Hadean protocrust reworking at the origin of the Archean Napier Complex (Antarctica)

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Geochemical Perspectives Letters

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Abstract

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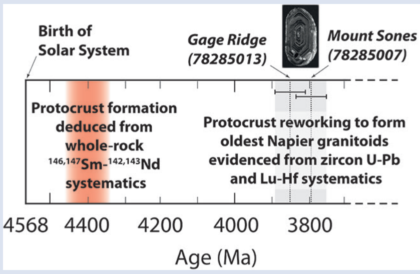

The origin of the first continents is still poorly constrained due to the great scarcity of >3.7 Ga rocks. The Napier Complex (East Antarctica) hosts such rocks but the extreme metamorphic conditions it experienced have compromised most isotopic systematics. Here we have studied Mount Sones and Gage Ridge orthogneisses from the Napier complex using microbeam (LA-MC-ICP-MS) U-Pb and Lu-Hf isotope measurements in zircon, together with ^{146,147}Sm-^{143,142}Nd isotope systematics in the corresponding whole rocks to uncover primary information about their origin. Our U-Pb results reveal that these orthogneisses formed at 3794 ± 40 and 3857 ± 39 Ma, respectively, by reworking of 4456-4356 Ma mafic protocrust, as testified to by ^{176}Lu-^{176}Hf and ^{147,146}Sm-^{143,142}Nd systematics. Other Eoarchean terranes in Greenland, Canada, and China also show involvement of Hadean crust(s) in their formation which suggests that protocrusts were massively reworked to form new continents around the Hadean-Eoarchean boundary. Such a mechanism would account for the absence of early-formed protocrust from the geological record despite recent models proposing rapid crustal growth in the Hadean (~25 % of present day volume or surface).

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Letter

The small number of localities hosting >3.7 Ga rocks, together with the absence of Hadean rocks from the geological record, is a limitation for our understanding of the early evolution of the Earth and the origin of the first continents (*e.g.*, Condie, 2007). The high metamorphic grade experienced by some of these Archean terranes further represents a challenge to uncover reliable information from their rocks and minerals. The Napier complex (East Antarctica) is one of the few Archean terranes that contain some of Earth's oldest rocks (Black *et al.*, 1986; Fig. S-1). This complex recorded Meso- and Neoarchean metamorphism that reached extreme conditions corresponding to granulite facies at 2.5 Ga (1050-1120 °C and 7-11 kbar; Table S-1) (Harley and Motoyoshi, 2000). Consequently, radiogenic isotope systematics (*e.g.*, Rb-Sr, Sm-Nd) were severely disturbed in most samples (*e.g.*, Black and McCulloch, 1987). Metamorphic events were recorded in zircon crystals that sometimes also preserved information about original crystallisation (Kelly and Harley, 2005). These grains show a greater complexity than commonly seen in ancient zircons (Williams *et al.*, 1984; Black *et al.*, 1986; Guitreau *et al.*, 2012; Kusiak *et al.*, 2013; Hiess and Bennett, 2016) and deconvoluting original igneous signatures from metamorphic overprints remains challenging. This is particularly well-illustrated by the great dispersion of data points in ε_{Hf} *versus* age space (Fig. S-2 and Table S-2). More importantly, the oldest signatures overlap enriched (negative ε_{Hf} values) and depleted (positive ε_{Hf} values) domains, hence, leaving open contrasting possibilities for the nature of the source to these ancient rocks. The analytical methods employed in previous studies do not allow these complexities to be understood, which justifies the present contribution.

Here we combine cathodoluminescence (CL) and back scattered electron (BSE) images with U-Pb age profiles by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) in zircons from two Napier orthogneisses, following the procedure outlined in Guitreau *et al.* (2018). We also measured Lu-Hf isotope systematics by LA-MC-ICP-MS within the same zircon crystals. Finally, we analysed ^{146,147}Sm-^{143,142}Nd isotope systematics in corresponding whole rock samples to constrain the early history of their source better. Information regarding analyses and results are provided in Methods (see Supplementary Information and Tables S-3 to S-11). The two studied samples are gran-ulitic orthogneisses labelled 78285007 (Mount Sones) and 78285013 (Gage Ridge). They are among the oldest rocks from this area (Black *et al.*, 1986; Harley and Black, 1997). Mount Sones exhibits chemical composition identical to that of typical Archean tonalite-trondhjemite-granodiorite (TTG) suites (*e.g.*, high Na_2O/K_2O, high Sr/Y, fractionated REE patterns; Moyen and Martin, 2012) with a normative composition intermediate between tonalite and trondhjemite (Black *et al.*, 1986; Fig. S-3). Gage Ridge has a composition

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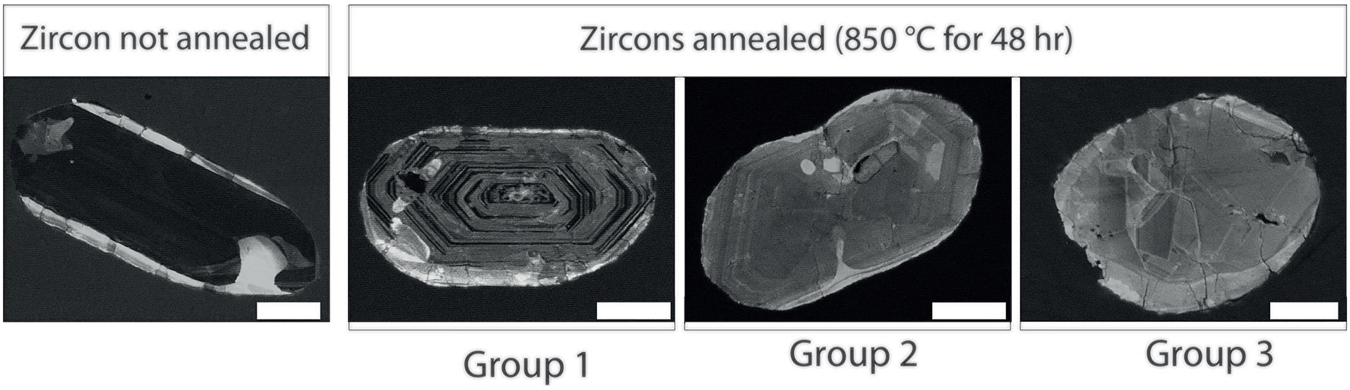

Figure 1 Cathodoluminescence images of representative crystals from Napier zircon populations with details of textures with and without annealing. This figure illustrates the CL signal enhancing effect of zircon annealing which, in turn, allows three groups to be identified based on internal textures (see text for details). Thick white bars represent 50 µm.

closer to that of granite (Harleyand Black, 1997) despite a strongly fractionated REE pattern with a pronounced positive Eu anomaly suggesting that it is likely a cumulate from a TTG melt (Fig. S-3).

Napier zircon crystals have experienced a complex geological history which is difficult to decipher given their high U and Th concentrations that are responsible for the faint signals in CL images (*e.g.*, Kusiak *et al.*, 2013). These issues prevented internal textures to be examined properly in previous studies as shown in Figure 1 (see also Figs. S-4 to S-7). We performed annealing on a subset of zircon crystals (850 °C for 48 hr) because this thermal process increases the intensity of the CL signal (Nasdala *et al.*, 2002). Annealed zircons exhibit well-defined textures that allowed us to identify three groups (Fig. 1). The first group shows fine oscillatory zoning, with large contrasts between growth zones, that we interpreted as magmatic (Fig. 1). The second group is also interpreted as magmatic because it exhibits fine oscillatory zoning, with local sector zoning, but with very little contrast between growth zones (Fig. 1). The third group consists in irregular and/or chaotic textures that resemble metamorphic zircons (Fig. 1, Figs. S-4 to S-7; Corfu *et al.*, 2003). The first and second groups are often surrounded by metamorphic overgrowths that, hence, belong to the third group (Figs. S-4 to S-7). All groups are present in Mount Sones, whereas only the first and third groups are represented in Gage Ridge.

In both samples, zircons from group 1 are characterised by large variations in $^{207}Pb/^{206}Pb$ ages, ranging from the oldest determined (3794 ± 40 in Mount Sones and 3857 ± 39 Ma in Gage Ridge) down to about 2500 Ma, and broadly consistent initial $^{176}Hf/^{177}Hf$ around the least radiogenic values (0.2802-0.2804), except for a few data points in Gage Ridge (Fig. S-8, Table S-7). This translates into major positive correlations in ε_{Hf} *versus* age diagram with all ε_{Hf} being negative (Fig. 2). Group 2 zircons, which are only found in Mount Sones, form a coherent cluster with $^{207}Pb/^{206}Pb$ ages between 2700-2900 Ma and initial $^{176}Hf/^{177}Hf$ among the most radiogenic (0.2806-0.2808; Fig. S-8, Table S-7) despite their corresponding initial ε_{Hf} values being all negative (Fig. 2). Group 3 zircons, contrary to group 1, show little variation in $^{207}Pb/^{206}Pb$ ages (2400-2700 Ma) but large variations in initial $^{176}Hf/^{177}Hf$, and therefore ε_{Hf}, that almost cover the entire range of measured values (Fig. 2). Contrary to the first two groups which exhibit Th/U values within the common igneous range (0.2-0.8; Fig. S-9; *e.g.*, Kirkland *et al.*, 2015), the third group in Mount Sones shows a great variability in Th/U (up to 2.9) in line with its metamor-phic origin in granulite facies (*e.g.*, Vavra *et al.*, 1999). Our new data comply very well with those already published (Guitreau *et al.*, 2012; Hiess and Bennett, 2016), as shown in Figure S-2, and allow observed patterns to be properly deconvoluted and reliably interpreted.

The ε_{Hf}-age pattern observed for group 1 is typical of ancient zircon populations (Fig. 2; *e.g.*, Guitreau and Blichert-Toft, 2014) which experienced metamorphism that resulted in re-opening of the U-Pb system without influencing the Lu-Hf system signifi antly. Therefore, we interpret group 1 as the original igneous population. The second group is also igneous and probably represents melt percolation in Mount Sones, given its similarity in timing and Hf isotope composition to Dallwitz Nunatak orthogneiss which is located between Mount Sones and Gage Ridge (Figs. S-1 and S-10; Guitreau *et al.*, 2012). Group 3 represents zircons that grew and/or recrystallised during long-lived Neoarchean metamorphism. Their formation likely involved *in situ* dissolution-reprecipitation of radiation-damaged zircons, as well as influx of radiogenic Hf from high Lu/Hf minerals (*e.g.*, amphibole, biotite, plagioclase), thereby accounting for the large range of ε_{Hf} observed. The large discrepancies between Napier zircon and whole rock initial ε_{Hf} at 3.8 Ga indicate that Lu-Hf isotope systematics were disturbed at the whole rock scale during later metamorphic events, most likely around 2.5 Ga (Fig. S-10).

Our oldest ages for Mount Sones and Gage Ridge orthogneisses determined at 3794 ± 40 and 3857 ± 39 Ma, respectively, compares well with previous estimates of 3851 ± 62 Ma (Harley and Black, 1997; Kelly and Harley, 2005). The initial Hf isotope composition of group 1 zircons from Mount Sones and Gage Ridge are 0.280238 ± 0.00004 (2 s.d.; n = 23) and 0.280169 ± 0.00007 (2 s.d.; n = 7), respectively, which translates into initial ε_{Hf} of -2.6 ± 1.5 and -3.6 ± 2.5 for Mount Sones and Gage Ridge, respectively. Therefore, our results indicate that an enriched reservoir was tapped during the formation of the protoliths to the oldest orthogneiss of the Napier craton. Major and minor element concentrations for Mount Sones suggest its derivation from a mafic crust (Fig. S-3; Black *et al.*, 1986). Gage Ridge exhibits a strong positive Eu anomaly that would indicate that it is a cumulate and, therefore, its composition no longer represents that of a liquid. Consequently, we cannot unambiguously estimate its source based on geochemistry.

Coupled $^{147,146}Sm$-$^{143,142}Nd$ measurements provide additional constrains on the nature of this crust and the timing of its formation. Firstly, our new ^{147}Sm-^{143}Nd isotope data for Mount Sones are consistent with those published in Black and McCulloch (1987) (Fig. S-11) and give an ε_{Nd} of -2.0 ± 0.3 at 3794 Ma, which compares well with the Hf isotope signature of group 1 zircons from this sample. Therefore, we suggest that Mount Sones exhibits a near-pristine Nd isotope signature in contrast to the arguably disturbed Sm-Nd isotope systematics in Gage Ridge. Moreover, Napier samples exhibit negative $\mu^{142}Nd$ anomalies of -8.7 ± 3.9 for Mount Sones and -12.1 ± 6.2 for Gage Ridge (Fig. 3, Table S-9) which indicates that they

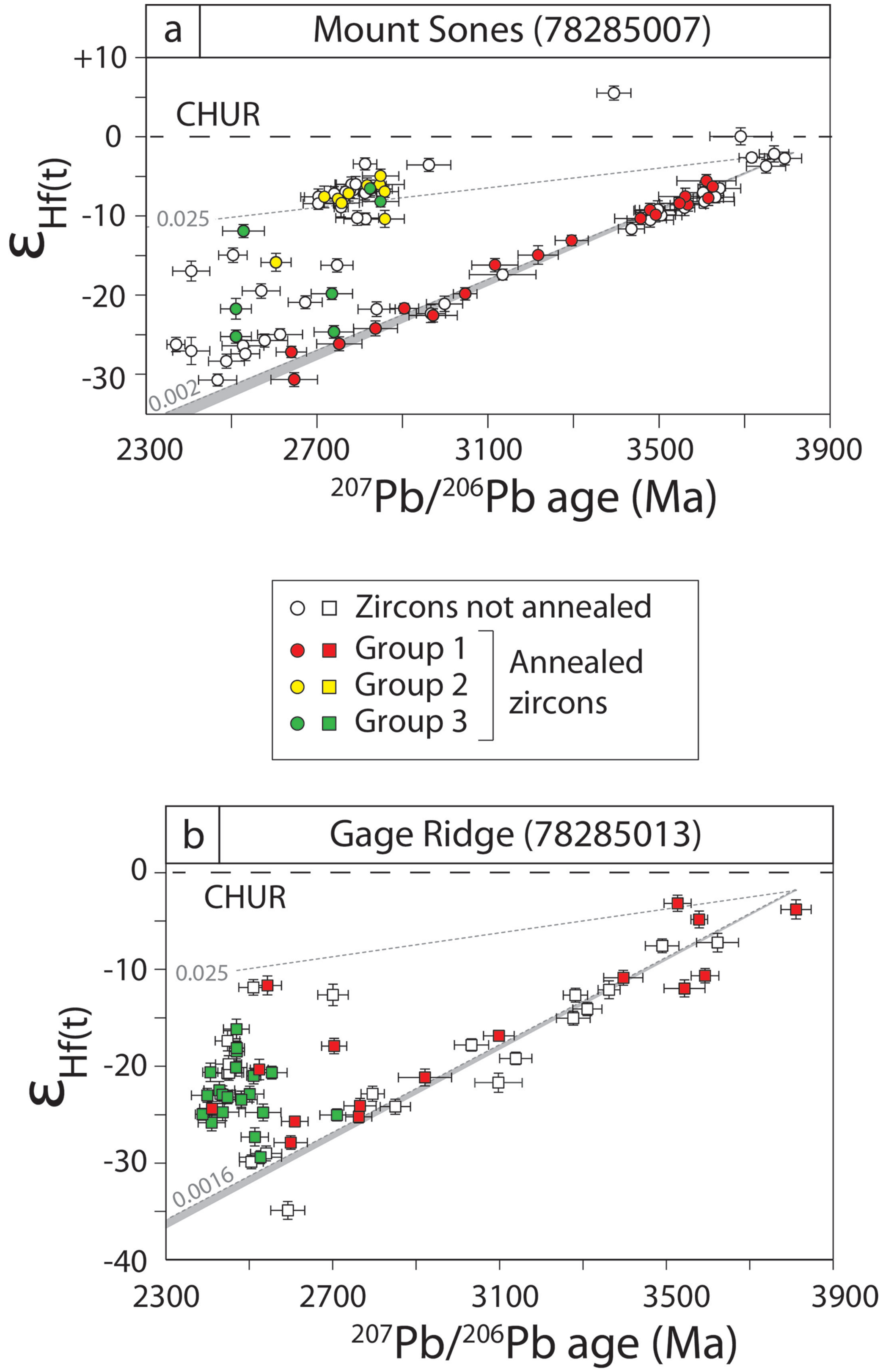

Figure 2 ε_{Hf} *versus* $^{207}Pb/^{206}Pb$ age diagrams for Mount Sones and Gage Ridge zircons. Black dashed lines represent the time-evolution of a CHUR reservoir (Iizuka *et al.*, 2015) formed at 4568 Ma (Bouvier and Wadhwa, 2010). Black dotted lines correspond to reservoirs that started with group 1 initial $^{176}Hf/^{177}Hf$ and evolved with $^{176}Lu/^{177}Hf$ ratios that are indicated on the left of the diagrams (*e.g.*, 0.025). The values of 0.002 and 0.0016 correspond to $^{176}Lu/^{177}Hf$ measured in whole rock powders of Mount Sones and Gage Ridge orthogneisses, respectively. The grey fields encompass evolutions of Napier zircons based on highest and lowest $^{176}Lu/^{177}Hf$ measured in Mount Sones and Gage Ridge zircon populations. The general positive correlation of data for group 1 highlights typical artefacts of ancient Pb loss (*e.g.*, Guitreau *et al.*, 2012). Therefore, the original Hf isotope signatures of corresponding zircon populations are indicated by the oldest (and most concordant) crystals, which happen to be sub-chondritic for both samples. Data are fully consistent between annealed and not-annealed zircons, hence, demonstrating that annealing did not influence any of the measured systematics.

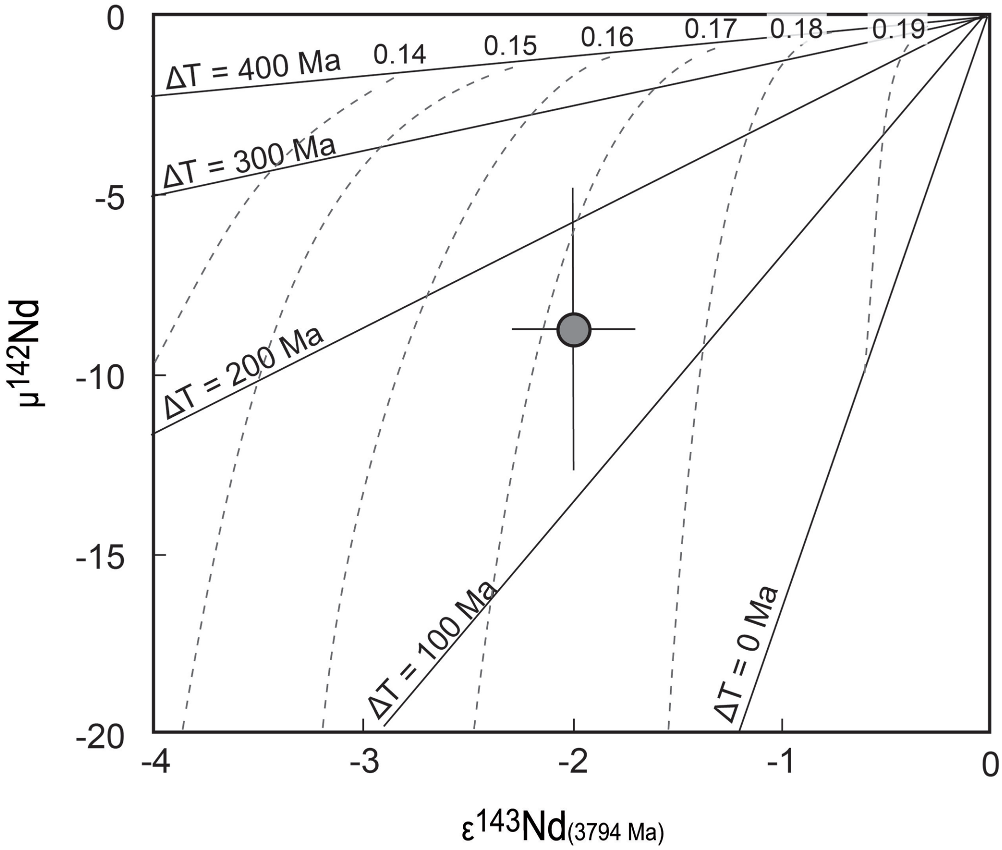

Figure 3 Coupled ^{146}Sm-^{142}Nd and ^{147}Sm-^{143}Nd plot showing the data obtained for Mount Sones orthogneiss (78285007) as well as the coupled evolution of μ^{142}Nd and ε^{143}Nd signatures for lithologies with various Sm/Nd ratios. Solid lines represent isochrons with respective ages indicated by ΔT, which means time after 4568 Ma. Dashed curves correspond to the coupled evolution of μ^{142}Nd and ε^{143}Nd signatures according to specific ^{147}Sm/^{144}Nd values that are indicated next to the curves (*i.e.* 0.14-0.19). Mount Sones μ^{142}Nd and ε^{143}Nd isotope signatures are compatible with a mafic source (^{147}Sm/^{144}Nd = 0.17) that separated from a reservoir with a chondritic REE pattern ~150 Myr after Solar System formation (*i.e.* ~4400 Myr ago). Here we assume that the initial ^{142}Nd/^{144}Nd ratio of the Earth is similar to that measured in the modern terrestrial mantle (μ^{142}Nd = 0), which is equivalent to the signature measured in enstatite chondrites from the EL sub-group (Boyet *et al.*, 2018).

both tapped an enriched reservoir that formed while ^{146}Sm was still extant, hence, during the first 300 Myr of Solar System history. Coupled Sm-Nd isotope systematics in Mount Sones further indicate that the enriched reservoir (precursor) formed between 4456 and 4356 Ma with a ^{147}Sm/^{144}Nd of ~0.17 (Fig. 3) which confirms i ts m afic na ture (*e.g.,* O' Neil an d Ca rlson, 2017). Using a global compilation of coupled Lu-Hf and Sm-Nd isotope systematics to estimate the equivalent ^{176}Lu/^{177}Hf to a ^{147}Sm/^{144}Nd of 0.17 (Albarède *et al.*, 2000), we obtain a value of 0.025 which is typical of a mafic c rust. Two s tage C HUR Lu-Hf model ages for Group 1 zircons give ages of 4212 ± 226 Ma for Mount Sones and 4422 ± 394 Ma for Gage Ridge, which are consistent with combined ^{147,146}Sm-^{143,142}Nd isotope systematics (See Methods in Supplementary Information). Our new results on Mount Sones and Gage Ridge orthogneisses, therefore, demonstrate that a very old Hadean mafic protocrust was reworked during the formation of the Napier craton.

Our conclusion echoes similar scenarios that have been proposed for other Archean terranes worldwide such as the Itsaq Gneiss Complex (Greenland; Kamber *et al.*, 2003; Kemp *et al.*, 2019), the Acasta Gneiss Complex (Canada; *e.g.*, Guitreau *et al.*, 2014; Roth *et al.*, 2014; Reimink *et al.*, 2018), the Nuvvuagittuq Supracrustal Belt (Canada; *e.g.*, O'Neil and Carlson, 2017; Caro *et al.*, 2017), and the North China craton (Li *et al.*, 2017). Therefore, we propose that Hadean proto-crusts (and proto-continents) were massively reworked at the Hadean-Eoarchean boundary in order to account for both the absence of Hadean crust in the present day and its little influence throughout the Archean (e.g., Guitreau *et al.*, 2012; Roth *et al.*, 2014; Kemp *et al.*, 2015) despite recent models proposing that crustal growth was rapid in the Hadean and Eoarchean (~25 % of present-day volume or surface Belousova *et al.*, 2010; Dhuime *et al.*, 2012).

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Additional Information

Supplementary Information accompanies this letter at http://www.geochemicalperspectivesletters.org/article1927.

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