RESEARCH FOCUS

The Origin of Habitats

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One of the overarching questions of humanity is the origin of life. When and where did life first emerge? Geologists contribute to this question in many ways. The emergence of life required a hospitable habitat with specific physical and chemical conditions. What were the tectonic conditions necessary to create those habitats? Was "Darwin's pond" a familiar habitat, like Yellowstone's hot springs or oceanic submarine vents, and did life emerge on felsic or mafic crust? Understanding the origin of suitable habitats for life is linked to understanding the growth of crust on the early Earth, and the emergence of plate tectonics and continents. For this, the rock record contains the only tangible evidence.

Zircons provide unique information about early Earth because of their durability and antiquity, and no other mineral allows direct correlation of U-Pb age with so much geochemical information. Importantly, detrital zircons are known that predate the oldest preserved rocks. New technical developments yield higher precision and accuracy from smaller samples and, when correlated to imaging, in situ analyses for multiple isotope systems can be made from volumes as small as individual growth zones within single zircon crystals (Cavosie et al., 2007).

In this issue of *Geology*, Pietranik et al. (2008, p. 875) present correlated in situ analyses of halfnium (Hf) and oxygen (O) isotope ratios and age in detrital zircons from the Slave craton. These results, combined with published data, point to formation of mafic crust in four punctuated events at 4.4–4.5 Ga, 3.8 Ga, 3.4 Ga, and 2.7–2.8 Ga, and thus provide strong new evidence to answer several longstanding questions: when did crust first form, was it mafic or felsic, how much crust was there, and was its formation continuous or punctuated?

The synthesis of Hf and O isotope data is especially powerful for answering these and related questions because of the contrasting nature of these elements. Oxygen is the most abundant element in the crust and mantle; it is an essential constituent of most minerals, fluids, and melts; and the $^{18}O/^{16}O$ ratio is stable with time. Oxygen isotope ratios are fractionated by low-temperature processes that affect sediments, but values of $\delta^{18}O$(zircon) are not significantly affected by high-temperature exchange or magmatic differentiation (Valley et al., 2005; Lackey et al., 2008). In contrast, Hf is a trace element that is excluded from most minerals, and the $^{176}Hf/^{177}Hf$ ratio is governed by long-lived radioactive decay. For these reasons, O isotope ratios in zircon are independent of time and most affected by low-temperature fluid-rock interactions of the pre-magmatic protolith. Hf isotope ratios, on the other hand, are unaffected by low-temperature alteration of the protolith, but are sensitive to magmatic differentiation and long-term radiogenic ingrowth. Pietranik et al. (2008) exploit the sensitivity of $\delta^{18}O$ values to detect alteration to determine if host magmas were newly derived from the mantle versus recycled material. This approach, first applied by Kemp et al. (2006), allows them to sort their Hf isotope data, that otherwise appear to be a continuum. In this manner, they resolve discrete events where mafic crust was separated from the mantle, often predating the age of the zircons they dated. The distinction of the age when material was first differentiated from the mantle versus the age of younger rocks that may contain that material is key here. Some of this mafic material was reworked and recycled into younger magmas that formed zircons, and zircons containing such recycled material are identified by their mildly elevated $\delta^{18}O$.

The O isotope discriminator applied by Kemp et al. (2006) and Pietranik et al. (2008) is premised on an understanding of the relation of $\delta^{18}O$ for detrital zircons to $\delta^{18}O$ of magmas. There are inherent assumptions: the detrital zircons must be igneous, and not metamorphic or reset by diffusion. Study of detrital zircons is advantageous because it can provide a broad sampling of many rocks, including some that are not known in outcrop and that may no longer exist, but detrital zircon suites could be questioned as not representing typical magmas (Moecher and Samson, 2006). Figure 1 shows that such data are representative of $\delta^{18}O$ throughout Earth's history. There is no significant difference between bulk analyses of zircons separated from known igneous parents and in situ analyses of isolated detrital zircons. The detrital zircons exactly mirror the bulk zircon samples, including the higher values of $\delta^{18}O$(zircon) that mark a pronounced increase of crustal recycling after 2.5 Ga (Valley et al., 2005). Likewise, values of $\delta^{18}O$(zircon) could be questioned because thermal history is unknown for detrital zircons, and diffusive resetting has been suggested. However, ion microprobe measurements of steep gradients in $\delta^{18}O$ using a focused 1 µm beam show that closure temperatures are above 800 °C and that $\delta^{18}O$(zircon) values will commonly be preserved through high-grade metamorphism and even anatexis (Page et al., 2007).

The formation of crust as early as 4.5 Ga, and preservation of a significant geochemical signature, must be reconciled with the widely accepted Moon-forming collision that would have caused wholesale melting of Earth at ca. 4.5 Ga. Thermal modeling indicates that Earth would start to crust over within 1–10 m.y. of such an impact (Sleep, 2008). But, was this rind differentiated, and did it last? The record from detrital zircons that

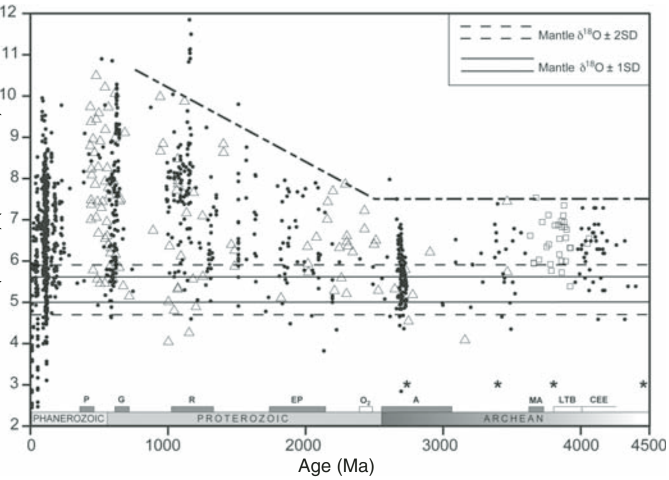

Figure 1. Oxygen isotope ratio of igneous zircons from 4.4 Ga to recent. The composition of zircon in high-temperature equilibrium with mantle $\delta^{18}O$ is shown at ± 1 and ± 2 SD. Symbols: dots, mostly multigrain zircon concentrates from known parent rocks, Valley et al., 2005; triangles and squares, single detrital zircons, Kemp et al., 2006, Wilde et al., 2008, respectively. Values of $\delta^{18}O$(zircon) range from mantle-like to mildly elevated in the Archean. Values of $\delta^{18}O$ above 7.5 ‰ reflect increased recycling of high $\delta^{18}O$ crustal material on the post-Archean Earth. Periods of supercontinent growth are shown by short bars at bottom: P—Pangea; G—Gondwana; R—Rodinia; EP—Early Proterozoic; A—Archean; MA—Middle Archean (Condie, 1998). LTB—Late Terminal bombardment; CEE—Cool Early Earth; O_2—rise of oxygen in the atmosphere. New crust-forming events based on Hf and O isotopes are shown by asterisks (Pietranik et al., 2008). Dash-dot line marks upper limit for $\delta^{18}O$ and highlights the secular trend to higher values due to increased supracrustal recycling after 2.5 Ga.

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contain quartz inclusions proves the existence of quartz-saturated granitic (sensu lato) magma as early as 4.4 Ga (Cavosie et al., 2007). The zircons do not indicate the amount of such magma.

Magmatic recycling creates felsic crust, and eventually creates continents; however, the age of the first continent is not known. Much has been written on this subject and it is beyond the scope of this note (see van Kranendonk et al., 2007; Sleep, 2008). Two lines of evidence from detrital zircons deserve special mention. Ti contents of pre–4 Ga detrital zircons have been used to infer that parent rocks were hydrous granites (Harrison et al., 2008), but Fu et al. (2008) report similar Ti concentrations in zircons from anorthosites and gabbros. Apparently, Ti content in detrital zircons is not indicative of rock type. Positive values of εHf in pre–4 Ga zircons were formerly interpreted to demonstrate the existence of depleted mantle and the formation of large granite (sensu stricto) continents at 4.5 Ga. (Harrison et al., 2005). It is significant that the εHf data of Pietranik et al. (2008) are mostly negative and that large positive εHf values have not been reproduced, as also reported by Harrison et al. (2008). Thus, the new data could represent small additions to a mafic crust and do not require large-scale mantle depletion or the growth of felsic continents at 4.4–4.5 Ga.

The conclusion that the input of mantle material into the crust is episodic during the Archean contrasts with the view that crust formation was the continuous result of plate tectonics with subduction beginning at 4.5 Ga. Continuous growth of the crust has been proposed based on studies that do not employ $\delta^{18}O$ to distinguish Hf data that come from zircons that had primitive-versus-recycled parent rocks (Harrison et al., 2005, 2008). Episodic crust formation has also been proposed based on clustering of zircon ages (Condie, 1998). It is reasonable to ask if zircon age peaks are really events or merely the result of sampling bias. More recent analysis shows these peaks to be comprised of multiple sub-events, but there is still not a continuum (Condie et al., 2008).

Primitive organisms existed earlier than the first stromatolites and microfossils, and probably earlier than the oldest carbon isotope "biosignatures." For most geologists, this points to events older than the ca. 3.8 Ga water-lain sediments at Isua in Greenland (Rosing, 1999; Schidlowski, 2001; but see Moorbath, 2005). Formerly called Hadean (hell-like), this earliest time in Earth's history is increasingly regarded as clement and habitable for life (Valley et al., 2002). When was the earliest that life could have appeared? Certainly, there was an early inhospitable period when the Earth was truly hell-like with magma oceans on the surface and a steam-rich atmosphere. The evidence from oxygen and lithium isotopes in detrital zircons suggests that these extreme conditions subsided before 4.3 Ga (Ushikubo et al., 2008). It has even been suggested that, because of fainter luminosity of the young Sun, the early surface conditions may have been a Snowball Earth rather than Hadean (Zahnle, 2006). If so, liquid water, essential for life, would have existed near hot vents, and Darwin's pool may have been confined by ice. In this scenario, nutrients derived by water-rock interactions could be confined and reach concentrations not possible in an open ocean. Whatever the environment, the emergence of life coincided with early crustal growth, and the physical and chemical characteristics of the first habitats suitable for life were controlled by the formerly mysterious tectonic processes that zircons are beginning to reveal. Enhanced understanding of the nature and tempo of tectonism will aid in deciphering the first habitats suitable for life.

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