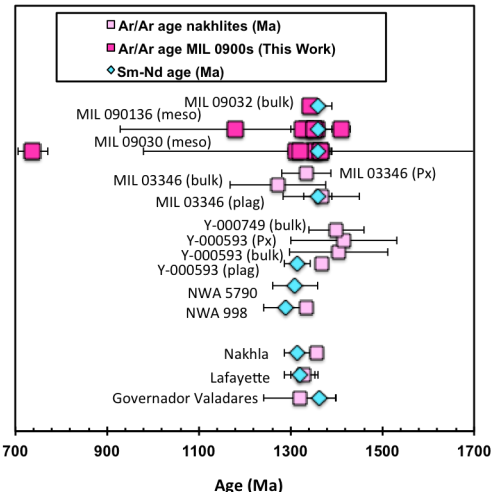
**$^{40}Ar/^{39}Ar$ AGES OF NAKHLITES Miller Range (MIL) 090030, 090032 and 090136.** J. Park[1,2], L. E. Nyquist[3], G. F. Herzog[1], B. D. Turrin[4], F. N. Lindsay[1], J. S. Delaney[1], C. C. Swisher III[4]. [1]Dept. Chem. & Chem. Biol., Rutgers Univ., Piscataway, NJ 08854 (jp975@rci.rutgers.edu), [2]Kingsborough Comm. Coll., Brooklyn, NY 11235, [3]XI/NASA-JSC, Houston TX 77058, [4]Dept. Earth Planet. Sci., Rutgers Univ., Piscataway, NJ 08854.

**Introduction:** We report the first $^{40}Ar/^{39}Ar$ ages of the paired nakhlites Miller Range (MIL) 090030, 090032 and 090136 [1, 2], hereafter MIL 30, 32, and 136. Nakhlites are cumulate Martian meteorites consisting of clinopyroxene (magnesian augite, $Fs_{22}Wo_{43}$-$Fs_{49}Wo_{34}$ for MIL 30, 32, and 136, [3]), olivine ($Fa_{57}$-$Fa_{89}$, [3]) and mesostasis enriched in incompatible elements of plagioclase and alkali feldspars, Fe-Ti oxides, silicic/basaltic glass, and quench olivine [e.g., 4]. Unlike shergottites, the nakhlites have given $^{40}Ar/^{39}Ar$ ages that agree closely with those obtained using other radiometric techniques and in particular Sm/Nd (Figure 1) [e.g., 5, 6, 7]. Also, nakhlites are known to contain iddingsite, which is a secondary product of the alteration of olivine [6, 8].

Figure 1. $^{40}Ar/^{39}Ar$ and Sm/Nd ages of Martian nakhlites and MIL 090030, MIL090032, 090136. (References are in [7] and this work). Meso: mesostasis, Px: pyroxene, plag: plagioclase separates.




**Experimental methods:** *Samples.* The MIL samples were generously allocated by the Meteorite Working Group. We gently crushed and hand-picked mesostasis from MIL 30 and MIL 136. Fifteen samples were prepared for Ar analysis: 7 from MIL 30 (mesostasis; 24 to 482 μg); 7 from MIL 136 (mesostasis; 11-285 μg) and 1 from MIL 32 (bulk; 165 μg).

*Ar analysis:* The samples were loaded in an Al-well plate, sealed in an evacuated quartz tube, and irradiated for 80 hours without Cd shielding at the USGS TRIGA reactor in Denver. Samples were heated with a $CO_2$ laser and the argon isotopes released were analyzed using a modified MAP 215-50 mass spectrometer [10, 11].

**Results:** *Plateau $^{40}Ar/^{39}Ar$ ages (T).* Among 15 nakhlite release spectra, 5 show plateaus (successive $\Delta T<1\text{-}\sigma$ for >50% of $^{39}Ar$ release) (Table 1); 7 show "forced plateaus" (3 successive steps with $\Delta T<1\text{-}\sigma$), and 3 are disturbed. 10 of the 12 plateau ages are in the narrow range of 1311 Ma to 1365 Ma, and are identical within errors to the crystallization age determined by Sm/Nd chronometry (Figure 1). Two samples have younger plateau ages: 738 ± 33 Ma (MIL30, id:21622-01) and 1180 ± 250 Ma (MIL136, Id: 21625-03). EDS and XRF analyses of selected material (Figure 2) confirmed the identity of the mesostasis and gave K concentrations from 0.057 to 3.2 wt%.

*Integrated $^{40}Ar/^{39}Ar$ ages (total fusion ages).* With two exceptions, the integrated ages fall within the wider range known for typical nakhlites of ~1.3-1.4 Ga (Table 1).

*Isochron ages.* Isochron ages of MIL 30 without corrections for cosmogenic $^{36}Ar$ are similar to the integrated ages, while those of MIL 136 and 32 are a bit older. The average isochron ages for MIL 30, 32, and 136 are 1373 ± 4 Ma, 1404 ± 9 Ma, and 1492 ± 4 Ma, respectively.

**Discussion:** *Pairings.* MIL 30, 32 and 136 were paired based on find location, mineralogy, and petrography [1, 2]. Identical $^{40}Ar/^{39}Ar$ ages support this pairing.

*Release patterns.* Figure 3 compares some release patterns for MIL 090xxx with one for the paired nakhlite MIL 03346 [9]. The integrated $^{40}Ar/^{39}Ar$ ages of MIL 03346 are 1272 ± 105 Ma (whole rock), 1413 ± 88 Ma (plagioclase) and 1404 ± 182 Ma (pyroxene). The step ages of MIL 03346 decrease steadily, from ~1.52 Ga down to <1.28 Ga [9]. The plateau ages are 1368 ± 83 Ma (Plagioclase, [9]) and 1334 ± 54 Ma

Figure 2. MIL 090136 sample and selected mesostasis with EDX data. PTS=Polished Thin Section; DST=Distance.

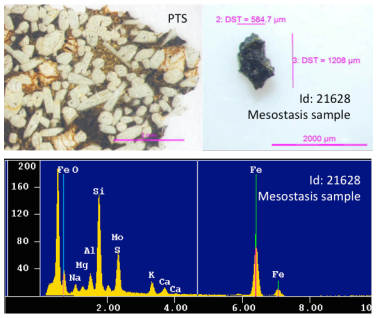


Table 1. Integrated, plateau $^{40}Ar/^{39}Ar$ ages and isochron ages of MIL 090030, MIL090032, 090136 and MIL 03346.

| Sample ID | Mass (ug) | Integrated Age (Ma) | Plateau Age (Ma) | Isochron Age (Ma) |
|---|---|---|---|---|
| **MIL 090030 (Mesostasis, This work)** | | | | |
| 21622-01 | 482 | 927±13 | 738±33* | 769±11 |
| 21622-02 | 72 | 1350±370 | No plateau | 2350±590 |
| 21622-03 | 29 | 1325±23 | 1353±18 | 1421±37 |
| 21623-01 | 54 | 1352±8 | 1365±19* | 1438±13 |
| 21623-02 | 25 | 1341±19 | 1311±15* | 1300±28 |
| 21624-01 | 98 | 1391±5 | 1365±23 | 1388±8 |
| 21624-02 | 38 | 1380±10 | 1319±13 | 1423±18 |
| **MIL 090136 (Mesostasis, This Work)** | | | | |
| 21625-01 | 139 | 1410±5 | No plateau | 1544±14 |
| 21625-03 | 11 | 1230±310 | 1180±250 | 1310±550 |
| 21626 | 49 | 1184±3 | 1357±16* | 664±10 |
| 21627-01 | 285 | 1366±2 | 1335±4* | 1493±5 |
| 21627-02 | 13 | 1277±28 | 1,327±26 | 1486±73 |
| 21628-01 | 81 | 1277±7 | 1351±11* | 1568±22 |
| 21628-02 | 40 | 1,306±32 | 1352±19 | 1525±85 |
| **MIL 090032 (Bulk, This Work)** | | | | |
| 22628 | 165 | 1418±7 | 1343±11* | 1404±9 |
| **MIL 03346 (Park et al., 2009)** | | | | |
| Bulk | 32470 | 1404±182 | No plateau | 1434±96 |
| Plagioclase | 12410 | 1413±88 | 1368±83 | 1368±83 |
| Pyroxene | 32470 | 1404±182 | 1334±54 | ~1300 |

*: forced plateau age

(pyroxene, [9]). The release pattern of MIL 03346 [9] is similar to that of MIL 32 (bulk), which supports the pairing. Overall, the ages obtained for these four MIL nakhlites are remarkably consistent.

*Young $^{40}Ar/^{39}Ar$ ages (Iddingsites?).* One sample of MIL 30 mesostasis (21622-01) with an age of 738 Ma (Figure 1 & 3) is younger by far than the others. Nakhlites are known to contain iddingsites, which are products of the aqueous alteration of olivine. Iddingsite could have escaped notice during the EDX analyses.

K-Ar ages from zero to 670 ± 91 Ma have been reported for iddingsites from Lafayette [9]. Rb-Sr ages of 0.65 ± 0.08 Ga and 1.30±0.02 Ga were reported for the nakhlite Yamato 000593 [12]. The former age was obtained for brownish alteration products (presumably iddingsite) sampled as two olivine leachates. It is consistent with our result for MIL 30 (21622-01).The latter Rb-Sr age refers to major minerals [12] and is consistent with most of the other ages. An average age of 633±23 Ma was suggested for iddingsite formation age from K-Ar and Rb-Sr methods [6]. Our $^{40}Ar$-$^{39}Ar$ age for 21622-01 is analytically robust and likely gives the time of aqueous alteration and iddingsite formation in MIL 30. Some release patterns also show evidence of intermediate ages of ~1180 Ma (e.g., MIL 136), which could result from mixing of radiogenic $^{40}Ar$ released both from secondary and primary minerals.

**Conclusions:** We conclude that MIL 30, like other nakhlites, crystallized ~ 1.3-1.4 Ga ago. Later it experienced an aqueous alteration event on Mars that produced iddingsite. Our new $^{40}Ar/^{39}Ar$ results set a robust limit of 0.6 to 0.7 Ga B.P. for the time of the alteration.

**References:** [1] McKay and Schwandt, 2005, *LPSC* 36,#2351. [2] Corrigan C. M. et al., 2011, LPSC 42, #2657. [3] Righter K. (2010) Antarctic Meteorite Newsletter 33, No2. Sep. [4] Treiman A. H. (2005) Chem. Erde-Geochem. 65, 203–270. [5] Nyquist L. E. et al. (2001) *Space Science Reviews*. 96, 105-164. [6] Borg L. and Drake M. J. (2005) *JGR, 110*, E12S03. [7] Park et al. (2013) GS, Special Publications, 378, 297–316. [8] Swindle T. D. et al. (2000) MAPS 35, 107-115. [9] Park J. et al. (2009) GCA 73, 2177-2189. [10] Turrin B.D. et al (2010) *$G^3$ 11,* Q0AA09, doi:10.1029/2009GC003013 (2010). [11] Lindsay F.N. et al. (2014) *GCA 129*, 96-110. [12] Misawa K. et al. (2005) Antarct. Meteorite Res., 18, 133-151.

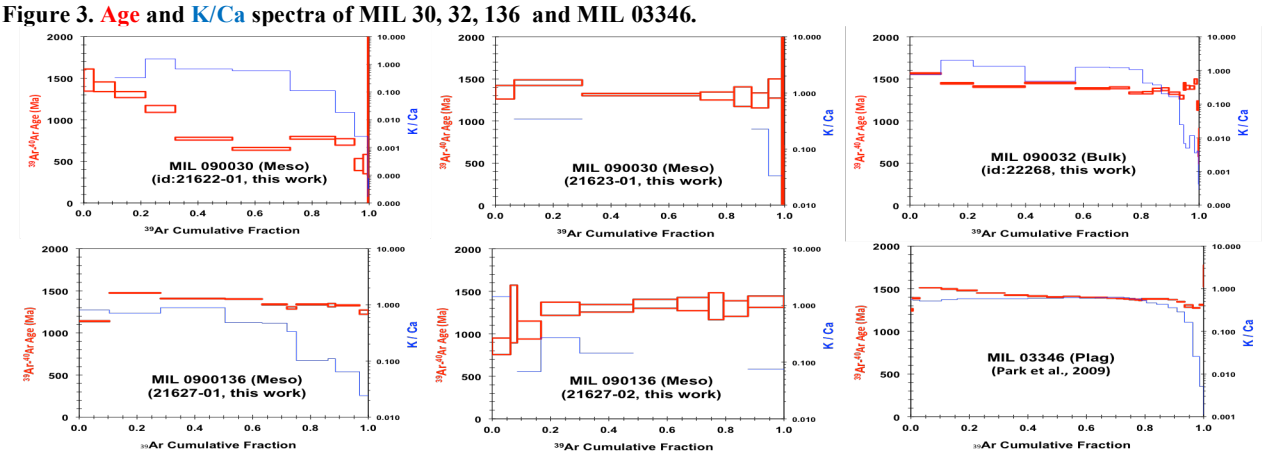



**Figure 3. Age and K/Ca spectra of MIL 30, 32, 136 and MIL 03346.**