Detrital zircon: a foggy window into early Earth evolution

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A basic tenet of terrestrial geochemistry is that the continental crust has been extracted from the mantle leaving the latter depleted in incompatible elements. Nd and Hf isotopes have long shown that this process has been an essential feature of the Earth throughout its history, yet the details of the isotopic record—and the implications for the timing and rates of mantle depletion and continental crust extraction—remain debated. Recently, much attention has been given to detrital zircons in both modern and ancient sediments. Integration of the crystallization history of the zircon from the U-Pb chronometer with its Hf isotopic composition can reveal whether the zircon derived from juvenile or reworked crust. This approach critically requires that the crystallization age of the zircons can be unambiguously determined. We suggest that this represents an important—but generally overlooked—limitation in the Hf isotope record from detrital zircons.

The quality filter most often used to assess the integrity of zircon U-Pb systematics is concordance; if a zircon is concordant, it is assumed that the U-Pb age is accurate. A concordance filter is less effective in old zircons because ancient Pb loss, viewed today, parallels concordia. Ancient Pb loss in zircons produces an apparent age less than the true magmatic age, and so the initial Hf isotopic composition will be anomalously low (by ~2.2 epsilon Hf units per 0.1 Ga). Hf model ages, calculated from these parameters, will be artificially old and spurious. The combination of unradiogenic Hf and Hf model ages > U-Pb ages in the zircon record are often given as prima facie evidence of crustal reworking and recycling during Earth's early history, and underpin models for large volumes of ancient continental crust. For many old zircons these features may simply reflect unrecognized ancient Pb loss.

A more robust picture of the isotopic evolution of the Earth can be gained from an integrated approach of Hf and Nd isotopes in well age-constrained magmatic samples: careful U-Pb zircon geochronology; Hf isotopic composition of the zircons; and Hf and Nd isotopic measurements of the whole-rocks. We also highlight strategies for minimising complexities from ancient Pb loss, with respect to Hadean detrital zircons from the Jack Hills and zircons from multiply metamorphosed Archean TTG gneisses of Greenland and Scotland. In these cases, oxygen isotopes, time-resolved Pb/U isotope profiles, trace elements and microstructures provide additional quality filters. An important part of this approach is the realization that not all rock samples (or zircons!) yield useful, unambiguous results. Inclusion of all Hf isotope data from large zircon databases, unscrutinized for quality and lacking in context, will do more to obscure the isotopic evolution of the first billion years of Earth history than to clarify it.

The Hf-Nd isotope barcode of crust formation in the Archean Earth

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Information from long-lived radiogenic isotope tracers has long been used to argue for the extraction of at least 50% of the Earth's continental crust before the end of the Archean [1]. This implies high, but largely cryptic rates of ancient silicate Earth differentiation not matched by preserved crustal materials of these ages. The geodynamic environment for the generation of these putative early continents remains enigmatic, and this affects models for mantle and atmospheric evolution. Plume-driven crustal growth accords with a hotter early Earth and with inferred episodicity in crust formation, but is difficult to test in the absence of diagnostic chemical signatures. Other studies invoke convergent plate margin processes by 3.8 Ga or earlier – yet, given evidence that crust generation and crust destruction rates are balanced at modern subduction zones, rapid crustal growth at ancient arcs would require a fundamentally different subduction regime to that of the present day. Impediments to understanding early Earth geodynamics include the fragmentary Archean geological record, preservation and sampling bias and overprinting by younger thermal events. It is also increasingly recognised that the isotope testimony of a key mineralogical witness to early Earth processes, zircon, is not always robust.

We examine the constraints on the timing and composition of crust formation from the Hadean to the end of the Archean Eon, focussing on the Hf-Nd isotope record. This information is compared to isotope-time patterns produced by igneous rocks of subduction-related Phanerozoic orogens. The simple Hf isotope-time array defined by the Hadean Jack Hills zircons is not consistent with arc magmatism in its modern guise, but suggests repeated remelting of a basaltic protocrust extracted from primitive mantle at ~4.5 Ga, perhaps during magma ocean solidification [2]. Felsic rocks of the oldest continental nuclei in Greenland (3.85-3.82 Ga) and the Pilbara Craton (3.65-3.42 Ga) appear to have tapped an undifferentiated, near-chondritic mantle source, possibly of deep-seated origin. Both cratons record distinct switches in Hf-Nd isotope signatures after 3.1 Ga that reflect changes in magma sources and enhanced recycling of crust into the mantle. The resulting temporal Hf-Nd isotope trends resemble those produced by plate tectonic processes involving arc accretion and ocean closure, and suggest a transition from a deep to a shallow mantle source of new continental crust after 3.1 Ga.

[1] McCulloch, M. and Bennett, V. (1993) *GCA* **58**, 4717-4738.
[2] Kemp, A.I.S. et al (2010) *EPSL* **296**, 45-56.