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Refining Hf crust formation ages in Precambrian terranes

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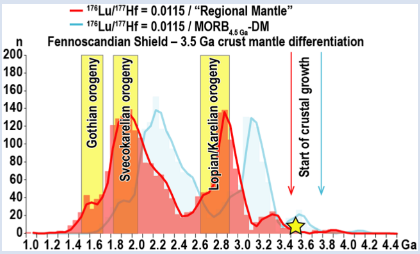
Abstract



The mechanisms and timing of long term chemical differentiation of the Earth are fundamental questions in the geosciences. We present detrital zircon U-Pb, O and Hf isotope data from Fennoscandia to assess how crustal growth can be reconciled with its known >1.5 billion year geological history. A broadly linear evolution (^{176}Lu/^{177}Hf = 0.0403), from chondritic mantle at the age of the oldest identified Fennoscandian crust, to present day MORB values ($\varepsilon_{Hf(0\ Ma)} \approx +16$), provides a good fit with the most radiogenic zircon and whole rock Hf isotope data from the region. This mantle reference gives crustal growth peaks that correlate with known regional orogenic events. In contrast, a conventional 4.5 Ga strongly depleted mantle generates growth peaks outside of known geologic activity. Applying the same approach to the East Pilbara Terrane and SW Greenland yields model age peaks that also align with known magmatic activity. We propose that more geologically relevant crust formation ages are obtained *via* referencing a mantle source defined by the most radiogenic zircons/samples in the studied region.

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Introduction

The mechanisms and timing of long term chemical differentiation of the Earth are fundamental questions in the geosciences. Depleted mantle curves based on Hf isotopes typically depict a quasi-linear evolution since planetary formation (*e.g.*, Vervoort and Blichert-Toft, 1999), and these curves have important implications when calculating continental crust formation ages (see Vervoort and Kemp, 2016). The most commonly used depleted mantle curves project from chondritic compositions at *ca.* 4.5 Ga to current radiogenic mid-ocean ridge basalt (MORB) values of $\varepsilon_{Hf} \approx +16$, herein termed MORB$_{4.5\ Ga}$-DM (*e.g.*, Vervoort and Blichert-Toft, 1999). A consequence of using MORB$_{4.5\ Ga}$-DM for estimating times of crust formation is that it regularly predicts up to several hundred million years between the juvenile crust extraction and subsequent reworking into felsic lithologies (*e.g.*, Lancaster *et al.*, 2011). This implies that crust generation and crustal differentiation may have occurred in different tectonic settings and requires a mechanism for long term survival of presumably mafic protocrust before reworking into continental materials. The inferred times of crust formation are also commonly cryptic, with little expression in the geological record, and therefore the geodynamic controls on crust generation are unclear (Vervoort and Kemp, 2016). Furthermore, it is increasingly recognised that radiogenic isotope data from juvenile felsic and mafic rocks in many Archean-Proterozoic terranes show indications of not being consistent with derivation from MORB$_{4.5\ Ga}$-DM. Instead, Nd and Hf isotope data suggest a globally near-chondritic to mildly depleted mantle source for Eo- to Paleoarchean continental crust (*e.g.*, Guitreau *et al.*, 2012; Fisher and Vervoort, 2018; Petersson *et al.*, 2019a, 2020; Whitehouse *et al.*, 2022; Kemp *et al.*, 2023).

One test of the applicability of a chosen mantle curve for calculating times of crust generation is whether the model crust formation ages can be reconciled with the observed geology. An ideal location to assess this question is the Scandinavian portion of the Fennoscandian Shield, which preserves a protracted orogenic history that spans from *ca.* 2.7 Ga to *ca.* 1.0 Ga. While there is abundant zircon Hf isotope data from central and southern Sweden (Andersson *et al.*, 2011; Petersson *et al.*, 2015, 2017; Petersson and Tual, 2020), comparatively few Hf isotope data exist from further north. Hence, to fully characterise the Archean-Proterozoic Hf isotope evolution of the Fennoscandian mantle, additional data from the central to northern regions are required.

We here examine the initial Fennoscandian crustal growth history through zircon U-Pb, O and Lu-Hf isotope data from detrital zircons from six major river systems in central to north eastern Sweden (Fig. 1). A model is developed to interpret these data, together with previously published zircon and whole rock Hf isotope data, in the context of a mantle source corresponding to the existing geological evolution of the region. An outcome of this model is that growth of Fennoscandian crust occurred mainly in Proterozoic orogenic events, with only limited crust formation in the Archean. We show that for Fennoscandia, and for several other Archean cratons, the approach of using a geologically constrained mantle source curve eliminates the requirement of long time gaps between initial crust extraction and differentiation to produce felsic crust, and leads to a better

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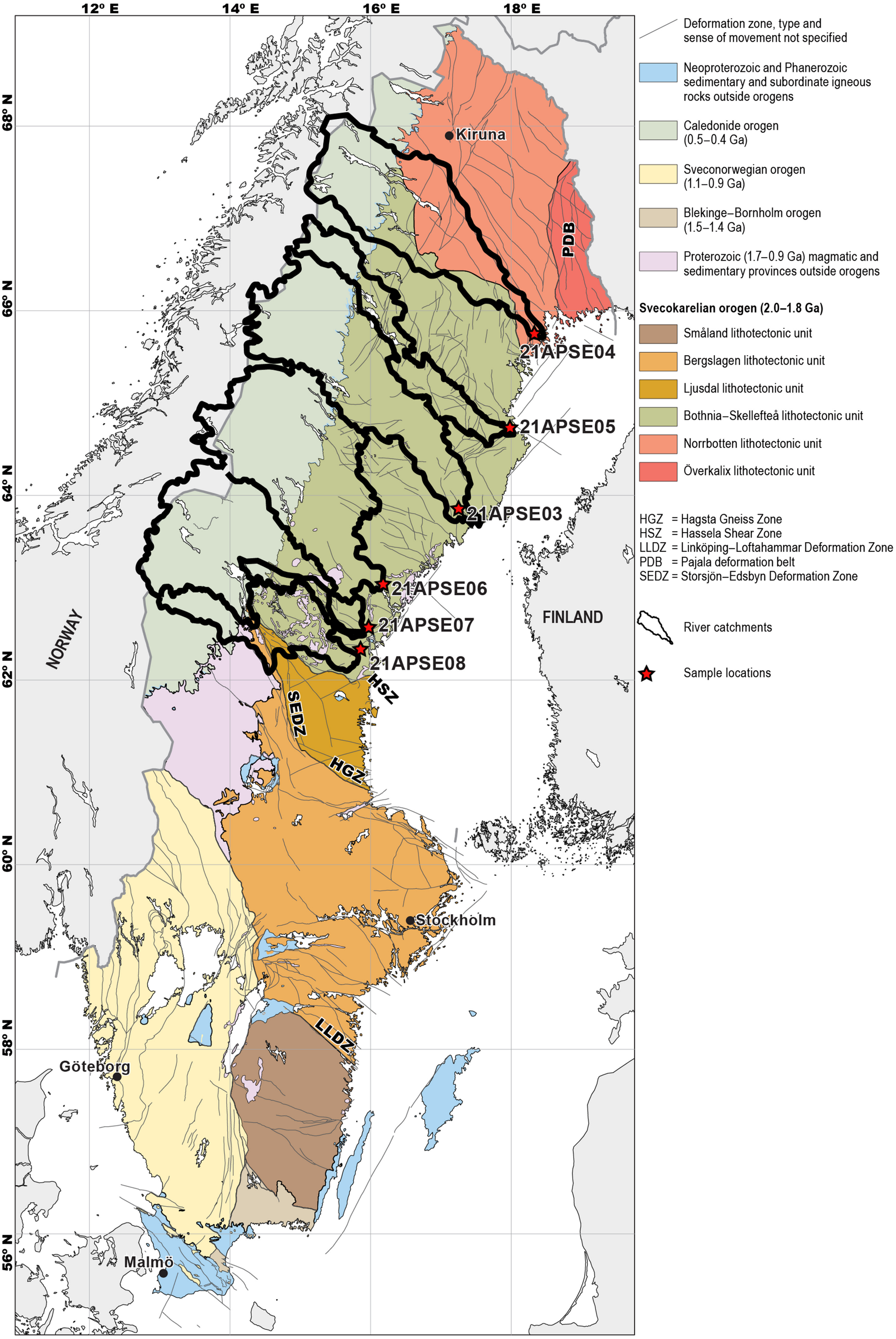

Figure 1 Simplified map of Sweden showing sample locations and the lithotectonic units of the 2.0–1.8 Ga Svecokarelian orogen and sampled river catchments. The map is largely based on the map of Stephens and Bergman (2020).

alignment between times of inferred crustal growth and periods of known orogenic activity.

Results

The zircon U-Pb, O and Hf isotope data from the Fennoscandian detrital zircon grains are summarised in Figure 2 (see Supplementary Information for details of the geological setting, sample information and analytical protocols). The age spectrum of the Fennoscandian detrital zircon grains matches the published igneous rock data from the region, with major age peaks at *ca.* 1.88 and 1.80 Ga, and a minor peak at 2.7 Ga. Zircon oxygen isotopes, expressed as $\delta^{18}O$ values, range between +4.7 ‰ and +10.7 ‰. Zircon grains with heavy $\delta^{18}O$ values (*i.e.* above the mantle range of 5.3 ± 0.6 ‰; Valley *et al.*, 2005) occur in all river samples. The Paleoproterozoic detrital zircon grains have a wide range of Hf isotope compositions ($\varepsilon_{Hf(t)}$ from −9.1 to +8.2), while Archean detrital grains cluster around the chondritic uniform reservoir (CHUR), with $\varepsilon_{Hf(t)}$ values between −2.7 and +3.5 (Fig. 2). Overall, there is good correspondence between the isotope signatures of detrital zircon from this study and previously reported Hf isotopes of zircon from (meta-)igneous rocks from the Fennoscandian Shield (Fig. 2).

Tracing the Fennoscandian Mantle Source. To accurately interpret the crustal growth, reworking and evolution of the Fennoscandian Shield using zircon isotope data requires characterisation of the mantle source from which the crust was ultimately extracted. In this context, we note that collectively, the most radiogenic Fennoscandian zircon and whole rock Hf isotope signatures increase with time, where the upper envelope of the large data compilation intersects CHUR at *ca.* 3.5 Ga (Fig. 2). Such a pattern is difficult to reconcile with crustal separation from a depleted mantle source formed at *ca.* 4.5 Ga. If crust was extracted from a $MORB_{4.5\ Ga}$-DM source mantle, this would require that crustal residence times increase systematically with age (see arrows on Fig. 2), exceeding several hundred million years for Archean zircons. However, the likelihood that the linear trend amongst the most radiogenic Fennoscandian Hf isotope data (*i.e.* the yellow line on Fig. 2) would be so well defined in such an *ad hoc* scenario seems unlikely (see Whitehouse *et al.*, 2022). As noted by Kemp *et al.* (2023), time scales for differentiation of basaltic protoliths into felsic igneous rocks may be short, far shorter than the >200 Myr required to generate the Hf isotope signatures seen in Fennoscandia if derivation from a $MORB_{4.5\ Ga}$-DM source is invoked. Additionally, data from mantle-derived (ultra-) mafic samples from Fennoscandia, which potentially represent the closest equivalents for source rocks for TTG magmatism and crustal differentiation, follow the same trend as the zircon Hf data (see Supplementary Information). Whether the evolution of the global depleted mantle Hf isotope composition is truly linear over Earth history is difficult to assess. It is conceivable that the periodicity of crust generation leads to complex spatio-temporal patterns of mantle depletion that produce multiple evolutionary trajectories in Hf *versus* time space, although such variably depleted mantle domains could be convectively mixed out on longer time scales. In any case, the approximately linear trend described by radiogenic Hf isotope data from the terranes studied herein, and the compatibility of crust formation calculations using this trend with the preserved geology, favours a broadly linear evolution for the mantle source of new crust through time.

When examining the zircon isotope data in $\delta^{18}O$ *versus* $\varepsilon_{Hf(t)}$ space (Fig. S-4), reworking of ancient continental crust unaffected by the hydrosphere ($\delta^{18}O <$ *ca.* 6 ‰) and supracrustal rocks affected by hydrosphere interaction ($\delta^{18}O >$ *ca.* 6.5 ‰) is inferred. Not surprisingly, due to larger volumes of crust and the Svecokarelian Orogeny, indications of reworking are stronger during the 2.0–1.8 Ga time period than during the

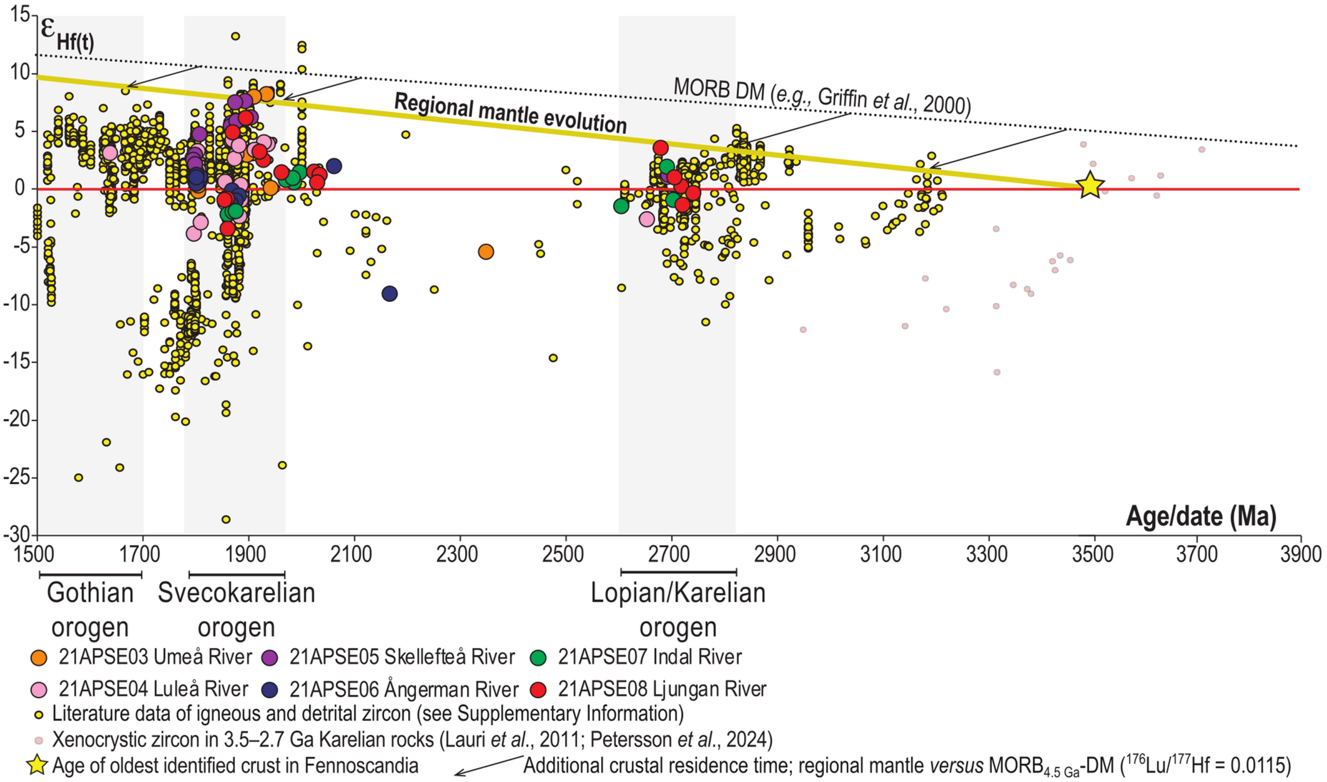

Figure 2 Zircon $\varepsilon_{Hf(t)}$ *versus* age of river zircon and Fennoscandian literature data. $\varepsilon_{Hf(t)} = [(^{176}Hf/^{177}Hf)_{unknown}/(^{176}Hf/^{177}Hf)_{CHUR} - 1)] \times 10^4$.

Archean, but both during the Archean and during the Paleoproterozoic, the combined zircon Hf and O isotope data trends project back to a *ca.* 3.5 Ga chondritic mantle. A few xenocrystic >3.0 Ga zircon cores from the Pudasjärvi Complex (Mutanen and Huhma, 2003; Lauri *et al.*, 2011; Petersson *et al.*, 2024a) have unradiogenic Hf isotope signatures that suggest reworking of >3.5 Ga crust (Fig. 2). These zircon hint at an even older crustal components in Fennoscandia, but as these have been shown to originate in the North Atlantic Craton they do not represent Fennoscandian crustal growth and/or mantle depletion (Petersson *et al.*, 2024a).

Linking Crust Formation to Regional U-Pb-Hf Isotope Signatures

The oldest rock in the Fennoscandian Shield is the Siurua gneiss of the Pudasjärvi gneiss complex in Finland, which has a protolith age of *ca.* 3.5 Ga (Mutanen and Huhma, 2003; Petersson *et al.*, 2024a). We infer that this sample represents the onset of crust formation in the area. Since the upper envelope of Hf isotope signatures project back to CHUR at this time (*ca.* 3.5 Ga), this intersection is interpreted to define the onset of significant Fennoscandian crust-mantle differentiation and crustal growth. Very few Hf isotope data plot above this line, attesting to the overall mildly depleted nature of the mantle from which Fennoscandian crust was extracted. Considering that laser ablation data typically have a reproducibility of ≥1.5 ε_{Hf} units (at 2 s.d.) when analysing REE-rich zircon (Fisher and Vervoort, 2018), data points plotting *ca.* 1.5 ε_{Hf} units above the true value are to be statistically expected. Hence, collectively, the Hf isotopic signatures of the most radiogenic zircon and whole rocks in Fennoscandia from 3.5 to 1.5 Ga suggest a mildly depleted non-MORB$_{4.5\ Ga}$-DM source.

Comparable situations are recognised in other Archean terranes. For example, in the East Pilbara Terrane, Australia, the upper envelope of Hf isotope signatures projects back to CHUR at the time of the oldest identified rocks in the craton, at 3.6 Ga (green line in Fig. 3b) (Amelin *et al.*, 2000; Kemp *et al.*, 2015, 2023; Petersson *et al.*, 2019a, 2019b, 2020). Similarly, in southern West Greenland the most radiogenic zircon Hf isotope signatures intersect CHUR at 3.9 Ga, where meta-igneous rocks with chondritic compositions suggest initial crustal growth at this time (orange line in Fig. 3c) (*e.g.*, Kemp *et al.*, 2009, 2019;

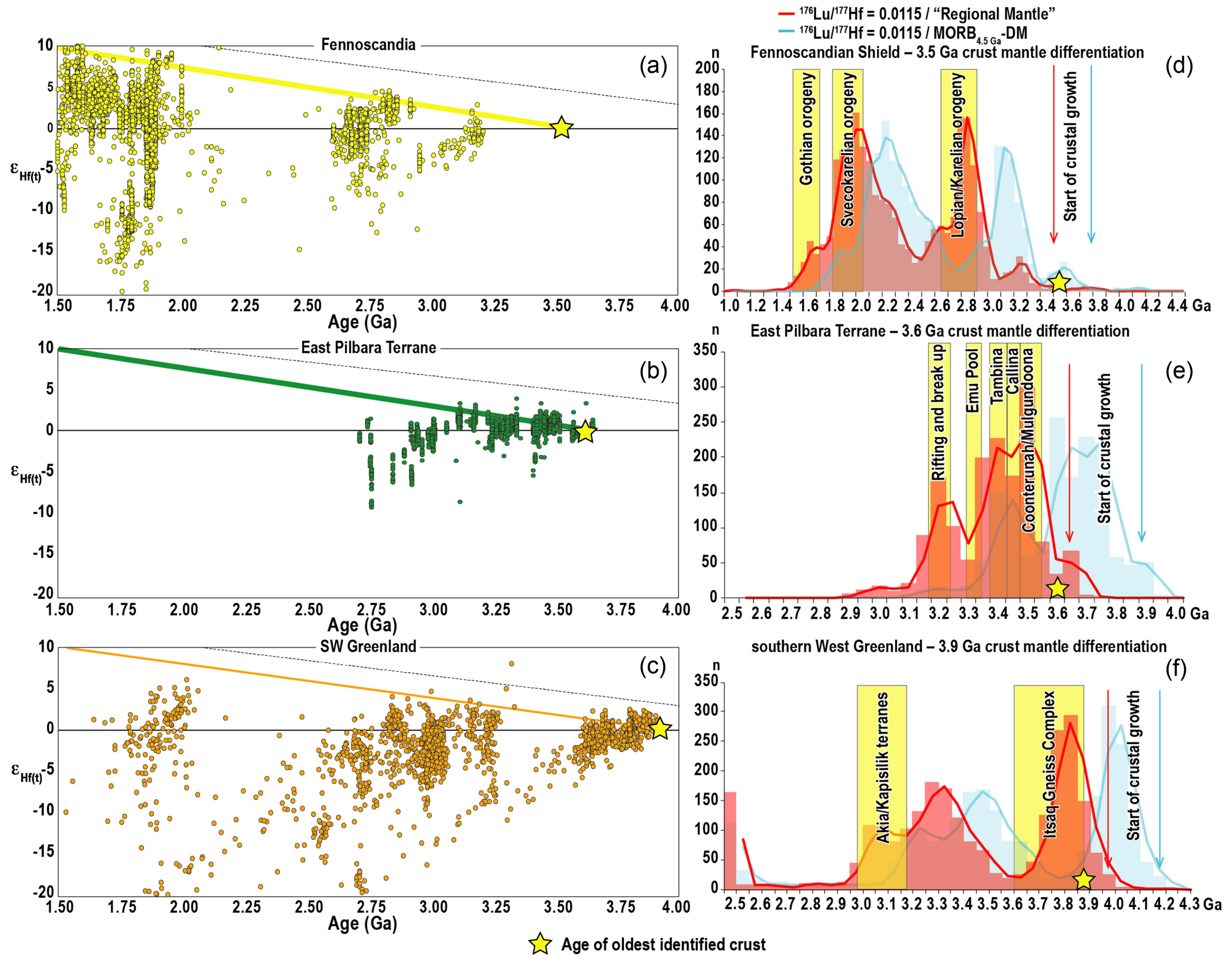

Figure 3 **(a–c)** Zircon $\varepsilon_{Hf(t)}$ *versus* age, showing regional mantle curves defined by the most radiogenic Hf isotope signatures traced back to a chondritic mantle at the age of the oldest known regional crust. **(a)** Fennoscandian Shield. **(b)** East Pilbara Terrane, Western Australia. **(c)** Southern West Greenland. **(d–f)** Histograms showing respective two stage model ages based on a bulk continental crustal $^{176}Lu/^{177}Hf$ = 0.0115 evolution. Red data using a regional mantle references and blue data are based on a MORB$_{4.5\ Ga}$-DM. Yellow boxes denote major events in each region; orogenies, rifting and major magmatic events.

Guitreau *et al.*, 2012; Fisher and Vervoort, 2018). Some data spread is apparent between 3.9 and 3.7 Ga, but always inside the expected reproducibility of a chondritic zircon analysed by LA-ICP-MS. We propose that a modelling approach, based on regional juvenile crustal rocks, better represents the evolution of the mantle in ancient terranes than an assumed linear evolution from a primordial composition at *ca.* 4.5 Ga to modern radiogenic MORB. As every craton and/or larger crustal region may be unique, crust formation ages are ideally calculated using mantle references that are specific to each region. The method implemented here applies to ancient terranes, and involves initial, significant crust-mantle differentiation at the time defined by the intersection between CHUR and the upper envelope of the most radiogenic Hf isotope signatures from the studied region. In the herein studied regions these intersections coincide with the time of the oldest identified crust in the area. Furthermore, the broadly linear trends of the upper envelopes (yellow, blue and red lines in Fig. 3a–c) project towards present day MORB values of $\varepsilon_{Hf} = +16$. We further propose that a similar approach could be used for other ancient cratons/regions in order to generate more geologically meaningful crust formation ages, that could be used in global crustal growth models or for comparing evolutionary histories of different tracts of Archean crust.

Linking Crust Formation Ages to Orogenic Events

In Figure 3, we calculate crust formation ages from the Fennoscandian zircon and whole rock Hf isotope data using a regional mantle curve, where initial depletion occurs at 3.5 Ga, and a bulk continental crustal $^{176}Lu/^{177}Hf$ of 0.0115 (Vervoort and Patchett, 1996). This yields crustal growth peaks that correlate with known orogenies, *i.e.* the 2.8–2.6 Ga Lopian/Karelian orogeny and 2.0–1.8 Ga Svecokarelian orogeny, and even a minor peak during the 1.7–1.5 Ga Gothian orogeny (Fig. 3d). Using the same crustal evolutionary trajectories, but a $MORB_{4.5\ Ga}$-DM, yields growth peaks at *ca.* 3.15 Ga and 2.3 Ga, which are periods of magmatic quiescence in Fennoscandia. Hf model ages calculated this way also suggest initial crust formation at *ca.* 3.8 Ga, much older than any known crust so far identified within the Fennoscandian Shield, and thus likely erroneous.

These results are based on a bulk continental crustal source with a $^{176}Lu/^{177}Hf$ of 0.0115 (Vervoort and Patchett, 1996). Changing the $^{176}Lu/^{177}Hf$ to values more typical of felsic (0.009) or more mafic (0.022) crust does not affect the peaks significantly when using a regional mantle model, but the shift in model age peaks is more marked for a $MORB_{4.5\ Ga}$-DM source mantle (Fig. 4).

In the East Pilbara Terrane, using a mantle reference that deviates from CHUR at 3.6 Ga (Fig. 3b), results in Hf model ages with peaks at *ca.* 3.5 Ga, 3.4 Ga and 3.2 Ga. These are all times of known juvenile magmatic activity within the East Pilbara Terrane, with 3.5 Ga being the time of emplacement of the Coonterunah Subgroup within the *ca.* 15 km thick Warrawoona Group, consisting mainly of komatiitic basalt, basalt, andesite and dacite (Hickman, 2021). At 3.4 Ga, the Tambina Supersuite and the Salgash Subgroup were emplaced, and 3.2 Ga is the inferred time of rifting and breakup of the Paleoarchean volcanic plateau, accompanied by voluminous eruption of basalt and komatiite (Hickman, 2021). Using a $MORB_{4.5\ Ga}$-DM reference yields major peaks at 3.75 Ga and 3.6 Ga, when the oldest known significant crustal growth event in the Pilbara Craton is 3.5 Ga and older material only being identified as sparse zircon xenocrysts in very limited outcrops (Fig. 3e; Petersson *et al.*, 2019a, 2020).

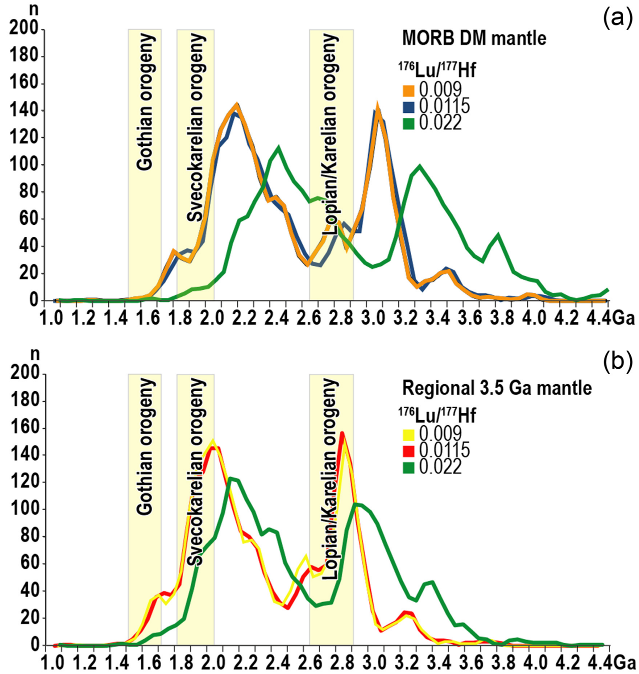

Figure 4 Probability density plots showing the change in crustal growth peaks with different $^{176}Lu/^{177}Hf$ values for the **(a)** MORB DM and **(b)** regional 3.5 Ga mantle sources.

Southern West Greenland primarily comprises tonalite-trondhjemite-granodiorite gneisses that range from *ca.* 3.9 Ga to 3.65 Ga. When using a mantle reference that diverges from CHUR at 3.9 Ga, the reference line tangents the most radiogenic Meso- to Neoarchean zircon Hf isotope data in the region (Fig. 3c). The main crustal growth peak calculated using this model mantle composition is at *ca.* 3.85 Ga, in line with known magmatic emplacement ages, and in stark contrast to the 4.1 Ga peak obtained using a conventional $MORB_{4.5\ Ga}$-DM, which is 200 Myr older than any identified crust on Greenland (Fig. 3f). A second growth peak at *ca.* 3.1–3.0 Ga coincides with the emplacement of the Akia and Kapisilik terranes (Nutman *et al.*, 2015). The geological evolution of the Pilbara Craton and southern West Greenland are very different from the Fennoscandian Shield with, for example, the Pilbara Craton evolving *via* episodic and protracted mantle derived mafic and felsic magmatism resulting in development of a classic dome and keel architecture (Petersson *et al.*, 2019a). Hence, the geodynamic processes that generated continental crust in these regions differ vastly, making it even more striking that the zircon Hf model ages, using a regional mantle curve, align with orogenic events in all three cratons.

The regions discussed above suggest different timing for initial crust-mantle differentiation (3.9–3.5 Ga), which would result in a heterogeneous, variably depleted global Eo-Paleoarchean mantle. Long and short lived isotope signatures in some mantle derived rocks such as komatiites show that parts of the mantle have been depleted (*e.g.*, Boyet and Carlson, 2005; O'Neil *et al.*, 2024). These depleted components are, however, not registered in the crustal record *via* zircons as they are highly infertile and do not melt to generate continental crust. A scenario where initial melting generating basalt and komatiite leaving a refractory harzburgitic residue and primordial fertile mantle is continuously tapped from a less depleted reservoir is envisaged by Petersson *et al.* (2024b). Stracke (2012) argues for a heterogeneous Archean mantle, but primarily attribute this to enrichment *via* erosion and subduction of the lower continental crust. However, in the regions outlined above, as the chondritic mantle composition at the time of initial significant crust generation may predate the onset of significant amounts of subduction, this becomes a less viable explanation. Instead, we favour a lack of wholesale crust-mantle differentiation as the primary cause behind the preserved chondritic signatures into the Eo- and Paleoarchean. We note that the ^{142}Nd anomalies recognised in some cratons suggest Hadean Sm/Nd fractionation (*e.g.*, Boyet and Carlson, 2005; O'Neil *et al.*, 2024). Such anomalies are yet to be found in the Pilbara Craton or in the Fennoscandian Shield, and it remains unclear whether the ancient Sm/Nd fractionation was associated with formation of continental crust, and whether the amount of mantle differentiation needed to generate ^{142}Nd anomalies had a resolvable effect on the Lu-Hf isotope system. Furthermore, this Hadean Sm/Nd differentiation episode(s) does not seem to have generated complementary global crust-mantle reservoirs with respect to long lived radiogenic systems such as Hf isotopes.

We conclude that global Hf isotope heterogeneity amongst different Archean-Proterozoic terranes warrant regional mantle references, based on the most radiogenic samples from each region, in order to obtain reliable crust formation ages that align with the known geological evolution of the studied region.

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Additional Information

Supplementary Information accompanies this letter at https://www.geochemicalperspectivesletters.org/article2435.

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