Available online at www.sciencedirect.com
ScienceDirect
Earth and Planetary Science Letters 256 (2007) 55 – 60
EPSL
www.elsevier.com/locate/epsl

The Martian meteorite paradox: Climatic influence on impact ejection from Mars?

Jörg Fritz *, Ansgar Greshake, Dieter Stöffler

Mineralogie, Museum für Naturkunde, Invalidenstrasse 43, 10115 Berlin, Germany

Received 12 October 2006; received in revised form 4 December 2006; accepted 7 January 2007
Available online 13 January 2007
Editor: G.D. Price

Abstract

The large number of Martian meteorites with "young" crystallization ages (especially shergottites formed ~170 Myr ago on Mars) represents a paradox, because it suggests that either the mean surface age of Mars is rather young or that specific source regions are preferentially amenable for impact sampling. We present a climate controlled scenario, in which surface regions of limited extent have been especially favored for impact ejection of Martian meteorites during the past ~5 Myr. This conclusion implies that the ejection ages of the shergottites may be used to constrain the end of the last major glaciations on Mars.

Keywords: Mars; Martian meteorite; Martian climate; impact ejection; interplanetary transfer

1. Introduction

Impact ejection and subsequent interplanetary transfer of rocks are documented by the discovery of lunar and Martian meteorites on Earth. Lunar meteorites comprise mare basalts, anorthositic highland breccias and regolith breccias, and KREEP bearing rocks, and, thus, appear to be representative for the varied compositions of surfaces on the Moon [1]. In contrast, Martian meteorites (MM hereafter) are exclusively mafic to ultramafic (~75%) and ultramafic igneous (~25%) rocks [2]. Regolith breccias, polymict impact breccias, and any type of felsic, metamorphic or sedimentary rocks are missing in the available suite of MM. In addition to these petrologic limitations, crystallization ages of MM (Fig. 1) are strongly biased, as all shergottites are younger than 0.6 Gyr (most crystallized between 0.15 and 0.20 Gyr ago), the ultramafic nakhlites and chassignites cluster around ~1.3 Gyr and only ALH84001 is derived from an ancient (~4.5 Gyr) lithology. Thus, the samples are not representative of the actual proportions of Noachian, Hesperian, and Amazonian terrains on Mars. This presents a widely discussed "paradox" [3–6], as either a major resurfing event at 0.15–0.20 Gyr ago has to be assumed, and/or only small regions on Mars were especially favored for the impact ejection of MM. Additionally, the ejection events of MM are distributed unevenly in time. The cosmic ray exposure ages and MM petrology (Fig. 2) indicate up to seven different ejection events at ~0.7, ~1.2, ~3, ~4, ~11, ~15 and ~20 Myr.

2. Ejection events of Martian meteorites

Based on petrology, crystallization and ejection ages the MM paradox is particularly distinct for the last

---

* Corresponding author. Tel.: +49 30 2093 8882; fax: +49 30 2093 8565.
E-mail address: joerg.fritz.1@rz.hu-berlin.de (J. Fritz).

0012-821X/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2007.01.009

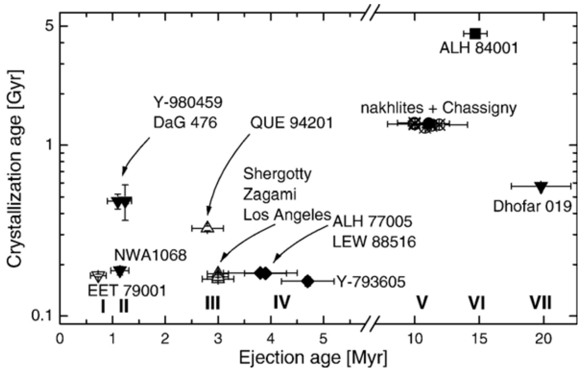

Fig. 1. Crystallization vs. ejection ages of MM. The ejection age is the sum of cosmic ray exposure age and the terrestrial residence time of the meteorite. Petrologic types of the meteorites are represented by different symbols. ▽ EET 79001 with olivine-phyric (A) and basaltic (B) lithology; ▼ olivine-phyric shergottites; △ basaltic shergottites; ◆ lherzolitic shergottites; ⊗ nakhlites (clinopyroxenite); ● chassignite (dunite); ■ orthopyroxenite ALH 84001. Crystallization and ejection ages are cited in Fig. 2.

~5 Myr, during which the four documented impact events sampled <5–10% of the Martian surface (area with surface ages <0.6 Gyr [7]), whereas ejection events >5 Myr ago sampled lithologies of different ages and different types of rocks. In the last 5 Myr four different ejection events (I–IV; Figs. 1 and 2) sampled shergottitic lithologies that crystallized 0.15–0.20 Gyr ago. No ejection event is recorded by MM between 5 and 10 Myr ago. Nevertheless, the large number of nakhlites recovered from the impact event at ~11 Myr supports results from orbital simulations of potential MM, which propose a constant flux that lasted over 15 Myr [4]. Consequently, the rather low frequency of documented MM ejection events between 5 to 20 Ma ago appears not to be a sampling artifact due to limited survival time of small rock fragments in space environment. A sampling artifact is rather improbable as, a) the terrestrial residence time of recovered MM is less than 0.4 Ma and, thus, rather short compared to their space residence time of 1–20 Ma (e.g. [8]), b) the current flux of MM on Earth is composed of MM with largely different ejection ages, e.g., Shergotty, Zagami (both ejected ~3 Ma ago), Chassigny and Nakhla (both ejected 11 Ma ago) which are all observed falls.

The present record of MM documents clearly that there is a preferred sampling of ~170 Ma old “basaltic” lithologies during the past 5 Myr (Figs. 1 and 2). In contrast, the MM from all three documented ejection events during the time between 5 and 20 Myr ago display significant variations in petrology and crystallization age. For these events which deliver mainly ultramafic rocks, no specific locations on Mars can be suggested and, therefore, surfaces on Mars appear to have been sampled randomly during 5–20 Ma ago.

3. Source regions of Martian meteorites

Based on petrology and crystallization ages, the most likely source regions for shergottites (mainly basaltic rocks) are Tharsis, Amazonis and Elysium Planitia [5]. Crystallization ages of shergottites correlate with volcanic activity ~0.2 Gyr ago at Arsia, Ascraeus and Olympus Mons in the Tharsis region and Hecates Tholus in the Elysium region [9]. Selective sampling of these tropical (low latitude) and highly elevated regions is in agreement with the physics of impact ejection from Mars, as they share the following characteristics:

1) High elevation above datum, with the Tharsis bulge rising >10 km above datum. At such elevation the atmospheric pressure is 2.3 times lower than that at datum. The minimum mass of fragments not decelerated below escape is controlled by the total mass of the atmosphere along the trajectory [8,10]. Less atmospheric mass (integrated over pressure and trajectory) is equivalent to less pressure and/or shorter trajectory. Atmosphere acts as a strong filter for small impacts, but is less effective for huge impacts. For a typical fragment size distribution of

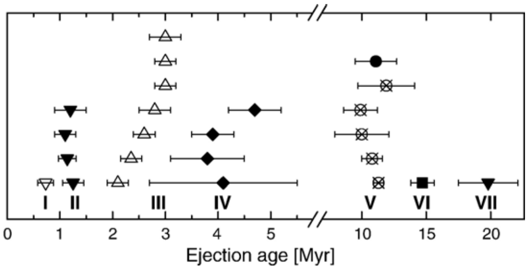

Fig. 2. Ejection ages of MM. Symbols for petrologic types, and data for ejection ages of MM as in Fig. 1. A maximum of seven different MM ejection events can be discriminated, as petrologically related meteorites show similar ejection ages. Proposed MM ejection events are indicated by bold numerals, with meteorites listed from bottom up. **(I)** EET 79001 [5]; **(II)** DaG 476 [5], NWA 1068 [23] (^{21}Ne age [24]), Y-980549 [17,25], SaU 005 [6]; **(III)** Dhofar 378 [26], NWA 480 [24], NWA 856 [24], QUE 94201 [5,6], Los Angeles [5,6], Zagami [5,6], Shergotty [5,6]; **(IV)** NWA 1950 [17], ALH 77005 [5,6], LEW 88516 [5,6], Y-793605 [5,27]; **(V)** Y000593/000749/000802 [17,28], Nakhla [4,5], Governador Valadarez [4], NWA 817 [24], Lafayette [5], Chassigny [5,6]; **VI:** ALH 84001 [5,6]; **(VII)** Dhofar 019 [5,29]. From the total of 35 known unpaired MM [2], all 24 with currently known ejection ages are considered in this figure. As the petrology of the remaining 11 MM is similar to the ones considered in this comparison [2], they may have been ejected by these same seven ejection events.

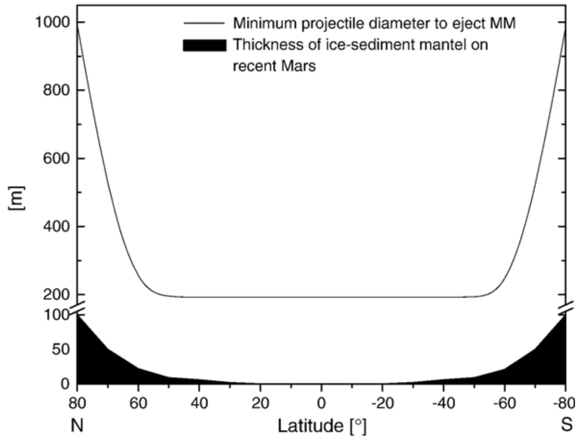

Fig. 3. Distribution of a sediment–ice mantle on current Mars and its influence on the minimum projectile diameter with the potential to eject MM. Thickness of the sediment–ice mantle with respect to Martian latitude is shown as a black area [10]. Note that latitude is restricted to the range from 80°N to 80°S; polar regions are not shown. The minimum projectile diameter is 200 m for an impact at datum altitude and without contribution of angular velocity [10]. As the sampling depth of an impacting projectile equals 0.1 times its diameter [10], the minimum projectile size increases by a factor of ten with increasing thickness of the sediment–ice mantle; consequently, regions with high latitudes do not represent a likely source for MM (see text).

impact ejecta, the total escaping mass is ∼20 times larger at half the given atmospheric pressure [8].

2) Restriction to low latitudes. The angular velocity that is 0.24 km/s on the equator (5% of the escape velocity) may add energy to the ejection process if it is in the same direction. Alternatively, it could be a hindrance, if ejection is in the opposite direction [8].
3) High strength material at the surface. The total amount of high velocity ejecta is higher for impacts into rigid and compact lithologies than for those into porous or brecciated targets [3]. Impact ejection of shergottitic (basaltic) lithologies with "young" crystallisation ages was proposed to be favored by a less impact gardened and, hence, rigid surface [3]. As the depth of the Martian meteorite source region is only 0.1 times the diameter of the impacting projectile [10], not only a thick regolith cover, but also a sedimentary cover (>10–20 m thickness) could reduce the area that could be sampled by the smallest possible and therefore most frequent projectiles (Fig. 3). Sedimentary deposits continuously mantle Mars in varying thickness of several tens of meters polewards from 60° latitude and of several meters between 30° and 60° latitude [11]. There is no evidence for a continuous cover at latitudes below 30°N and 30°S respectively [11]. In conclusion, as atmospheric pressure acts as an effective filter for small fragments (<10 cm ⊘ at present datum pressure [10]), a largely wind-deposited ice–dust mantle that should be strongly biased towards small grain sizes, does not represent a likely source for MM.

The described characteristics of tropical and highly elevated regions strongly favor impact ejection of sizable solid rock fragments from Mars by rather small projectiles. By comparison, no region appears to be particularly favored for the impact ejection of meteorites on the Moon, as it 1) lacks an atmosphere, 2) is in synchronous orbit with Earth and, 3) is ubiquitously covered with regolith.

4. Climatic influence on impact ejection

On Mars multiple impact sampling of shergottitic lithologies seems to be restricted to the past ∼5 Myr (Figs. 1 and 2), and hence, earlier conditions were likely less favorable. Because the change in the frequency of MM ejection events and characteristics of the sampled lithologies was rapid ($<10^6$ Myr), a climatic influence on the mechanical properties of the uppermost surface and/or variations in atmosphere pressure has to be considered.

Such a major climatic change ∼5 Myr ago has been inferred from numerical integration of the planetary motion of Mars [12] (Fig. 4). These calculations resulted in a substantial increase in obliquity, of an average of some 25° for the last 5 Myr, to an average around 35° for the time interval between 5 and 20 Myr. This substantial long-lasting increase in obliquity of the Martian spin axis coincides in time with the onset of frequent impact sampling of MM (shergottitic lithologies) at ∼5 Myr ago.

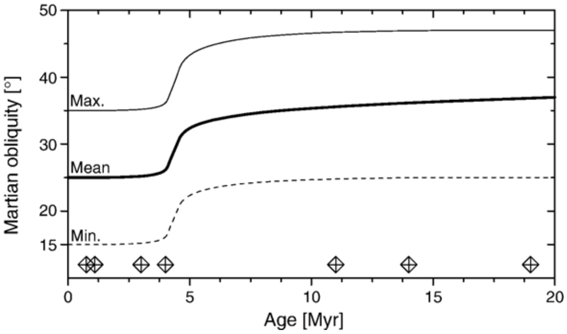

Fig. 4. Obliquity of the Martian spin axis over time [12]. Only the mean obliquity is considered, because impact sampling is random in time. The seven documented impact events, as identified in Figs. 1 and 2, are represented by diamonds. Note the strong correlation of increase in obliquity and decreasing frequency of MM ejection events above ∼5 Myr.

Various geological evidences for substantial climatic change in the recent past of Mars have been reported. Latitude dependent water–ice-rich mantling deposits [11], youthful ice-rich deposits [13], and layered polar deposits [14] document repeated climatic cycles. Sedimentary deposits at the base of the large Olympus and Tharsis montes represent remnants of tropical glaciers that formed and degraded in the recent past [9,15,16]. These observations document the extent of ice and dust redistribution during glacial/interglacial transitions. On Mars, glacial ice–sediments progress towards lower latitudes in times of high obliquity, because of an increase of polar insulation which leads to enhanced sublimation of the polar caps [11].

As the large number of documented MM ejection events during the past 20 Myr demand small and consequently frequently formed source craters (in the order of 3 km ⌀) [3,10,17], and the sampling depth is restricted to 0.1 times the diameter of the impacting projectiles (e.g., 20 m [10]), the latitudinal distribution of a sediment–ice mantle can control the minimum projectile size capable to eject solid igneous rocks from Mars (Fig. 3).

A sediment–ice-rich glacial cover exceeding 10–20 m thickness would hinder the smallest projectiles required to sample shergottitic source rock in times of high obliquity and tropical glaciations with sufficient frequency. Climatic models of Mars during high obliquity (35–45°) predict seasonal ice accumulation of 30–70 mm, which after a few thousand years accumulate to several hundred meter thick glaciers on regions of Tharsis, Olympus and Elysium montes [18], which may represent the shergottitic source region(s). During low obliquity a degrading of a tropical ice–sediment mantle, or a retreat of glaciers on the large volcanic constructs, could result in the exposure of rigid shergottitic lithologies. These regions are favored by high elevation, low latitude and lack of a sedimentary cover for the launch of rock from Mars. Thus, rather small projectiles can eject "young" shergottites during interglacial rather frequently.

An increase in global atmospheric pressure represents another mechanism to decrease the total mass of impact ejected rock fragments before ~5 Myr ago [4,8]. In contrast to glacial sediments which shield only the covered area the atmospheric pressure acts as a global filter. Whether atmospheric pressure varies during climatic changes on Mars depends on the total amount of volatiles (especially CO_2) available in the regolith, polar cap and atmosphere reservoirs. At high obliquity of Mars and thermally instable polar caps the atmospheric pressure remains ≤ 6 mbar in a "thin" model, whereas in a "thick" model atmospheric pressure increases to ~80 mbar [19]. Compared to the current atmospheric pressure of ~6 mbar, an atmospheric pressure of ~80 mbar would substantially reduce the total mass ejected in a given small impact event [8].

5. Size of Martian meteorite source craters

As discussed in the foregoing sections there are two climatically different time periods (0–5 and 5–20 Myr ago) during which MM were ejected from Mars and delivered to Earth with different frequency (Figs. 1, 2, 4). The MM of these two periods of time originate obviously from two distinctly different regions of Mars which differ in the size and geographical location, in the thickness of ice–sediment deposits mantling the substratum of igneous source rocks, and in the composition and age of these rocks.

The MM with young ejection ages (<5 Myr) and young crystallization ages (<0.6 Gyr) must originate from a restricted ice–sediment-free basaltic region of high altitude and low latitude. Moreover, their ejection/delivery/recovery frequency is 5 times higher than during the time period 5–20 Myr ago. Therefore, their source craters must be rather small in order to be sufficiently frequent. The size limitations for these craters are constrained by the time dependent size-frequency statistics of craters on Mars [7,20] and by the efficiency to eject and deliver MM into Earth crossing orbits [3,4,8,10]. These boundary conditions yield a minimum diameter for the source craters of about 2 km. For example, craters within the size range of 2.0–2.83 km (size bin of the counting statistics of [20]) form on Mars with a frequency of 7×10^{-8} km^{-2} Ma^{-1} [20] which yields 14 impacts per 1 Myr on the whole surface of Mars. Using the Schmitt and Housen scaling law [21] for Martian cratering events at an average impact velocity of 10 km/s [22] reveals that 2 km sized Martian craters were formed by 100 m diameter sized projectiles. Such projectiles have the potential to eject rock fragments from the upper 10 m of rigid igneous Martian lithologies [10].

During the time period from 5 to 20 Myr ago MM were obviously ejected 5 times less frequent than later. This decrease of the ejection frequency by a factor of 5 would require to double the diameter of the source craters from 2.0–2.83 to 4.0–5.66 km provided that the thickness of an ice–sediment cover of the igneous source region does not exceed 15 m and the extent of the source region remains the same. Such craters correspond to a projectile size of 250 m, and a sampling depth of 25 m, allowing to sample a 10 m thick layer of rigid igneous Martian lithologies from beneath the 15 m thick ice–sediment blanket. However, there are two problems: (1) the source region of MM during the time period 5–20 Myr ago was much larger than the source region of the young shergottites produced during the past 5 Myr, because the former vary greatly in composition and texture (mafic to ultramafic and plutonic to volcanic) and in age (0.6, 1.3 and 4.5 Gyr), and (2) the conditions in this much larger source region were such that a mantling of porous or brecciated material (e.g, ice–sediments, sediments, or regolith) of up to 100 m thickness must be expected and taken into account. As these two conditions are counteracting we arrive at diameters of 4–16 km for the source craters of MM with ejection ages of 5–20 Myr if we assume a four times larger source region than that one of the young shergottites. The projectile diameters for these craters range from 250 to 1000 m and the sampling depths from 25 to 100 m, respectively.

6. Conclusion

Impact ejection of Martian meteorites first of all depends on mass, velocity, and angle of the impacting projectile [3,10]. However, for a given projectile the probability to eject MM is influenced by the integrated atmospheric mass along the trajectory of the ejected fragments, the planet's angular velocity, and mechanical surface properties at the impact site [3,8,10]. Consequently, the MM paradox, which appears to be pronounced during the recent interglacial, can be resolved by considering the physics of impact ejection in combination with the dynamics of the Martian climate and its effects on the surface properties of Mars.

Acknowledgements

We are very grateful to Boris Ivanov for the constructive review and for providing the quantitative estimates concerning minimum sizes of MM source craters. Financial support for JF by Saalbau-HP Weltraumprojekt.

References

[1] B.L. Joliff, M.A. Wieczorek, C.K. Shearer, C.R. Neal, New views of the Moon, Reviews in Mineralogy and Geochemistry, vol. 60, The Mineralogical Society of America, Chantilly, Virginia, USA, 2006.

[2] C. Meyer, The Martian Meteorite Compendium, 2006 http://curator.jsc.nasa.gov/antmet/mmc/index.cfm.

[3] J.N. Head, J.H. Melosh, B.A. Ivanov, Martian meteorite launch: high-speed ejecta from small craters, Science 298 (2002) 1752–1756.

[4] B. Gladman, Destination Earth: Martian meteorite delivery, Icarus 130 (1997) 228–246.

[5] L.E. Nyquist, D.D. Bogard, C.-Y. Shih, A. Greshake, D. Stöffler, O. Eugster, Ages and geologic histories of Martian meteorites, Space Sci. Rev. 96 (2001) 105–164.

[6] O. Eugster, H. Busemann, S. Lorenzetti, D. Terribilini, Ejection ages from krypton-81–krypton-83 dating and pre-atmospheric sizes of Martian meteorites, Meteoritics Planet. Sci. 37 (2002) 1345–1360.

[7] W.K. Hartmann, G. Neukum, Cratering chronology and the evolution of Mars, Space Sci. Rev. 96 (2001) 165–194.

[8] J. Fritz, N.A. Artemieva, A. Greshake, Ejection of Martian meteorites, Meteoritics Planet. Sci. 40 (2005) 1393–1411.

[9] G. Neukum, R. Jaumann, H. Hoffmann, E. Hauber, J.W. Head, A.T. Basilevsky, B.A. Ivanov, S.C. Werner, S. van Gasselt, J.B. Murray, T. McCord, HRSC Co-Investigator Team, Recent and episodic volcanic and glacial activity on Mars revealed by the high resolution stereo camera, Nature 432 (2004) 971–979.

[10] N.A. Artemieva, B.A. Ivanov, Launch of Martian meteorites in oblique impacts, Icarus 171 (2004) 84–101.

[11] J.W. Head, J.F. Mustard, M.A. Kreslavsky, R.E. Milliken, D.R. Marchant, Recent ice ages on Mars, Nature 426 (2003) 797–802.

[12] J. Laskar, A.C.M. Correia, M. Gastineau, F. Joutel, B. Levrard, P. Robutel, Long term evolution and chaotic diffusion of the insulation quantities of Mars, Icarus 170 (2004) 343–364.

[13] B. Levrard, F. Forget, F. Montmessin, J. Laskar, Recent ice-rich deposits formed at high latitudes on Mars by sublimation of unstable equatorial ice during low obliquity, Nature 431 (2004) 1072–1075.

[14] J. Laskar, B. Levrard, J.F. Mustard, Orbital forcing of the Martian polar layered deposits, Nature 419 (2002) 375–377.

[15] J.W. Head, G. Neukum, R. Jaumann, H. Hiesinger, E. Hauber, M. Carr, P. Masson, B. Foing, H. Hoffmann, M. Kreslavsky, S. Werner, S. Milkovich, S. van Gasselt, HRSC Co-Investor Team, Tropical to mid latitude snow and ice accumulation, flow and glaciation on Mars, Nature 434 (2005) 346–351.

[16] A. Marquèz, C. Fernàndez, F. Anguita, A. Farelo, A. Anguita, M.-A. de la Casa, New evidence for a volcanically, tectonically, and climatically active Mars, Icarus 172 (2004) 573–581.

[17] F. Christen, O. Eugster, H. Busemann, Mars ejection times and neutron capturer effects of the nakhlites Y000593 and Y000749, the olivine-phyric shergottite Y980459, and the lherzolitic NWA1950, Antarct. Meteorite Res. 18 (2005) 117–132.

[18] F. Forget, R.M. Haberle, F. Montmessin, B. Levrard, J.W. Head, Formation of glaciers on Mars by atmospheric precipitation during high obliquity, Science 311 (2006) 368–371.

[19] C.V. Manning, C.P. McKay, K.J. Zahnle, Thick and thin models of the evolution of carbon dioxide on Mars, Icarus 180 (2006) 38–59.

[20] W.K. Hartmann, Martian cratering 8: isochron refinement and the chronology of Mars, Icarus 174 (2005) 294–320.

[21] R.M. Schmidt, K.R. Housen, Some recent advances in the scaling of impact and explosion cratering, Int. J. Impact Eng. 5 (1987) 543–560.

[22] B.A. Ivanov, Mars/Moon cratering rate ratio estimates, Space Sci. Rev. 96 (2001) 87–104.

[23] C.-Y. Shih, L.E. Nyquist, H. Wiesmann, J.A. Barrat, Age and petrogenesis of picritic shergottite NWA1068: Sm–Nd and Rb–Sr isotopic studies, Lunar Plan. Sci. XXXIV (2003) CD-ROM, abstract #1439, Houston, Texas.

[24] K.J. Mathew, B. Marty, K. Marti, L. Zimmermann, Volatiles (nitrogen, noble gases) in recently discovered SNC meteorites, extinct radioactivities and evolution, Earth Planet. Sci. Lett. 214 (2003) 27–42.

[25] C.E. Shih, L.E. Nyquist, H. Wiesmann, Y. Reese, K. Misawa, Rb–Sr and Sm–Nd dating of olivine-phyric shergottite Y-

980459: petrogenesis of depleted shergottites, Antarct. Meteorite Res. 18 (2005) 46–65.

[26] J. Park, K. Nagao, Noble gas studies of Dhofar 378 Martian meteorite, Meteoritics Planet. Sci. 38 (2003) A5144.

[27] K. Misawa, K. Yamada, N. Nakamura, N. Morikawa, G. Kondorosi, K. Yamashita, W.R. Premo, Sm–Nd isotopic systematics of lherzolitic Shergottite Yamato-793605, Lunar Plan. Sci. XXXVII (2006) CD-ROM, #abstract 1892, Houston, Texas.

[28] K. Misawa, C.-Y. Shih, H. Wiesmann, L.E. Nyquist, Crystallization and alteration ages of the antarctic nakhlite Yamato 000593, Lunar Plan. Sci. XXXIV (2003) CD-ROM, #abstract 1556, Houston, Texas.

[29] L.E. Borg, L.E. Nyquist, Y. Reese, H. Wiesmann, C.-Y. Shih, M. Ivanova, M.A. Nazarov, L.A. Taylor, The age of Dhofar 019 and its relationship to the other Martian meteorites, Lunar Plan. Sci. XXXIII (2001) CD-ROM, #abstract 1144, Houston, Texas.