Timing the beginnings of continental crust formation

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It is widely believed that earth's continental crust did not develop until ~ 4 b.y. ago and thereafter it is supposed to have grown steadily. However, this classic view had to be revised in the wake of discoveries of detrital zircons 4.0–4.4 b.y. old in Western Australia[1,2], as these implied the existence of stable crusts prior to this date. The beginnings of such early crust formations had so far remained speculative. But, now after breakthroughs in mass spectrometric instrumentation to probe microscopic areas in minerals, the potential of Sm–Nd and Lu–Hf rare earth isotopic systems to study early earth processes, particularly crust formation, has come to be exploited.

Geochemically, rare earth elements are lithophiles, and therefore, during episodes of early differentiation they tend to separate into the newly formed silicate or the continental crust fraction, thereby bringing depletion of these elements in the residual melt (mantle). This selective separation of the rare earths brings about changes in the ratios of the radioactive decay products of Sm and Lu isotopes in the newly formed crusts and in the depleted mantle reservoir. Zircons growing from such melts incorporate these changed ratios. As this mineral is refractory and resistate, the ratios are preserved unchanged within them for millions of years, thus making them available for studying early earth processes. Departures of these ratios relative to their initial ratios, i.e. ratios present in all of the earth minus its metallic core, also termed the bulk silicate earth (BSE), indicate occurrence of differentiation events. The initial ratios in the BSE are assumed to be the same as in the chondritic meteorites, which are the building blocks of planetary systems and therefore selected as reference material to monitor geochemical and isotopic changes during fractionation events.

In the last three years alone, studies on the decay of Sm isotope to Nd isotope have confirmed that global differentiation in silicate earth must have operated much earlier than hitherto conceived[3,4]. Metallic core formation was earth's earliest fractionation event, but because of the geochemical preference of these rare earths to enter the silicate rather than the metallic fraction in the differentiating melt, their isotopic systems are left unaffected during this event. ^{146}Sm decays to ^{142}Nd (half-life of 103 m.y.) and ^{147}Sm to ^{143}Nd (half-life 106 m.y.) and in the BSE, the Sm/Nd and ^{143}Nd/^{144}Nd and ^{142}Nd/^{144}Nd initial ratios are taken to be almost the same as in the chondritic meteorites. Besides, this ratio can occur only where the global differentiation had taken place within the lifetime of ^{146}Sm (^{146}Sm becomes extinct by ~ 4.2 Ga). Though the initial abundance of ^{146}Sm and ^{142}Nd is extremely small, and since ^{142}Nd in early earth rocks remains unaffected by metamorphism, this chronometer has been applied to study several early earth rocks. The ^{142}Nd/^{144}Nd ratios in some old mantle-derived samples such as metabasalts, metagabros, carbonatites and kimberlites are found to be at least 20 ppm higher than in the chondrites[3]. This departure from the chondritic values is interpreted as a clear evidence for the depleted state of their mantle source left after an earlier global differentiation event. Calculations have led to the conclusion that to evolve this 20 ppm excess, differentiation may have occurred around 4.53 b.y. ago[3].

Following the Sm–Nd isotope application to trace early earth's fractionation events, investigations reported late last year using Lu/Hf system in zircons have also concluded that continental crust began forming soon after the main stage earth formation 4.567 b.y. ago. This method utilizes the slow radioactive decay of ^{176}Lu to ^{176}Hf (half-life 37 b.y.) estimated as ^{176}Hf/^{177}Hf in the zircons. Since zircons have low Lu/Hf ratios, their ^{176}Hf/^{177}Hf record near initial ratios at the time of their Pb–U age. Geochemical affinity of Hf to fractionate into the crust leaves the mantle depleted in Hf and a consequent high Lu/Hf ratio relative to the crust. With progress of time, the build-up of ^{176}Hf in the mantle from the decay of ^{176}Lu results in higher or positive ^{176}Hf/^{177}Hf ratio here relative to BSE, whereas the corresponding crust acquires negative ^{176}Hf/^{177}Hf ratio.

A recent investigation[5] has estimated ^{176}Hf/^{177}Hf in several of the zircons from Jack Hills, Western Australia whose ages ranged between 4.01 and 4.37 b.y. From the data of Lu/Hf and the absolute values of ^{176}Hf/^{177}Hf ratios in precisely dated zircons belonging, for example, to younger geologic periods, the $^{176}\text{Lu} \rightarrow {}^{176}\text{Hf}$ growth rates were back-calculated to yield the date when the parent magma of the zircons must have formed to evolve the observed ^{176}Hf/^{177}Hf ratios. This has indicated development of mantle reservoir with Lu/Hf consistent with the formation of continental crust as early as 4.5 Ga and a corresponding depleted mantle[5]. Further, from other studies made earlier on the Jack Hills zircons[6] and mantle-derived rocks[7], it is inferred that early crustal formation was punctuated and that most of the juvenile crusts were recycled quickly back into the mantle (an early earth version of modern-day plate tectonism) by the high recycling rates of the Hadean times (~ 10 times faster than now), aided by strong convection current operating in the low viscous mantle of the period[8].

Even though Lu/Hf isotope system has proved to be a robust tracer to study early earth's differentiation events, certain aspects of the materials chosen for the study have come up for criticism[9]. Zircons usually exhibit domains or zones within the crystal (Figure 1), each with varying composition and age – sometimes covering a span of 300–400 m.y. or more between core and rim of the crystal. The grains also display overgrowths and from the

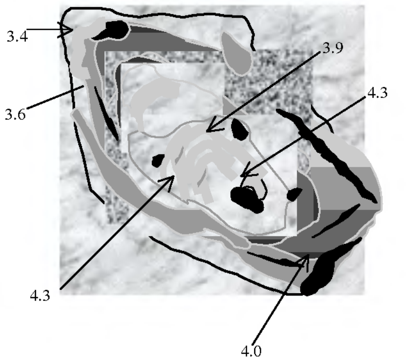

Figure 1. A typical zircon occurring in Jack Hills area, Western Australia, showing domains of different compositions and ages. Numerals represent ages in billions of years (adapted from Cavosie *et al.*[6]).

$^{207}Pb/^{206}Pb$ age distribution pattern seen in such zircons, it is evident that these overgrowths formed on the original crystal during younger magmatic episodes[6]. The different overlapping ages and consequent changes to $^{176}Hf/^{177}Hf$ ratios with time in the melt reservoir from which the secondary overgrowths grew, are therefore, bound to adversely influence the conclusions. Aware of these shortcomings, the recent study[5] has shown how errors due to such heterogeneities in zircons could be overcome through suitable analytical procedures to discriminate the signals. Though the criticism appears quite valid, presently there are no alternate tough geological materials like zircons that have the ability to survive for millions of years, preserving the signatures to their prehistory. The drawbacks pointed out by the critics only stress the need to develop advanced mass spectrometer with ultra precise capabilities to probe, resolve and analyse micro-areas within the mineral for extremely small amounts of the short-lived isotopes[9].

Doubts have also been expressed about the appropriateness of chondritic ratios as references for Lu/Hf and $^{176}Hf/^{177}Hf$ ratios in the bulk silicate earth. The serious objection pertains to the fact that our earth and the undifferentiated asteroids may have come from different source reservoirs and further, the Lu/Hf in chondrites themselves may also vary[10]. These aspects, therefore, call for proper choice of meteorite data and meteorite models for use as reference values[11].

There is also the high probability of re-homogenization of the early crust and the depleted mantle due to bombardment by meteorites that are believed to have continued battering the earth unabated during the first 500 m.y.[12] These highly energetic collisions could have triggered voluminous decompression melting, and impact-induced magmatism in the juvenile earth's crust, all of which could have restructured and reset the clock and the average $^{176}Hf/^{177}Hf$ ratios. There is evidence to this in the form of a strong divergence of the average $^{176}Hf/^{177}Hf$ and Sm–Nd isotopes from the chondritic values in some mantle derived rocks formed around ~ 4 b.y. period[3,7,13].

With such an early earth scenario, it is not surprising to note the doubts expressed on some of the claims made from the 4.3 to 4.4 Ga Western Australian detrital zircons about the existence of older crusts inasmuch as these zircons may as well represent felsic differentiates and partial melts from dominant mafic magmatic 4.4–4.3 Ga Hadean crust[13], or they may have even grown in melts related to large meteorite impacts, though the latter mode of origin is ruled out on the basis of zircon morphology[6]. In other words, the zircons studied may not be representative of the older crusts. The events of the first half billion years appear to be so destructive to the survival of pristine geologic records, that attempts to time the fractionation of the mantle which led to the birth of the earliest continental crust, has so far remained mired in doubts and debates.

At the same time, some are of the view that the turbulent geodynamics visualized above is actually contradicted by the detrital nature of the Jack Hills zircons, many of them well-rounded, pointing to the existence of running water and sedimentary basins, all of which imply cool (< 100°C) and relatively quiet conditions. This scenario is further supported by high $\delta^{18}O$, suggesting water–rock interactions[2], and growth by wet crustal fusion[14], though such high $\delta^{18}O$ may also result from diffusional exchange with hydrous environment during recycling over extended periods[13].

The dual scenario that has now emerged about the earth's first half billion years, strengthens the view that our planet must have evolved through spells of catastrophic geodynamics triggered by heavy bombardment between 4.0 and 3.9 b.y. ago, as well as periods of relative tranquility between 4.4 and 4.0 b.y. ago, when the crusts that had formed remained stable, exposed to the hydrosphere, active weathering and developed conditions ripe for life to emerge[2]. The Jack Hills zircons obviously are products of such halcyon times[8].

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