

EVAPORATIVE FRACTIONATION OF POTASSIUM ISOTOPES DURING THE FIRST NUCLEAR DETONATION AND IMPLICATION ON THE FORMATION OF THE MOON. H. Chen^{1,2}, A. P. Meshik^{1,3}, O. V. Pravdivtseva^{1,3}, J. M. D. Day⁴ and K. Wang(王昆)^{1,2}, ¹McDonnell Center for the Space Sciences, ²Department of Earth and Planetary Sciences, ³Department of Physics, Washington University in St. Louis, One Brookings Drive, St. Louis, MO 63130 (chenheng@levee.wustl.edu); ⁴Scripps Institution of Oceanography, La Jolla, CA 92093, USA

Introduction: It has long been known that volatile elements are depleted to different degrees in achondrites and in the terrestrial planets (relative to CI chondrites) [1-2]. Although the volatile depletions have very important implications for the accretion and evolution of the early Solar System, their origins are not well understood. As the elemental compositions of planetary materials were modified by various geochemical processes, isotopic signatures of volatile elements could provide important information about these processes in the early Solar System [3].

Potassium (K), is a moderately volatile element with the 50% condensation temperature (T_c) of ~1006 K [4], and it is also a major element in planetary crusts. Compared with other isotopic systems (*e.g.* Cu and Zn), mass-dependent fractionations of K isotopes in planetary materials have not been well characterized, which is mainly due to the difficulty of making the high-precision analysis. The attempt of using K isotopes as a tracer of volatile depletion started as early as 1995 [5]; however, at that time no variation between the Earth, Moon, and meteorites was observed due to the large analytical uncertainty using Secondary Ion Mass Spectrometer (SIMS). In the last two years, the analytical breakthrough on Multi-Collector Inductively-Coupled-Plasma Mass-Spectrometer (MC-ICP-MS) improved the precision of potassium isotopes by an order of magnitude, making it possible to distinguish the marginal isotopic differences [6-9].

It was recently reported by Wang and Jacobsen [10] that there are significant K stable isotope differences (0.4‰) between the Earth and the Moon, and the enrichment of the heavy K isotopes in lunar rocks is most likely the result of the incomplete condensation from a Bulk Silicate Earth (BSE) vapor formed by the Moon-forming Giant Impact event. This K isotope result favors the model of a High-energy High-angular-momentum Giant Impact origin of the Moon [11]. However, the mechanisms of enriching heavier K isotopes in lunar rocks are still debated.

Trinity was the code name of the first detonation of a nuclear weapon which took place on July 16, 1945, in the Jornada del Muerto desert, New Mexico. The Trinity historic nuclear test site provides an ideal place to study elemental and isotopic behavior during volatile redistribution at high temperature for the following reasons: (1) “Trinitites”, the post-detonation materials

from the Trinity site are available for public research; (2) The temperature and pressure that produced molten glasses are higher than those achieved and maintained by laboratory experiments, and more comparable with that at the surfaces of planetary bodies in the earliest stages of their formation; (3) Compared with other natural analogs (*e.g.*, tektites and fulgurites), the forming conditions of trinitites (*e.g.*, temperatures, cooling rates, starting materials, *etc.*) are better documented.

The purpose of this study is to understand the isotopic behavior of K during evaporation by measuring the K isotopic compositions of a series of “Trinitites”, which formed at different temperatures and cooling rates. This could provide important analogs that approximated planetary-scale volatile processes.

Samples and Methods: Samples investigated in this study are a collection of trinitites taken at different distances from the location of detonation of the Gadget (ground zero). IF, is the sample taken within 10m from ground zero. It contains two parts: melted green trinitite (IF_m), which formed at 1663 K and cooled within 17 minutes of emplacement, and incomplete melted gray part (IF_i). The 100m sample, IG, formed at 1593 K and cooled within 5 minutes of emplacement. T1, T2, and T3 are three peripheral samples, which likely formed at a lower temperature and higher cooling rates, and samples T2 and T3 had large quantities of unmelted desert sand adhering to them [12].

To measure the isotopic composition of bulk sample, ~ 20 mg of each bulk sample were digested through a standard two-step protocol (first in concentrated HF/HNO₃ mixture and then in 6 N HCl). In order to find elemental and isotopic heterogeneity within fragments of trinitites, we took powdered splits of IF_i, IF_m, and IG (~120 mg each), and subjected them to a three-step leaching and etching process following the method described in [13]: (1) Milli-Q ultrapure H₂O for 20 min, with ultrasonication at 30°C. (2) 3 N HCl for 20 min, with ultrasonication at 30°C. (3) 1 N HF-HNO₃ for 2 hours on a hot plate at 60°C. The etching residues after step 3 were dried down first and then digested by the same method used on bulk samples.

The fully digested bulk samples and etching residues, together with leachates and etchates were all dried down and first loaded on big 17 mL Bio-Rad AG50W-X8 cation exchange resin (100 to 200 mesh) chromatography columns in 0.7 N HNO₃, and then the

process was repeated on small 2.4 mL columns in 0.5 N HNO₃ to further purify K [9]. The isotopic compositions of all samples were measured on a Neptune MC-ICP-MS at Washington University in St. Louis. Potassium isotope compositions are reported using the standard per mil (‰) notation of $\delta^{41}\text{K}$ for a $^{41}\text{K}/^{39}\text{K}$ ratio, where $\delta^{41}\text{K} = [((^{41}\text{K}/^{39}\text{K})_{\text{sample}}/(^{41}\text{K}/^{39}\text{K})_{\text{standard}} - 1) \times 1000]$. The standard used in this study is NIST SRM 3141a. The internal (within-run) reproducibility is typical $\sim 0.05\%$. The long-term (~ 11 months) reproducibility of this method has been evaluated as 0.12% (2 s.d.).

Results and Discussion: The bulk samples IF_m (10 m), IF_i (10m), and IG (100 m) have $\delta^{41}\text{K}$ values of -0.24 , -0.47 , and -0.45% respectively (see Fig.1). The bulk compositions reconstructed from leachates, etchates, and residues are same to the measured values for bulk. For IF_m (10m), hydrochloric acid leachate is isotopically lighter than the bulk-rock sample, in contrast, for hydrochloric acid leachates of IF_i (10m) and IG (100m) are isotopically indistinguishable from bulk-rock samples. The HF-HNO₃ etchates, which are interpreted to attack silicate materials in the trinitites, are all similar in isotopic composition to the bulk samples, so are the residues after etching.

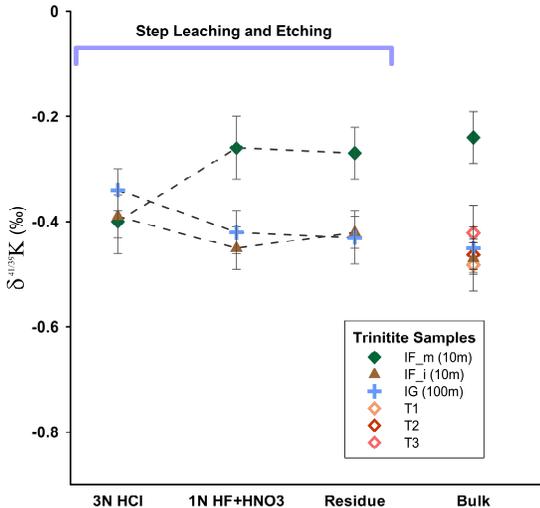


Fig.1. Potassium isotope compositions ($\delta^{41}\text{K}$) of the bulk samples and sequential leaching products. The error bar represents 2 standard errors of repeat measurements.

Among all trinitites, only the completely melted green trinitite IF_m (10m) displays $\sim 0.2\%$ higher $\delta^{41}\text{K}$, which we attribute as the result of the isotopic fractionation during volatile losses. IF_i (10m) and IG (100m), have the $\delta^{41}\text{K}$ values similar to the least melted and peripheral trinitite samples (T1, T2, and T3), and all are within uncertainty of the estimated BSE value of $-0.48 \pm 0.03\%$ [6].

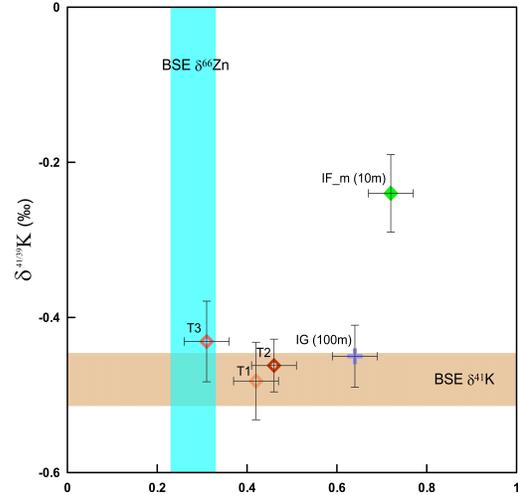


Fig. 2. $\delta^{66}\text{Zn}$ versus $\delta^{41}\text{K}$ for trinitites. $\delta^{66}\text{Zn}$ data are from [13]. The blue vertical band represents the $\delta^{66}\text{Zn}$ value of BSE, i.e., $0.28 \pm 0.05\%$ (2s.d.) from [14]. The orange horizontal band represents the $\delta^{41}\text{K}$ value of BSE, i.e., $-0.48 \pm 0.03\%$ (2s.d.) from [6]. The error bar represents 2 standard errors of repeat measurements.

Both K and Zn are moderately volatile elements; however, Zn isotopic compositions in all trinitites but T3 are heavier than the BSE value and display a clear trend of decreasing of $\delta^{66}\text{Zn}$ with the increasing distance from ground zero [13]. Zn isotopes also show larger fractionation ($\sim 0.4\%$ for $\delta^{66}\text{Zn}$) in IF_m than K isotopes ($\sim 0.2\%$ for $\delta^{41}\text{K}$). Comparison of Zn and K isotopes indicates that Zn isotopic compositions are more prone to be altered during evaporative fractionation, and K is much less volatile than Zn. The 50% condensation temperatures for K and Zn are 1006 K and 726 K [4]. Although some planetary processes that lead to evaporative losses, such as volcanic outgassing and magma ocean degassing, can significantly fractionate Zn isotopes [3], it is not evident that these processes can fractionate K isotopes. This observation supports that the enrichment of the heavy K isotope in lunar rocks is more likely achieved through the catastrophic Moon-forming Giant Impact [10].

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