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The Shergottite Age Paradox and the Relative Probabilities of Ejecting Martian Meteorites of Differing Ages

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Abstract

The apparent paradox that the majority of impacts yielding Martian meteorites appear to have taken place on only a few percent of the Martian surface can be resolved if all the shergottites were ejected in a single event rather than in multiple events as expected from variations in their cosmic ray exposure and crystallization ages. If the shergottite-ejection event is assigned to one of three craters in the vicinity of Olympus Mons that were previously identified as candidate source craters for the SNC (Shergottites, Nakhlites, Chassigny) meteorites, and the nakhlite event to another candidate crater in the vicinity of Ceraunius Tholus, the implied ages of the surrounding terranes agree well with crater density ages. Even for high cratering rates (minimum ages), the likely origin of the shergottites is in the Tharsis region, and the paradox of too many meteorites from too little terrane remains for multiple shegottite-ejection events. However, for high cratering rates it is possible to consider sources for the nakhlites which are away from the Tharsis region. The meteorite-yielding impacts may have been widely dispersed with sources of the young SNC meteorites in the northern plains, and the source of the ancient orthopyroxenite, ALH84001, in the ancient southern uplands. Oblique-impact craters can be identified with the sources of the nakhlites and the orthopyroxenite, respectively, in the nominal cratering rate model, and with the shergottites and orthopyroxenite, respectively, in the high cratering rate model. Thus, oblique impacts deserve renewed attention as an ejection mechanism for Martian meteorites.

Introduction

The interpretation of the radiometric ages of the shergottite meteorites has been controversial (*cf. Shih et al.,* 1982; *Jones,* 1986). Early attempts to date these meteorites often led to discordant ages. This, combined with the ubiquitous presence of shock metamorphic features in the meteorites, led to the interpretation that the youngest ages dated the most recent "major" events, i.e., shock metamorphism (*Shih et al.,* 1982). For most of the shergottites, the Rb-Sr dating technique yielded the youngest ages, typically ~160-180 Ma (million years). However, subsequent work has shown that shock *per se* cannot reset the Rb-Sr system (*Nyquist et al.,* 1987). Neither does post-shock thermal metamorphism appear to be strong enough to account for the age resetting. Thus, isotopic data, particularly the Rb-Sr isotopic data, appear to require most of the shergottites to have been molten ~170 Ma ago (*Jones,* 1986; *Nyquist et al.,* 1995). The currently dominant view is that most shergottites crystallized from endogenously generated magmas at about that time, although a minority view is that some, and perhaps all, of the ~170 Ma shergottites are impact-generated melts. Thus, an earlier corollary to the ~170 Ma "shock age" of the shergottites, i.e., that this age dated ejection from Mars, has given way to the alternate view that ejection times are given by combined cosmic ray exposure plus terrestrial residence ages (*Eugster et al.,* 1997). However, this interpretation leads to the paradox that the majority of rock-ejecting impacts on Mars must have been on the youngest Martian surface terranes, which compose only a few percent of the total surface area. Here, we present this paradox in detail and conclude that it can be resolved if the shergottites were ejected together in a single impact.

Our approach and general conclusions are similar in some respects to those presented by *Treiman* (1995). However, we now have available additional data for the crystallization and cosmic ray exposure ages of the Martian meteorites (*Borg* et al., 1997; *Eugster* et al., 1997; *Shih* et al., 1996, 1997). In particular, the recently determined Rb-Sr and Sm-Nd ages of QUE94201 establish its crystallization age to be ~330 Ma, about twice the widely accepted value of ~170 Ma for other shergottites, and thus the ages of potential Martian source terranes are increased correspondingly. A separate crystallization age for QUE94201 also increases the possible number of separate shergottite-ejecting events from three (*Eugster* et al., 1997) to four. We examine the implications of multiple shergottite-ejecting events and find such a scenario to be inconsistent with the relative percentage of the Martian surface which could be parental to the shergottites, leading us to conclude that a single-crater origin for the shergottites is more probable. Like *Treiman* (1995), we conclude that the relative proportions of Martian meteorite-ejecting events are most easily obtained if the Martian cratering rate was higher in the past.

Crystallization and ejection ages of Martian meteorites

Three parameters relevant to defining the number and circumstances of events in which meteorites were ejected from Mars are summarized in Figure 1. The first is the "ejection age", the sum of the cosmic ray exposure and terrestrial ages, and interpreted to be the time when the meteorite was ejected from Mars (*Eugster et al.,* 1997). A second parameter is the rock type. Rocks ejected from a single crater might be expected to be of a single rock type, or of a limited range of rock types. Finally, the crystallization age gives the time when the meteorite crystallized as part of a rock unit on the Martian surface.

Cosmic ray exposure ages are the dominant component of the ejection ages and have been known for some time for the SNC (Shergottites, Nakhlites, Chassigny) meteorites, i.e., those Martian meteorites exclusive of orthopyroxenite ALH84001. *Bogard et al.,* (1984) presented three scenarios (I-III) for interpreting the exposure ages of SNCs. *Eugster et al.* (1997), like most recent authors, chose to discuss their ejection ages in the context of Scenario II; i.e., that small rock fragments were ejected from Mars and came directly to earth without undergoing collisions and further breakup in space. They identified five different times when Martian meteorites were ejected: 14.4±0.7, 11.0±0.9, 3.84±0.64, 2.76±0.06, and 0.82±0.20 Ma, respectively. These ejection ages were derived for, respectively, the orthopyroxenite ALH84001, nakhlites (clinopyroxenites) and Chassigny (dunite), lherzolitic shergottites, most basaltic shergottites, and basaltic shergottite EET79001. *Eugster et al.* (1997) suggested that a separate, sixth event might be required for the dunite Chassigny because it differs mineralogically from the nakhlites. In the favored model for meteorite ejection (*Melosh,* 1984, 1985), craters >12 km in size are required if fragments a few tens of centimeters are ejected (*Vickery and Melosh,* 1987). It seems likely that craters this large would contain more than a single rock type, and we consider the case for a separate event for Chassigny to be weak.

An alternative model for the cosmic ray exposure ages, (Scenario I; *Bogard et al.,* 1984), leads to different conclusions about the number of meteorite-ejecting impacts and the probable source terrane. In this scenario, a single large impact is hypothesized to have ejected all the SNC meteorites together. The spectrum of exposure ages is surmised to have developed as a consequence of secondary collisions in space which exposed previously shielded portions of ejecta to the cosmic radiation. This scenario was developed in part because of the interpretation that the discordances in the "crystallization" ages of the heavily shocked shergottites, as calculated from the long-lived radioactivities ^{40}K, ^{87}Rb, and ^{147}Sm, are due to variable degrees of resetting of the isotopic systems in a post-shock thermal environment (*Bogard et al.,* 1979; *Nyquist* et al., 1979). This allowed the Rb-Sr ages of ~170 Ma, found to be common to most (originally all) analysed shergottites, to be interpreted as the "shock age" and also the time of ejection of the shergottites from Mars (*Shih et al.*, 1982). This interpretation has been questioned because of (a) the very long calculated annealing times (~10^4 yrs, *Bogard et al.,* 1979; *Nyquist et al.,* 1979) required for isotopic resetting at the low post-shock annealing temperature of ≤400°C deduced by *Duke* (1968) for Shergotty, (b) the observation that impact melt glasses, presumably contemporaneous with shock-produced maskelynite in shergottite EET79001, did not isotopically equilibrate with their surroundings (*Jones,* 1986), (c) the possibility of interpreting the isotopic chraracteristics of shergottites as resulting from assimilation of Martian crustal materials by mantle-derived melts (*Jones*, 1986, 1989; *Jagoutz*, 1989), and (d) alignment of individual analyses of maskelynite from ALHA 77005 along a "shock melt isochron" of 15±15 Ma (*Jagoutz*, 1989). Thus, significant consensus has built around the interpretation that the Rb-Sr ages of ~170 Ma, characteristic of most shergottites, are crystallization ages rather than shock ages (*cf. McSween*, 1994).

The crystallization ages of the Martian meteorites are important in part because they can be linked to observable planetary features, i.e., the relative ages of Martian terranes as determined from the densities of craters per unit surface area. Antarctic shergottite QUE94201, for which *Borg et al.* (1997) recently determined a crystallization age of ~330 Ma, provides a significant exception to the ~170 Ma ages of other analysed shergottites. Concordant Rb-Sr and Sm-Nd ages for QUE94201 seem to clearly establish the crystallization age of this meteorite. Perhaps the most significant features of QUE94201 in the context of the present discussion are that (a) like Zagami, it has concordant Rb-Sr and Sm-Nd internal isochron ages (*Borg et al.*, 1997; *Nyquist et al.*, 1995); (b) these ages of ~330 (QUE94201) and ~170 Ma (Zagami), respectively, are *different*, in spite of the fact that QUE94201 has the same Martian ejection age of ~2.76 Ma as Zagami and Shergotty (*Eugster et al.*, 1997). If indeed QUE94201 was ejected at the same time as Shergotty and Zagami, it could have been come from an older, deeper lava flow on the Martian surface. In terrestrial settings, often many different lava flows will be stacked one on top of another within a radius of a few hundred meters. Excavation from a deep vertical series of flows is not easily accommodated within the confines of the *Melosh* (1984) model for meteorite ejection, however. *McCoy et al.* (1992) concluded that Zagami crystallized in a lava flow > 10 m thick. Thus, if QUE94201 was derived from a stratum in a vertical column below Zagami, the "near surface spall" envisioned in the Melosh (1984) model would also be > 10 m thick, requiring a crater of diameter >100 km (*Vickery and Melosh*, 1987). Alternatively, QUE94201 could be from an older, but adjacent flow. Nevertheless, we also must consider the possibility of its separate ejection from another part of the Martian surface, raising the maximum number of shergottite-ejecting impacts from three (*Eugster et al.,* 1997) to four.

Although significant consensus in interpreting the isotopic data of the shergottites has developed, some uncertainty remains. For example, the interpretation of the young, ~170-180 Ma ages of shergottites as crystallization ages is consistent with the isotopic data for the Zagami shergottite (*Nyquist et al.,* 1995) only if short range (cm-scale) Sr-isotopic heterogeneities were maintained within the Zagami parent magma during crystallization. Thus, although the Sm-Nd and Rb-Sr ages are concordant, (*Nyquist et al.,*1995) suggested that impact melting, as well as magmatic melting, should be considered as a possible mode of petrogenesis of Zagami. Subsequently, *Mittlefehldt et al.* (1997) presented an impact-melting model to explain the petrographic and chemical composition of EETA79001 in detail. Most recently, *El Goresy et al.* (1997) have reexamined the textural features of maskelynite in Shergotty and concluded that they were produced by shock-induced melting and subsequent quenching of plagioclase glass under high pressure; i.e, at much higher temperatures than the ≤400°C deduced by *Duke* (1968). Their observations may necessitate re-examination of current interpretations of the radiometric age data. Indeed, if further work shows that the ~170 Ma ages of most shergottites are *not* their igneous crystallization ages, then the "paradox" which is the topic of this paper is lessened considerably. Nevertheless, we will examine the consequences of the current "consensus" on shergottite ages; i.e. that radiometric ages of ~170 Ma give the time of crystallization from parent magmas which solidified to cover significant areas of the Martian surface.

Comparison of meteorite crystallization ages to Martian terrane ages

Figure 2 compares the maximum possible number of different samplings of Martian surfaces of different ages as inferred from the crystallization and ejection ages of Martian meteorites, to the percentages of the total Martian surface composed of volcanic rocks of differing ages as inferred from crater densities (*Tanaka et al.*,1992). Following *Tanaka et al.* (1986), Martian cratering history is broken into the following epochs: (1) early, middle, and late Noachian (EN, MN, LN); (2) early and late Hesperian (EH, LH); and (3) early, middle, and late Amazonian (EA, MA, LA). Figure 2 shows a sampling event into ancient, ~4.0 Ga terrane as required for ALH84001 by its very old crystallization and Ar retention ages, its old ejection age, and its distinct mineralogy. The figure also shows an event into ~1.3 Ga terrane for the clinopyroxenites Nakhla, Lafayette, and Governador Valadares, and a separate event for the dunite Chassigny, a possibility suggested by *Eugster et al.* (1997). Although we consider the case for a separate event for Chassigny to be weak, it is included here to show the maximum number of surface samplings that might be required. The figure shows three cratering events into ~170 Ma old terrane corresponding to the three different ejection ages identified by *Eugster et al.* (1997) for basaltic and lherzolitic shergottites with crystallization ages of ~170 Ma. Finally, a fourth shergottite-ejecting impact into older terrane is shown corresponding to the crystallization age of QUE94201. The number of meteorite-ejecting impacts on Mars is thus raised from the five or six suggested by *Eugster et al.* (1997) to six or seven.

Although the exact number of sampling events that are required to be on different Martian terranes may be debated, it is clear that shergottite-sampling events are over-represented compared to the fraction of the Martian surface which is volcanic and of an appropriately young age. If there really were a total of six or seven events which sampled the Martian surface and delivered meteorites to us, then having predominantly "young" Martian meteorites derived from a population of predominantly "old' Martian surface rocks (Figure 2) is a paradox that cannot be simply ascribed to the "statistics of small numbers". Those impacts from which we have samples probably are only a small subset of the total meteorite-ejecting impacts striking Mars. Thus, the total number of impacts on Mars from which this subset is drawn is sizable, and the fraction of those striking a given terrane should be proportional to the ratio of the terrane area to the total Martian surface area. These ideas are quantified more rigorously in the following discussion.

Over-representation of shergottite events among meteorite-ejecting impacts

The extent to which shergottite-ejecting events are over-represented among the total meteorite-ejecting events on Mars can be quantified by comparing the percentages of the Martian surface that are of appropriate ages to be parental to the various meteorite types. Volcanic rocks cover about 60% of the Martian surface (*Tanaka et al.,* 1992). Since all the Martian meteorites are igneous, the frequency of occurrence of different crystallization ages among them ought to be proportional to the relative areas of volcanic units of different ages on Mars, at least in the ideal case that (a) meteorites with identical crystallization ages can be grouped to determine a single event, and (b) no two surfaces are exactly the same age. Here, we assume four crystallization age groups: ~170 Ma, ~330 Ma, ~1300 Ma, and 3840-4560 Ma, respectively, (Figure 1). The large range in ages given for the oldest meteorite (ALH84001) encompasses ages reported in the literature: 3840±50 Ma (Rb-Sr; *Wadwha et al.,* 1996); 4000±100 Ma (^{39}Ar-^{40}Ar: *Ash et al.,* 1996); 3800-4300 Ma (^{39}Ar-^{40}Ar: *Bogard and Garrison,* 1997); 4500±130 Ma (Sm-Nd: *Nyquist et al.,* 1995); and ~4560 Ma (*Jagoutz,* 1994). Although Sm-Nd ages are preferred as most reliably giving the crystallization age of a meteorite, in the case of heavily cratered terranes, the ^{39}Ar-^{40}Ar ages most directly date the time of impact-related Ar-outgassing, and thus may be preferable for comparison to crater retention ages. In Figure 1 we show both the crystallization age of 4500±130 Ma (solid symbol, *Nyquist et al.,* 1995) and the Ar retention age of 4000±100 Ma (open symbol, *Ash et al.,* 1996).

Tanaka et al. (1992) estimated that of a total volcanic surface area of ~84 x 10^6 km^2, ~2.1 x 10^6 km^2, or ~2.5%, belongs to the earliest unit, the Early Noachian (EN) which extends from 4.56 to ~3.92 Ga ago in the HT (Hartmann-Tanaka) cratering model. Thus, on average one might expect to collect meteorites from ~40 events before finding one as old as the ~4.50 Ga crystallization age of ALH84001. However, considering only EN terrane may be too restrictive, since the presence of *some* EN terrane among younger MN terrane is geologically plausible. Furthermore, in the Neukum-Wise (NW) model the EN extends from 4.56 to only ~4.50 Ga ago and the Middle Noachian (MN) only to ~4.30 Ga ago (*Tanaka et al.,* 1992). Also, the impact-related ^{39}Ar-^{40}Ar ages of ~4.0 Ga (*Ash et al.,* 1996; *Bogard and Garrison,* 1997) are more appropriate for comparison to the terrane ages. Thus, it probably is justifiable to include the ~20 x 10^6 km^2 of MN age, and to consider the ratio [area of (EN+MN) volcanics]: [total area of volcanics]. Then the ratio of target area to total volcanic area improves to ~1:4, and finding a very old Martian rock from six or seven recovered sampling events becomes probable. This line of reasoning is weakened by the age uncertainties, but it is instructive, nevertheless, to extend it to the other Martian meteorites as well.

The ~1.3 Ga nakhlites and Chassigny, whose crystallization ages are well determined, provide the strongest support for the idea that the relative abundances of the Martian meteorites are determined by the relative proportion of Martian terrane of appropriate age. The ages of the nakhlites and Chassigny appear to stem from the Early Amazonian (EA) era, using the HT (Hartmann-Tanaka) cratering model (*Tanaka et al.,* 1992). The EA covers ~12.7 x 10^6 km^2 of the Martian surface, or ~ 15% of the volcanic surface area. Thus, the relative frequency with which their source terrane would be sampled is commensurate with the relative frequency of nakhlite ejection events, i.e., one or two out of six or seven events according to Figure 2. In contrast, the 170-330 Ma shergottites must come from the ~3.3 x 10^6 km^2 of Late Amazonian (LA) terrane, and are thus expected to represent only ~4% of the total events sampling Martian volcanic terrane. They appear to represent three or four out of the six or seven recovered sampling events (i.e., about 50% of the total) and thus are overabundant in our collection by about an order of magnitude.

This paradox of too many recovered shergottite sampling events from too little Martian terrane of appropriate age is the main topic of this paper. Unlike the situation with ALH84001, using the NW model doesn't resolve the paradox; rather, because the NW model yields older terrane ages, it makes the paradox more difficult to resolve. Thus, for example, the NW model restricts the nakhlites to the Middle Amazonian terrane, which covers ~7.3 x 10^6 km^2 of the Martian surface, or ~ 9 % of the volcanic surface area. So, on average, a total of eleven events would be expected to yield one nakhlite event, a somewhat greater discrepancy than found with HT, for which only seven events are required on average. Although such observations don't establish a strong preference for HT, we show later that the meteorite data suggest a model having an even higher cratering rate than HT, at least at young ages, not a lower one as does NW. The shergottites are implied to derive from LA terrane in both the HT or NW models. In the following we restrict our considerations for the younger Martian meteorites (i.e., the SNC) to the HT or closely related *BVSP* (1981) models, while noting that NW better accounts for the presence of the very old ALH84001.

Figure 3 and Table 1 summarize the relative probability of obtaining meteorites from various Martian terranes. Here all "fertile" impacts over the entire Martian surface area of 144 x 10^6 km^2 are considered, where "fertile" refers to any event capable of ejecting rocks from the Martian surface. The figure shows that of all such impacts, assuming equal ejection probabilities from different Martian terranes, 1 in 7 should have struck terrane of early or middle Noachian age, yielding meteorites similar in age to orthopyroxenite ALH84001; 1 in 11 should have struck terrane of early Amazonian age, yielding meteorites similar in age to the nakhlites and Chassigny, but only 1 in 44 should have struck terrane of late Amazonian age, similar to the ages of shergottites. Furthermore, if there were indeed 3 shergottite ejection events as proposed by *Eugster et al.*, (1997), or 4 as shown in Figure 2, some 130 to 175 fertile events must have occurred Mars-wide. Three or four events on LA (shergottite) terrane would be 8- to 16-fold over-represented relative to events on EA (nakhlite) terrane. That is, 175 events Mars-wide should give ~16 EA (nakhlite) events, not one or two as observed. Similarly, 175 events Mars-wide should give ~25 events on old (EN+MN) terrane; thus the shergottite events are ~25-fold over-represented relative to "old"-meteorite events on (EN+MN) terrane.

It has been suggested that one or more of the shergottites may be impact melts *(Nyquist et al.,* 1995; *Mittlefehldt et al.,* 1997), so we also have considered the relative probability of striking impact-resurfaced terrane. Since ~11% of the total Martian area is impact resurfaced (*Tanaka et al.,* 1992), that probability is comparable to the probability of striking either old volcanic terrane (EN+MN), assumed parental to the orthopyroxenite, or Early Amazonian terrane, assumed parental to the Nakhlites and Chassigny. Thus, the number of "impact-melt" shergottite events would be commensurate with the number of nakhlite events, and also with the number of events on "old" surfaces if (a) impact resurfaced areas could be equated to the exposed area of impact melt, and (b) only one shergottite event were allowed. Criteria (a) will not be rigorously true, but the amount of impact melt could be considerable. For example, *Clifford* (1993) estimated that a volume of impact melt equivalent to a global layer 0.5 km thick would have been produced by the cumulative flux of impacts over Martian history. This volume of melt, if concentrated into the 11% of the surface which is impact-resurfaced, would yield an impact melt layer 4-5 km thick. Thus, if the estimates of resurfaced area and melt volume are both reasonably accurate, a high proportion of the material in the impact-resurfaced areas will also have been impact melted. Furthermore, if the lunar experience is a guide, impact melt rocks may be mistaken for volcanic rocks in orbital photographs, as was the case, for example, with the Cayley Formation at the Apollo 16 landing site. Finally, an impact melt hypothesis necessarily reduces the number of required shergottite-ejecting impacts on Mars, since the common ~170 Ma age of most shergottites requires them, with the possible exception of QUE94201, to have participated in the same impact melting event ~170 Ma ago, and thus to have been ejected in only one event. However, impact melt formed only ~170 Ma ago would be only a tiny fraction of the Mars-wide impact melt, so that later impact ejection of the meteorites is very improbable. Nevertheless, we cannot statistically exclude a single, rare event.

Possible source craters for the SNCs

All of the uncertainties in interpreting the shergottite data would be diminished if we knew their actual source crater(s). Although it will not be possible to identify the source crater(s) with certainty, it nevertheless is useful to examine the properties of *candidate* source craters to see whether there are properties which those corresponding to a particular meteorite type might share. *Mouginis-Mark et al.* (1992) identified some possible source craters for the SNC meteorites. They noted that the Tharsis region of Mars is the only area with regionally extensive young lava flows, and thus the likely source terrane. In evaluating possible source craters they gave preference to comparatively large craters (>10 km) to accommodate the spallation ejection model (*Melosh,* 1984, 1985), or to elongated craters made by oblique impact to accommodate the oblique impact ejection model (*Nyquist,* 1983, 1984; *O'Keefe and Ahrens*, 1986). The criteria used by *Mouginis-Mark et al.* (1992) for crater selection are based on somewhat different assumptions than those in this paper, but they can be usefully adapted for our purposes. The constraint to large craters derives from an assumption that all SNCs were simultaneously ejected. We do not impose that assumption. It requires that blocks several meters in size be ejected, in order to account for the entire spectrum of cosmic ray exposure ages of the SNCs as in Scenario I of Bogard et al. (1984). However, *Vickery and Melosh* (1987) concluded that craters ≥12 km in diameter would be required even if fragments only up to ~0.5 m in size were ejected, as would be true if nakhlites were ejected separately from shergottites. *Mouginis-Mark et al.* (1992) imposed the additional criteria that the craters must be fresh and on "young" terrane, which for them meant craters ≤ 180 Ma old on terrane ≤ 1300 Ma old. For the shergottites, the corresponding criteria are for craters that are ≤ 4 Ma old on terrane that is ≤ 330 Ma old. For the nakhlites, the criteria are for craters that are ≤ 11 Ma old on terrane that is ≤ 1300 Ma old. Thus, our criteria are very similar to those of *Mouginis-Mark et al.* (1992), except that we will not consider craters on the youngest terrane as possible sources for the nakhlites, nor craters on the oldest terrane they considered as possible sources for the shergottites.

Of the nine craters identified by *Mouginis-Mark et al.* (1992), two offer especially intriguing possibilities as the parent craters for shergottites and nakhlites, respectively. First, if shergottites are really ≤ 330 Ma old, they must derive from some of the very youngest Martian terrane, i.e., the central Tharsis volcanic plains (unit 31 of *BVSP,* 1981) or the Olympus Mons volcano itself (unit 34 of *BVSP,* 1981). Candidate crater #3 of *Mouginis-Mark et al.* (1992; their Figure 6) is located near the summit of Olympus Mons, and appears to be a fresh crater that possibly overlaps a pre-existing crater, all of which make it especially interesting. Firstly, the low atmospheric pressure near the summit of Olympus Mons would have allowed ejecta to reach escape velocity more easily than from elsewhere on the planet. Secondly, this crater is on one of the very youngest Late Amazonian (LA) volcanic units on Mars. Its location suggests the possibility of repeated lava flows in the area, consistent with variation in the ages of shergottites, if all the shergottites are magmatic. Finally, since it appears to overlie a pre-existing crater that is a possible impact-melt source, its location is permissive of an impact melt origin for some of the shergottites. It is tempting to hypothesize that this crater was created ~3-4 Ma ago (the oldest ejection age of the shergottites) by impact into 330 Ma old terrane on which a prior impact had created a melt pool ~170 Ma ago. Although this sequence of events may appear to have a low probability *a priori*, crater #3 provides at least a hint of evidence for it. Formation of some of the shergottites via impact melting could account for some of the puzzling isotopic data.

The source crater for the nakhlites should lie on older terrane than the source crater for the shergottites, assuming an ~170-330 Ma crystallization age for the latter. Crater #5 of *Mouginis-Mark et al.* (1992) satisfies this requirement because it is on older Early Amazonian

(EA) terrane. It has an elongate shape, indicative of an oblique impact, and thus possibly of an enhanced probability of meteorite ejection via entrainment within a "richochetting" debris cloud (*Nyquist,* 1983; *O'Keefe and Ahrens,* 1986). It is part of the extended Tharsis volcanic plains (unit 35 of *BVSP,* 1981), and occurs on the northern lower flank of the volcano Ceraunius Tholus. This crater was first suggested as a possible source crater of the SNCs by *Nyquist* (1983) and as noted by *Mouginis-Mark et al.* (1992) is a good crater for sampling multiple rock types. It probably excavated material from both the flanks of Ceraunius Tholus and the surrounding lava plains, including both extrusive and intrusive rocks, and thus, it is a good candidate to have sampled both the clinopyroxenite nakhlites and the dunite, Chassigny, of the ~11 Ma ejection age group.

Martian meteorite ages and the crater densities on candidate source terranes

Although we cannot know whether these tentative identifications of parent craters of the shergottites and nakhlites are correct, it is informative to examine the implications of these identifications within the context of the relationship between Martian crater densities and inferred crater retention ages. Figure 4 reproduces data from Table 8.6.1 of *BVSP* (1981) for the crater densities on various Martian geologic provinces, relative to that on the average lunar mare. The average absolute age of the lunar maria is taken to be 3.45 Ga from lunar sample data. Calibration of the cratering rate for Martian surfaces assumes that the most likely Martian cratering rate is twice the lunar rate, that the maximum likely rate is four times the lunar rate, and that the minimum likely rate equals the lunar rate (*BVSP,* 1981).

We have fit the data in Figure 4 with a 5th order polynomial to obtain a curve of Martian crater density versus crater retention age for the "Best Estimate" crater retention age that is a mirror image of the curve in *BVSP* (1981) except at the lowest and highest crater retention ages (see their Figure 8.6.3). The dotted curves show fits for the minimum and maximum age estimates, respectively. If we assume the craters we identified are the actual source craters of the nakhlites and shergottites, we can compare the implied absolute ages of their stratigraphic terranes to values given by the crater frequency curve. Specifically, the large, filled data points in Figure 4 assume the Olympus Mons volcano (unit 32 of BVSP, 1981) and the extended Tharsis volcanic plains (unit 35) to be 330 and 1370 Ma old, respectively, as inferred from the crystallization ages of shergottite QUE94201 and nakhlite Governador Valadares (*Borg et al.*, 1997; *Shih et al.*, 1996, 1997).

Figure 4 shows that the meteorite data plot close to the Best Estimate cratering age curve. This is, of course, partly a circular result because terrane age was one of the criteria used to select potential source craters. Nevertheless, the figure confirms that our choices for source craters and terranes were appropriate. It also illustrates that a rock as old as the ALH84001 orthopyroxenite must come from heavily cratered terrane. Furthermore, the figure illustrates the large uncertainty in crater density ages permitted for the source terranes of the shergottites and nakhlites. The ~1370 Ma age of nakhlites, for example, only restricts the source to time-stratigraphic units ranging in age from Mid-Amazonian (MA, low cratering rate limit) to Late Hesperian (LH, high cratering rate limit). The 330 Ma age of QUE94201 appears to restrict its source terrane to Early-to-Mid Amazonian or younger. Thus, the uncertainty in absolute calibration of the crater density versus crater retention ages allows the possibility that the meteorites were derived from "lower" stratigraphic units than the nominal ones.

By placing the nakhlites and shergottites in lower stratigraphic units, the relative abundances of the Martian meteorites can be made to more closely match expectations based on the relative areas of those units. In Figure 5 we assume that only hard, volcanic rocks are ejected. as suggested by the absence of non-volcanic rocks in the meteorite collection. We then find that if we consider the relative surface areas of the Middle Amazonian (MA), Late Hesperian (LH), and the combined Early and Mid-Noachian (EN+MN) time-stratigraphic units, that the relative abundances of the Martian meteorites correspond approximately to expectation. The figure illustrates the hypothetical case of 9 meteorite-ejecting events over the entire Martian "volcanic" surface. Of these, 0.75 (~1) would be expected from MA terrane (shergottites), 1.25 (~1) would be expected from LH terrane (nakhlites), and 2.5 (~3) from the Early and Mid Noachian terranes. These terrane units together make up ~50% of the Martian surface, and the expected yields thus should make up ~50% of the total ejected meteorites. The relatively modest shortfall of 1-2 old meteorites could be attributed to our failure to recover them. Similarly, the lack of meteorites from other terranes could be attributed to their failure to be recovered. Thus, the apparent paradox of the overabundance of shergottites can be resolved if (a) all shergottites were ejected in a single event, and (b) if the Martian time-stratigraphic units based on crater densities are somewhat younger in absolute age than the nominal values, i.e, the cratering rate is higher than customarily assumed.

Figure 6 illustrates the scenario we suggest for meteorite-ejection events on Mars. In it we show a revised plot of the ages of Martian surfaces (i.e., time-stratigraphic units) versus their proportional areas for a high cratering rate model. In accordance with the foregoing assumptions, we restrict consideration to volcanic surfaces (*Tanaka et al.,* 1992). The crater densities for the boundaries of the time-stratigraphic series were taken from Figure 4. With these parameters and assumptions, the number of recovered events corresponds approximately to expectation if there is only one shergottite event rather than three or four.

Implications

We have argued that the ejection of shergottites in three or four events is incompatible with the proportion of the Martian surface that is as young as their ~170-330 Ma crystallization ages. What other observations, besides the exposure and crystallization ages themselves, bear on the number of ejection events? One observation is the number of actual craters available to be sources of the shergottites. As shown by *Mouginis-Mark et al.* (1992) there are nine candidate source craters for the SNCs on terrane of estimated age ≤ 1.3 Ga, but only three of these are on terrane young enough to be parental to the shergottites. It could be argued that as many as four source craters are required. If so, the number of craters required exceeds by one the number of candidate craters identified, so other scenarios seem preferable. If we assume that QUE94201, although older, was ejected simultaneously with Shergotty and Zagami, the required number of source craters is reduced to three, the number of identified candidate craters. It seems intuitively improbable that material from each of those craters would be recovered on earth, but *Gladman et al.* (1996) calculated the yield of Martian ejecta arriving at earth to be ~7.5%, so, if a large number of fragments (>100) are ejected from Mars in each event, the probability of some reaching earth is high. The probability of finding one or more of them as meteorites is lower by an unknown, but probably significant amount, however.

One also must consider the probability of having at least three *consecutive* shergottite-ejecting events within ~4 Ma. For this calculation, we assume the first event has unit probability. (It selects the terrane to be shergottite-like and defines the starting point for the calculation.) Assuming the shergottite event is in the Late Amazonian, we calculate the ratio of shergottite (LA) events to non-shergottite (non-LA) events to be ~4×10^{-2} for a single event (impacts into volcanic rocks), and the probability for two shergottite events in succession as $(4 \times 10^{-2})^2$, or ~1.6×10^{-3}. Even if the shergottites are derived from more abundant MA terrane, this ratio improves only to ~8×10^{-3}.

If one assumed that the basaltic and lherzolitic basalts were ejected simultaneously, only one additional event would be required on terrane of the same age to yield basaltic shergottite EET79001. Thus, the above calculation suggests that the probability of two consecutive events, rather than three, rises to ~4%. Alternatively, if a very large number of fragments were ejected in an initial event, the probability of collisions in the resultant densely populated meteor stream might have been high, leading to secondary break-ups in space, and making a second event on Mars unnecessary. Assuming this to have been the case, then we have recovered at least five of those fragments, consistent with the assumption that a large number were ejected initially. This seems to be a plausible way of explaining the young exposure age of EETA79001, and also could account for the difference between the exposure ages of the basaltic and lherzolitic shergottites.

The above scenario involving multiple break-ups in space seems the most promising way of accomodating arguments for a single shergottite ejection event with observations of several different exposure ages among the shergottites. Nevertheless, two consecutive impacts on similar terrane on Mars without secondary break-up in space needs to be considered also because of the non-neglible probability of a few percent calculated above for such a scenario. It would require that the basaltic and lherzolitic shergottites have the same ejection ages, and thus that the uncertainties in cosmic ray exposure ages be larger than estimated by *Eugster et al.* (1997). Their derived ejection ages for the basaltic and lherzolitic shergottites of 3.84±0.64 and 2.76±0.06 Ma, respectively, are based on exposure ages having average uncertainties of ~±0.58 Ma for the lherzolitic basalts and ~±0.27 Ma for the basaltic shergottites. The uncertainties given by *Eugster et al.* (1997) reflect the reproducibility of the ages that were averaged, but those averages included only two lherzolitic shergottites and three basaltic shergottites. For such a small statistical samples, the calculated standard deviations may have been too small. An alternate way to calculate age uncertainties would be to utilize the uncertainties assigned to the individual exposure ages. Using that approach, we find the average cosmic ray exposure ages of the two groups to be 3.73±0.67 Ma and 2.66±0.38 Ma, respectively. Thus, the exposure ages are only just resolved when the uncertainty is calculated in this manner. (The terrestrial ages are ignored here).

Because the production rates of some of the noble gases are strongly dependent on the chemical composition of the meterorites. the possibility of systematic biases in one or the other of the exposure age calculations needs to be considered as well. The chemistry-corrected production rates used by *Eugster et al.*(1997) to calculate the exposure ages of the lherzolitic shergottites were based on analyses of LEW88516, a small meteorite (13 g), which is texturally heterogeneous (*Harvey et al.,* 1993). Heterogeneity can affect the chemistry-corrected production rates as well as the measured noble gas contents, thus introducing a potential source of error in the calculated exposure ages. Determining accurate exposure ages for the lherzolitic basalts requires that noble gas concentrations and chemical compositions be measured on aliquots of the same sample.

Finally, corrections to the production rates are made for shielding; thus, the shielding dependence of the production rates must be accurately known. For the important cosmogenic nuclide ^{21}Ne, *Eugster et al.* (1997) applied a eucrite-derived shielding correction to the basaltic shergottites, but a diogenite-derived shielding correction to the lherzolitic shergottites. For the basaltic shergottite Zagami and the lherzolitic shergottite LEW88516, for which all the relevant noble gas and chemical data are given by *Eugster et al.* (1997), one sees that it is this shielding correction which results in the difference in the calculated ^{21}Ne exposure ages of the two meteorites. When only chemical corrections are made, the ^{21}Ne production rates, as calculated following *Eugster and Michel* (1995), are 0.208 x 10^{-8} cm^3 STP/g per Ma and 0.332 x 10^{-8} cm^3 STP/g per Ma, respectively. These production rates, when applied to avererage cosmogenic ^{21}Ne concentrations of ~0.58 x 10^{-8} cm^3 STP/g and ~0.94 x 10^{-8} cm^3 STP/g for the two meteorites (*Eugster et al.,* 1997) give nearly identical exposure ages of ~2.77 Ma and ~2.81 Ma, respectively. The shielding- related cosmogenic ^{22}Ne/^{21}Ne ratios for the two samples are identical within error limits at 1.238±0.025 and 1.227±0.035, respectively, but when these ratios are used with the eucrite and diogenite production rate equations of *Eugster and Michel* (1995, Table 5) the production rates thus obtained yield differing exposure ages of ~3.18 Ma for Zagami and ~4.59 Ma for LEW88516. However, when the diogenite production rate equations are used for Zagami, the calculated exposure age becomes ~4.68 Ma, in agreement with that for LEW88516.

As discussed by *Eugster and Michel* (1995), determining the shielding-corrected eucrite production rate equation is complicated by diffusive loss of ^{3}He from feldspar, a phenomenon which could affect basaltic shergottites as well. Thus, the ^{3}He ages of the basaltic shergottites could be preferentially biased towards lower values than for the lherzolitic shergottites because of the greater modal abundance of feldspar in the former, even if the two shergottite types had the same exposure age. Because presently available cosmic ray exposure ages of the basaltic and lherzolitic shergottites are subject to a variety of non-random uncertainties, it is probably premature to conclude that these two meteorite types need be ejected from Mars in different events.

We have noted the possibility of tentatively assigning shergottite ejection to one of three craters in the vicinity of Olympus Mons. Although we prefer Crater #3 of *Mouginis-Mark et al.* (1992), our conclusions would not be significantly affected if the shergottites came from one of the other two craters. Pursuing this reasoning, the nakhlites may be assigned to any of the craters #4-9 identified by *Mouginis-Mark et al.* (1992) without greatly affecting the degree to which the meteorite data match the crater density versus age curve (Figure 4). Our preference for Crater #5 for the nakhlites is because of the possibility of an enhanced probability for meteoroid ejection accompanying oblique impact cratering (*Gault and Wedekind,* 1978; *Nyquist,* 1983; *O'Keefe and Ahrens,* 1986).

The identification of these two areas of the Tharsis region with the shergottites and nakhlites, respectively, is plausible because the crater densities of the candidate terranes plot very close to the "best estimate" crater density versus age curve (Figure 4) when meteorite ages are used for terrane ages. Nevertheless, it is informative to consider how a higher Martian cratering rate, as implied by the distribution of meteorite events shown in Figure 6, would affect identification of candidate source craters. Assuming a cratering rate at the high limit of uncertainty of the estimates given in Table 8.6.1 of *BVSP* (1981); i.e, using the minimum absolute age estimated for a given crater density, allows us to consider derivation of the shergottites and nakhlites from more heavily-cratered terranes than previously considered (shown by the arrows in Figure 4). Thus, the Mid-Amazonian (MA) and the Late Hesperian (LH) might be considered for the shergottites and nakhlites, respectively, in a high cratering rate model. Nevertheless, the Tharsis region remains the most probable source of the shergottites. Candidates for the shergottite parent crater then would be more profitably sought among craters #4-9 of *Mouginis-Mark et al.* (1992) than among their craters #1-3. Craters #4-9 are on unit 34 of *BVSP* (1981) which has a minimum likely age of ~0.3 Ga, compared to ~0.1 Ga for Olympus Mons. At this higher cratering rate the search for the nakhlite source shifts away from the Tharsis region to include other possibilities in the northern plains, such as Chryse Planitia or Lunae Planum, which have minimum likely ages of ~1.2 and ~1.3 Ga, respectively (units 42 and 43, respectively, of *BVSP,* 1981). Provinces in the Martian eastern hemisphere such as the Elysium volcanics and Isidis Planitia, (units 38 and 39, respectively, of *BVSP,* 1981) which have best estimate ages of ~2.6-2.8 Ga, but minimum likely ages of ~0.7-0.8 Ga, also are possible candidates for the source of nakhlites in this model.

In a high cratering rate model it is possible to tentatively assign two of the hypothesized three meteorite-yielding impacts to oblique impacts. The shergottites could be assigned to crater #5 of *Mouginis-Mark et al.* (1992), whereas *Barlow* (1997) has identified an oblique impact crater on old terrane suitable to be the source of ALH84001. Furthermore, one or more of the ~175 oblique impact craters classified by *Schultz and Lutz-Garihan* (1982) is likely to lie on LH terrane, the source terrane for the nakhlites in the high cratering rate model. Identification of candidate craters with each of the hypothesized impacts would allow the cratering curve to be "calibrated" at young (shergottite), intermediate (nakhlite), and old (orthopyroxenite) ages. High quality orbital geochemical data would allow additional evaluation of the crater assignments from the viewpoint of the composition of the terrane on which proposed parent craters were found. Thus, we believe oblique impacts deserve renewed attention as a possible mechanism for meteorite ejection. If oblique impacts were shown to be the preferred ejection mechanism, the characteristic shapes of the resultant craters would provide a way to identify candidate source craters. By limiting the possible source terranes for the Martian meteorites, the information obtained from them could be placed more firmly into the Martian geological context.

Conclusions

With only one event each for (a) the shergottites, (b) the nakhlites plus Chassigny, and (c) the orthopyroxenite, the degree by which shergottites are over-represented among Martian meteorites is greatly reduced to about fourfold relative to the other two meteorite types in a nominal cratering rate model (such as the Hartman-Tanaka model), and is eliminated in a high cratering rate model with twice the nominal Martian rate and four times the lunar rate. The high cratering rate model allows possible places of origin for the nakhlites to be sought in the eastern hemisphere. Because ALH84001 must be on southern highland terrane, an eastern northern hemisphere origin of the nakhlites coupled with a single-crater origin of shergottites in the western northern hemisphere, would imply that the Martian meteorites in our collections derive from three impacts randomly distributed on the Martian surface. If so, the shergottite age paradox would be resolved.

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Table 1. Relative Number of Ejection Events - Nominal Cratering Rate Model.

	Assumed Recovered	Predicted Total
Shergottites (LA)	4	175
	3	132
	2	88
	1	44
Nakhlites/Chassigny (EA)	2	23
	1	11
Othopyroxenite (EN+MN)	1	7
Impact Resurfaced	1	9

Table 2. Relative Number of Ejection Events - High Cratering Rate Model.

	Predicted for Type	Assumed Total
Shergottites	0.75 ~ 1	9
Nakhlites/Chassigny	1.25 ~ 1	9
Othopyroxenite	2.50 ~ 3	9

FIGURE CAPTIONS

Figure 1. Ejection times (T_{ej}) and crystallization ages (T_{xtn}) of Martian meteorites. Meteorite types are as given in the figure. Ejection times are from *Eugster et al.* (1997) and are the sum of the cosmic-ray exposure and terrestrial ages. From these data *Eugster et al.* (1997) derived averaged ejection times (Ma ago) of 14.4±0.7 (ALH84001), 11.0±0.9 (nakhlites and Chassigny), 3.84±0.62 (lherzolitic shergottite), 2.76±0.06 (basaltic shergottites), and 0.82±0.20 (EET79001), respectively. Crystallization ages are (in Ga) 4.50±0.13 (ALH84001)[a], 1.26±0.07 (Nakhla)[b], 1.37±0.02 (Governador Valadares)[c], 1.33±0.03 (LaFayette)[f], 1.36±0.06 (Chassigny)[g], 0.33±0.02 (QUE94201)[h], 0.19±0.01 (ALH77005)[i], 0.17±0.01 (LEW88516)[d], 0.16±0.01 (Shergotty)[a], 0.17±0.01 (Zagami)[a], and 0.18±0.03 (EET79001)[e]. An Ar retention age of 4.00±0.10 Ga is also shown for ALH84001[j]. [a]*Nyquist et al.* (1995); [b]*Nakamura et al.*(1982), [c]*Shih et al.* (1996,1997); [d]*Chen and Wasserburg* (1993), [e]*Wooden et al.* (1979), [f]*Podosek* (1973), [g]*Jagoutz* (1996), [h]*Borg et al.* (1997), [i]*Shih et al.* (1982), [j]*Ash et al.* (1996).

Figure 2. Maximum number of events sampling Martian surfaces of different ages, as obtained from the crystallization and ejection ages of Martian meteorites, and compared to the percentage of the total Martian surface from: (1) early, middle, and late Noachian (EN, MN, LN); (2) early and late Hesperian (EH, LH); and (3) early, middle, and late Amazonian (EA, MA, LA). The number of sampling events shown is the maximum given by *Eugster et al.*(1997), augmented by one to account for the older crystallization age of QUE94201 compared to the other shergottites (*Borg et al.*, 1997). The datum for ALH84001 is plotted at the Ar-retention age of 4.0±0.10 Ga (*Ash et al.*, 1996) as most appropriate for comparison to crater retention ages. The Martian time-stratigraphic units are as given by *Tanaka et al.* (1986), whereas the area of each unit and the time duration of the corresponding epoch is given by *Tanaka et al.* (1992).

Figure 3. An over-representation of shergottites among Martian meteorites is shown by comparing the percentages of the Martian surface of ages appropriate to the various meteorite types. For a chosen number of meteorite-ejecting events on the ordinate, the required number of similarly "fertile" impacts over all of Mars is read from the abscissa. Thus, for each impact ejecting meteorites from EN or MN terrane (orthopyroxenite ALH84001), ~ 6 meteorite-ejecting impacts should have occurred elsewhere on Mars; for each impact ejecting meteorites from EA terrane (nakhlites and Chassigny), ~10 should have ejected meteorites elsewhere, and for each impact ejecting meteorites from LA terrane (shergottites) ~ 43 should have ejected meteorites elsewhere. Thus the shergottites are four- to six-fold over-represented among the Martian meteorites even if there was only one shergottite-ejecting event. The over-representation of shergottites is worsened if there was more than 1 shergottite-ejection event. (See text and Table 1).

Figure 4. Comparison of the absolute ages of nakhlites and shergottites (represented by QUE94201) to the crater density curve (*BVSP,* 1981, Chap. 8). The small, open circles are for the "best estimate" ages and crater densities expressed relative to an average of 188 craters/10^6 km^2 of diameter >4 km on the lunar maria as given in Table 8.6.1 of *BVSP* (1981). The dotted curves are fit to the minimum and maximum likely ages, respectively. The smaller filled points are the densities of craters >5 km in diameter versus age from *Tanaka* (1986) and *Tanaka et al.* (1992) for the Martian time-stratigraphic series defined by *Tanaka* (1986) adjusted to 50% higher values to fit the *BVSP* (1981) curve. The crater-density boundaries of the time-stratigraphic series also have been correspondingly adjusted. Craters #3 and #5 of *Mouginis-Mark et al.* (1992) were assumed to be parental to the shergottites and nakhlites, resp., and the larger, filled points plotted assuming the corresponding terrane have the ages given by the meteorites. The uncertainty in

absolute calibration of the crater density curve also allows the meteorites to have been derived from older terranes. (See text.).

Figure 5. The relative surface areas of MA, LH, and combined (EN+MN) time-stratigraphic units approximately correspond to the relative frequency of ejection of Martian meteorites of different types if only hard, volcanic rocks are ejected in a high cratering rate model. For every 9 meteorite-ejecting events over the entire Martian "volcanic" surface, ~0.75 events would be on MA terrane (shergottites), ~1.25 on LH terrane (nakhlites), and ~2.5 on ancient (EN+MN) Noachian terrane. This scenario assumes the minimum likely age of each Martian province as given by *BVSP* (1981). These minimum ages assume a cratering rate which is twice the most likely value and four times the lunar rate (*BVSP*, 1981).

Figure 6. A revised plot of the times of sampling Martian surfaces belonging to different time-stratigraphic units versus their proportion of the total volcanic surface area for a high cratering rate model. Consideration is restricted to "volcanic" surfaces (*Tanaka et al.,* 1992). To construct the curve, the ages at which the crater density limits for the Martian time-stratigraphic series intersected the upper dotted curve in Figure 4 (minimum likely age for a given crater density) were used to determine the chronological boundaries of the series. As in Figure 2 the datum for ALH84001 is plotted at the Ar-retention age of 4.0±0.10 Ga (*Ash et al.,* 1996) as most appropriate for comparison to crater retention ages. The relative number of recovered events corresponds approximately to expectation if there were one shergottite, one nakhlite, and one orthopyroxenite event. If the shergottites were sampled in four separate events they would still be overabundant relative to the other Martian meteorites even in this high cratering rate model.

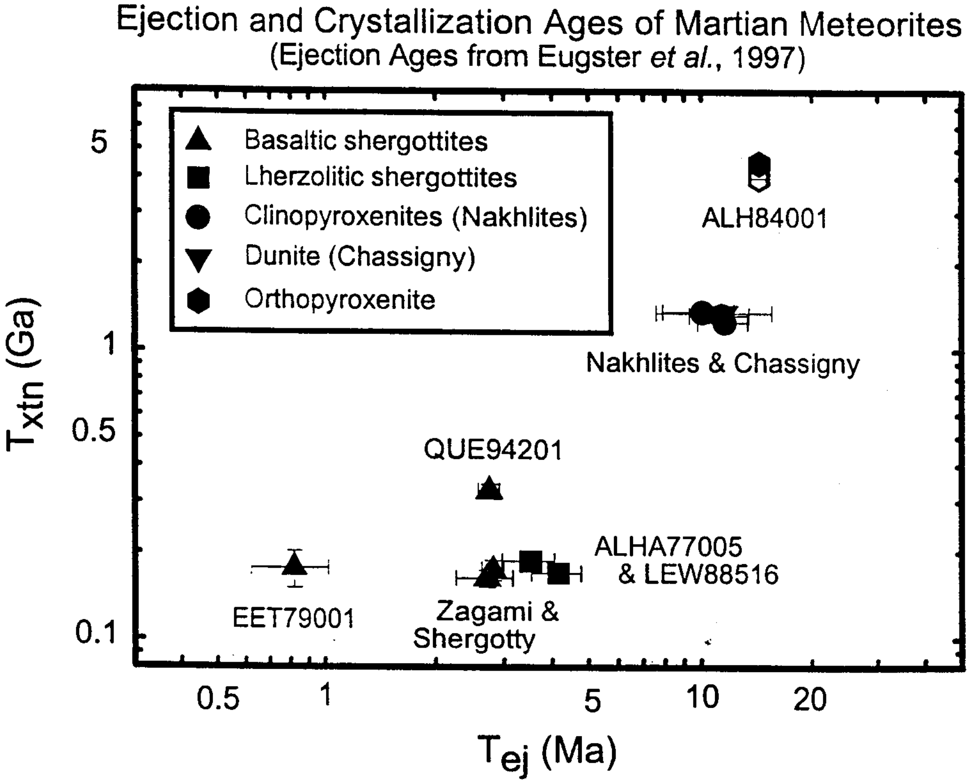


Figure 1.

Nyquist et al.

Shergottite Age Paradox...

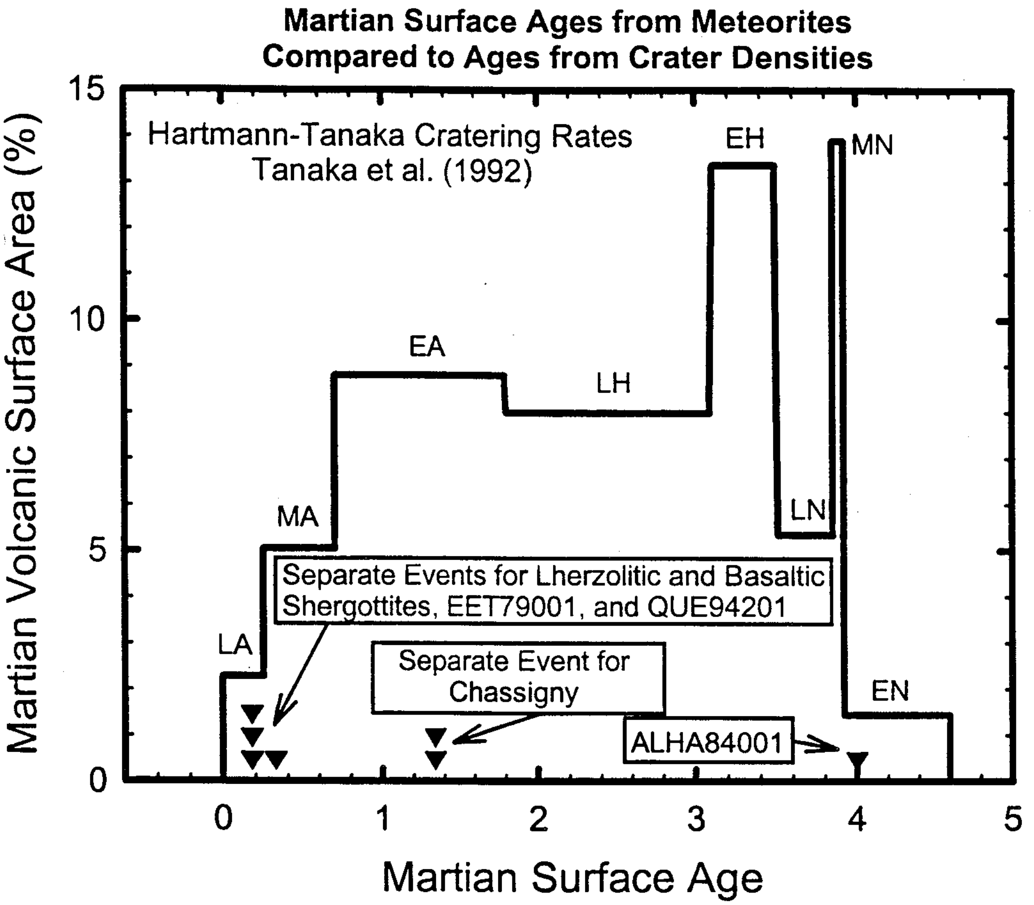
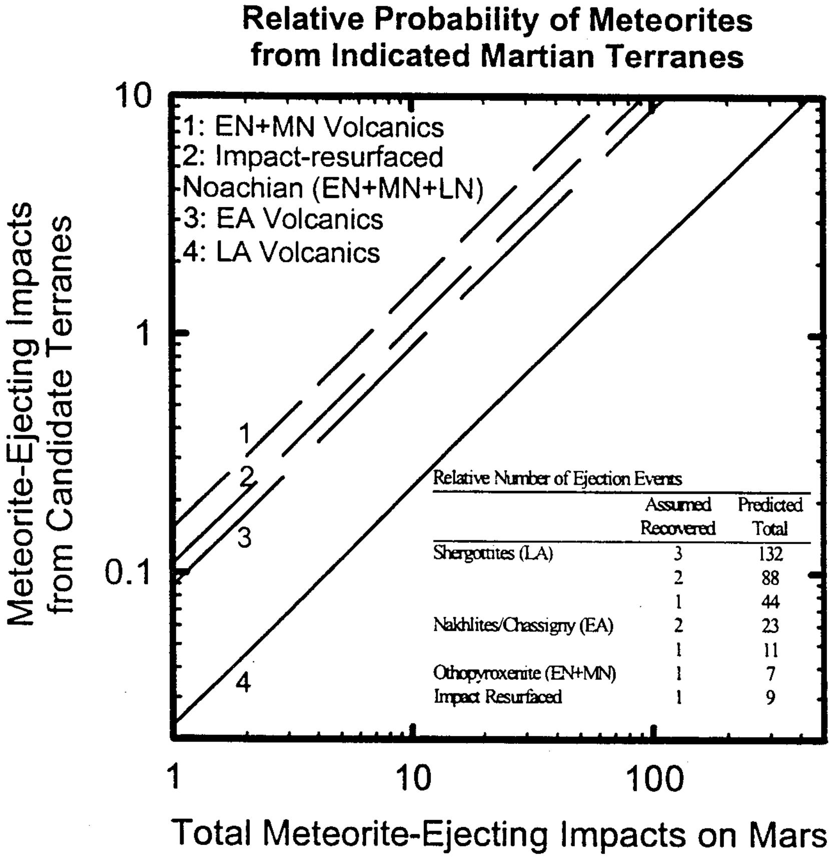


Figure 2

Nyquist et al.

Shergottite Age Paradox…



Relative Probability of Meteorites from Indicated Martian Terranes

Relative Number of Ejection Events

	Assumed Recovered	Predicted Total
Shergottites (LA)	3	132
	2	88
	1	44
Nakhlites/Chassigny (EA)	2	23
	1	11
Othopyroxenite (EN+MN)	1	7
Impact Resurfaced	1	9

Figure 3

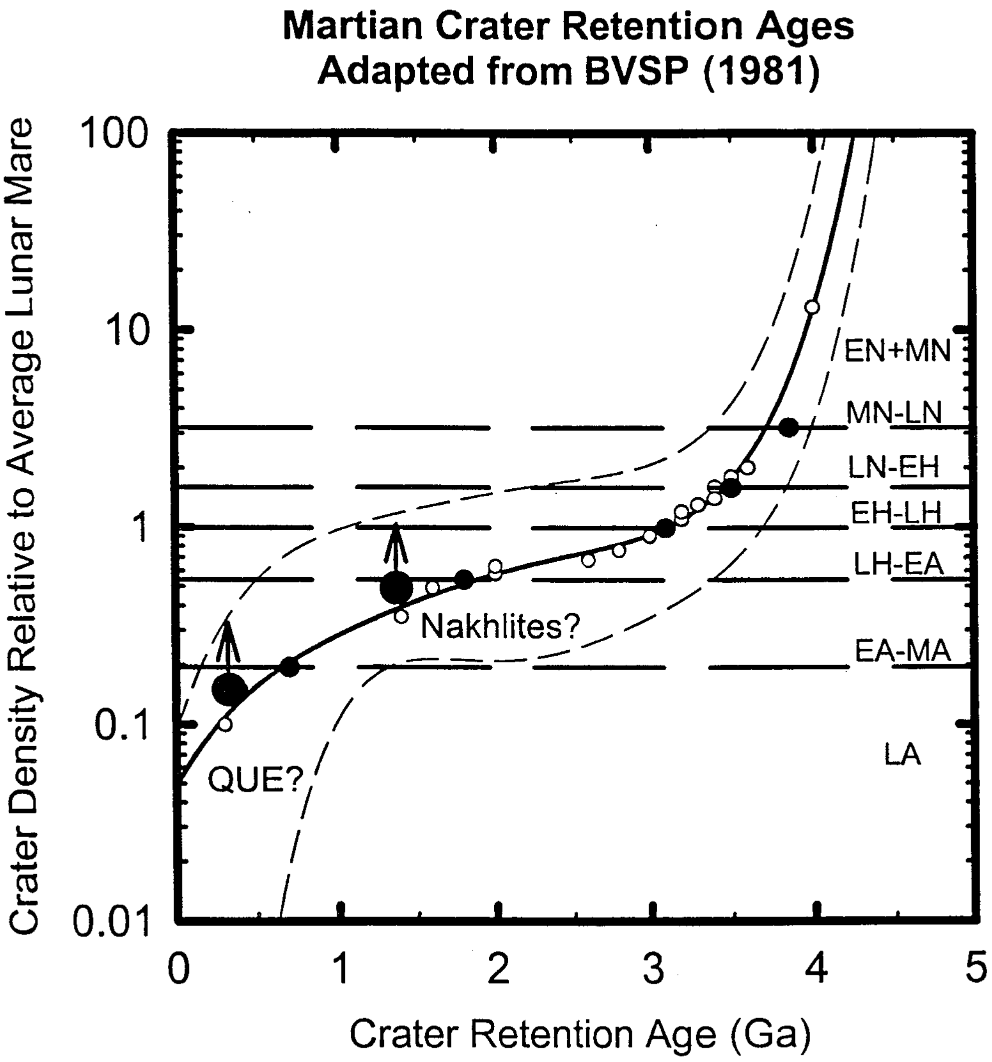


Figure 4

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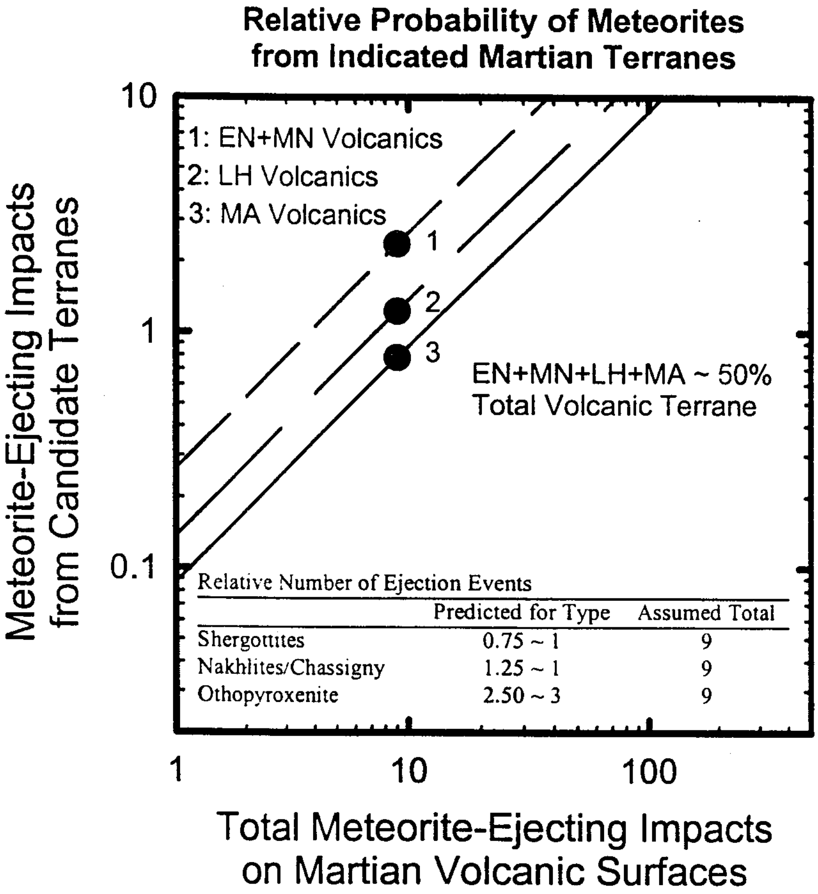
Shergottite Age Paradox…



Relative Number of Ejection Events

	Predicted for Type	Assumed Total
Shergottites	0.75 ~ 1	9
Nakhlites/Chassigny	1.25 ~ 1	9
Othopyroxenite	2.50 ~ 3	9

Figure 5

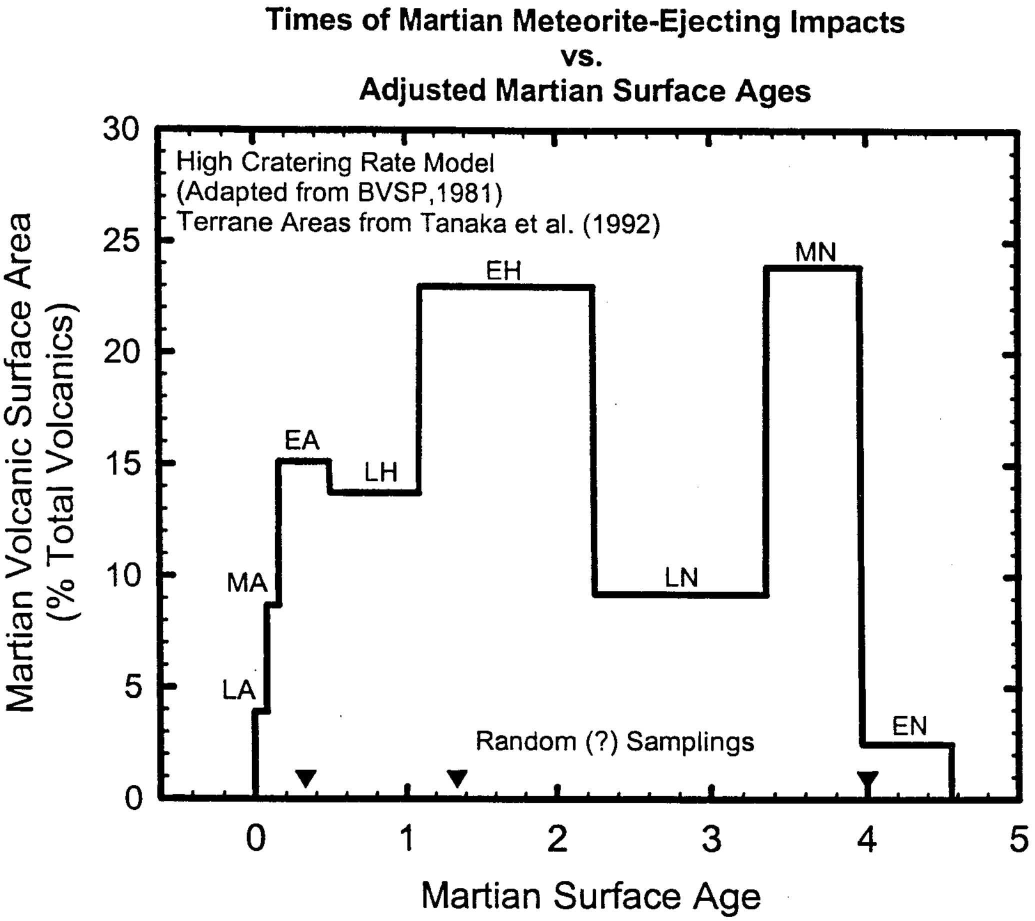


Figure 6

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Shergottite Age Paradox…