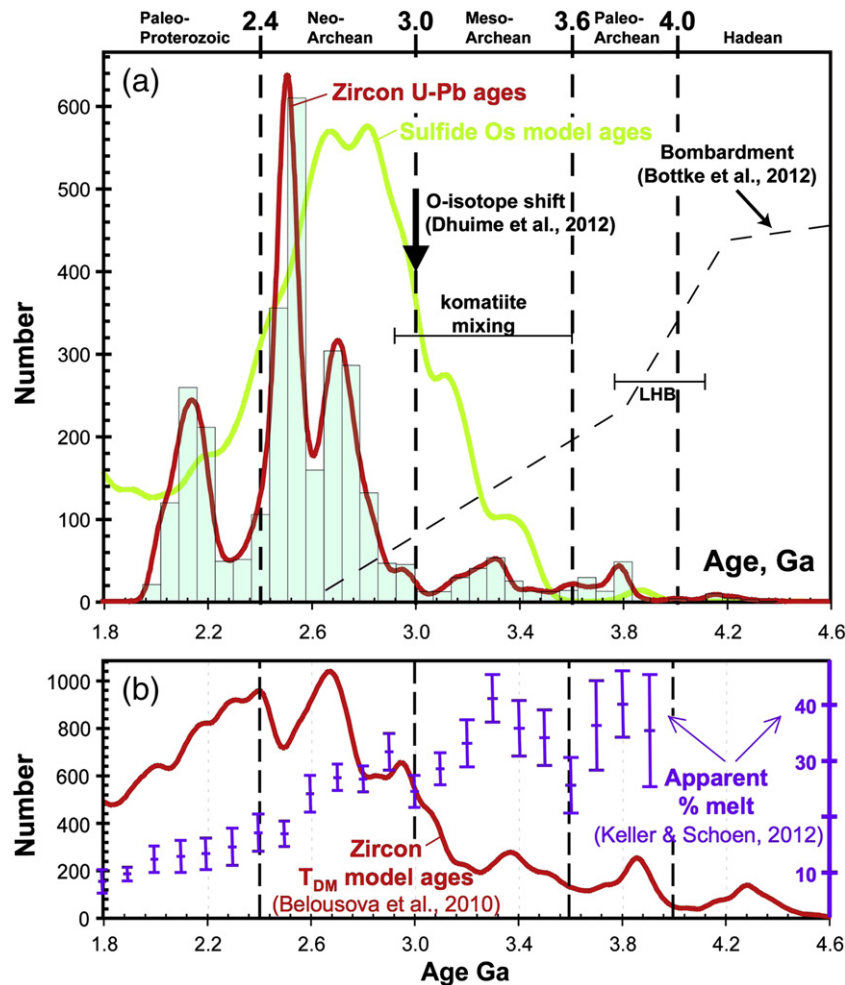


Fig. 10. Summary of crust–mantle evolution. Grey histogram shows distribution of all zircons in the database for the time period shown; red line shows the probability distribution of these ages. Green line shows distribution of Re–Os T_{DM} model ages for sulfides in mantle-derived xenoliths and xenocrysts. The revised distribution of meteorite bombardment intensity (Bottke et al., 2012) and a generalized summary of older interpretations of the “Late Heavy Bombardment” are shown as LHB. The homogenization of PGE contents in komatiites from 3.5 to 2.9 Ga (Maier et al., 2010) may mark the major mantle-overturn/circulation events discussed in the text. The O-isotope shift noted by Dhuime et al. (2012) marks the beginning of a quiescent period, or perhaps the destruction of the crust during the major overturns from 3.5 to 2.9 Ga.

The situation appears to change significantly beginning with the juvenile peak at 3.35–3.4 Ga (Figs. 5; 9b). There are still populations that can be defined by constant Hf_i over a range of ages, but there also is a clear rise in the mean values of Hf_i from ca 3.3 to 3.1 Ga. This period also includes many more zircons derived from truly felsic melts (Fig. 4b), in contrast to the earlier periods. The pattern suggests a pulse of juvenile input, followed by 200–300 Ma of real crustal reworking with continuing minor juvenile contributions.

Overall, the Hadean–MesoArchean Hf-isotope pattern, defined by several peaks in juvenile material followed by long tails of resetting (or reworking), is not that of Phanerozoic subduction systems (e.g. Collins et al., 2011). We suggest that the pattern of the data from 4.5 Ga to ca 3.4 Ga (Fig. 1) represents an essentially stagnant outer Earth (c.f. Kemp et al., 2010), affected by two interacting processes. One is large-scale meteorite bombardment, producing localised reworking at each major impact site, as observed in the Sudbury complex but probably on even larger scales. The second is the periodic overturn of the asthenospheric mantle beneath the stagnant lid, bringing up bursts of new melt to disrupt, recycle and replenish the lid, at intervals of 150–200 Ma, as illustrated in Figs. 7 and 8.

4.2.4. Late Archean – the formation of the SCLM (and plate tectonics)

In contrast, the markedly different pattern shown by the NeoArchean zircons, with a continuous wide range of ε_{Hf} over 100–200 Ma, is more consistent with a subduction-type environment.

The original crust, now repeatedly reworked, is still evident in the data until ca 3.4 Ga (ε_{Hf} values down to $-15 \approx -20$; T_{DM} model ages ≥ 3.8 Ga), but is less obvious after that. In several ways, the 3.4 Ga “overturn” may mark the beginning of a different tectonic style. The sulfide data presented above (Figs. 6, 10a) suggest that most of the SCLM was formed between 3.3 and 2.7 Ga. This is consistent with the results of the Global Lithosphere Architecture Mapping project, which has concluded that at least 70% of all existing SCLM had formed before 2.7 Ga (Begg et al., 2009, 2010; Griffin et al., 2009, 2011). The Archean SCLM is unique; it differs clearly from later-formed SCLM in having anomalously low Fe contents (relative to Mg#). This is a signature of very high-degree melting at high P (4–6 GPa; Griffin et al., 2009; Herzberg and Rudnick, 2012), which is consistent with the melting of deep-seated peridotitic mantle during rapid upwelling.

As noted above, there is a gap in the zircon data as a whole (Fig. 1), and in the degree of juvenile input (Fig. 2) around 3.1–2.9 Ga, coinciding with the rapid buildup of the SCLM recorded in the sulfide data (Fig. 10a). A recent summary of most existing compositional data on crustal rocks (Keller and Schoen, 2012) shows a marked change in crustal composition at ca 3 Ga. MgO, Ni, Cr, Na and Na/K are high in the most ancient rocks and drop sharply at ca 3 Ga; from 3.0 to 2.5 Ga indicators of more felsic crust increase steadily (Fig. 10b). Dhuime et al. (2012) have defined a significant change in the O-isotope compositions of crustal zircons at 3 Ga, corresponding to a “marked decrease in production of juvenile crust” (Fig. 10). This time period also coincides with the late stages of mixing

between older (mantle) and newer (surficial, from meteorite bombardment) PGE reservoirs, as recorded in komatiite data (Maier et al., 2010; Fig. 10a).

We suggest that the apparent gap in the zircon record around this time reflects larger, more rapid mantle overturns, during which most of the SCLM was produced. This could cause very chaotic conditions at the surface, resulting in the loss of contemporaneous crust. In the upper mantle, it could lead to the mixing observed in the komatiite PGE record, and to the homogenization and loss of the Hadean mantle reservoir as a source of crustal magmas (Figs. 1 and 10).

We also infer from these data that the intense magmatism of the 2.9–2.5 Ga period may reflect not only continued mantle overturns, but the advent of a modern form of plate tectonics. A comparison of Figs. 1 and 2 shows a marked difference in the relative heights of the 2.75 Ga and 2.5 Ga peaks; the younger episode of magmatism contains a much higher proportion of juvenile material. In contrast to the earlier pattern of growth spurts followed by long periods of quiescence, the overall pattern of the data in this time period shows both intense reworking of older material (low ϵ_{Hf}) and increased input of juvenile material (high ϵ_{Hf}). In the Phanerozoic record, this pattern is seen in the orogens internal to the assembly of Gondwana (Collins et al., 2011), and contrasts with the upward trend of the data from external orogens (i.e. Pacific rim-type settings). These patterns may be related to the 2.9–2.5 Ga assembly of a supercontinent (Kenorland) and imply that much of the surviving crust from that period represents NeoArchean internal orogens involved in that assembly.

Naeraa et al. (2012) used zircon data (included here) from the ancient rocks of W. Greenland to argue for a major change in the dynamics of crustal growth at this time, a suggestion confirmed by data from many other regions (Fig. 1). The rapid appearance of large volumes of highly depleted (and thus both rigid and buoyant) SCLM moving up to, and about, the surface of the planet would provide a mechanism for the initiation of modern-style plate tectonics. These volumes of buoyant SCLM also would provide “life rafts” that would enhance the possibility of preserving newly formed (and some older) crust.

In summary, the combined zircon and sulfide data suggest that during the Hadean and earliest Archean periods, Earth's surface was essentially stagnant, and probably dominated by mafic rocks. This crust probably was continually reworked by meteorite bombardment to produce a range of mafic to felsic melts, analogous to those exposed in the Sudbury intrusion. The Hadean and early Archean were marked by a series of mantle overturns or major plume episodes, each followed by 150–300 Ma of quiescence. This regime may have continued up to at least 3.5 Ga, after which one or more large melting events (mantle overturns) finally produced the buoyant, highly depleted residues that formed the first stable SCLM. This activity peaked in the Neo-Archean and then ceased abruptly by 2.4 Ga. The end of this activity may have marked the final assembly of the Kenorland supercontinent. Piper (2013), using paleomagnetic data, has argued that most of the crust existing by 2.5 Ga accumulated into this land mass, resulting in a dramatic drop in mean plate velocities, which could in turn be linked to the marked decrease in magmatic activity from 2.4 to 2.2 Ga (Fig. 2).

4.3. Revising the geologic time scale

The International Geologic Time Scale sets the Hadean–Archean boundary at 4.0 Ga, and divides the Archean into four approximately equal time slices (Fig. 1): Eo-Archean (4.0–3.6 Ga), Paleo-Archean (3.6–3.2 Ga), Meso-Archean (3.2–2.8 Ga) and Neo-Archean (2.8–2.5 Ga). There is no obvious basis in the present datasets for these divisions, and we suggest a simplified subdivision, based on the apparent changes in tectonic style (Fig. 8) at identifiable times.

In the absence of better data, we accept the Hadean–Archean boundary at 4.0 Ga, although we suggest that the stagnant-lid regime may have continued for another 500–800 Ma. We propose that the

term *Eo-Archean* be dropped, since there is little preserved evidence of magmatic activity between 4.2 Ga and 3.8 Ga, and that *PaleoArchean* be used for the period 4.0–3.6 Ga, which contains the oldest preserved crust, and perhaps evidence for one major overturn. *MesoArchean* could be applied to the period 3.6–3.0 Ga, during which overturns became more prominent, ending with the buildup towards the major 2.8–2.55 Ga magmatism that accompanied the building of the bulk of the Archean SCLM. *NeoArchean* can be usefully applied to the period 3.0–2.4 Ga, which marks a new tectonic style with frequent plume activity, the beginning of some form of plate tectonics, and the preservation of large volumes of continental crust. The zircon data suggest that this activity continued up to ca 2.4 Ga, and then ceased rather abruptly, marking a natural end to the Neo-Archean period.

This suggested revision appears to be a natural one in terms of the datasets summarised in Fig. 10. It will be interesting to see how well it stands the test of time, as more data sets emerge.

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.lithos.2013.08.018>.

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References

- Aulbach, S., Griffin, W.L., Pearson, N.J., O'Reilly, S.Y., Kivi, K., Doyle, B.J., 2004. Mantle formation and evolution, Slave Craton: constraints from HSE abundances and Re–Os systematics of sulfide inclusions in mantle xenocrysts. *Chemical Geology* 208, 61–88.
- Aulbach, S., Creaser, R.A., Pearson, N.J., Simonetti, S.S., Heaman, L.M., Griffin, W.L., Stachel, T., 2009. Sulfide and whole rock Re–Os systematics of eclogite and pyroxenite xenoliths from the Slave Craton, Canada. *Earth and Planetary Science Letters* 283, 48–58.
- Begg, G.C., Griffin, W.L., Natapov, L.M., O'Reilly, S.Y., Grand, S.P., O'Neill, C.J., Hronsky, J.M.A., Poudjom Djomani, Y., Swain, C.J., Deen, T., Bowden, P., 2009. The lithospheric architecture of Africa: Seismic tomography, mantle petrology and tectonic evolution. *Geosphere* 5, 23–50.
- Begg, G.C., Hronsky, J.M.A., Arndt, N., Griffin, W.L., O'Reilly, S.Y., Hayward, N., 2010. Lithospheric, cratonic and geodynamic setting of Ni–Cu–PGE sulfide deposits. *Economic Geology* 105, 1057–1070.
- Belousova, E.A., Griffin, W.L., O'Reilly, S.Y., Fisher, N.I., 2002. Igneous zircon: trace element composition as an indicator of host rock type. *Contributions to Mineralogy and Petrology* 143, 602–622.
- Belousova, E.A., Kostitsyn, Y.A., Griffin, W.L., Begg, G.C., O'Reilly, S.Y., Pearson, N.J., 2010. The growth of the continental crust: constraints from zircon Hf-isotope data. *Lithos* 119, 457–466.
- Beyer, E.E., Brueckner, H.K., Griffin, W.L., O'Reilly, S.Y., 2012. Laurentian provenance of Archean mantle fragments in Proterozoic Baltic crust of the Norwegian Caledonides. *Journal of Petrology* 53, 1357–1383.
- Bottke, W.F., Vokrouhlicky, D., Minton, D., Nesvornyy, D., Morbidelli, A., Brasser, R., Simonson, B., Levison, H.F., 2012. An Archean heavy bombardment from a destabilized extension of the asteroid belt. *Nature* 485, 78–81.
- Bouvier, A., Vervoort, J.D., Patchett, P.J., 2008. The Lu–Hf and Sm–Nd isotopic composition of CHUR: constraints from unequilibrated chondrites and implications for the bulk composition of terrestrial planets. *Earth and Planetary Science Letters* 273, 48–57.
- Carlson, R.W., Pearson, D.G., James, D.E., 2005. Physical, chemical and chronological characteristics of continental mantle. *Reviews of Geophysics* 43, RG1001. <http://dx.doi.org/10.1029/2004RG000156>.
- Cavosie, A.J., Wilde, S.A., Liu, D., Weiblen, P.W., Valley, J.W., 2004. Internal zoning and U–Th–Pb chemistry of Jack Hills detrital zircons: a mineral record of early Archean to Mesoproterozoic (4348–1576 Ma) magmatism. *Precambrian Research* 135, 251–279.
- Cavosie, A.J., Valley, J.W., Wilde, S.A., E.I.M.F., 2005. Magmatic $\delta^{18}\text{O}$ in 4400–3900 Ma detrital zircons: a record of the alteration and recycling of crust in the Early Archean. *Earth and Planetary Science Letters* 235, 663–681.
- Cavosie, A.J., Valley, J.W., Wilde, S.A., E.I.M.F., 2006. Correlated microanalysis of zircon: trace element, $\delta^{18}\text{O}$ and U–Th–Pb isotopic constraints on the igneous origin of complex >3900 Ma detrital grains. *Geochimica et Cosmochimica Acta* 70, 5601–5616.

- Collins, W.J., Belousova, E.A., Kemp, A.I.S., Murphy, J.B., 2011. Two contrasting Phanerozoic orogenic systems revealed by hafnium isotope data. *Nature Geoscience* 4, 334–337.
- Condie, K., O'Neill, C., 2010. The Archean–Proterozoic boundary: 500 My of tectonic transition in Earth history. *American Journal of Science* 310, 775–790.
- Condie, K.C., O'Neill, C., Aster, R., 2009. Evidence and implications of a widespread magmatic shut down for 250 Myr on Earth. *Earth and Planetary Science Letters* 282, 294–298.
- Davies, G.F., 2006. Gravitational depletion of the early Earth's upper mantle and the viability of early plate tectonics. *Earth and Planetary Science Letters* 243 (3), 376–382.
- Debaille, V., O'Neill, C., Brandon, A.D., Haenecour, P., Yin, Q.-Z., Mattielli, N., Treiman, A.H., 2013. Stagnant-lid tectonics in early Earth revealed by ^{142}Nd variations in late Archean rocks. *Earth and Planetary Science Letters* 373, 83–92.
- Dhuime, B., Hawkesworth, C.J., Cawood, P.A., Storey, C.D., 2012. A change in the geodynamics of continental growth 3 billion years ago. *Science* 335, 1334–1336.
- Gao, Y., Snow, J.E., Casey, J.F., Y.J., 2011. Cooling-induced fractionation of mantle Li isotopes from the ultraslow-spreading Gakkel Ridge. *Earth and Planetary Science Letters* 301, 231–240.
- Geng, Y., Du, L., Ren, L., 2012. Growth and reworking of the early Precambrian continental crust in the North China Craton: constraints from zircon Hf isotopes. *Gondwana Research* 21, 517–529.
- Gerya, T., 2012. Precambrian geodynamics: concepts and models. *Gondwana Research*. <http://dx.doi.org/10.1016/j.gr.2012.11.008>.
- Gonzalez-Jimenez, J.M., Gervilla, F., Griffin, W.L., Proenza, J.A., Auge, T., O'Reilly, S.Y., Pearson, N.J., 2012a. Os-isotope variability within sulfides from podiform chromitites. *Chemical Geology* 291, 224–235.
- Gonzalez-Jimenez, J.M., Griffin, W.L., Gervilla, F., Kerestedjian, T.N., O'Reilly, S.Y., Proenza, J.A., Pearson, N.J., Sergeeva, I., 2012b. Metamorphism disturbs the Re–Os signatures of platinum-group minerals in ophiolite chromitites. *Geology* 40, 659–662.
- Gonzalez-Jimenez, J.M., Griffin, W.L., Gervilla, F., Proenza, J.A., O'Reilly, S.Y., Pearson, N.J., 2013. Chromitites in ophiolites: How, where, when and why? Part I. A review and new ideas on the origin and significance of platinum-group minerals. *Lithos* 189, 127–139.
- Grange, M.L., Wilde, S.A., Nemchin, A.A., Pidgeon, R.T., 2010. Proterozoic events recorded in quartzite cobbles at Jack Hills, Western Australia: new constraints on sedimentation and source of >4 Ga zircons. *Earth and Planetary Science Letters* 292, 158–169.
- Griffin, W.L., Pearson, N.J., Belousova, E., Jackson, S.E., O'Reilly, S.Y., van Acherberg, E., Shee, S.R., 2000. The Hf isotope composition of cratonic mantle: LAM-MC-ICPMS analysis of zircon megacrysts in kimberlites. *Geochimica et Cosmochimica Acta* 64, 133–147.
- Griffin, W.L., Spetsius, Z.V., Pearson, N.J., O'Reilly, S.Y., 2002. In-situ Re–Os analysis of sulfide inclusions in kimberlitic olivine: new constraints on depletion events in the Siberian lithospheric mantle. *Geochemistry, Geophysics, Geosystems* 3, 1069.
- Griffin, W.L., Graham, S., O'Reilly, S.Y., Pearson, N.J., 2004a. Lithosphere evolution beneath the Kaapvaal Craton. Re–Os systematics of sulfides in mantle-derived peridotites. *Chemical Geology* 208, 89–118.
- Griffin, W.L., O'Reilly, S.Y., Doyle, B.J., Pearson, N.J., Coopersmith, H., Kivi, K., Malkovets, V., Pokhilenko, N.V., 2004b. Lithosphere mapping beneath the North American Plate. *Lithos* 77, 873–902.
- Griffin, W.L., O'Reilly, S.Y., Afonso, J.C., Begg, G., 2009. The composition and evolution of lithospheric mantle: a re-evaluation and its tectonic implications. *Journal of Petrology* 50, 1185–1204.
- Griffin, W.L., Begg, G.C., Dunn, D., O'Reilly, S.Y., Natapov, L.M., Karlstrom, K., 2011. Archean lithospheric mantle beneath Arkansas: continental growth by microcontinent accretion. *Bulletin of the Geological Society of America* 123, 1763–1775.
- Griffin, W.L., Nikolic, N., O'Reilly, S.Y., Pearson, N.J., 2012. Coupling, decoupling and metasomatism: evolution of crust–mantle relationships beneath NW Spitsbergen. *Lithos* 149, 115–139.
- Harrison, T.M., Blichert-Toft, J., Müller, W., Albarede, F., Holden, P., Mojzsis, S.J., 2005. Heterogeneous Hadean hafnium: evidence of continental crust at 4.4 to 4.5 Ga. *Science* 310, 1947–1950.
- Harrison, T.M., Schmitt, A.K., McCulloch, M.T., Lovera, O.M., 2008. Early (≥ 4.5 Ga) formation of terrestrial crust: Lu–Hf, d18 O, and Ti thermometry results for Hadean zircons. *Earth and Planetary Science Letters* 268, 476–486.
- Herzberg, C., Rudnick, R., 2012. Formation of cratonic lithosphere: an integrated thermal and petrological model. *Lithos* 149, 4–14.
- Keller, C.B., Schoen, B., 2012. Statistical geochemistry reveals disruption in secular lithospheric evolution about 2.5 Ga ago. *Nature* 485, 490–495.
- Kemp, A.I.S., Wilde, S.A., Hawkesworth, C.J., Coath, C.D., Nemchin, A., Pidgeon, R.T., Vervoort, J.D., DuFrame, S.A., 2010. Hadean crustal evolution revisited: new constraints from Pb–Hf isotope systematics of the Jack Hills zircons. *Earth and Planetary Science Letters* 296, 45–56.
- Korenaga, J., 2011. Thermal evolution with a hydrating mantle and the initiation of plate tectonics in the early Earth. *Journal of Geophysical Research: Solid Earth* (1978–2012) 116 (B12).
- Kusiak, M.A., Whitehouse, M.J., Wilde, S.A., Nemchin, A.A., Clark, C., 2013. Mobilization of radiogenic Pb in zircon revealed by ion imaging: implications for early Earth geochronology. *Geology*. <http://dx.doi.org/10.1130/G33920.1> |.
- Maier, W.D., Barnes, S.J., Campbell, I.H., Fiorentini, M.L., Peltonen, P., Barnes, S.-J., Smithies, H., 2010. Progressive mixing of meteoritic veneer into the early Earth's deep mantle. *Nature* 460, 620–623.
- Marchesi, C., Griffin, W.L., Garrido, C.J., Bodinier, J.-L., O'Reilly, S.Y., Pearson, N.J., 2010. Persistence of mantle lithospheric Re–Os signature during asthenospherization of subcontinental lithospheric mantle: insights from in situ analysis of sulfides from the Ronda peridotite (S. Spain). *Contributions to Mineralogy and Petrology* 159, 315–330.
- Moresi, L., Quenette, S., Lemiale, V., Meriaux, C., Appelbe, B., Mühlhaus, H.B., 2007. Computational approaches to studying non-linear dynamics of the crust and mantle. *Physics of the Earth and Planetary Interiors* 163 (1), 69–82.
- Moresi, L., Solomatov, V., 1998. Mantle convection with a brittle lithosphere: thoughts on the global tectonic styles of the Earth and Venus. *Geophysical Journal International* 133 (3), 669–682.
- Naeraa, T., Scherstein, A., Rosing, M.T., Kemp, A.I.S., Hofmann, J.E., Koldelt, T.F., Whitehouse, M.J., 2012. Harnium isotope evidence for a transition in the dynamics of continental growth 3.2 Ga ago. *Nature* 485, 627–630.
- Nemchin, A.A., Pidgeon, R.T., Whitehouse, M.J., 2006. Re-evaluation of the origin and evolution of >4.2 Ga zircons from the Jack Hills metasedimentary rocks. *Earth and Planetary Science Letters* 244, 218–233.
- Nimmo, F., Price, G.D., Brodholt, J., Gubbins, D., 2004. The influence of potassium on core and geodynamo evolution. *Geophysical Journal International* 156 (2), 363–376.
- O'Neill, C., Debaille, V., Griffin, W.L., 2013. Deep Earth recycling in the Hadean and constraints on surface tectonics. *American Journal of Science* (in press).
- O'Neill, C., Lenardic, A., Weller, M., Moresi, L., Quenette, S., 2013. A window for plate tectonics in terrestrial planet evolution. *Geophysical Journal International* (in revision).
- O'Neill, C., Lenardic, A., Moresi, L., Torsvik, T., Lee, C.A., 2007. Episodic Precambrian subduction. *Earth Planetary Science Letters* 262, 552–562.
- O'Reilly, S.Y., Griffin, W.L., 2012. Mantle metasomatism. In: Harlow, D.E., Austrheim, H. (Eds.), *Metasomatism and the chemical transformation of rock*. Lecture Notes in Earth System Sciences. Springer-Verlag, Berlin Heidelberg, pp. 467–528. http://dx.doi.org/10.1007/978-3-642-28394-9_12.
- Pearson, N.J., Alard, O., Griffin, W.L., Jackson, S.E., O'Reilly, S.Y., 2002. In situ measurement of Re–Os isotopes in mantle sulfides by laser ablation multi-collector inductively-coupled mass spectrometry: analytical methods and preliminary results. *Geochimica et Cosmochimica Acta* 66, 1037–1050.
- Pietranik, A.B., Hawkesworth, C.J., Storey, C.D., Kemp, A.I.S., Sircombe, K.N., Whitehouse, M.J., Bleeker, W., 2008. Episodic mafic crust formation from 4.5–2.8 Ga: new evidence from detrital zircons, Slave Craton, Canada. *Geology* 36, 875–878.
- Piper, J.D.A., 2013. A planetary perspective on Earth evolution: lid tectonics before plate tectonics. *Tectonophysics*. <http://dx.doi.org/10.1016/j.tecto.2012.12.042>.
- Rasmussen, B., Fletcher, I.R., Muhling, J.R., Wilde, S.A., 2010. In situ U–Th–Pb geochronology of monazite and xenotime from the Jack Hills belt: implications for the age of deposition and metamorphism of Hadean zircons. *Precambrian Research* 180, 26–46.
- Rasmussen, B., Fletcher, I.R., Muhling, J.R., Gregory, C.J., Wilde, S.A., 2011. Metamorphic replacement of mineral inclusions in detrital zircon from Jack Hills, Australia: implications for the Hadean Earth. *Geology* 39, 1143–1146.
- Scherer, E., Munker, C., Metzger, K., 2001. Calibration of the Lutetium–Harnium clock. *Science* 293, 683–687.
- Shi, R., Alard, O., Zhi, X., O'Reilly, S.Y., Pearson, N.J., Griffin, W.L., Zhang, M., Chen, X., 2007. Multiple events in the Neo-Tethyan coeanic upper mantle: evidence from Ru–Os–Ir alloys in the Luobusa and Dongquao ophiolitic podiform chromitites, Tibet. *Earth and Planetary Science Letters* 261, 33–48.
- Silver, P.G., Behn, M.D., 2008. Intermittent plate tectonics? *Science* 319, 85–88.
- Spetsius, Z.V., Belousova, E.A., Griffin, W.L., O'Reilly, S.Y., Pearson, N.J., 2002. Archean sulfide inclusions in Paleozoic zircon megacrysts from the Mir kimberlite, Yakutia: implications for the dating of diamonds. *Earth and Planetary Science Letters* 199, 111–126.
- Ushikubo, T., Kita, N.T., Cavosie, A.J., Wilde, S.A., Rudnick, R.L., Valley, J.W., 2008. Lithium in Jack Hills zircons: Evidence for extensive weathering of Earth's earliest crust. *Earth and Planetary Science Letters* 272, 666–676.
- Valley, J.W., Peck, W.H., King, E.M., Wilde, S.A., 2002. A cool early Earth. *Geology* 30, 351–354.
- Valley, J.W., Cavosie, A.J., Wilde, S.A., 2006. What have we learned from pre-4 Ga zircons? Goldschmidt Conference Abstracts, p. A664.
- van Hunen, J., Moya, J.-F., 2012. Archean subduction: fact or fiction? *Annual Review of Earth and Planetary Sciences* 40, 195–219.
- Wilde, S.A., 2010. Proterozoic volcanism in the Jack Hills Belt, Western Australia: some implications and consequences for the world's oldest zircon population. *Precambrian Research* 183, 9–24.
- Wilde, S.A., Valley, J.W., Peck, W.H., Graham, C.M., 2001. Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Ga ago. *Nature* 269, 175–178.
- Zeit, M.J., Marsh, B.D., 2006. The Sudbury igneous complex: viscous emulsion differentiation of a superheated impact melt sheet. *Bulletin of the Geological Society of America* 117, 1427–1450.