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The Large Crater Origin of SNC Meteorites

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A large body of evidence strongly suggests that the shergottite, nakhlite, and Chassigny (SNC) meteorites are from Mars. Various mechanisms for the ejection of large rocks at martian escape velocity (5 kilometers per second) have been investigated, but none has proved wholly satisfactory. This article examines a number of possible ejection and cosmic-ray exposure histories to determine which is most plausible. For each possible history, the Melosh spallation model is used to estimate the size of the crater required to produce ejecta fragments of the required size with velocities ≥5 kilometers per second and to produce a total mass of solid ejecta consistent with the observed mass flux of SNC meteorites. Estimates of crater production rates on Mars are then used to evaluate the probability that sufficiently large craters have formed during the available time. The results indicate that the SNC meteorites were probably ejected from a very large crater (>100 kilometers in diameter) about 200 million years ago, and that cosmic-ray exposure of the recovered meteorites was initiated after collisional fragmentation of the original ejecta in space at much later times (0.5 to 10 million years ago).

A CONSIDERABLE AMOUNT OF PETROLOGICAL, GEOCHEMICAL, isotopic, and noble gas information (*1*) strongly suggests that the shergottite, nakhlite, and Chassigny (SNC) meteorites originated on Mars. The major problem with the martian hypothesis has been the dynamic one of how large, coherent masses of rock might be launched to martian escape velocity, 5 km sec^{-1}, especially since many of the SNC meteorites show little or no evidence of extensive shock damage. This article investigates a number of possible ejection histories to find the most plausible one.

One of the most unusual characteristics of the SNC meteorites is that they are very young. The nakhlites and Chassigny have well-established crystallization ages of ~1.3 Ga (1 Ga = 10^9 years) (*1*). The isotopic systematics of the shergottites are complicated and difficult to interpret because of heavy shock damage. There is some evidence for a ~1.3-Ga crystallization age in the samarium-neodymium system (*2*), but Chen and Wasserburg (*3*) found no evidence for a 1.3-Ga event in the uranium-lead system. Rubidium-strontium and uranium-lead internal isochrons (*2–4*) give ages of 180 to 200 Ma (1 Ma = 10^6 years), which these investigators (*2–4*) believe dates the shock event. Chen and Wasserburg (*3*) interpreted the old (~4.5 Ga) rubidium-strontium whole rock ages and the differing initial lead ratios among the shergottites as indicating that they were closed systems between ~4.5 Ga and 200 Ma ago; that is, the whole rock ages are the crystallization ages. Other investigators (*5*) postulated that the shergottites crystallized as recently as 180 to 300 Ma ago. In sum, the nakhlites and Chassigny are 1.3 Ga old, and the shergottites may be the same age, much older, or much younger.

The ages of the SNC meteorites are important to the dynamic problem of the ejection of rocks from Mars because only 10 to 15% of the surface area of Mars, on which the largest crater is ~30 km in diameter, is believed to be less than 2 Ga old (*6*). Thus, if all the SNC meteorites are ≤1.3 Ga old, they must come from a restricted portion of Mars and must have been ejected from a crater or craters ≲30 km in diameter; alternatively there might be a young volcanic center in terrane that is classified as old, or the hypothesized chronology of the martian surface is inadequate. The most severe dynamic problem for a martian origin of the SNC meteorites is that shock pressures great enough to accelerate material from rest to 5 km sec^{-1} or more are generally expected to melt or vaporize the material (*7*). Melosh (*8, 9*) demonstrated that near-surface material, subjected to low shock pressures but high stress gradients, is ejected at high velocity and may be in the form of relatively large fragments. If the source crater were ≲30 km in diameter, however, the largest spall from the near-surface zone that is ejected at ≥5 km sec^{-1} would be ≲1 m in size (*10*). A study of the drag acceleration of solid ejecta by an impact-generated vapor cloud (*11*) similarly showed that the maximum size fragment that can be accelerated to ≥5 km sec^{-1} is ≲1 m. Nyquist (*12*) proposed that high-velocity, ricocheting projectile debris from a very oblique impact could accelerate entrained rocks to very high velocities, but numerical modeling of this process (*13*) showed that only small (≲10 cm) rocks lying on the surface before the impact could become entrained in the downrange jet and survive acceleration to martian escape velocity. Thus, if all the SNC meteorites are from the young terrane of Mars, they must have been ejected from a crater or craters ≲30 km in diameter, which is only possible if the original fragments were ≲1 m in diameter.

Two kinds of evidence can constrain the sizes of these original fragments. The most straightforward is based on recovered mass. Nakhla has the largest recovered mass, ~40 kg (*14*). The velocity

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with which martian ejecta enter Earth's atmosphere is believed to be only slightly greater than Earth's escape velocity (*15*), so the mass lost by ablation should be ~50% (*16*). A mass of 80 kg corresponds to a spherical rock ~40 cm in diameter. By this criterion, therefore, it would have been possible to eject the SNC meteorites from a crater or craters ≤30 km in diameter.

Other lines of evidence, however, suggest that the proto-shergottites (that is, the rocks originally lofted from the parent body) may have been much more than a few tens of centimeters in size. If the 180- to 200-Ma event recorded by the rubidium-strontium and uranium-lead internal isochrons is a shock event, it is logical to assume that the shergottites were ejected from Mars at that time. The cosmic-ray exposure age of three of the shergottites (Shergotty, Zagami, and ALHA 77005) is only ~2.5 Ma, and that of the fourth (EETA 79001) is only 0.5 to 1 Ma (*17, 18*). These ages imply that the proto-shergottites must have been massive enough to shield their inner portions from cosmic rays until collisional fragmentation in space 0.5 to 2.5 Ma ago. Further, they must have been big enough that the probability of recovering a fragment of the shielded interior was much greater than the probability of recovering a fragment of the unshielded outer "rind." By this argument, the minimum reasonable size of the proto-shergottites is ~15 m (*15*). This model requires that each of the shergottites must have been derived from a different 15-m-diameter fragment, since the probability of obtaining even two of them from the same body is 2×10^{-4} (*15*).

A number of other possible ejection and exposure histories imply smaller sizes for the proto-SNCs. The cosmic-ray exposure ages of the nakhlites and Chassigny cluster around 10 Ma (*17*). One possible ejection and exposure history is that all of the SNC meteorites were ejected by a single event 10 Ma ago, the nakhlites and Chassigny as rocks tens of centimeters in dimension, and the shergottites as larger rocks that were collisionally fragmented in space ~2.5 Ma and ~0.5 Ma ago. This history requires proto–EETA 79001 to have been ≳6 to 7 m in diameter. A second possibility is that the nakhlites and Chassigny were ejected as small rocks 10 Ma ago, and the shergottites were all ejected at 2.5 Ma, three of them as small rocks and the fourth, EETA 79001, as a ≳3-m rock that was collisionally fragmented ~0.5 Ma ago. A third possibility is that the SNC meteorites may all have been ejected as small (tens of centimeters) rocks in three separate events at 10, 2.5, and 0.5 Ma ago. Lastly, the shergottites may have been ejected as large fragments 200 Ma ago, and the nakhlites and Chassigny, as small fragments 10 Ma ago.

Mass-Flux and Fragment-Size Constraints on Source Crater Size

There are eight SNC meteorites out of a total of 2000 stony meteorites. If we assume a similar size distribution for SNCs and other stony meteorites and assume that the terrestrial preatmospheric flux of stony meteorites is $\sim 10^5$ kg year^{-1} (*19*), the SNC (or martian meteorite) flux is $\sim 4 \times 10^2$ kg year^{-1}. The flux times the number of years over which the meteorites have fallen must equal the initial mass ejected from Mars times the fraction of that mass that survives passage to Earth and impacts during that time. According to Wetherill (*15*), if the SNCs were launched from Mars as 15-m rocks 180 Ma ago, 20% of these rocks would survive 175 Ma in space without collisional fragmentation. Of these, 6 to 7% will be fragmented within the next 10 Ma; of these, ~0.3% will impact Earth within that 10-Ma time span. Therefore, the fraction of the original fragments that reaches Earth with cosmic-ray exposure ages similar to those of the SNCs is $\sim 0.20 \times 0.07 \times 0.003 = 4.2 \times 10^{-5}$, and the original mass ejected from Mars must be $M_0 = (4 \times 10^2 \text{ kg year}^{-1} \times 10^7 \text{ years})/4.2 \times 10^{-5} \simeq 1 \times 10^{14}$ kg. The mass-flux constraints for ejection histories involving small fragments ejected within the last 10 Ma are more complicated (*15*), because fragments with shorter Mars-to-Earth transit times "remember" more of the initial conditions, such as ejection velocity and the inclination and eccentricity of the orbit of Mars at the time of ejection. In our calculations, we used the values of yield (the fraction of material ejected from Mars that reaches Earth within 10 Ma) as a function of ejection velocity in table 1 of (*15*).

The spallation model (*9*) will be used to estimate the diameter of the crater that produces the required mass flux and rocks of the required size for the various possible SNC ejection histories. The volume of spall material ejected with a velocity, v_{ej}, greater than or equal to v, relative to the volume of the crater-forming projectile, V_p, is approximately (*9*, adapted from equation 6)

$$\frac{V(v_{ej} \geq v)}{V_p} = 4.8\left(\frac{T}{\rho c_L U}\right)\left[1 - \left(\frac{2v}{U}\right)^{1/3}\right] \qquad (1)$$

where T is the dynamic tensile strength, U is impact velocity, ρ is target density, and c_L is the longitudinal stress-wave propagation velocity. The mass of spalls ejected with a velocity greater than v is simply ρV; for a spherical projectile of radius a, $V_p = 4/3\pi a^3$, so that

$$M_{ej}(v_{ej} \geq v) = 4.8\left(\frac{4}{3}\pi a^3\right)\left(\frac{T}{c_L U}\right)\left[1 - \left(\frac{2v}{U}\right)^{1/3}\right] \qquad (2)$$

The projectile radius can be estimated from the Schmidt-Holsapple gravity-regime crater-size scaling relation for nonporous silicate targets (*20*):

$$0.62\left(\frac{r}{a}\right)\left(\frac{\rho}{\delta}\right)^{1/3} = 0.8\left(\frac{3.22ga}{U^2}\right)^{-0.22} \qquad (3)$$

where r is crater radius, δ is impactor density, and g is surface gravity (3.73 m sec^{-2} on Mars). In the spallation model, a near-surface stress-wave interference zone exists in which the maximum compressive stress experienced ranges from zero at the surface to a maximum at the base of the interference zone, corresponding to the maximum in the direct pulse in the absence of interference. The uppermost spall layer separates where the tensile strength of the material is first exceeded by the tensile stress. Material deeper within the interference zone experiences greater stress, although still less than the maximum outside the interference zone, and is ejected with slightly lower velocity. The shergottites experienced shock pressures up to ~50 GPa (*1*), so we replace T with P_{max}/β, where P_{max} = 50 GPa and β, the ratio of the pulse decay time to the pulse rise time, is ~4. We assume for simplicity that $\rho = \delta$. A very dense projectile, such as an iron meteorite, would reduce the size projectile required to form a given size crater (Eq. 3) and thereby also reduce the spalled mass ejected at a given velocity (Eq. 2). A low-density projectile, such as a comet, would have the opposite effect. Substituting Eq. 3 into Eq. 2, with $T = P_{max}/\beta$ = 12.5 GPa, assuming that for a large magnitude event $c_L \simeq 10$ km sec^{-1}, and rearranging, the diameter D of a martian crater that ejects a mass M of spalled material with velocity ≥5 km sec^{-1} and maximum shock pressure ≤50 GPa is

$$D = 0.02\left\{\frac{MU^{2.69}}{\left[1 - \left(\frac{10^4}{U}\right)^{1/3}\right]}\right\}^{0.26} \qquad (4)$$

For $U \leq 10$ km sec^{-1}, the denominator on the right side of Eq. 4 is ≤0, which implies that no spall ejecta achieves velocities ≥5 km sec^{-1} for these impact velocities. Crater diameters as a function of

M and U were calculated; the results are shown in Fig. 1 as contours of M on a plot of D versus U.

The spallation model was also used to estimate the size crater required to eject fragments of a given size with velocities ≥ 5 km sec^{-1}. Spalls with $v_{ej} \gtrsim 1$ km sec^{-1} break up after ejection [because of stored elastic stresses (9)] into fragments whose sizes can be predicted by the Grady-Kipp rock fragmentation model (21). The diameter of the Grady-Kipp fragments (L_{GK}) is given by (9, adapted from equation 5)

$$L_{GK} = \frac{2T\dot{a}}{\rho v_{ej}^{2/3}\, U^{4/3}} \tag{5}$$

Eliminating a between Eqs. 3 and 5, assuming $\rho = \delta = 3 \times 10^3$ kg m^{-3}, and using $T = 100$ MPa (22), we obtain the diameter of the crater necessary to produce fragments at least as large as L_{GK} with $v_{ej} = 5$ km sec^{-1}:

$$D = 0.025 L_{GK}^{0.783} U^{1.48} \text{ (SI units)} \tag{6}$$

A much lower tensile strength is used for this calculation because it is assumed that the spall fragments break up during flight, at which time they are not being subjected to the same sort of stress-wave interference that occurs in the interference zone. Figure 2 shows contours of fragment size (L_{GK}) on a plot of D versus U. We use this graph to determine the size of the martian crater required to produce fragments of a given size with ejection velocities of at least 5 km sec^{-1} for a given impact velocity.

Crater Production Rates

The process of estimating crater production rates is far from straightforward [see Hartmann *et al.* (6) for a comprehensive discussion of the uncertainties]. The first step is to determine the number distribution of craters as a function of size. In general, $N(D) = kD^b$, where N is the number of craters with diameters between D and $\sqrt{2}\,D$, and k and b are constants to be fitted. Next, if absolute age data are available, as for terrestrial and some lunar craters, an absolute time scale for crater production can be estimated. For other planets, it is necessary to estimate the flux of impactors relative to the fluxes on the moon and Earth in order to assign a time scale for crater production. Hartmann *et al.* compiled data on the number distribution of craters as a function of size for various regions on Mercury, the moon, Earth, and Mars (6, table 8.3.1), and they estimated crater retention ages for those regions (6, table 8.6.1), in terms of the minimum likely, most likely, and maximum likely ages. We took values for the number distribution of craters on Mars calculated by Hartmann *et al.*'s preferred method B, divided by the crater retention ages, and averaged over the values for the different regions on Mars to arrive at crater production rates (CPR) on Mars. The number of craters with diameters between D and $\sqrt{2}$ D is $\text{CPR}(D) = k'D^b$ per square kilometer per year, where D is in kilometers, $b = -1.75$, and k' depends on the assumed crater retention age. The value of k' for the maximum likely CPR is 1.29×10^{-12}, for the most likely CPR is 3.81×10^{-13}, and for the minimum likely CPR is 2.29×10^{-13}.

We then used these relations to estimate the probability of occurrence of craters large enough to satisfy the fragment-size and mass-flux constraints for the proposed ejection and exposure histories of the SNC meteorites. If we assume that the crater formation probability follows a Poisson distribution, then the probability of n craters during a time t is

$$P_n = \frac{(t/\tau)^n}{n!} e^{-(t/\tau)} \tag{7}$$

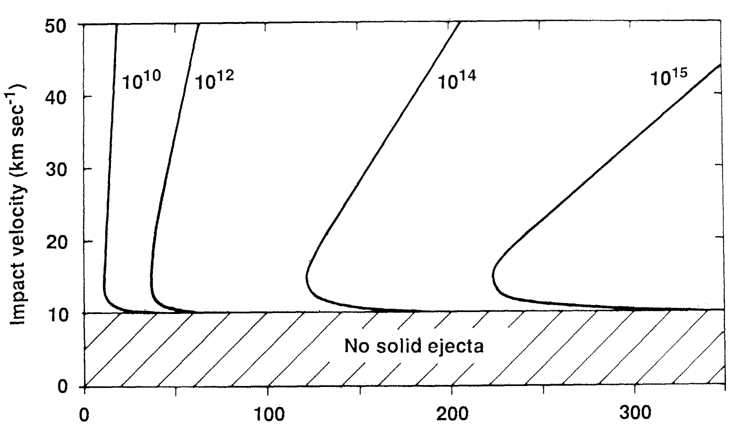
where τ is a recurrence interval for crater formation. The probability of forming at least one crater is

$$\sum_{n=1}^{\infty} P_n = 1 - e^{-(t/\tau)} \tag{8}$$

Similarly, the probability of forming at least m such craters is

$$\sum_{n=m}^{\infty} P_n = 1 - e^{-(t/\tau)} \sum_{n=0}^{m-1} (t/\tau)^n/n! \tag{9}$$

To estimate τ, we sum $\text{CPR}(D)$ over D from the minimum crater diameter required to a D_{max} such that $\text{CPR}(D_{max}) \leq 0.1$ $\text{CPR}(D_{min})$, and used $\tau = [\Sigma(\text{CPR}) \times A]^{-1}$, where A is the target area. The expected number of such craters is $\Sigma(\text{CPR})$ times A times t. Although there is considerable uncertainty in estimating these quantities, we are primarily interested in the relative probability of the various scenarios, which the use of a consistent set of relations allows us to evaluate. The probabilities cited in the text were calculated by using the CPRs corresponding to Hartmann *et al.*'s (6) most likely crater retention ages; these, plus the probabilities



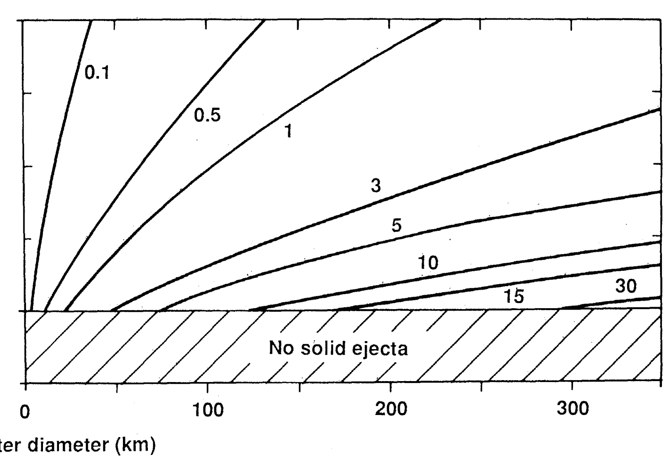


Fig. 1 (**left**). Total mass of spall material ejected at ≥ 5 km sec^{-1} as a function of impact velocity and transient crater diameter. The labels on the contours are mass in kilograms. No solid spall fragments are ejected at ≥ 5 km sec^{-1} for impact velocities ≤ 10 km sec^{-1}.

Fig. 2 (**right**). Maximum sizes of rock fragments ejected from spall zone with velocities ≥ 5 km sec^{-1} as a function of impact velocity and transient crater diameter. Labels on contours are fragment size in meters. No spall fragments are ejected at ≥ 5 km sec^{-1} for impact velocities ≤ 10 km sec^{-1}.

calculated by means of CPRs corresponding to the minimum and maximum likely crater retention ages are listed in Table 1.

The calculations for the five cases are summarized below.

1) *All SNCs ejected in single event 200 Ma ago.* If all the SNCs were ejected 180 to 200 Ma ago, the crater must have been large enough to produce $\gtrsim 10^{14}$ kg of spalled ejecta and to eject 15-m rocks, both with velocities ≥ 5 km sec^{-1}. The mass constraint is satisfied by craters ≥ 120 km in diameter (Fig. 1), and the fragment size constraint is satisfied by craters ≥ 175 km in diameter (Fig. 2).

There are no craters this large on the young terrane of Mars. The nakhlites and Chassigny could not have been ejected in such an event unless they were part of a localized region of young rocks, such as a small volcanic center, within terrane that is generally older than 2 Ga. The crater production rate for craters ≥ 175 km is 9.07×10^{-17} km^{-2} year^{-1}, and the surface area of Mars is $\sim 1.4 \times 10^{8}$ km^{2}, so the characteristic crater recurrence interval $\tau \sim 7.88 \times 10^{7}$ years. The probability of forming at least one such a crater in the last 200 Ma is ~92%.

2) *All SNCs ejected in single event 10 Ma ago.* The mass flux constraints for this case and the next one are unclear because they involve fragment sizes intermediate between the two cases (15-m rocks launched 200 Ma ago and 30-cm rocks launched within the last 10 Ma) studied by Wetherill (*15*). Some fragments must be ≥6 to 7 m in diameter to shield the shergottites from cosmic rays for several million years. This size requires a crater at least 85 km in diameter for an impact velocity of 11 km sec^{-1} (Fig. 2), and the required crater size increases rapidly with impact velocity. Since there are no craters this large on the young terrane, this ejection history can be ruled out, unless the impact excavated a localized young volcanic center in the old terrane. The crater production rate for craters ≥ 85 km is $\sim 3.21 \times 10^{-16}$ km^{-2} year^{-1}; the probability of forming such a crater somewhere on Mars within 10 Ma is ~36%. This is much less probable than case 1 and requires the same ad hoc assumption of a young volcanic center in the old terrane.

3) *Nakhlites and Chassigny ejected as small fragments 10 Ma ago, and all the shergottites ejected together at 2.5 Ma.* If all the shergottites were ejected in a single event, proto–EETA 79001 must have been ≥3 m in diameter to shield the inner portion from cosmic rays for ~2 Ma until collisional fragmentation in space. This requires a crater ≥50 km in diameter (Table 1, case 3a). This history can be ruled out if the shergottites are from the young terrane. If the shergottites are from the old terrane, the ~200-Ma event might have been a result of either crystallization in a young, localized volcanic center or shock metamorphism. The probability of forming a crater ≥50 km in diameter somewhere on Mars within 2.5 Ma is ~25%, which is an upper limit on the probability of such a crater intersecting a young volcanic center.

If the 200-Ma event were shock-induced metamorphism, we must then examine the probability of having two overlapping cratering events, one ~200 Ma ago and the second ~2.5 Ma ago, with the second one having produced a crater ≥50 km in diameter. In this case, the first-generation crater may be relatively small and may occur anywhere on the old terrane of Mars. We computed the probability of occurrence of craters from ≥5 km in diameter on the old terrane over 200 Ma, and, for those craters for which the probability is essentially 1.00, the number of such craters that would be expected. The permissible target area for the second-generation craters is not the entire old terrane, rather it is the area covered by the first-generation craters plus their shocked ejecta. The target area for each first-generation crater was taken to be the area of the crater plus its continuous ejecta blanket, assumed to extend one crater diameter from the rim, that is, $A = \pi(1.5\ D_1)^2$, where D_1 is the diameter of the first-generation crater. The second-generation crater is required to eject the previously shocked material at velocities ≥5 km sec^{-1}; such ejection velocities are achieved only within one to two projectile diameters of the center of the crater, and the condition for "overlap" is therefore that the center of the second crater lie no more than 1.5 D_1 from the center of the first crater.

Table 1. Probabilities of cratering events associated with proposed ejection and exposure histories.

Case	Crater production rates: Maximum likely (%)	Most likely (%)	Minimum likely (%)
1	100	92	78
2	78	36	24
3a	62	25	16
3b	6.15	0.15	0.05
3c	100	87	71
4	100	54	25
5	100	80	55

Each size subdivision among the first-generation craters contributes $\pi(1.5\ \overline{D}_1)^2\ N(D_1)$ to the total target area for the second-generation craters, where $N(D_1)$ is the number of craters with diameters between D_1 and $\sqrt{2}\ D_1$, and D_1 is the midpoint of this range. The characteristic formation time of second-generation craters with diameters between D_2 and $\sqrt{2}\ D_2$ on the area covered by first-generation craters with diameters between D_1 and $\sqrt{2}\ D_1$ is

$$\tau_2 = [k'D_2^{-1.75}\pi(1.5\ \overline{D}_1)^2 N(D_1)]^{-1} \qquad (10)$$

and the probability of formation is

$$P_2 = 1 - e^{-(t/\tau_2)} \qquad (11)$$

where t is 2.5 Ma. The probabilities of first- and second-generation craters were convolved and then summed over the entire size range. The probability of occurrence of an impact within the last 2.5 Ma that produced a crater ≥50 km in diameter overlapping a crater ≥5 km in diameter formed within the last 200 Ma is ~0.15% (Table 1, case 3b).

The nakhlites and Chassigny could have been ejected as <0.5-m fragments from a crater ≥12 km in diameter for an impact velocity of 11 km sec^{-1}. The probability of forming at least one crater ≥12 km in diameter on the young terrane of Mars in 10 Ma is ~87% (Table 1, case 3c). The probability of forming craters ≥12 km in diameter somewhere on Mars in 10 Ma is high enough that there should be five to six times as many such craters on the old terrane as on the young terrane. This implies that if such a small magnitude event launched the nakhlites and Chassigny, then there should be approximately five to six times as many old martian meteorites as young ones. The mass ratio of shergottites to nakhlites plus Chassigny is roughly 3:4 (*14*), so that even if the shergottites were presumed to be old (*3*), they cannot account for the discrepancy in the observed and predicted mass ratios.

This ejection and exposure history is, therefore, extremely unlikely on three grounds. First, if the 200-Ma event in the shergottites were crystallization, this model requires the same ad hoc assumption of a young, hidden volcanic center as cases 1 and 2, and is less probable than either case 1 or 2 because of the more severe time constraints. Second, if the 200 Ma-event is assumed to have been shock-induced metamorphism, there is a very small probability of the shergottites having been ejected 2.5 Ma ago from a crater ≥50 km in diameter that overlapped a preexisting crater ≤200 Ma old. Third, if the nakhlites and Chassigny were ejected as small rocks from a crater ≥12 km in diameter 10 Ma ago there should be five times as much old martian meteoritic material as young, which is not observed.

4) *The SNC meteorites ejected as small fragments at times correspond-*

Table 2. Well-preserved martian craters ≥100 km in diameter (*27*).

Crater	Diameter (km)	Location	Classification
Lyot	227	MC-5-NW	c_3 or c_4
Gale	161	MC-23-NW	c_3
Lohse	158	MC-26-NE	c_3
Bakhuysen	157	MC-20-SW	c_4
Holden	145	MC-19-SW	c_3
Hale	143	MC-26-NE	c_3
Liu Hsin	131	MC-24-SW	c_3*
Fournier	130	MC-21-NE	c_3
Curie	115	MC-11-NE	c_4
Lamonosov	113	MC-4-NE	c_3
Milankovic	112	MC-2-NE	c_3
Cerulli	107	MC-5-SW	c_4
Radau	106	MC-11-NE	c_4
Mie	104	MC-7-NW	c_3

*May be exhumed.

ing to their cosmic-ray exposure ages. In this case, the required fragment size is reduced to a few tens of centimeters that can be satisfied for craters >12 km in diameter; the high probability of craters this size makes this model quite appealing. As argued for case 3, however, if small craters were ejecting meteorites from Mars, we would expect a dispersion in ages, which is not observed. Furthermore, application of the mass-flux constraints from Wetherill's "small-body" model (*15*) shows that this is not a good explanation for the martian origin of the SNC meteorites.

We used the spallation model to estimate the mass ejected in velocity bins corresponding to those in Wetherill (*15*, table 1) for the crater sizes from 5 to 225 km in diameter. The upper limit of 225 km was chosen because that is the size of the largest crater on Mars, excluding the ancient basins. The calculations of mass ejected as a function of velocity and crater size depend also on impact velocity (Eq. 3). We used an impact velocity of 11 km sec^{-1}, which is approximately the mean impact velocity expected for Mars-crossing asteroids (*23*). No spall material is ejected at ≥5 km sec^{-1} for impact velocities ≤10 km sec^{-1} (Fig. 1), and the mass yield (amount of material that reaches Earth within 10 Ma) from a given size crater decreases as impact velocity increases above 11 km sec^{-1}. The crater sizes were again divided into diameter bins of D to $\sqrt{2}\,D$. The mass at each ejection velocity, weighted by the yield for that velocity (the fraction of the material ejected from Mars that reaches Earth within 10 Ma), was summed for each crater size. The crater production rates derived from (*6*) were used to estimate the number of craters in each size bin expected anywhere on Mars in 10 Ma. The mass ejected per crater was multiplied by the expected number of craters, excluding those craters with less than 50% probability of occurrence, and summed. The calculated mass flux for the optimal impact velocity of 11 km sec^{-1} ranges from $\sim 6 \times 10^{-2}$ to 3 kg $year^{-1}$, depending on the CPR used, compared to the required 400 kg $year^{-1}$ (*15*). Equation 1 is an analytic approximation and may be in error by a factor of 2, and the estimated CPR (*6*) is at least as uncertain, but no reasonable variation in the assumed parameters can give a sufficient mass flux to account for the SNC meteorites. Thus, although the idea of launching the SNC meteorites from Mars as small objects in three separate events from craters as small as 10 km in diameter at times corresponding to their cosmic-ray exposure may intuitively seem the most likely, this proposed scenario must be discarded.

5) *Shergottites ejected as large fragments 200 Ma ago, and nakhlites and Chassigny ejected as small fragments 10 Ma ago*. In this case, the mass flux requirement to eject shergottites as large fragments is reduced because that single event is not responsible for the total mass flux. The fragment size constraint, however, remains the same as in case 1, that is, a crater ≥175 km in diameter, for which the probability is ~92%. As in case 3, the probability of a crater of sufficient size (≥10 km) to eject the nakhlites and Chassigny 10 Ma ago is ~87%. The probability of both events is thus ~80%. This proposed combination of events has two advantages over cases 1 and 2: it does not require a young volcanic center hidden in the old terrane, if we assume the shergottites are old (*3*), nor does it require that all of the martian meteorite flux results from a single cratering event. It shares, however, the problem of cases 3 and 4 that if relatively small craters are capable of contributing significantly to the martian meteorite flux, then we should see five to six times as many old meteorites as young ones produced by cratering events of similar magnitude.

Discussion and Conclusions

The dynamically most plausible explanation for the martian origin of the SNC meteorites is that they were ejected from Mars in a single, very large magnitude event ~200 Ma ago. A large crater origin for the SNC meteorites may also explain the apparent discrepancy between the mass ratio of lunar meteorites to putative martian meteorites. Wetherill (*15*) estimated that the mass yield of lunar meteorites should be $\sim 2.5 \times 10^3$ times that of martian meteorites, but the mass ratio of SNC meteorites to lunar meteorites is ~100. Wetherill suggested that there is some special characteristic of the martian surface, such as the presence of volatiles, that greatly facilitates the acceleration of ejecta fragments to very high velocities. A very large crater is an unusual event that ejects much more material at high velocity than a small crater: From Eqs. 2 and 3, the mass ejected at a given velocity varies with crater diameter as $M \propto D^{3.84}$. That is, a 100-km crater ejects ~7000 times as much material at or above escape velocity as a 10-km crater. Furthermore, a large crater ejects much larger rocks than a smaller one, and larger rocks are more likely to survive transit to Earth. Thus, the mass yield of meteorites from a single, very large crater is expected to be so much greater than that from several much smaller craters that ejecta from the small craters have not been seen in meteorite flux. Most of the ejecta from a lunar crater that will reach Earth does so within a few million years (*24*); lack of a large-magnitude event on the moon during the last few million years then explains the apparent discrepancy between the expected and observed mass ratios of lunar to martian meteorites.

This hypothesis is, in principle, testable, because a very large crater on Mars that is only ~200 Ma old should be recognizable. The only crater on Mars that is larger than 175 km in diameter and is fresh enough to have well-preserved ejecta deposits and secondary craters is Lyot, D = 227 km, located at latitude ~51°N, longitude ~330°. A recent study of small primary craters superposed on Lyot and its ejecta indicates that it is approximately the same age as Arsia Mons (*25*). The best estimate of the age of the Tharsis volcanoes is ~2.0 Ga, although they may be as young as 600 Ma (*6*), which implies that Lyot is too old to have been the source crater for the SNC meteorites.

We assume that the estimate of the required crater size may be imprecise by a factor of ~2. There are approximately 20 craters larger than 100 km in diameter on Mars with well-preserved ejecta deposits (*26*). Some of these have clearly been buried and then exhumed, so they may be very old. After eliminating these from consideration, however, 14 craters ≥100 km in diameter (including Lyot) remain that have been classified by the U.S. Geological Survey mappers as c_3 or c_4 (Table 2) (*27*), that is, as relatively young and well-preserved. One of the principal differences between c_3 (older) and c_4 (younger) craters is the radial extent of the ejecta deposits. At least one investigator (*28*) has suggested that this difference may be due to a difference in target material (possibly the amount of volatiles) rather than to a difference in age, so that c_3 craters are not necessarily older than c_4 craters and need not be eliminated from consideration here.

Relative ages from superposed crater densities are not available for these craters, except for Lyot. Dating young craters in this size range is intrinsically difficult (*25*) because one expects only a few small superposed primaries that are difficult to distinguish from the secondary craters surrounding the large crater to be dated; furthermore, age calibration based only on small craters is extremely uncertain. Thus it is impossible at this point definitely to say that a sufficiently large and young enough crater exists, but there are several possible candidates.

We conclude it is most plausible that the SNC meteorites were ejected from a very large crater ~200 Ma ago as relatively large fragments that were collisionally fragmented in space at times corresponding to their cosmic-ray exposure ages. This model would be more satisfying if there were some SNC meteorites with older cosmic-ray exposure ages and evidence of two-stage exposure. Rock fragmentation experiments may provide an explanation (*29*); the outer portion of collisionally fragmented bodies tends to break into relatively smaller fragments, and the inner portion ("core") tends to break into a few, relatively large fragments. In the case of the SNC meteorites, the larger, previously shielded fragments from the core of the original body would have a greater chance of surviving both further collisional fragmentation and passage through Earth's atmosphere, and are therefore more likely to be recovered as meteorites on Earth. A final possibility is that the SNC meteorites are not from Mars at all. This alternative, however, which most investigators find increasingly unlikely, has many problems of its own (*30*).

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