PRESERVATION OF ISOTOPIC RECORDS FROM LATE ACCRETION IN ARCHEAN SAMPLES: A REASSESSMENT. R. C. J. Steele[1,2*], C. Münker[3] and M. Schönbächler[2], [1]STAiG, School of Earth and Environmental Sciences, University of St Andrews, UK. *rcjs@st-andrews.ac.uk [2]Institute of Geochemistry and Petrology, ETH Zürich, Switzerland, [3]Department of Geology and Mineralogy, University of Cologne, Germany.

Introduction: The last material accreted to Earth holds the key to understanding the volatile budgets of terrestrial planets. In addition, this material represents a record of the material present after the main formation phases of terrestrial planets. Therefore, understanding late accretion provides powerful constraints on both terrestrial planet formation and the transport of material between different regions of the early Solar System.

Late accretion to Earth can be investigated by examining the record of the oldest rocks on Earth, for example the rocks of southwest Greenland. Chemical and isotopic differences between mantle samples from these Archean terranes and the present-day mantle can be used to constrain the composition of this late accreted material. Comparison with chondritic meteorite isotope compositions can fingerprint the provenance of these sources within the early Solar System.

Several isotope systems yield anomalies between Archean and modern mantle samples including Nd, Ru and W [1, 2, 3]. Ru isotope anomalies reflect mixing of material with different nucleosynthetic histories. They likely result from a lack of addition of a late veneer (late accretion) component in the Archean samples, with a late veneer best represented by ~0.3 % of Earth mass ($M_⊕$) of CM chondrite [2]. The $ε^{182}$W isotope anomalies reflect decay of the short-lived ^{182}Hf and may either result from a missing late veneer component [3, 4] or are due to early silicate differentiation [5]. Importantly, the Moon and Earth have different $ε^{182}$W isotope compositions [6]. These may reflect (i) different contributions of late accreted material to the Moon and the Earth [6] or (ii) input from decay of ^{182}Hf due to different Hf/W ratios in the Moon and Earth [7]. The $ε^{142}$Nd isotope anomalies are caused by decay of the short-lived ^{146}Sm and may have a small late veneer component but are likely dominated early silicate differentiation. Key to constraining the origin of late accreted material and the role of early silicate differentiation is the extent of mixing in the Earth's early mantle.

Chromium is another element, like Ru, which has pronounced nucleosynthetic anomalies in meteorites [8] and thus might show a difference between Archean and modern mantles due to variable delivery of a late veneer component. We have previously reported ultra-high precision Cr isotope compositions of Archean and modern mantle samples [9,10]. We found that the modern and Archean mantles are identical within analytical uncertainty. Therefore, Cr places additional constraints on the mass and composition of a late accreted component and the extent of mixing required to yield a homogeneous Cr isotope composition and anomalies in W and Ru.

Methods: We present multi-stage isotope mixing models which examines both the extent of mixing between the modern mantle and late accreted components, but also the intermediate stage of the Archean mantle, for a range of delivered masses and compositions of late accreted material.

To place further constraints on the formation of early reservoirs and potential extent of mixing by the time of the separation of the Archean mantle source we have applied statistical models of mantle homogenization [following the approach of 11]. We assume a late veneer component is either fully or partially (~60 %) delivered after the Moon forming giant impact. We then model how long this component takes to homogenize into the prior composition of the bulk silicate Earth (BSE).

Results: The multi-stage mixing models demonstrate that even small masses of late accreted material must be homogenized with significant proportion of the BSE to avoid residual anomalies. Using our Cr compositions for modern and Archean mantles and a CI late veneer [composition from 8], we find that a late veneer of 0.5 % $M_⊕$ requires mixing with ~60 % of the BSE to homogenize the signature. For W, our results show that a CI late veneer requires mixing with >90 % of the BSE to achieve the homogeneous signature observed in Archean samples [3, 4, 5].

The mantle homogenization models indicate that for a late veneer component partially delivered (~60 % of a 0.5 $M_⊕$ late veneer) the mantle takes at least 600 Ma to achieve a homogeneous signature in W for the shortest stirring timescale studied (250 Ma) and largest sampling volume (50 km). For smaller sampling volumes and longer mixing timescales, this timeframe increases up to over ~900 Ma for a 500 Ma stirring time and 30 km sampling volume.

Discussion: The presented models can relate the homogenization of the late veneer into the silicate Earth to the timescale of delivery and the formation of early sample sources such as the Archean samples. Using the Isua Greenstone Belt as an example, the emplacement of these terranes occurred at 3.8-3.65 Ga [12], although they may have an older memory pointing to a potential isolation from the Hadean mantle at 4.3-4.1 Ga [13]. These ages are similar to the timescales of homogenization of late accreted material indicated by our models. However, the longer timescales to mix and homogenize 0.35 $M_{\oplus}$ CI late veneer show that the mantle would still be significantly heterogeneous with an Isua source that was emplaced (3.8-3.65 Ga). This scenario cannot yield the homogeneous signature observed in the Archean samples. Even the shortest timescale to achieve a homogeneous signature for the silicate Earth still yields significant heterogeneity at 4.3-4.1 Ga, the time the Isua source is thought to have formed and separated from the bulk mantle.

Therefore, homogenizing the late veneer component by the time of the formation or emplacement of the Isua source, or those of other Archean terranes, is challenging. This is particularly problematic because the Archean W isotopic composition is widespread and homogenous [e.g. 3, 5]. This suggests that the different Archean terranes sample an already largely homogenous mantle with a single W isotope composition. One possibility is a smaller late veneer ($<<0.2$ $M_{\oplus}$) component was initially delivered because a small mass could be fully homogenized. This then presents the homogenous signature observed in the Archean samples. A second possibility is that the initial late veneer component was delivered very soon after the giant impact into a partially or fully molten mantle which would dramatically reduce the timescale of homogenization. This enables ~0.2-0.3 $M_{\oplus}$ (~60-90 %) of the late veneer to fully homogenize by the time of formation of the Archean mantle source. In both scenarios subsequent delivery of additional late accreted material can account for the isotopic differences between the modern and Archean mantles [e.g. 2, 3].

Conclusions: The Archean mantle (e.g. sampled by Isua) appears to possess a homogeneous isotopic composition for several important elements (e.g. W, Ru) which is distinct from that of the modern mantle, likely due to a missing part of the late veneer [2, 3, 5]. This suggests that any late accreted component added by this time was fully homogenized. Mixing models show that the missing late veneer component must be mixed with a significant proportion of the BSE to result in a homogenous signature. Mantle homogenization models show that mixing even modest (~0.2 $M_{\oplus}$) late veneer contributions into Earth's mantle within the allowed timeframe, prior to the formation of the early Archean mantle source, is problematic. This suggests that the contribution of the late veneer present in the Archean mantle was delivered very soon after the Moon forming giant impact, while the mantle was still molten allowing for more efficient mixing.

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