THE NAKHLITES SAMPLE MULTIPLE IGNEOUS UNITS: EVIDENCE FROM $^{40}Ar/^{39}Ar$ CHRONOLOGY AND GEOCHRMISTRY. B. E. Cohen[1,2], D. F. Mark[1], M. R. Lee[2], W. S. Cassata[3], S. Griffin[2], C. L. Smith[4], and T. Tomkinson[1], [1]Scottish Universities Environmental Research Centre, UK (ben.cohen@glasgow.ac.uk), [2]School of Geographical and Earth Sciences, University of Glasgow, UK, [3]Lawrence Livermore National Laboratory, California, USA [4]Natural History Museum, London, UK.

Introduction: Mars hosts the solar system's largest volcanoes. Here we present $^{40}Ar/^{39}Ar$ ages of six nakhlites, meteorites that were ejected from Mars by a single impact event. These chronologic results were recently published in *Nature Communications* [1]. These age data can also be used to inform the search for the nakhlite source crater, and through the geochemistry of the nakhlite meteorites, to show how the magmatic system evolved through time. If the location of the nakhlite source crater can be confirmed, the chronological data for the nakhlites (cosmogenic exposure age for the crater, and age of the source terrain lavas) will also provide an 'absolute' temporal anchor for the surface of Mars that could underpin a Martian crater counting calibration model, while the chemical data could provide a useful ground-truth point for remote-sensing studies.

Methods: High-resolution (n43–45 steps) laser step-heating $^{40}Ar/^{39}Ar$ dating was undertaken on multiple aliquots (n2–5) of six nakhlites [1]. Cosmogenic (^{38}Ar) exposure ages were also obtained [1]. The cosmogenic exposure ages allow for accurate correction of cosmogenic and chlorine-derived contributions to the bulk isotope measurements and for determination of accurate $^{40}Ar/^{39}Ar$ age data [2]. The REE data were compiled from published sources.

Results: Analyses of unirradiated fragments of each of the six nakhlites yielded concordant cosmogenic exposure ages, and a weighted mean of 10.7 ± 0.8 Ma (2σ). These indistinguishable cosmogenic exposure ages confirm that the nakhlites are launch-paired, i.e., ejected from Mars in a single impact event.

$^{40}Ar/^{39}Ar$ ages reveal that the nakhlites sample a stratigraphically layered volcanic sequence, and temporally constrain at least four discrete eruptive events spanning 93 ± 11 Ma (1,416 ± 7 Ma to 1,322 ± 9 Ma [2σ], Fig. 1a). Our robust $^{40}Ar/^{39}Ar$ results are a product of the high-resolution approach to the step-heating experiments, and employment of procedures to make appropriate corrections for cosmogenic and chlorine-derived ^{36}Ar and ^{38}Ar [2] – which is important given the abundance of chlorine in the nakhlites (often >1,000 ppm Cl [3]). The highly reproducible age data (Fig. 1a) are consistent with the near-pristine character of the meteorites and associated low degrees of shock metamorphism [4].

Discussion: Our stratigraphic model is consistent with the geology of Martian volcanoes. High-resolution satellite imagery has revealed sequences of lava flows, with individual layers typically 4–26 m thick [5]. Our model of a layered volcanic sequence (Fig. 1) differs from a previous interpretation of the nakhlites that invoked sampling from a single thick flow/intrusive unit [e.g., 6]. Such a model would require all of the nakhlites to have the same cooling age, which is inconsistent with our $^{40}Ar/^{39}Ar$ data (Fig. 1).

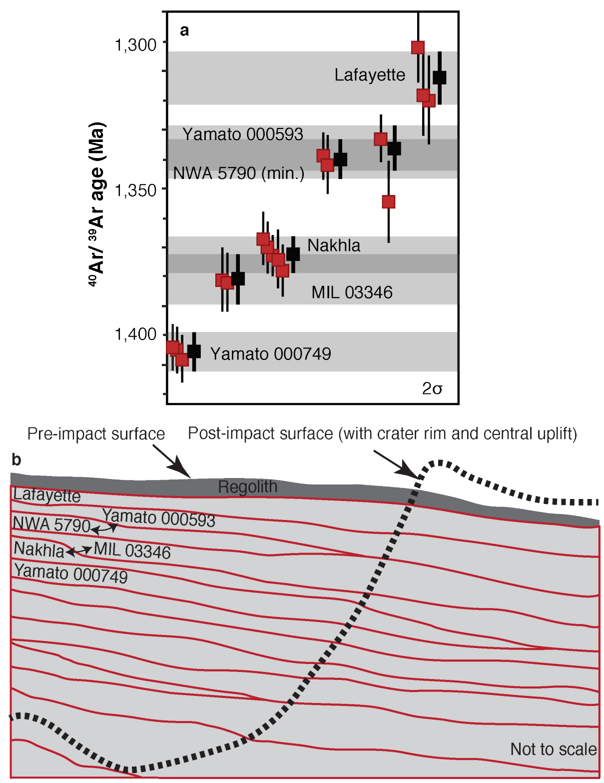

Figure 1. Stratigraphic model for the nakhlite meteorites, from [1]. (a) Summary of $^{40}Ar/^{39}Ar$ age data. Each meteorite has multiple aliquots with highly reproducible ages (red squares). Bold black squares and horizontal grey bars represent weighted mean ages. (b) Schematic cross-section for a layered lava flow sequence, with nakhlite stratigraphic relationships and outline of post-impact structure.

Our $^{40}Ar/^{39}Ar$ and cosmogenic exposure ages constrain the provenance of the nakhlites on the surface of Mars, including their ejection crater, and properties of their source volcano. More than seven different Martian craters have been suggested as potential sources for the nakhlites [7-9]. However, when we use the recent re-mapping of the Martian surface by NASA [10], we find that only one of these craters is situated in a mid-Amazonian volcanic terrain compatible with our $^{40}Ar/^{39}Ar$ results (Fig. 2). This crater has preserved ejecta rays that are indicative of a recent impact event. It has a diameter of 6.5 km, which is large enough for the impact to have had sufficient energy to have excavated and ejected material beyond Mars' orbit [11].

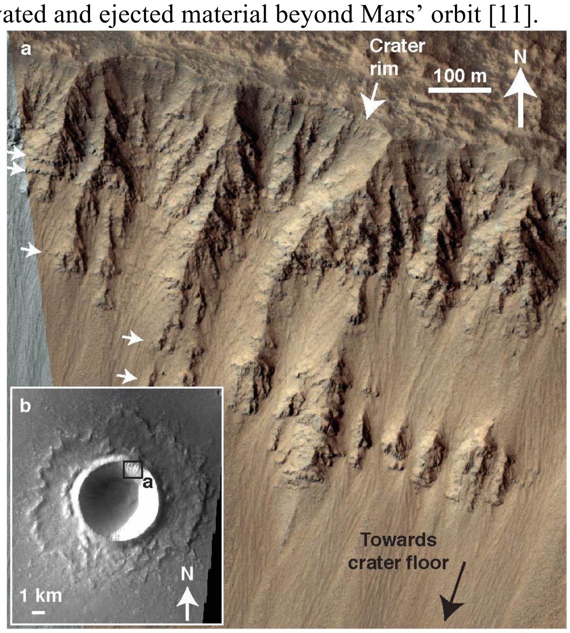

Figure 2. A potential nakhlite source crater, located on the Elysium lava plains at 130.799°E, 29.674°N. (a) Detail of the crater rim, showing numerous sub-horizontal layers (arrows), which are interpreted as lava flows. Part of HiRISE image ESP 017997_2100, NASA/JPL/University of Arizona. (b) Overview of the 6.5 km wide crater. THEMIS image V13713007, Band 3, NASA/ASU.

A layered volcanic sequence (Fig. 1b) is consistent with the mineralogical, petrological, and geochemical differences between nakhlites (e.g., Fig. 3), which we interpret as due to changes in magma composition between related but temporally distinct units. This scenario is unsurprising if one considers an analogy of a moderate-sized bolide hitting a volcano on Earth, and the number of chemically similar yet temporally distinct igneous units that could be ejected. An important requirement in interpreting nakhlite chemistry is to untangle the effects of crystal settling on the data, and we plan further investigation of the REE and other nakhlite chemical data in order to understand the evolution of their source volcano through time.

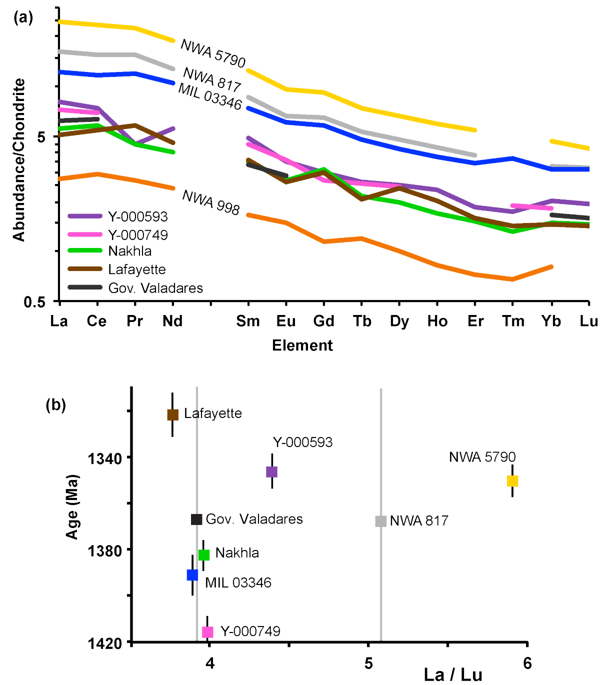

Figure 3. (a) Compilation of published REE data demonstrating the nakhlites have a considerable compositional range. (b) The REE slope (i.e., La/Lu) also differs significantly between nakhlites, which is significant as the ratio is sensitive to variations in degree of melting, and is not substantially effected by crystal fractionation. Ages are from [1]. Note that NWA 817 and Gov. Valadares lack precise ages.

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