Goldschmidt 2025 Abstract
https://doi.org/10.7185/gold2025.30157

Elemental, Sr and Pb isotopic variability of alteration phases in Nakhla and Yamato 000593: Insights from step leaching experiments

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Nakhlites are a suite of augite-bearing basaltic meteorites, inferred to have come from Mars, with pre-existing alteration patterns that imply an episode of Martian alteration. Nakhla (pristine fall) and Yamato 000593 (find) represent two widely documented examples. Here we report on step leach experiments on crushates from these two stones to disentangle the strontium and lead isotopic systematics of the primary mineralogy versus Martian, versus terrestrial (Antarctic) alteration.

A protocol involving nine leach stages (from cold then hot water, through dilute acids to 6M HCl) was designed to dissolve alteration products, yet leave intact as much as possible of the primary mineralogy. Leachates from each step were measured for trace elements via SF-ICP-MS, Rb-Sr relationships (via ID-TIMS) and Pb isotopes using ^{202}Pb-^{205}Pb double spike TIMS methods.

Trace element results included an evolved crustal signature in the REE patterns for both stones. However, >30% of the total Na yield from Nakhla was released in the first cold water leach. Rb-Sr relationships of the Nakhla leach fractions then show wild divergence on the ^{87}Rb/^{86}Sr isochron plot and yield no rational age systematics. For example, the water leachates yield unsupported radiogenic ^{87}Sr/^{86}Sr values >0.77 indicating derivation from an evolved, ancient crustal terrane (cf. Malarewicz et al., 2025, Nat. Geosci., in press). In contrast, Yamato shows an Rb-Sr release pattern with much less radiogenic components. The Pb-isotopic systematics for both stones show parallel relationships; for example Nakhla water leaching steps yield radiogenic Pb values that are unsupported by the bulk rock U/Pb ratios and distinct from any terrestrial Pb composition.

The residual minerals were then separated, dissolved using conventional HF-HNO_3 digestion, and measured as per the leachates. Data for these minerals from both stones yield a closely constrained isochron age in ^{87}Rb/^{86}Sr space, indistinguishable from those reported in earlier studies (e.g., Gale et al., 1975, EPSL, 26, 195). Pb isotopic data, however, yield no viable isochron.

Key implications of this work are: 1) the Nakhla host rock was impregnated by water- and weak acid-soluble components derived from an evolved, old crustal terrane; and 2) the alteration in Nakhla and Yamato was open-system.