Making Earth's earliest continental crust
- an analogue from voluminous Neogene silicic volcanism in NE-Iceland

Sylvia E. Berg[1, 2*], Valentin R.Troll[1], Steffi Burchardt[1], Morten S. Riishuus[2], Frances M. Deegan[1, 3], Chris Harris[4], Martin J. Whitehouse[3] & Ludvik E. Gústafsson[5]

[1]Dept. of Earth Sciences, CEMPEG, Uppsala University, Uppsala, Sweden. [2]Nordic Volcanological Center, Inst. of Earth Sciences, University of Iceland, Reykjavik.[3]Dept. of Geosciences, Swedish Museum of Natural History Stockholm, Sweden. [4]Dept. of Geological Sciences, University of Cape Town, Rondebosch, South Africa. [5]Samband Islenskra Sveitarfélag, Reykjavik, Iceland.
*correspondence: sylvia.berg@geo.uu.se

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Figure 1. Hvitserkur ignimbrite is one of the largest ignimbrite sheets in the whole of Iceland, and it formed during explosive volcanism of a degree unusual for Iceland.

Hypothesis

Concentrated large-volume silicic magmatism in Iceland is an enormous challenge to our understanding of magmatic processes, and touches on the problem of crustal growth in a subduction–free early Earth (e.g. ≥ 3 Ga, Kamber et al., 2005). Because NE-Iceland satisfies most of the observations from Hadean terrains, such as **1)** a dominantly basaltic environment (e.g. Kamber et al., 2005), **2)** bimodal volcanic association (Cawood et al., 2013), **3)** high net growth (Dhuime et al, 2012), **4)** a subduction free setting (Van Kranendonk, 2011), and **5)** plume dominance (Dhuime et al, 2012; Cawood et al., 2013), it affords us with a **window into the processes that led to the formation of silicic proto-continental crust in early Earth** (c.f. Willbold et al., 2009).

Here we report SIMS zircon U-Pb ages and $\delta^{18}O$ values from the Borgarfjörður Eystri region in NE-Iceland to unravel what causes silicic volcanism in this otherwise basaltic province.

1 Voluminous silicic rocks in NE-Iceland

Voluminous silicic volcanism in Iceland represents a **long-standing petrological dilemma** (e.g. Carmichael, 1964; Charreteur et al., 2013).

The Neogene volcanic complexes around Borgarfjörður Eystri are the **second-most voluminous exposure of silicic eruptive** rocks in Iceland (Fig. 1 & 2). However, the origin, significance and duration of the **>300 km^3 of dominantly explosive silicic activity** is not yet constrained (c.f. Gústafsson et al., 1989).

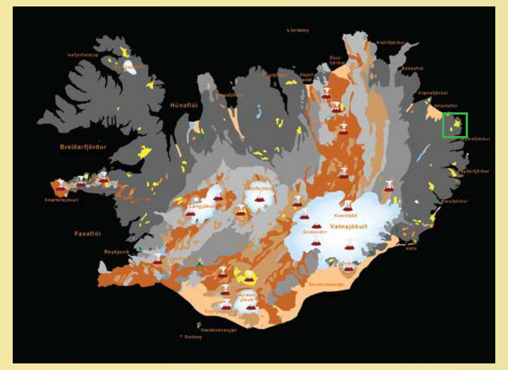


Figure 2. Geological map of Iceland, field area in NE-Iceland boxed in green.

» Exposed **silicic rocks amount to ~25 %** of the rock mass in the region (Gústafsson et al., 1989), exceeding the usual ≤12 % in Iceland as a whole (e.g. Jonasson, 2007).

» Total post-erosional volume of silicic rocks is ≥ 60 km^3, and only ~1 km^3 of intermediate rocks, which both represent some estimated ~20 % of the pre-erosional eruptive volume.

» The four central volcanoes are characterised by sub-volcanic rhyolite domes, inclined sheet swarms, collapse calderas, silicic lava flows, and **voluminous ignimbrite sheets** (Fig. 1).

» **Magmatic bimodality, mixing and mingling** are evidenced by:
1) Plagioclase disequilibrium textures (Fig. 3A-D).
2) A variety of mafic enclaves (Fig. 3E-F).
3) Liquid-liquid contact between melt batches in ignimbrites (Fig. 3F).

» **Strong compositional bimodality** of whole rocks (Bunsen-Daly gap) (Fig. 4).

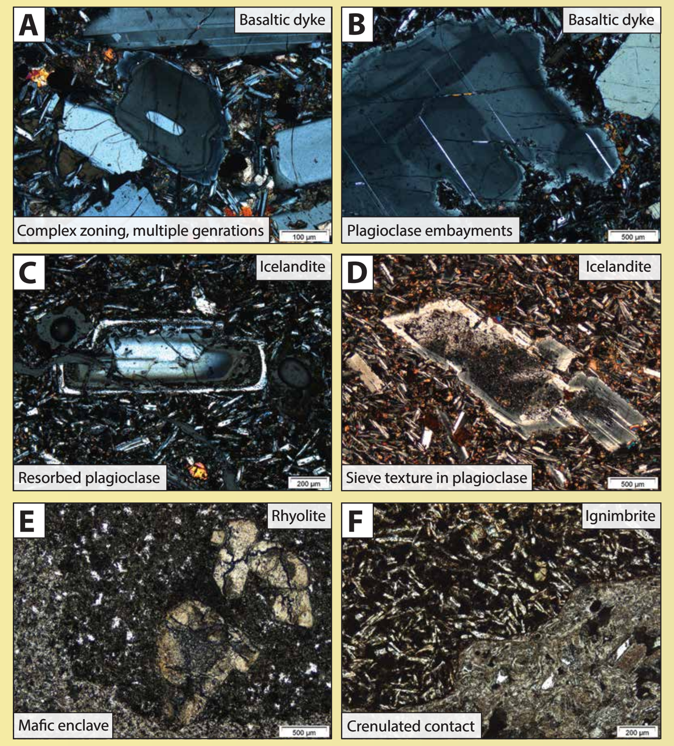
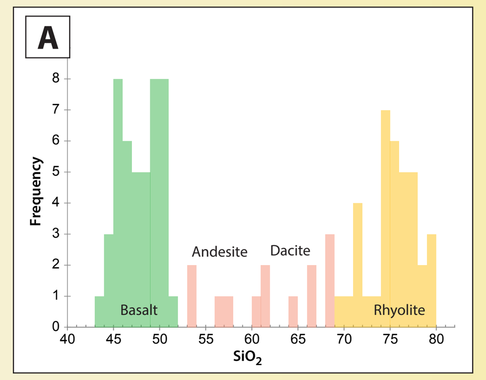
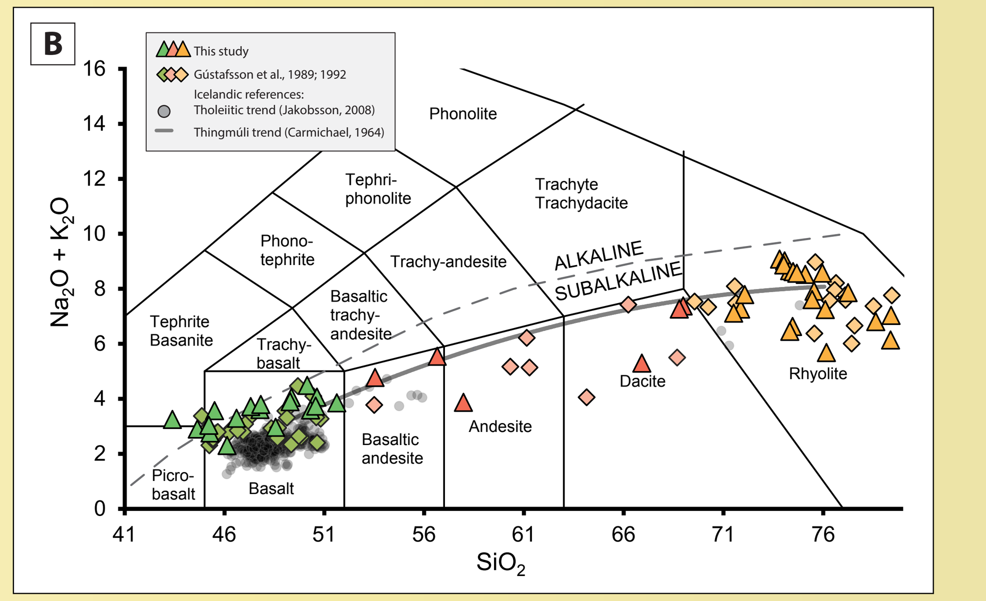


Figure 3. Photomicrographs of **A)** complex zoning and multiple generation plagioclase, **B)** and **C)** plagioclase embayments and resorption, **D)** sieve textured plagioclase, **E)** mafic enclave in rhyolite, **F)** crenulated margin of mafic enclaves in Hvitserkur ignimbrite.

Figure 4. A) SiO_2 frequency distribution plot of all analysed rocks from the region (this study & Gústafsson et al., 1989; 1992. **B)** TAS diagram with regional data in colour (colour scheme as in A) and literature references plotted in grey, showing a subalkaline trend and a characteristic bimodal volcanic association (c.f. A).





2 Zircon U/Pb geochronology

Precise in-situ **SIMS** zircon U-Pb ages from 15 key lithological units in the region (Fig. 5A-B) show a **3-stage evolution** of silicic volcanism:

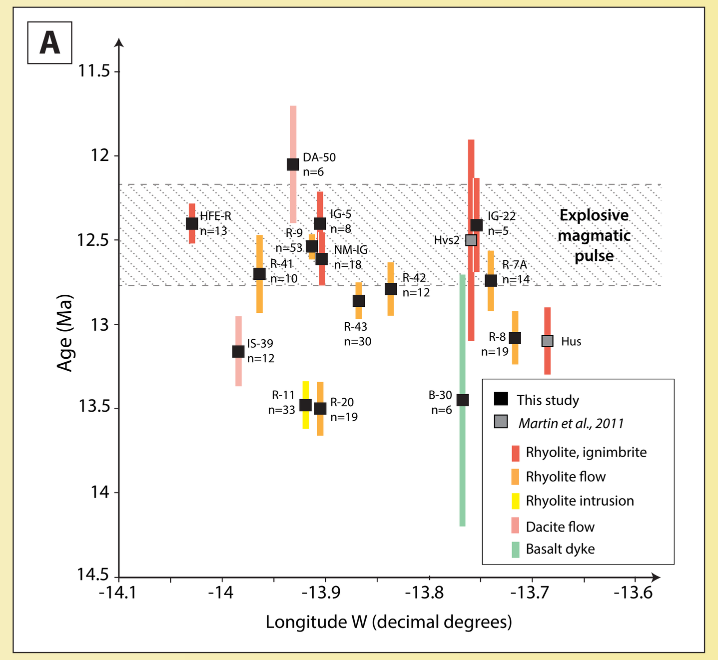
1) Silicic igneous activity commenced with extrusion of **rhyolite lavas at 13.5 to 12.8 Ma.**

2) Closely followed by **simultaneous large caldera-forming ignimbrite eruptions** from Njarðvik (12.61 Ma), Breiðavik (12.41 Ma), Dyrfjöll (12.40 Ma) and from Herfell central volcanoes (12.40 Ma).

3) Silicic activity ended abruptly with dacite lava from Dyrfjöll at 12.10 Ma, and was followed by small-scale basaltic eruptions.

Flood-basalt volcanism later covered these central volcanoes (Oskarsson & Riishuus, 2013).

This defines a ≤ 2 Myr long window of silicic volcanism.



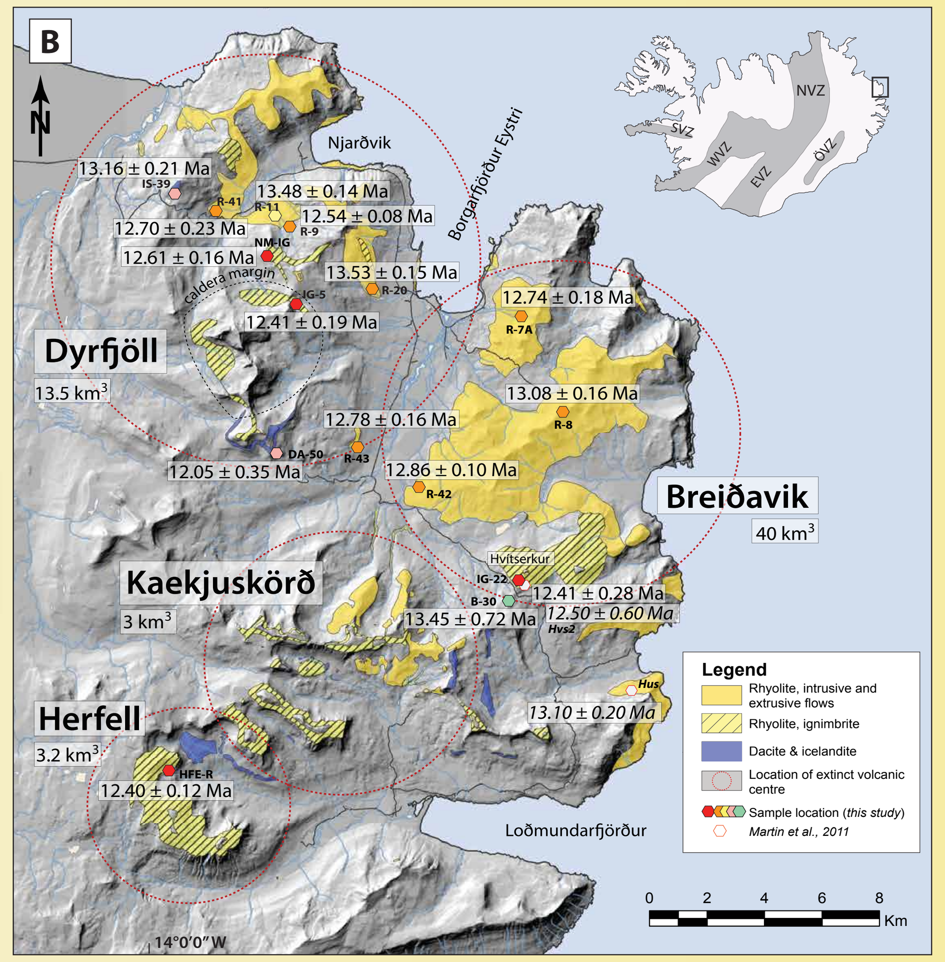


Figure 5. A) Age distribution along W, reference samples in grey. Hatched area represents a late explosive volcanic phase. **B)** Geological map of the silicic volcanic complexes around Borgarfjörður Eystri, NE-Iceland. Post-erosional silicic rock volumes are presented for each centre. Sample localities of the U-Pb dated rock units are marked, colour scheme as in Fig.5A.

3 Zircon oxygen isotopes

» The zircon oxygen isotope dataset spans from **1.2 to 4.4 ‰** (± 0.2 ‰, n= 337), giving a range from **2.8 to 5.9 ‰ for the parental magma(s)** (Fig. 6 & 7, c.f. Lackey et al., 2008).

» **Magma $\delta^{18}O$ values are less than expected for rhyolites** following Rayleigh fractionation (FC), where $\delta^{18}O$ ~ 6.2 to 6.7 ‰ (Fig. 6 & 7, e.g. Bindeman, 2008).

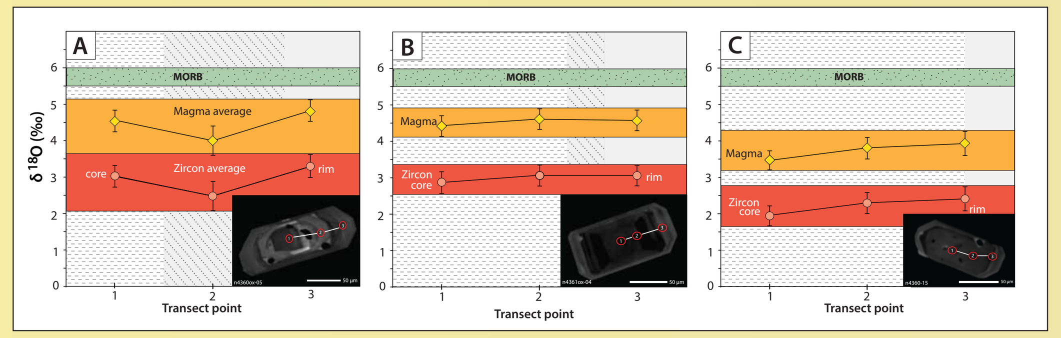


Figure 6. A - C) Zircon $\delta^{18}O$ core - rim traverses by SIMS (Nordsim, Stockholm). Background patterns symbolise zircon zoning, which is also apparent in the insets of cathodoluminescence zircon annotated with spot location.

Zircon $\delta^{18}O$ core-rim traverses (Fig. 6)

» Most crystals show no statistical variation from core to rim, **no isotopic zoning** of $\delta^{18}O$.

» The **magma's $\delta^{18}O$ composition predates zircon crystallisation!**

» Absence of significant **$\delta^{18}O$ increase with differentiation indicate ongoing assimilation.**

Magma $\delta^{18}O$ variation over time shows a **two-step trend** (Fig. 7):

1) Rhyolites become progressively lower in $\delta^{18}O$ until they reach a minimum at ~12.8 Ma.

2) Followed by a **$\delta^{18}O$ increase** along with extrusion of **large volume ignimbrites** in the whole region, to finally approach MORB-like values around ~12 Ma as dacite and basalt erupt (see arrow in Fig. 7B).

Low $\delta^{18}O$ magmas culminated at ~12.8 Ma.

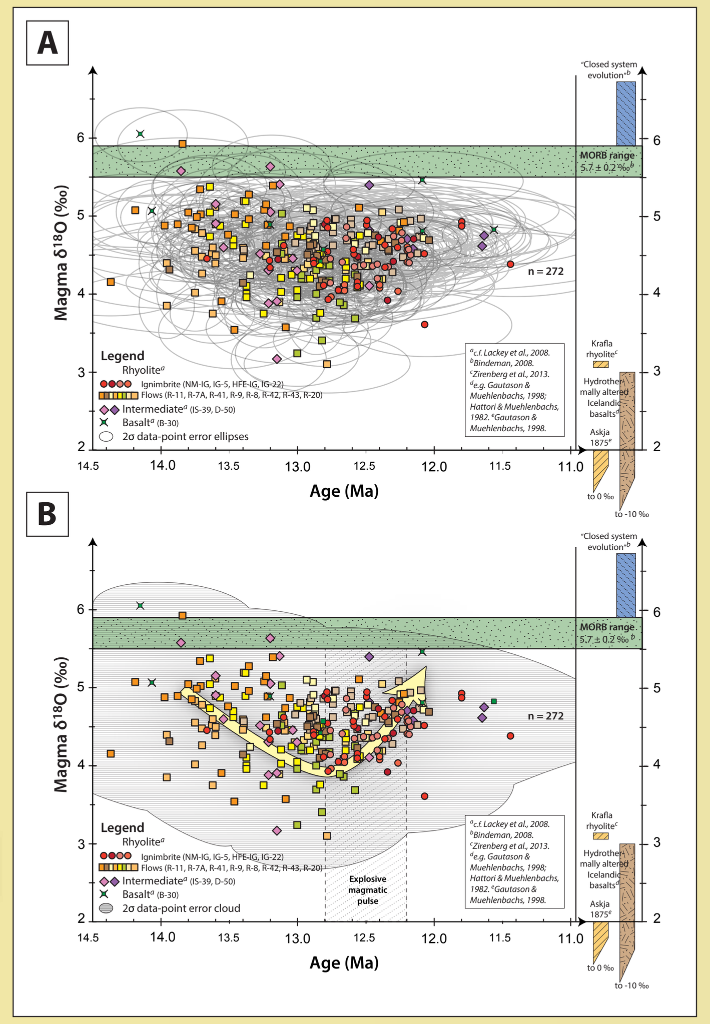


Figure 7. **A)** Magma $\delta^{18}O$ variation versus age of the rock units. Reference data is presented on the right hand side of the diagram. **B)** Interpretation of A), error ellipses represented by a grey cloud.

4 Assimilation model

» **Hydrothermally metamorphosed** basalts are widespread in Iceland, and record a wide range of negative $\delta^{18}O$ values, down to -12 ‰ (Fig. 8A, e.g. Hattori & Muehlenbachs, 1982).

» A conservative low $\delta^{18}O$ **contaminant of 0 ‰** (hydrothermally altered basalts) shows that **~50 % of high silica crustal melt** into mantle-derived basalt is required to explain the lowest $\delta^{18}O$ values recorded in zircon (Fig. 8A-B).

» This model also satisfies the required mass balance constraints for SiO_2.

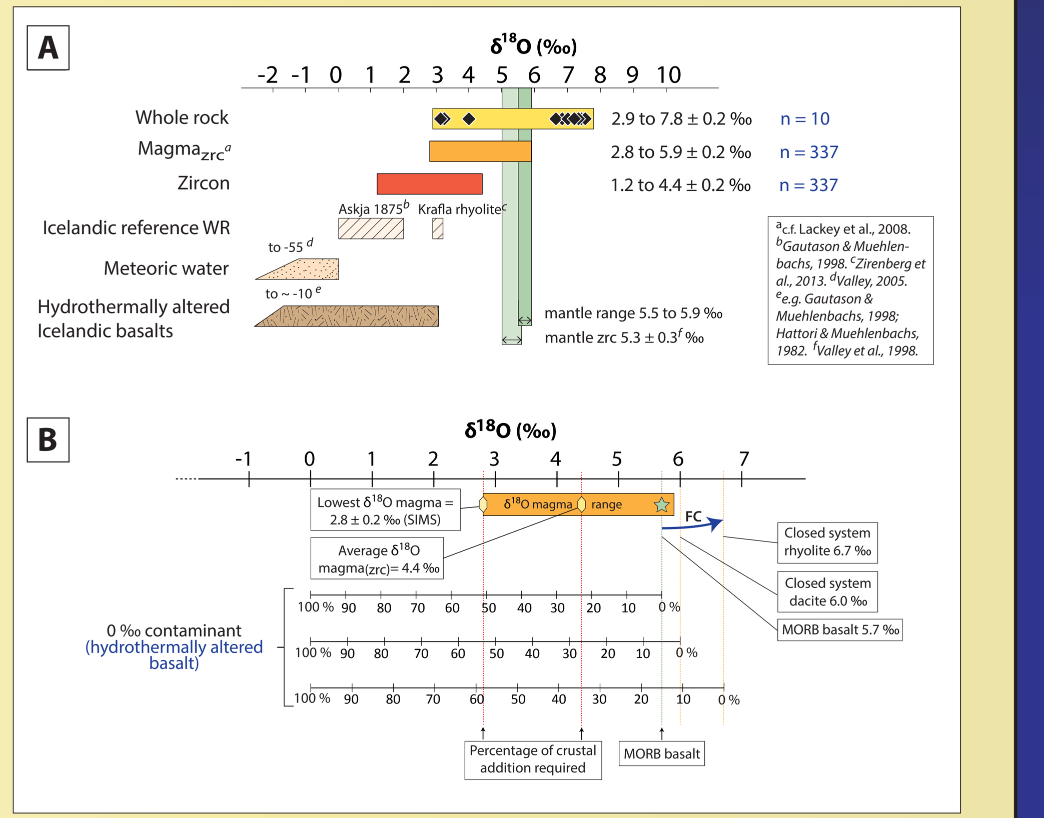


Figure 8. A) $\delta^{18}O$ variation in our zircon and whole rock (red to yellow bars), and literature data in brown to beige bars. **B)** Assimilation model with a 0 ‰ contaminant and three different starting materials. The orange bar represents our recorded zircon $\delta^{18}O$ values, and blue arrow shows FC-trend.

5 Neogene plume flare within Plume-Related Flank-Rift Zone

» High assimilation rates require special circumstances that can explain the **rapid generation of silicic magmas**, as well as the **sudden end of silicic volcanism** in the region.

» Voluminous outburst of silicic volcanism (Fig. 1 & 9) was likely caused by either:

Figure 9. Hvitserkur ignimbrite formed during one single large eruption at 12.4 Ma.

1) A **Neogene rift relocation** (Martin et al., 2011).

2) The **birth of a flank-rift zone** east of the mature rift, associated with a **Neogene flare of the Iceland plume** (c.f. Óskarsson & Riishuus, 2013), i.e. a plume-related flank-rift zone (c.f. Öræfajökull) brought mantle-derived magma into contact with fertile hydrothermally-altered basaltic crust. This interaction triggered a **massive crustal melting event** that became highly effective for a limited period of time (e.g. Annen et al., 2006) and generated mixed-origin silicic melts.

The plume-related magmatic regime offers a plausible **analogue for the pulsatory formation of (the earliest) voluminous proto-continental silicic crust in a pre-subduction (> 3 Ga) early Earth** (c.f. Hawkesworth & Kemp, 2006).

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