CONSTRAINTS ON THE ZIRCONIUM ISOTOPE COMPOSITION OF THEIA AND CURRENT MOON FORMING THEORIES. W. M. Akram[1] and M. Schönbächler[1], [1]Institut für Geochemie & Petrologie, ETH Zürich, 8092 Zürich, Switzerland (waheed.akram@erdw.ethz.ch).

Introduction: The giant impact theory – a collision between the protoEarth and a small Mars-sized impactor, Theia ~ 4.6 billion years ago – is one of the most promising theories to explain the origin of the Moon. Its success is mainly due to the models' abilities to accurately reproduce key dynamical and geochemical constraints pertaining to the Earth-Moon system, such as the relatively high angular momentum of the system (L_{EM}) and the small iron core of the Moon [1,2]. In the canonical model [3,4], the majority of the Moon-forming material originates from the impactor, not the protoEarth. However, the similarity in the isotopic composition of the Moon with the bulk silicate Earth (BSE) reported for several elements (O, Si, Cr, Ti, W [5-9]) argue for the dominant fraction of the Moon derived from the protoEarth. Five solutions to this isotopic irregularity are suggested. Taking the giant impact models at face value, (i) the composition of Theia must be comparable to BSE [10] or (ii) chemical equilibration between the BSE and the Moon forming disk occurred by post-impact mixing processes [11]. Alternatively, by allowing for the pre-impact Earth-Moon system to possess a higher angular momentum (~ 2 L_{EM}) than today, more variants of the impact scenarios can be considered, each one lowering the amount of impactor material in the Moon: (iii) hit and run impact [12], (iv) impact with a fast-spinning protoEarth [13] and (v) a collision between two half Earth-mass bodies [14]. Compelling arguments against the first two cases (i and ii) (e.g. see [11, 13]) have been offered and are thus not considered here. However, the plausibility of each of the three remaining giant impact scenarios is assessed by calculating the isotopic composition of Theia required to produce the isotopic uniformity of the Earth-Moon system. These compositions are compared to known solar system material in order to infer the likely origin of Theia.

The element Zr is ideally suited to carry out this exercise because it is a very refractory element [15], with minimal, if no contributions from galactic cosmic rays to its solar system abundance [16,17]. Variations in $^{96}Zr/^{90}Zr$ ratios, however, are reported within bulk solar system materials, arising from variable contributions of (1) potentially r-process enriched CAIs and (2) s-process material [18,19].

Method: High-precision Zr isotope data were acquired using protocols from [19], where also part of the data were previously reported. The data set includes whole-rock lunar samples (15555, 71566), pyroxene (77516) and ilmenite (77516, 70035) separates (Fig.1) The Zr isotope ratios are expressed relative to a synthetic Alfa Aesar Zr standard solution after correcting for instrumental mass bias relative to $^{94}Zr/^{90}Zr$. Mass-balance calculations were performed for four different giant impact models [3,4,12-14] to predict the isotopic composition of Theia ($\varepsilon^{96}Zr_T$) based on the observed Zr isotope composition of the Earth ($\varepsilon^{96}Zr_E$) and Moon ($\varepsilon^{96}Zr_M$) today. Theia's composition is a function of ($\varepsilon^{96}Zr_E$), ($\varepsilon^{96}Zr_M$), the Zr concentrations of Theia and the protoEarth, and the relative Zr mass fractions of the Moon and Earth derived from Theia – *f* and *g*, respectively. The calculation considers pre-impact (protoEarth, Theia) and post-impact (Earth, Moon, escaping mass) components, assuming (i) a negligible mass escaping and (ii) identical Zr concentrations (C^{Zr}) for both the protoEarth and Earth (~10.5 ppm). The fractions *f* and *g*, for the successful Moon-forming scenarios, of each models are taken from [12-14]. The uncertainties on $\varepsilon^{96}Zr_T$ are obtained using the upper and lower bounds of the measured $\varepsilon^{96}Zr_{\oplus}$ and $\varepsilon^{96}Zr_M$ values.

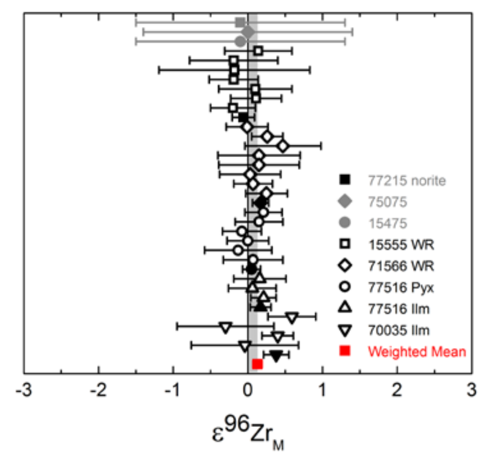

Figure 1: Zr isotope data for lunar samples. Gray symbols: data from [17], black open symbols: individual measurements with internal error (2σ) (this study), filled black symbols: weighted average of each group (2σ weighted mean uncertainties), red symbol: weighted mean of all lunar measurements, grey band: terrestrial Zr isotope composition (weighted mean).

Results and Discussion: All lunar samples display identical Zr isotope compositions within uncertainty, and define an average $\varepsilon^{96}Zr_M = 0.13 \pm 0.06$ (Fig. 1). This average agrees with previous work ($\varepsilon^{96}Zr_M = -0.06 \pm 0.81$ [20]), but is of considerable higher precision. The lunar data match the terrestrial Zr isotope composition ($\varepsilon^{96}Zr_E = 0.06 \pm 0.04$ [20]), within uncertainty. These $\varepsilon^{96}Zr$ values are used to constrain $\varepsilon^{96}Zr_T$ based on four giant impact scenarios (Fig. 2). Each scenario predicts different *f* and *g* values, which leads to unique $\varepsilon^{96}Zr_T$ values for each model:

Canonical (*f* = 0.7, *g* = 0.1, [3,4]). In the canonical model, a substantial amount of the Moon (~70%) originates from the impactor, while only a small fraction of the Earth (~10%) is Theia material. This restricts the Zr isotope composition of Theia to $\varepsilon^{96}Zr_T$ = 0.17 ± 0.11 (Fig. 2), which overlaps with the terrestrial and CI chondrite ($\varepsilon^{96}Zr_{CI}$ = 0.30 ± 0.22) composition.

Hit and run (*f* = 0.45, *g* = 0.1, [12]). In this scenario, the amount of impactor material in the Moon is reduced by 25%, relative to the canonical model, but yields a similarly confined isotope composition for Theia ($\varepsilon^{96}Zr_T$ = 0.24 ± 0.22), which is consistent with the Earth, CI chondrites, eucrites ($\varepsilon^{96}Zr_{Euc}$ = 0.41 ± 0.06) and ordinary chondrites ($\varepsilon^{96}Zr_{OC}$ = 0.41 ± 0.12).

Fast-spinning protoEarth (*f* ~ 0.08 – 0.18, *g* = 0.04, [13]). The successful Moon-forming simulations for this model predict the lowest fraction of lunar material originating from Theia, spanning a range from 8% - 18% (Fig. 2). As the fraction *f* decreases from 18% to 8%, the resulting $\varepsilon^{96}Zr_T$ increases from ~0.5 to ~1.5. Hence, models with lower *f* values produce increasingly high $\varepsilon^{96}Zr_T$ values, which are outside the Zr isotope composition reported for bulk solar system materials [18]. Therefore, the Zr isotope data favor variants of this model with high *f* values, that predicted $\varepsilon^{96}Zr_T$ in the range of solar system materials.

Two half-Earth-mass protoEarths (*f* ~ 0.5, *g* ~ 0.46-0.55, [14]). Roughly the same fraction of impactor material ends up in the Moon here as in the hit and run model. However, the fraction of impactor derived material in the Earth increases substantially. As a result, the Earth's isotopic composition is heavily altered and shifts towards the isotopic composition of Theia, and the Moon (which inherits a significant amount of Theia material). Therefore, Theia can carry a more extreme isotopic composition (relative to the Earth) than in the hit and run scenario, and still reproduce the uniformity of Earth and Moon. For cases where the relative amount of impactor material in the Earth exceeds the amount of impactor material in the Moon (i.e. case g > f, Fig. 2), Theia assumes negative $\varepsilon^{96}Zr_T$. The absence of solar system materials with negative $\varepsilon^{96}Zr$ [17, 18] renders half Earth-mass scenarios with *g* > *f* unlikely.

Varying Zr concentration of Theia. The Zr concentration of Theia is unknown and was approximated at 10.5 ppm (BSE value). Similarly qualitative results, as those shown in Fig. 2 are obtained by varying the Zr concentration of Theia. For a fixed value of *f* (and *g*), as the concentration of Theia reduces towards more CI-like concentrations (~ 4 ppm Zr), the Moon's overall isotopic composition is dominated by material from the protoEarth, not Theia. As a result, the calculated $\varepsilon^{96}Zr_T$ values can deviate more from $\varepsilon^{96}Zr_E$, leading to a larger range of potential Zr isotope compositions for Theia compared with those shown in Fig. 2.

Other isotope systems: Similar calculations as for Zr isotopes were also performed for Ti and O based on the data from [8] and [21], respectively. The results are comparable to those of Zr with the exception that the Ti isotope compositions exclude Theia to be CI-like.

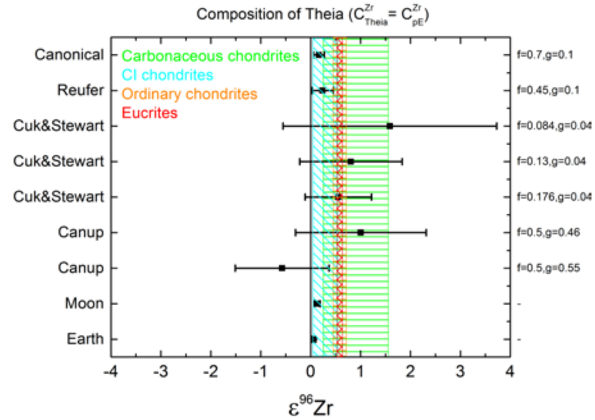

Figure 2: Predicted $\varepsilon^{96}Zr_T$ values for different giant impact scenarios: Canonical (Canonical), hit and run (Reufer), fast-spinning protoEarth (Cuk&Stewart) and the two half Earth-mass merging protoEarths (Canup). The range of measured Zr isotope compositions for different solar system materials are displayed in the colored bands.

Conclusions: The Zr isotope compositions of the BSE and Moon are identical, within uncertainty. To account for this uniformity, four giant impact models are tested. In all cases, the calculated $\varepsilon^{96}Zr_T$ largely falls within the known range of Zr isotope compositions for solar system materials, constituting all models plausible. All models are satisfied with Theia exhibiting a terrestrial or CI-like Zr isotope composition. However, when combined with Ti isotope data, a CI-like Theia can be excluded and eucrites provide the best match for Theia. This conclusion is supported by O isotope data.

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