Ar-Ar Ages of Nakhlites Y000593, NWA998, and Nakhla and CRE Age of NWA998.

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Introduction. The seven known Martian nakhlites are Nakhla, Lafayette, Governador Valadares, and four recent finds from hot and cold deserts: MIL03346 from the Transantarctic Mountains, a paired group from the Yamato Mountains (Y000593, Y000749, and Y000802; 1), and two from Morocco (NWA998 and NWA817; 2). Radiometric ages (Sm-Nd, Rb-Sr, U-Pb, and Ar-Ar) for the first three nakhlites, along with Chassigny, fall in the range of 1.19-1.37 Gyr and may suggest a common formation age (e.g., 3). These meteorites also show very similar cosmic-ray (space) exposure ages, which suggests a single ejection event from Mars (3). The ages for nakhlites are different from those of Martian shergottites, whose radiometric ages vary by nearly a factor of three (~165-475 Myr) and whose space exposure ages vary over a factor of ~20 (3). Shergottite ages suggest that multiple locations on the Martian surface have been sampled, whereas nakhlite data imply that only one Mars surface location has been sampled. Because older Martian surfaces are expected to be more abundant, it seems surprising that all nakhlites would represent only one Martian impact event. To address this issue, we are measuring the ^{39}Ar-^{40}Ar ages of Y-000593, NWA-998, Nakhla, and MIL-03346, and the space (CRE) exposure age of NWA998.

NWA-998. A sample received from A. Irving (2) was sieved, and the 100-200 mesh size used to produce a low magnetic susceptibility fraction, which was then cleaned to remove the abundant clay terrestrial weathering products common in hot desert meteorites. The Ar-Ar age spectrum as a function of cumulative release of ^{39}Ar (produced from ^{39}K during neutron irradiation) is shown in Fig. 19. (In these figures, ages =rectangles on left scale and K/Ca ratios =stepped line on right scale.) The first ~20% of the ^{39}Ar release gave higher K/Ca ratios, consistent with terrestrial weathering of grains, and slightly younger ages, consistent with diffusion loss of ^{40}Ar. Across 24-80% of the ^{39}Ar release, both the K/Ca ratio (~0.2) and the Ar age are relatively constant and probably represent degassing of the mesostasis. Sixteen extractions give an average age of 1.332 ±8 Myr (1-•). Above 80% ^{39}Ar release a decrease in the K/Ca ratio indicates degassing of Ar from a second phase with a lower K/Ca ratio, possibly plagioclase. We interpret the decrease in Ar-Ar age for these extractions to be the result of degassing of ^{39}Ar that recoiled during production in the reactor and was implanted in grain surfaces of this second phase. Our sample gave no indication for the presence of trapped Martian Ar.

Y-000593. The Ar-Ar age spectrum of a 47 mg whole rock sample was determined as part of a consortium study of radiometric ages (4) and is shown in Fig. 2. Most of the ^{39}Ar release derives from the mesostasis with a K/Ca ratio of ~0.2-0.9. The first 5-10% of the ^{39}Ar release suggests a small amount of ^{40}Ar diffusive loss, but there is no indication in these data for a Martian weathering age of ~0.67 Gyr, as has been suggested for some other Nakhlites (5). Between ~10-90% ^{39}Ar release the age decreases from ~1.5 Gyr to ~1.36 Gyr. A small ^{39}Ar recoil effect is suggested at ~95% ^{39}Ar release, where a substantial decrease in the K/Ca ratio implies the onset of Ar degassing from plagioclase and/or pyroxene. Collectively, the Ar data imply the presence of a trapped Ar component, which can be separated from radiogenic ^{40}Ar by use of a ^{40}Ar/^{36}Ar versus ^{39}Ar/^{36}Ar isochron plot. Because an isochron assumes a two-component Ar mixture, we first utilized the lowest ^{36}Ar/^{37}Ar ratios to calculate the cosmogenic ^{36}Ar concentration in each extraction, and then subtracted this value from the measured ^{36}Ar (6). The corrected isochron plot for extractions releasing 15-84% of the ^{39}Ar gives an Ar-Ar age of 1.359 ±0.005 Gyr (1-•), a precise R^2 of 0.99998, and a ^{40}Ar/^{36}Ar intercept of 1502 ±159. This trapped ^{40}Ar/^{36}Ar ratio is very similar to the trapped Martian atmospheric value we determined in some shergottites (7). The corrected isochron age falls at the upper range of various nakhlite ages. It is also possible that Y593 contains some excess radiogenic ^{40}Ar, which was inherited from the melt, resides in late-forming mesostasis, and is not resolved by the isochron. Our sample contained ~2 x10^{-10} cm^{3}STP/g of trapped ^{36}Ar, likely Martian.

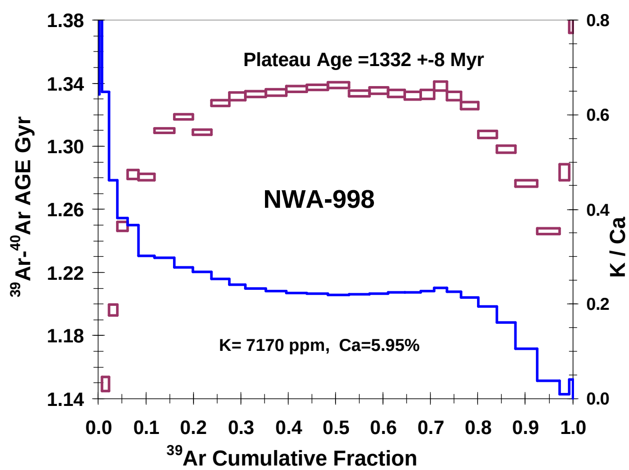
Nakhla. The Ar-Ar age spectrum for a whole rock sample is shown in Fig. 3. The first ~10% of the ^{39}Ar release indicates diffusive loss of radiogenic ^{40}Ar, and the pronounced decrease in age above ~90% ^{39}Ar release is attributed to degassing of recoiled ^{39}Ar from surfaces of plagioclase or pyroxene grains. Seven extractions releasing ~61-91% of the ^{39}Ar give an apparent plateau age of 1.359 ±0.006 Gyr (1-•). The elevated age over ~11-41% ^{39}Ar release is attributed to a trapped Martian Ar component. An isochron plot of

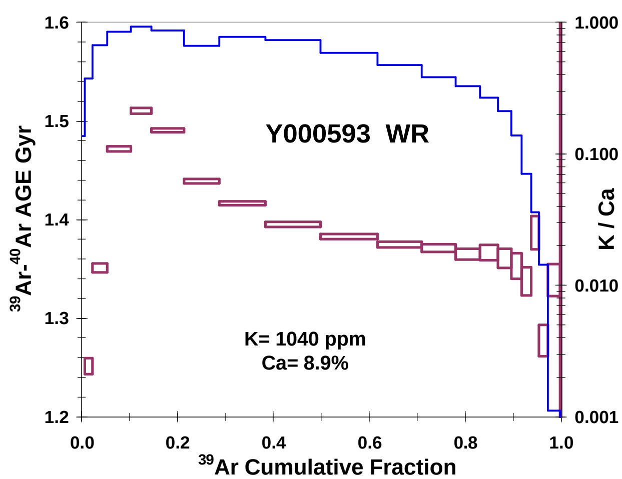
$^{40}Ar/^{36}Ar$ versus $^{39}Ar/^{36}Ar$ for five extractions (11-51% ^{39}Ar release; R^2=0.999; corrected for cosmogenic ^{36}Ar) suggests an age of 1.33 ±0.02 Gyr and an intercept of 3691 ±638. The high trapped $^{40}Ar/^{36}Ar$ value indicates that both Martian atmospheric Ar and excess radiogenic ^{40}Ar are present. A corrected isochron for nine extractions (41-91% ^{39}Ar release; R^2=0.9998) gives an age of 1.357 ±0.007 Gyr (1-•) and a $^{40}Ar/^{36}Ar$ intercept of 9 ±186. Our sample contained up to ~5 x10^{-10} cm^3ST/g of trapped Martian ^{36}Ar. The slight disagreement in the isochron ages for 11-51% ^{39}Ar release and 41-91% ^{39}Ar release, and the presence of trapped Martian Ar only at lower temperatures, has two explanations. Either the K-Ar age for Nakhla is ~1.36 Gyr and extractions below ~50% ^{39}Ar release have experienced some diffusive loss of radiogenic ^{40}Ar; or, the age is ~1.33 Gyr and excess radiogenic ^{40}Ar was released at all extractions. Our Ar age for Nakhla is slightly older than Ar-Ar ages of 1.32-1.33 Gyr recently reported for whole rock samples of Nakhla and Lafayette by (5), who also found elevated ages at intermediate extraction temperatures and derived their ages from higher temperature argon releases.

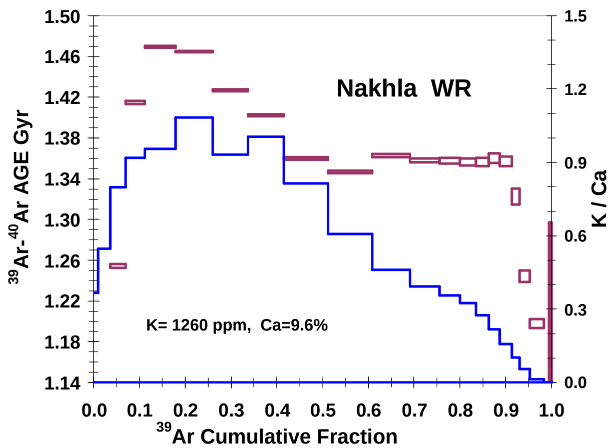
Space (CRE) Exposure Ages. We analyzed a pure olivine separate of NWA998 (furnished by A. Irving) for cosmogenic noble gases, and from these data calculated the space, or cosmic ray exposure age. We used the determined chemical composition of the olivine and the chemical-based production rates given by (8). The ages are ^{3}He= 12.7 Myr, ^{21}Ne= 12.3 Myr, and ^{38}Ar= 9.3 Myr. The cosmogenic $^{22}Ne/^{21}Ne$=1.164. These ages are virtually identical to analogous ages reported for Nakhla, Lafayette, Governador Valadares (9) and to the Yamato paired nakhlites (10, 11). Average CRE ages for five nakhlites are ^{3}He= 12.2 ±0.4, ^{21}Ne= 11.7 ±1.6, and ^{38}Ar= 9.4 ±0.25 Myr. All nakhlite CRE ages based on Ar are significant younger than those based on He and Ne, a characteristic also observed among some shergottite CRE ages.

Conclusion. The preferred radiometric ages of three nakhlites were listed as 1.27-1.33 Gyr (Nyquist et al, 2001), which may leave open the question of whether the nakhlites have a common formation age. The Ar-Ar age of NWA998 is identical to Ar ages for Governador Valadares (3) and Nakhla and Lafayette (5). The slightly older Ar-Ar ages we obtained for Y000593 and Nakhla are likely caused by radiogenic ^{40}Ar in the original melt, which was incorporated into late-crystallizing mesostasis. Thus, we suggest that all dated nakhlites probably have a common Ar-Ar age. In addition, the CRE ages determined for all nakhlites are the same within calculation uncertainties. This implies that all nakhlites were ejected from Mars in a single impact event from a common Martian location.

References. (1) Kojima et al., *Antarctic Meteorites XXVII*, 66-69, NIPR, Tokyo, 2002; (2) Irving et al., *Meteoritics Planet Sci. 37,* A70, 2002; (3) Nyquist et al., Ages of Martian meteorites, *Space Science Rev.* 96, 2001; (4) Misawa et al., *Antarctic Meteorite Res.*, in press, 2004; (5) Swindle & Olsen, *Meteoritics Planet. Sci. 39*, p.693, 2004; (6) Garrison et al., *Meteoritics Planet. Sci. 35*, p.419, 2000; (7) Bogard & Garrison, *Meteoritics Planet. Sci. 39*, p.451, 1999; (8) Eugster & Michel, *Geochim. Cosmochim. Acta 59*, p.177, 1995; (9) Eugster et al., *Geochim. Cosmochim. Acta 61*, p.2749, 1997; (10) Okazaki et al., *Antarctic Meteorite Res. 16*, p.58, 2003; (11) Christen et al., *Antarctic Meteorites XXVIII*, p.6, 2004.






Nakhla WR
K= 1260 ppm, Ca=9.6%
^{39}Ar-^{40}Ar AGE Gyr
K / Ca
^{39}Ar Cumulative Fraction
1.50
1.46
1.42
1.38
1.34
1.30
1.26
1.22
1.18
1.14
1.5
1.2
0.9
0.6
0.3
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0