Chromium isotopic constraints on the origin the ureilite parent body.

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Introduction: Ureilites are primitive achondrites that represent the mantle of a now disrupted partially differentiated parent body (UPB), and some primitive geochemical information have survived from isotopic homogenization (e.g. during a magma ocean stage) in ureilites [1, 2]. Therefore, the geochemical signatures of ureilite meteorites can provide valuable information about not only the origin of the UPB but also early evolution of the Solar System. For instance, individual ureilite meteorites cover a range of Fe/Mn ratios and $\Delta^{17}O$ values which further correlate with the Mg# of their olivine cores. However, the origin of these co-variations is highly debated [1-4], and the heterogeneous $\Delta^{17}O$ features contradict to their homogenous $\varepsilon^{54}Cr$ [5, 6]. Moreover, the formation time for UPB is also poorly constrained, due to the low-radiogenic Pb (decay from U), Nd (decay from Sm) and Sr (decay from Rb) content in monomict ureilites (mantle restites) and lack of variation for Hf/W, Al/Mg and Mn/Cr among them. In order to better constrain the timescale of differentiation using volatile-sensitive ^{53}Mn-^{53}Cr system ($T_{1/2}$ = 3.7 Myrs) [7, 8, 10] and the degree of Cr isotopic heterogeneity of the UPB [8, 10], a larger variety of ureilite samples must be studied. Here, we report high precision Cr isotope data for eleven monomict ureilites and one ureilitic trachyandesite clast (ALM-A [9]) which has a complementary crustal composition.

Analytical methods: Around 10 mg of ureilite samples were well dissolved using Teflon bombs and an *Analab EvapoClean*, which is the same as [10]. Chromium was purified from 50% aliquots based on a procedure involving a three-step chromatographic ion-exchange purification protocol described in [11], and the total yield ranges from from 84% to 98%. The mass-independent Cr isotopic compositions of all the samples except for ALM-A were determined using the Neptune Plus located at the StarPlan, University of Copenhagen. Detailed analytical and data reduction method are described in [12]. ALM-A was measured on Triton TIMS here alongside the samples reported in [10] and the related methods have been described in detail in previous studies [13, 16].

Results: The $\varepsilon^{54}Cr$ values of all the monomict ureilites, vary from -1.06 ± 0.04 to -0.78 ± 0.05 with an average value of -0.91 ± 0.15 (2SD, N =18, including the data in [5]). A regression of the monomict ureilite $\varepsilon^{53}Cr$ values with their respective $^{55}Mn/^{52}Cr$ ratios calculated by *IsoplotR*, yields a slope of 0.569 ± 0.094 and an intercept of -0.28 ± 0.07 (MSWD = 2.0). The ALM-A clast investigated in this study has the highest $^{55}Mn/^{52}Cr$ ratio (1.35), $\varepsilon^{53}Cr$ (0.45 ± 0.05) and $\varepsilon^{54}Cr$ values (-0.68 ± 0.09). Notably the $\varepsilon^{53}Cr$ ($^{55}Mn/^{52}Cr$) and $\varepsilon^{54}Cr$ values appear to correlate. Also, the Cr isotope variation correlates with Mg# and Fe/Mn in olivine cores.

Discussion: These $\varepsilon^{54}Cr$ variations among monomict ureilites reflect primitive mantle heterogeneity of the UPB, which therefore did not experience a global-scale magma ocean. Furthermore, the $\varepsilon^{54}Cr$ values, Mn/Cr ratios, C isotopic composition [14], Mg# and Fe/Mn ratio in the olivine cores for the ureilites are correlated with each other, confirming that the UPB represent the the mixing of least two chemically and isotopically distinct reservoirs, rather than resulting from smelting process [3] or ice melting [4]. All the monomict ureilite fall on a well-defined ^{53}Mn-^{53}Cr isochron corresponding to a $^{53}Mn/^{55}Mn$ ratio of (6.45 ± 1.07) × 10^{-6}. This represents the first external Mn-Cr isochron obtained for the UPB, which can be translated to 4567.1 ± 1.0 Ma (within 1 Ma after CAIs), when anchored to U-corrected D'Orbigny angrite. We argue that this age represents the formation of the ureilite precursors (ureilite planetesimals). There is a ~4 Ma age discrepancy between the external isochron in this study and internal isochron ages for the polymict ureilites (e.g. [5, 9, 15, 16]), likely reflect the early impact history of the UPB.

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