MARTIAN SURFACE PALEOTEMPERATURES FROM THERMOCHRONOMETRY OF METEORITES.

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Abstract: Relying on more than thirty years of published noble gas and petrographic data, we have been conducting thermochronometric calculations to constrain the temperature histories of the Martian meteorites. We find that the nakhlites have been at most mildly heated since their formation, should retain magnetization acquired on Mars, and were apparently not heat-sterilized during ejection. *Combined with our previous calculations for ALH84001* [1], *these results are the first quantitative thermochronometric constraints on ambient Martian near-surface paleotemperatures over the last four billion years, implying that average long-term conditions on Mars are unlikely to have been much higher than the present cold state.*

Methods: Our goal is to constrain the maximum temperature the nakhlites experienced since their K/Ar chronometers were last completely reset. K/Ar and ^{40}Ar/^{39}Ar dating of five nakhlites [2-12] give ages of ~1.3 Ga, nearly identical to the crystallization ages specified by the Rb/Sr, U/Pb, and Sm/Nd chronometers [13]. Therefore, the spatial distribution of radiogenic ^{40}Ar (^{40}Ar*) within the samples today reflects the thermal perturbations that the samples experienced since 1.3 Ga.

Using the ^{39}Ar release data of Swindle and Olson [6] and (following the methods of [1]), we estimated the temperature-dependence of the ^{39}Ar diffusion coefficients $D(T)$ through Nakhla and Lafayette. The presence of multiple diffusion domains is revealed in the observed ^{39}Ar Arrhenius plot as distinct arrays clearly separated by breaks in slope (Fig. 1*A*). From this, we identify three primary arrays from the ^{39}Ar data and adopt the interpretation of [6] that the first two domains (LRD and HRD) likely represent iddingsite and feldspar. The final ~20% appears to be from a phase affected by ^{39}Ar recoil [6, 9].

Our approach was to characterize the spatial distribution of ^{40}Ar* and the Ar diffusion kinetics in the HRD alone, which corresponds to the ~1.3 Ga ^{40}Ar/^{39}Ar age plateau identified by [6]. A two-domain model was calculated by assuming that the ^{39}Ar distributions were initially uniform within two distinct domains, and gas was not permitted to exchange between them. The HRD diffusion kinetics are well constrained even though our two-domain model is a non-unique solution. We derive the following diffusion parameters for the HRD of Nakhla: activation energy E_a = 117 kJ mol^{-1} and $\ln(D_o/a^2)$ = 5.3 ln(s^{-1}) for diffusivity at infinite temperature D_0, and diffusive length scale a. Nearly identical results were obtained for the nakhlite Lafayette and another Nakhla subsample.

In the following calculations, we assume that this Arrhenius relationship and corresponding a have held for the nakhlites' HRD since 1.3 Ga. Although the nakhlites were shock-fractured sometime after their formation [14], this assumption is supported by the fact that ^{40}Ar/^{39}Ar ages of mineral separates match that of bulk samples [9]. The model LRD diffusion parameters predict essentially no ^{40}Ar retention over geologic time, which is consistent with the zero age ^{40}Ar*/^{39}Ar in the first ~3% of extracted ^{39}Ar observed by [6].

With the two-domain model shown in Fig. 1*A*, the methods described by [15] and a preatmospheric size of 0.2 m [16], we simulated the expected ^{40}Ar* distributions within the sample following various diffusively cooling thermal perturbations. The model ^{40}Ar* distributions were calculated for the HRD and then passed through a simulated degassing experiment to produce a set of ^{40}Ar* release fractions (Fig. 1*B*).

Results: Our calculations conservatively demonstrate that ~1% of the ingrown ^{40}Ar* has been lost from the HRD of Nakhla and Lafayette since 1.3 Ga. This places stringent constraints on the maximum amount of heating experienced since that time. We find that the central temperatures of the meteorites could not have exceeded ~350 °C for even short periods of time (no more than a few hours) since 1.3 Ga (Fig. 1*B*). This is a conservative upper limit because we have assumed no other diffusive loss of ^{40}Ar* for the other 1.3 Gy of history. Given the petrographic similarities that link the nakhlites, it is likely that the conclusions drawn here from Nakhla and Lafayette extend to the five other known meteorites in this class.

Our results are consistent with petrographic studies which suggest that the nakhlites have only been mildly shocked, with peak pressure and temperatures of 10-20 GPa and -50-100 °C, respectively (following [14, 17] and using ambient Martian surface temperatures between -120 and 0 °C). They are also in agreement with the very old (~770 Ma) (U-Th)/He ages estimated for Nakhla and Lafayette [4].

Implications:

Age and nature of magnetization in the nakhlites. Since the magnetization of the nakhlites is thought to be dominated by titanomagnetite with a Curie point of ~500-550 °C [18], much of the magnetization measured in the nakhlites is likely to have been a thermoremanence that originated on Mars at 1.3 Ga. However, this remanence is likely to have been modified by shock (e.g., [19]).

Panspermia. As stated above, our thermal constraint is consistent with but less restrictive than the -50 °C to 100 °C limits implied by the weak shock textures identified in the nakhlites. This means that like ALH84001 [1, 20], the

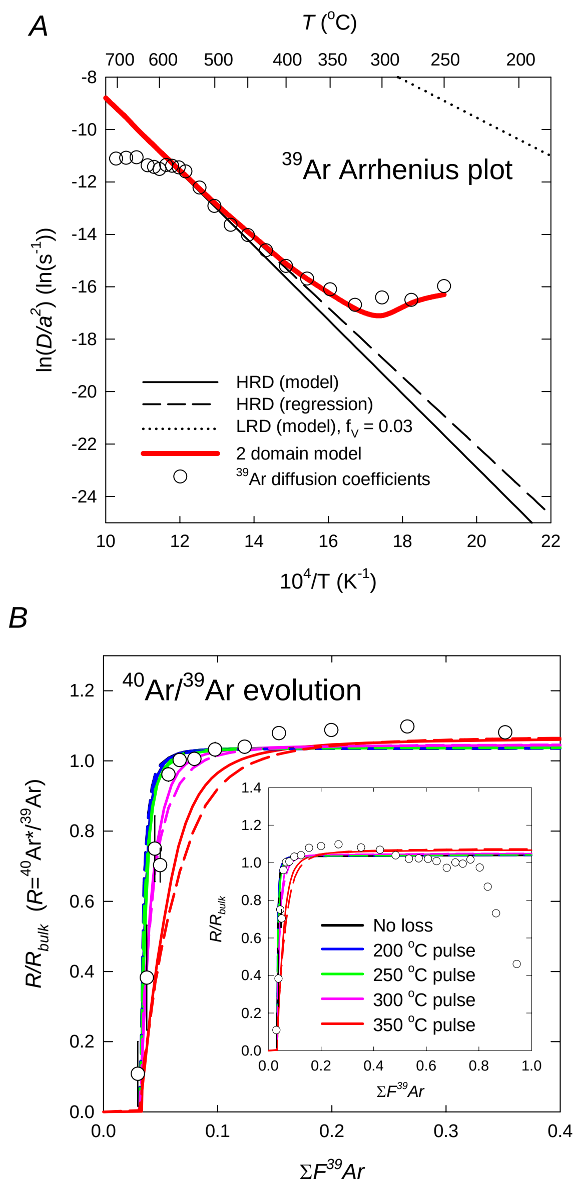

Figure 1. Thermochronology of Nakhla using the $^{40}Ar/^{39}Ar$ data of Swindle and Olson [6] ***A)*** *Arrhenius plot showing the calculated diffusion coefficients (D) of ^{39}Ar. Red curve: best-fit two-domain model. Solid and dotted black lines: model $D(T)/a^2$ for the HRD and LRD, respectively. Dashed black line: linear regression through the subset HRD array.* ***B)*** *Model $^{40}Ar^*/^{39}Ar$ ratio evolution spectra for the two-domain model shown in 1A and various assumed diffusively-cooling thermal pulses experienced by the HRD. The LRD was assumed to contain no $^{40}Ar^*$. Shown is the calculated $^{40}Ar^*/^{39}Ar$ ratios, R (normalized to the bulk ratio, R_{bulk}). Circles are the $^{40}Ar^*/^{39}Ar$ data of [6]. Solid curves correspond to various temperature pulses during ejection from Mars at 11 Ma: black = no heating, blue = 200 ℃, green = 250 ℃, purple = 300 ℃, red = 350 ℃. Dashed curves are the same calculations using the HRD subset regression shown in 1A. Similar results are obtained for both a second Nakhla subsample and for Lafayette.*

nakhlites were not heat-sterilized during ejection from Mars and transfer to Earth.

Martian surface paleotemperatures. Our new results on the nakhlites, taken together with our previous thermal constraints on ALH84001, suggest that at least a fifth of all known Martian meteorites have seen only mild temperature excursions for billions of years. This gives extraordinary testimony to the difference in thermal histories between Mars and Earth.

In particular, the small amounts of degassing observed for the nakhlites and, particularly, ALH84001 requires that they must have been at very low temperatures for nearly their entire histories. Linearly extrapolating the HRD Arrhenius relationship (e.g., Fig. 1*A*) to low temperatures, we find that the three nakhlites could not have been at a constant temperature exceeding 5 °C to -35 °C (depending on which Arrhenius model for HRD is used) during the last 1.3 billion years. For the same reasons as described above, these are conservative upper limits. A constant temperature of no more than 0 °C lasting for the first ~600 My of the Nakhla's history is also required. This is in general agreement with our previous analysis of ALH84001 which found that temperatures during the last 4 Gy could not have exceeded -25 to -70 °C for all but the briefest periods. The fact that five subsamples of three rocks taken from two Martian meteorite classes with vastly different ages, petrographic textures, compositions and different activation energies give similar constraints on Martian temperatures supports the accuracy of these extrapolations.

Our calculations suggests that for nearly all of the last four billion years, average temperatures near the Martian surface have not been significantly warmer than present cold (subzero) conditions. These represent direct quantitative thermochronometric constraints on Martian surface paleotemperatures averaged over long (Gyr) time periods.

Acknowledgements: We thank Tim Swindle for generously sharing his Ar data with us.

References: [1] B. P. Weiss et al. (2002) *EPSL*, *201*, 465. [2] F. A. Podosek & J. C. Huneke (1973) *MAPS*, *37*, 667. [3] D. D. Bogard & L. Husain (1977) *GRL*, *4*, 69. [4] R. Ganapathy & E. Anders (1969) *MAPS*, *33*, 775. [5] F. A. Podosek (1973) *EPSL*, *19*, 135. [6] T. D. Swindle & E. K. Olson (2004) *MAPS*, *39*, 755. [7] U. Ott (1988) *MAPS*, *52*, 1937. [8] T. D. Swindle et al. (2000) *MAPS*, *35*, 107. [9] R. Burgess et al. (2000) *J. Conf. Abs.*, *5*, 266. [10] J. D. Gilmour et al. (1998) *LPS XXIX* abstract #1788. [11] K. J. Mathew et al. (2003) *EPSL*, *214*, 27. [12] R. Okazaki et al. (2003) *Antarct. Meteorite Res.*, *16*, 58. [13] H. Y. McSween & A. H. Treiman (1998) in *Planetary Materials* (Ed.: J. J. Papike), MSA, Washington, DC, pp. 6. [14] J. Fritz et al. (2003) *LPS XXXIV*, abstract #1335. [15] D. L. Shuster & K. A. Farley (2004) *EPSL*, *217*, 1. [16] O. Eugster et al. (2002) *MAPS*, *37*, 1345. [17] N. Artemieva & B. Ivanov (2004) *Icarus*, *171*, 84. [18] D. W. Collinson (1997) *MAPS*, *32*, 803. [19] S. A. Gilder et al. (2004) *GRL*, *31 (10)*. [20] B. P. Weiss et al. (2000) *Science*, *290*, 791.