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Martian Parent Craters For The SNC Meteorites

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The young ages (~1.3 Ga) and the basaltic to ultramafic compositions of the shergottites, nakhlites, and chassignites meteorites severely restrict their potential source regions on Mars. We have used this age and compositional information, together with geologic data derived from Viking Orbiter images, to identify 25 candidate impact craters in the Tharsis region of Mars that could be the source crater for these meteorites. None of these craters are close to the size (~100 km diameter) implied by the dynamical study of SNC ejection developed by Vickery and Melosh (1987). The craters in our study were selected because they are >10 km in diameter, have morphologies indicative of young craters, and satisfy both the petrologic criteria of the SNCs and the proposed 1.3 Ga crystallization ages. Of these 25 craters, only nine are found on geologic units believed to be young (crater density is less than 570 craters of greater than 1 km diameter per 10^6 km^2). No crater exists to satisfy well the criteria of sampling both a 1.3 Ga surface (nakhlites and Chassigny) and a 180 Ma surface (shergottites) without at the same time imposing significant constraints on the chronology of Mars as inferred from the cumulative crater curves. The relatively young age (based on their inferred position in the stratigraphic column of Tharsis (Scott et al., 1981)) of the SNCs implies that volcanic activity on the plains of the Tharsis region extended well past 1.3 Ga.

INTRODUCTION

The SNC (shergottites, nakhlites, chassignite) meteorites are a group of nine rocks thought, on the basis of their young age, basaltic composition, and noble gas concentrations, to be impact debris ejected from Mars [e.g., *Wood and Ashwal*, 1981; *Shih et al.*, 1982; *Bogard et al.*, 1984; *Becker and Pepin*, 1984; *Swindle et al.*, 1984; *McSween*, 1985]. A number of authors have made attempts, based on various lines of reasoning, to locate the parent crater(s) of these rocks on Mars [e.g., *Wood and Ashwal*, 1981; *Nyquist*, 1983, 1984; *McSween*, 1985; *Jones*, 1985; *Vickery and Melosh*, 1987]. Here we address this problem by using the extensive photogeologic data base provided by the Viking Orbiter images, combined with information on a number of key properties of the SNCs. These properties include their young ages and basaltic to ultramafic compositions which, taken together, severely restrict potential source regions on Mars. We also make use of the present knowledge of ejection mechanisms [e.g., *Melosh*, 1985; *Vickery and Melosh*, 1987], which indicate that the SNCs were most likely near-surface rocks that were subjected to low shock but high stress gradients, and that the material was ejected in the form of relatively large fragments (>1 m in size). Because SNCs are rare materials in the meteorite collection, it is also likely that they were ejected by an unusual cratering event on Mars.

In this analysis, we first review the constraints imposed on the parent terrain and crater by our knowledge of the petrology and ages of the SNC meteorites. We then discuss the geomorphic properties of impact craters on Mars in the context of identifying relatively young examples. These constraints are then applied to identify probable SNC ejection craters in the Tharsis region of Mars, which appears to be the only area on the planet that meets both the petrologic and young age constraints and possesses relatively large superposed impact craters that may have ejected the meteorites. On the basis of arguments presented below, we choose craters >10 km in diameter as candidate craters. Finally, on the basis of the constraints implied by the identification of the candidate source craters, we make some interpretations of the absolute chronology of Mars.

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CONSTRAINTS

Below, we discuss a number of properties of the SNCs and Mars in an attempt to constrain the number of potential parent craters for the SNC meteorites.

Petrologically Diverse Volcanic Terrain

The SNCs are a petrologically diverse group of igneous meteorites that range in mineralogy from basalts to dunite, sampling both extrusive and intrusive rocks. Numerous attempts have been made to relate the SNCs to one another through simple geologic processes such as fractionation [*Shih et al.*, 1982; *Longhi and Pan*, 1989]. When all of the relevant data are considered, it appears that the SNCs probably came from different initial magmas which experienced varying degrees of partial melting, fractional crystallization, magma mixing and, possibly, wall rock assimilation. The parent crater is therefore inferred to have formed on materials from two different volcanic centers or to have formed on a single volcanic center that had evolved this petrologic diversity through time.

Young Terrain

Previous workers have used a variety of age dating techniques to derive the ages of the SNC meteorites. Crystallization ages on both whole rocks and mineral separates for the nakhlites (Nakhla, Governador Valadares, and Lafayette) and Chassigny are well constrained at approximately 1.3 Ga [*Papanastassiou and Wasserburg*, 1974; *Bogard and Husain*, 1977; *Bogard and Nyquist*, 1979; *Wooden et al.*, 1979; *Nakamura et al.*, 1982]. Shergottites have whole rock Sm-Nd ages of 1.27 Ga [*Nyquist et al.*, 1984], but internal mineral isochrons yield Rb-Sr, Sm-Nd and U-Th-Pb ages around 180 Ma [*Shih et al.*, 1982; *Jagoutz and Wänke*, 1986; *Chen and Wasserburg*, 1986]. Plagioclase shock melts and associated crystallization products in ALH A77005 record an age of ~15 Ma [*Jagoutz*, 1989], synchronous with the cosmic ray exposure age for this rock.

This geochronology has traditionally been interpreted as crystallization of shergottites at 1.27 Ga with shock and ejection of large boulders at 180 Ma and breakup of these boulders around 15 Ma. Some authors [e.g., *Jones*, 1986; *Jagoutz*, 1989; *Longhi*, 1991] disagree with this interpretation, arguing that the shergottites crystallized at 180 Ma with shock and ejection at around 15 Ma. Regardless of this age debate, all authors would agree that the SNC ages imply that their parent terrain on Mars is relatively young. It is also implicit that if the SNCs are young, then the parent crater that ejected the rocks also has to be young and should show all of the morphological characteristics of young impact craters on Mars, as discussed below.

Single Impact for Ejection

Cosmic ray exposure ages for the SNCs cluster in three groups: 11 Ma (Nakhla, Governador Valadares, Lafayette, and Chassigny), 2.6 Ma (Shergotty, Zagami, and ALH 77005), and 0.5 Ma (EETA 79001). Some investigators have argued that these groupings might record separate impact events on Mars [e.g., *Wetherill*, 1984; *Vickery and Melosh*, 1987]. This seems unlikely, because it is unclear why three random impact events would deliver young volcanic samples to Earth, when these terrains make up a very small part of the surface of Mars (<5% [*Greeley and Spudis*, 1981]). Indeed, we would have expected all of the SNCs to come from impacts into the older Martian regions such as the ridged plains, smooth plains, or in the cratered highlands. We have considered the possibility that only samples from the young volcanic regions would be coherent enough to survive the passage to Earth. However, large, apparently coherent boulders exist outside of the young volcanic regions of Mars, as evidenced by imaging from the two Viking landers [cf. *Mutch et al.*, 1977], so that it seems likely that massive rocks could have been ejected from these areas had an appropriate impact event occurred. Thus the range of cosmic ray exposure ages observed from the SNCs must have resulted from the in-space breakup of large pieces from a single site.

Young Crater

Constraining the age of the ejection of the SNC meteorites from Mars allows us to specify the maximum age of the parent crater; this is a key factor that was omitted by *Wood and Ashwal* [1981] and by *McSween* [1985] when they tried to identify candidate SNC parent craters solely on the basis of the age of the target material as inferred from the number of superposed impact craters. Whether the 180 Ma age is the shock age or the crystallization age, the SNCs could not have been ejected from Mars prior to 180 Ma. Thus we need to find impact craters which are very young (less than 180 Ma). We identify young craters (those craters designated as C_4 craters [e.g., *Chapman et al.*, 1989]), by their sharp and well-preserved rims, steep walls, deep and rough floors, and extensive and well-preserved ejecta deposits.

Crater Size and Geometry

As noted above, it appears that a single impact ejected all of the SNC meteorites. Thus some feature of this unique cratering event caused it to eject material from Mars, while other craters did not deliver meteorites to Earth. The SNC parent crater appears to be even more unusual when we consider that any impact event on Mars which ejected material in the last 300 m.y. would still be delivering material to Earth [*Wetherill*, 1983, 1984]. Thus the SNC parent crater appears to be the only crater to have ejected material from Mars in the last 300 m.y., requiring even more unusual circumstances. This has prompted us to consider craters which are larger than most other craters or which have unusual characteristics (i.e., the crater was formed by a highly oblique impact). *Melosh* [1985] argued that craters >30 km in diameter were necessary for ejection of the SNCs. More recent calculations by *Vickery and Melosh* [1987] have suggested that a crater >100 km in diameter may have been required to eject the SNCs. These theoretical considerations of SNC ejection are based on impact events that produced circular craters, rather than oblique impacts. However, when the above petrologic and age constraints are applied to Mars, no crater larger than 100 km diameter fits all of the boundary conditions. Indeed, as we discuss below, there are only two craters >40 km diameter (57 km and 69 km) of any degradational state that are preserved on lava flows in the Tharsis region. In order to consider a larger number of craters, we therefore choose to relax the requirement of a large crater, limiting our candidate craters to >10 km diameter.

In this analysis we give preferential consideration to unusual crater morphologies in order to help address the unique ejection mechanism of the SNC parent crater. *Nyquist* [1983, 1984] and *O'Keefe and Ahrens* [1986] have evaluated oblique impacts as a mechanism for ejection of the SNCs, concluding that the ejecta from such an event have an increased likelihood to escape Mars when compared to near-vertical impacts. Laboratory experiments generate elongate craters from oblique impacts only at impact angles of 5° or less [*Gault and Wedekind*, 1978]. *Schultz and Lutz-Garihan* [1982] identified 175 craters that probably formed by oblique impacts on Mars, but only 122 of these craters possess well-preserved ejecta blankets (and are thus inferred to be relatively young craters), and only six are found on young volcanic terrain. Furthermore, all but two of the 175 craters believed to have been produced by grazing impacts are either outside the area that we use to define young Tharsis lava flows (Figure 1) or are <10 km in diameter [*Schultz and Lutz-Garihan*, 1982] and thus would not meet our selection criteria for the identification of the SNC parent craters. The two craters in the list of *Schultz and Lutz-Garihan* [1982] (their craters 33 and 37) that meet our selection criteria are also included in our study (craters 2 and 5, respectively; Table 1).

CANDIDATE TERRAINS

Young volcanic surfaces on Mars are quite rare. The Tharsis region is the only area on Mars with regionally extensive young volcanic flows. It is possible that other areas of Mars may have young volcanic flows (specifically the Elysium region [*Plescia*, 1990]), but such areas do not contain superposed craters >10 km in diameter that could eject the meteorites. Since the Tharsis region appears to be the most likely source of the SNC meteorites, it is worth considering the general setting and history of this area. For the purpose of this investigation, our designation of the perimeter of the Tharsis region (Figure 1) includes the lava plains extending around the volcanoes Olympus Mons and Alba Patera, as well as the Tharsis ridge volcanoes (Arsia Mons, Pavonis Mons, and Ascraeus Mons). All of these volcanoes are enormous by terrestrial standards, rising as much as 27 km above the surrounding plains. At least six other smaller volcanoes can also be found in Tharsis [*Carr*, 1981]. The Tharsis ridge volcanoes and these smaller constructs all lie on the Tharsis bulge, centered at approximately 10°S, 110°W, which is a broad upwarped region that is ~5000 x 6000 km in size and, depending on what is taken to be its base, is ~10 km high at its center.

We use the lava flow maps produced by *Scott and Tanaka* [1981*a*,*b*] and *Scott et al.* [1981*a*,*b*,*c*] to define the stratigraphy of the Tharsis region. The volcanic units of Tharsis can be placed in stratigraphic sequence on the basis of mapping of lava flow units and the morphology of the lava flows [*Scott et al.*, 1981*a*]. Crater counts for the various units were made by Scott and coworkers to verify these age relations and to obtain some degree of correlation between flows in widely separate areas, where overlap relations could not be established. *Scott and Tanaka* [1981*c*] identified six stratigraphic events in Tharsis that represent major periods of volcanism that resurfaced the basement terrains. Most of the volcanic flows evidently originated from the summits and flanks of the volcanoes, although some issued from fractures and fissures in the surrounding plains. We have chosen not to assign absolute ages to these units because of the uncertainty in correlating cumulative crater curves and surface ages on Mars [e.g., *Neukum and Hiller*, 1981; *Barlow*, 1988]. Our approach for selecting candidate craters is similar to that taken by *Wood and Ashwal* [1981] and *McSween* [1985] but uses the detailed geologic maps of the Tharsis region to provide the relative chronology and stratigraphy. We give preference to craters where petrologic diversity can be readily demonstrated, but we cannot rule out

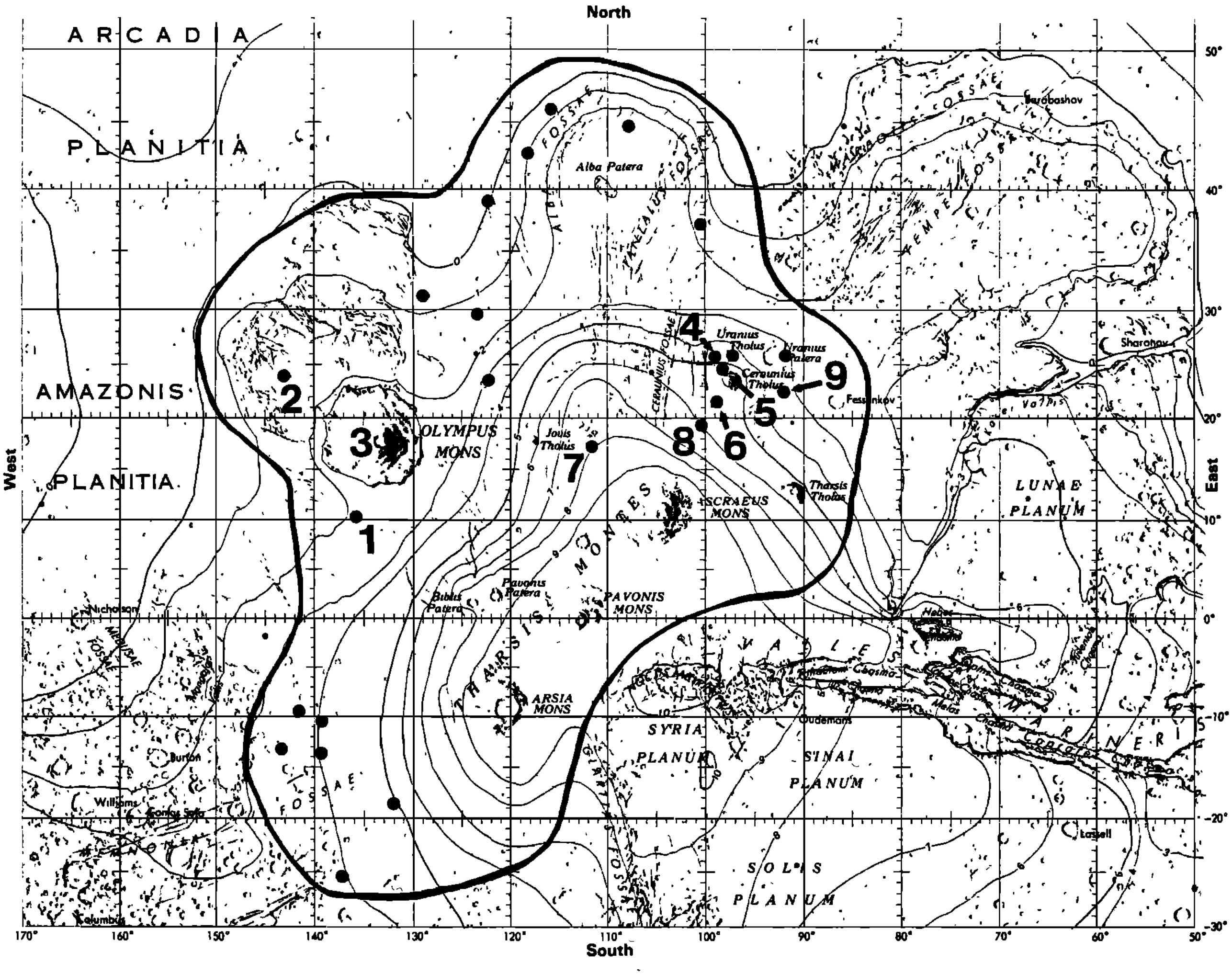

Fig. 1. Map showing location (dot) of each candidate SNC parent crater. All 25 craters larger than 10 km in diameter that may be the parent crater for the SNCs are shown, but only the best candidates referred to in the text are numbered. The solid line shows the boundary of the relatively young lava flows in the Tharsis region. Base map is the 1:25,000,000 topographic map of Mars prepared by the *U.S. Geological Survey* [1976] and extends from longitude 50° to 170° and from latitude 50°N to 30°S. Contours are elevations in kilometers above the Mars datum. For scale, 10° longitude at the equator is 590 km.

TABLE 1. Locations, Diameters, Image Resolution, and Viking Orbiter Frame Numbers for 25 Candidate SNC Craters

Crater	Latitude, degrees	Longitude, degrees	Diameter, km	Resolution, m/pixel	Frame	Unit
1	10.8	135.2	11.6	148	888A15	Aop
2	24.8	142.1	29.2	198	512A45	Aeu
3	18.5	131.9	14.8	91	890A68	Aom$_2$
4	26.3	98.1	13.7	201	516A23	Atm
5	25.2	97.6	34.2 x 18.2	200	516A24	Atm
6	22.2	98.0	33.8	200	516A24	Atm
7	17.8	111.0	21.9	189	516A53	Atm
8	19.5	99.8	18.3	190	516A45	Atm
9	22.7	92.0	12.0	249	857A48	Atm
10	26.4	96.9	11.1	201	516A23	AHvu/Atm
11	-18.7	131.3	17.4	268	639A61	Aam$_4$
12	44.9	106.7	21.3	72	253S05	Aap$_3$
13	46.0	115.1	18.0	83	252S36	Aap$_3$
14	-9.6	141.8	22.2	284	639A34	Aam$_3$
15	-13.9	139.5	15.4	272	639A35	Aam$_3$
16	-10.8	139.4	15.0	283	639A36	Aam$_3$
17	-13.3	143.8	12.1	273	639A33	Aam$_3$
18	-25.5	136.6	15.2	256	639A39	Aam$_2$
19	26.6	91.2	10.0	248	857A46	AHvu
20	39.2	120.8	14.7	243	853A03	AHap$_2$
21	43.1	117.5	22.6	72	252S09	AHap/Aap$_3$
22	29.9	123.5	16.7	243	853A10	AHap$_2$
23	24.1	121.2	21.9	178	890A04	AHap$_2$
24	37.7	99.5	18.5	87	254S48	AHap$_2$
25	31.7	128.3	16.9	73	251S05	AHap$_1$

Unit designations come from the maps prepared by the U.S. Geological Survey. Craters are presented in terms of the apparent relative age of the units (youngest is 1).

underlying flows or dikes to provide petrologic diversity at other craters.

CANDIDATE CRATERS

We need to identify impact craters on Mars which are <180 Ma, and we use 10 km as the minimum diameter of the parent crater in order to consider a representative number of craters in Tharsis. Because of its young age the SNC parent crater should have experienced comparatively little modification (due, for instance, to eolian erosion or meteorite bombardment) compared to other impact craters on Mars and should appear "fresh." Morphological criteria for the absolute identification of young, fresh, Martian impact craters do not exist, because the geometry and appearance of the crater is influenced by a combination of factors, including projectile and target rock properties (stratification, volatile content, and strength), the role of regional weathering processes (eolian erosion and creep due to subsurface volatiles), and the effects of subsequent cratering events. However, as a general guideline to the interpretation of the relative ages of Martian impact craters, we use the U.S. Geological Survey's criteria [e.g., *Chapman et al.*, 1989]. These criteria state that interior features of young impact craters (the C_4 craters) should include sharp and well-preserved complete rims, steep walls, and deep rough floors. Exterior ejecta deposits should be extensive and well preserved, often have radial striations on their surfaces, and commonly terminate in prominent distal ridges (or "ramparts"). There should be a lack of small superposed primary craters on the ejecta blanket. Secondary craters should also often be found, and these should be well preserved (relatively deep), forming pitted terrain around the parent crater. Only those craters that fit the C_4 classification are included in our search for candidate SNC parent craters.

We have carried out an investigation of the Viking Orbiter images that have a spatial resolution better than 300 m/pixel for the Tharsis region of Mars. The 300 m/pixel cutoff was chosen so that the smaller morphologic features on the ejecta blankets (such as radial striations, distal ramparts, and secondary craters) could be seen and used as criteria for the identification of the youngest craters. At a resolution of 300 m/pixel or better, all areas of Tharsis can be included in our study. Our search has identified 25 craters larger than 10 km in diameter with well-preserved ejecta blankets (Figure 1). Table 1 lists the geographic locations, diameters, image resolution, image frame numbers, and geologic units of each of these craters. Figure 2 places these candidate SNC parent craters into their relative stratigraphic ages.

Stratigraphic age is the second important consideration in the identification of the candidate SNC parent crater. Although Tharsis is a geologically young area on Mars, 23 different stratigraphic units have been identified by Scott and coworkers on the basis of superposition relationships and the cumulative size frequency distribution of impact craters on each unit. These 23 units clearly represent different stages in the formation of Tharsis, which could have spanned a time interval of hundreds of millions of years [*Neukum and Hiller*, 1981]. From Figure 2 it is apparent that many of the candidate SNC parent craters formed on geologic units that are intermediate or old when compared to other geologic

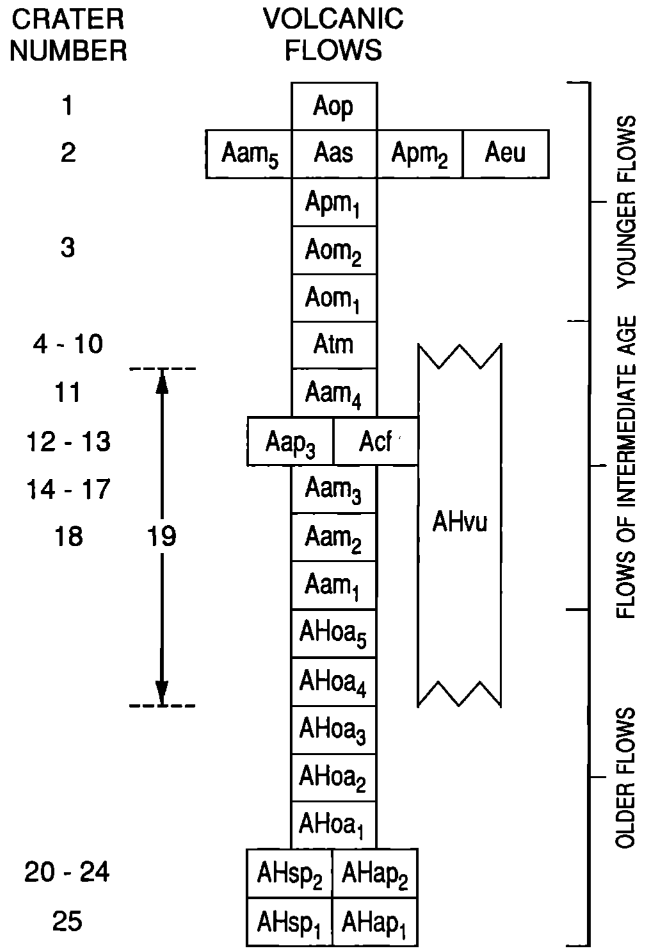

Fig. 2. Stratigraphic column for the lava flows in the Tharsis region of Mars, showing the relative chronology for the 25 craters identified as candidates for the SNC parent crater. Unit names and relative chronology were derived by *Scott and Tanaka* [1981*a*, *b*] and *Scott et al.* [1981*a*, *b*, *c*]. Note that we place unit Aeu at the top even though as mapped the unit is of uncertain origin.

units in Tharsis. While this age classification is only relative, it does imply that if the SNC parent crater formed on some of the older rocks in Tharsis, then the 1.3 Ga age of the SNC meteorites would compress a considerable amount of volcanism into a period of time from 1.3 Ga until the present; it is hard to believe that all of Tharsis formed this recently. The number of candidate parent craters for the SNCs can therefore be reduced by excluding all craters that did not form on stratigraphically recent target materials. For this further selection of candidate craters, we include only fresh craters >10 km diameter that formed on the units classified as Aop through Atm in the stratigraphic column. This corresponds to units that have less than 570 craters >1 km diameter per 10^6 km^2. The range of units included in our sample of craters encompasses the youngest lavas in the Tharsis region (Aop), depositional materials associated with the Olympus Mons aureole (Aeu), lava flows originating from crestal areas and flanks of Olympus Mons (Aom_2), and the late-stage lava flows extruded from Arsia, Pavonis, and Ascraeus Montes (Atm). Obviously, if it were to transpire that unit Atm has an age older than expected, fewer candidate craters should be included here (i.e., one should select only craters toward the top of the stratigraphic column in Figure 2). Conversely, if unit Atm is younger than expected, more of the identified craters should be considered as candidates (i.e., one should select more craters toward the middle of the stratigraphic column).

A total of nine craters listed in Table 1 fall into our category of forming on young geologic units in Tharsis. However, none of our nine preferred candidate craters were included in the sets selected by *Wood and Ashwal* [1981] or by *McSween* [1985]. In these earlier studies, craters were chosen only on the basis of the approximate age of the target material; the need for very young (<180 Ma) craters was not taken into account. This morphological criterion eliminated all of the craters of *Wood and Ashwal* [1981] and *McSween* [1985] from our list of preferred candidates. The two candidate craters (25 km and 27 km in diameter) identified by *Jones* [1985] are on the plains in Amazonis Planitia (i.e., outside the boundary of the Tharsis region shown in Figure 1). These two craters are not included in our sample, because the target material (unit Aps of *Scott and Tanaka* [1981b]) is of uncertain origin due to the mantle of windblown material that covers the basement rocks. As a result of its unusual elongate shape and relative youth, crater 5 in our data set was also suggested by *Nyquist* [1983] to be a suitable parent crater for the SNCs.

We now discuss the specific characteristics of the nine craters which we believe are the most likely candidates for the parent crater of the SNC meteorites, concentrating on the attributes which are the best and worst for satisfying the criteria of a young crater (≤180 Ma) on a petrologically diverse, young (≤1.3 Ga) terrain.

Crater 1: 11.6 km Diameter, 10.8°N, 135.2°W

Best attributes: This crater was formed on a very young surface (unit Aop of *Scott and Tanaka* [1981*a*]) to the south of Olympus Mons (Figure 3). The crater has two pronounced discontinuities in its rim crest, suggesting a somewhat unusual layering in the target. In addition, the crater seems to be very young because it has a prominent swirl texture on its floor and appears to have a hummocky ejecta blanket, suggestive of ballistic (rather than fluidized) emplacement.

Worst attributes: From the mapping of the main lava flow units in the Tharsis region [*Scott and Tanaka*, 1981*a*], it appears highly likely that the surface material in this part of Tharsis comprises only one lava type. Obtaining petrologically diverse SNC meteorites from the surface would therefore be difficult from this site, although we cannot entirely rule out the possibility of a thin flow overlying a second flow that is now totally buried. In addition, this crater is relatively small and has a typical geometry for fresh impact craters on Mars. If this particular crater, which is common in every way, ejected material from Mars, so should many other craters superposed on both Tharsis and older terrains. On the basis of calculations presented by *Wetherill* [1983, 1984], one would expect the delivery times of ejecta to Earth from such craters to be extended over hundreds of millions of years, so that the probability of receiving ejecta from typical craters such as this one should be high if they did indeed eject material from the surface. This "problem" of

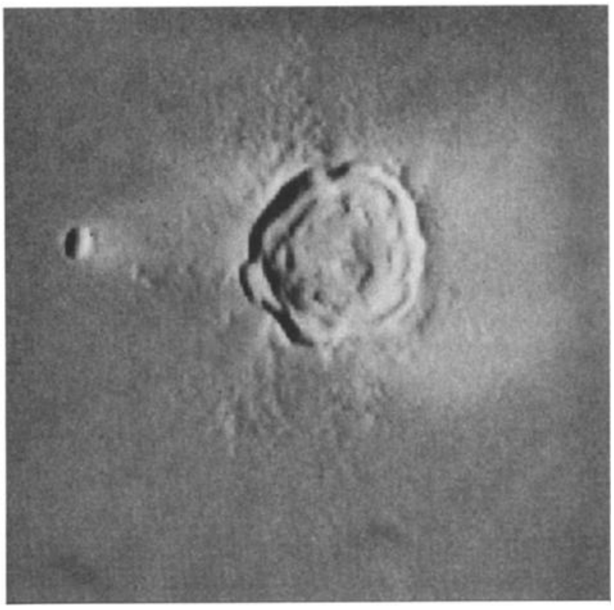

Fig. 3. Crater 1, 11.6 km diameter, located ~120 km south of the Olympus Mons escarpment. High-albedo feature is a wind streak associated with eolian activity not part of the ray system of the crater. Image resolution is 148 m/pixel. This is Viking Orbiter image 888A15.

receiving samples on Earth from only one crater when many typical circular craters should have the same ability to eject the SNCs is a common situation for other craters in our sample (specifically, craters 3, 4, 6, 7, 8, and 9). For brevity in the discussion that follows, we will refer to this situation as "the circular crater problem." For craters 3, 6, 7, 8, and 9, the lack of apparent petrologic diversity allows us to refer to "the circular crater, single-lava-type problem."

Crater 2: 29.2 km Diameter, 24.8°N, 142.1°W

Best attributes: This is an elongate crater interpreted to have been produced by an impact into a morphologically fresh segment of the Olympus Mons aureole material (Figure 4). The crater appears to be very young, based on the swirl pattern of its interior deposits and the numerous well-preserved secondary crater chains that extend more than 80 km away from the rim of the crater. These secondary chains are very long compared to the size of the crater [*Schultz and Singer*, 1980], and possess a marked asymmetry to their distribution that indicates that the crater was formed by an oblique impact event. No fluidized ejecta lobes exist around the rim of this crater.

In the context of the SNC samples, a key attribute of this target material is that it may have originated as a landslide deposit associated with failure of the lower flanks of the volcano Olympus Mons. Numerous landslides can be seen to originate from the basal escarpment of Olympus Mons [*Lopes et al.*, 1982], and it is possible that this process may have placed many different rock types close to the surface of this single deposit. Because of this possibility for sampling rocks of two drastically different ages (180 Ma and 1.3 Ga), crater 2 is the leading candidate for the SNC parent crater if the shergottites have a crystallization age of 180 Ma due to the inferred very young age of some lava flows on Olympus Mons [*Neukum and Hiller*, 1981; *Landheim and Barlow*, 1991].

Worst attributes: The origin and age of the Olympus Mons aureole is unclear, and several different models have been proposed to explain the origin of this enigmatic feature [e.g., *Harris*, 1977; *Lopes et al.*, 1982; *Francis and Wadge*, 1983; *Tanaka*, 1985]. Because of this uncertainty in the origin of the target rocks, it is possible that these materials may not even be volcanic. In addition, their age is also uncertain; they could appear to be young because they are unconsolidated and are continually being rejuvenated by eolian erosion. The target rocks for crater 2 could thus be very old (>2–3 Ga?), since they may come from basal layers of Olympus Mons rather than the lava flows at the present-day surface.

Crater 3: 14.8 km Diameter, 18.5°N, 131.9°W

Best attributes: This crater is found at the summit of Olympus Mons (Figure 5), where it is possible that the low atmospheric pressure may have aided SNC ejection. The crater has a morphology more typical of fresh lunar impact craters than that associated with Martian craters, with swirl deposits on the crater floor and a hummocky ejecta blanket. An asymmetry on the crater rim suggests either a smaller, preexisting crater or a multiple impact event. Owing to its location and low number of superposed impact craters, the target surface appears to be one of the very youngest volcanic units on Mars.

Worst attributes: Like crater 1, this crater has few unusual characteristics when compared to other Martian craters of this size and suffers from the circular crater, single-lava-type, problem.

Crater 4: 13.7 km Diameter, 26.3°N, 98.1°W

Best attributes: This crater formed on the western edge of the volcano Uranius Tholus and may thus have sampled both the surrounding lava plains and the flanks of the volcano (Figure 6). The sharp edges of the rampart lobes on the ejecta blanket, which in places rise up the lower flanks of the volcano, demonstrate the relative youth of the crater. Stratigraphic relationships of the target permit the identification of Uranius Tholus as being older than the surrounding plains, since the basal flanks of the volcano are embayed by the lavas. Although numerous valleys can be seen on the flanks of the volcano [*Reimers and Komar*, 1979], none of these valleys extend onto the lava plains; rather, the lower portions of the valleys appear to be buried by the plains materials.

Worst attributes: Uranius Tholus has a number of fairly large impact craters on its surface, indicating that it is likely to be old compared to the surrounding plains, even though the crater statistics are too poor to draw any firm conclusions. While it seems likely that two different geologic units were sampled, one of these units is almost certainly much older than the other, which is inconsistent with the similarity in ages of the SNCs. Also, this crater suffers from the circular crater problem.

Crater 5: 34.2 x 18.2 km Diameter, 25.2°N, 97.6°W

Best attributes: This crater is the most obvious elongate impact crater on lava flows in the Tharsis region and formed on the northern lower flank of the volcano Ceraunius Tholus

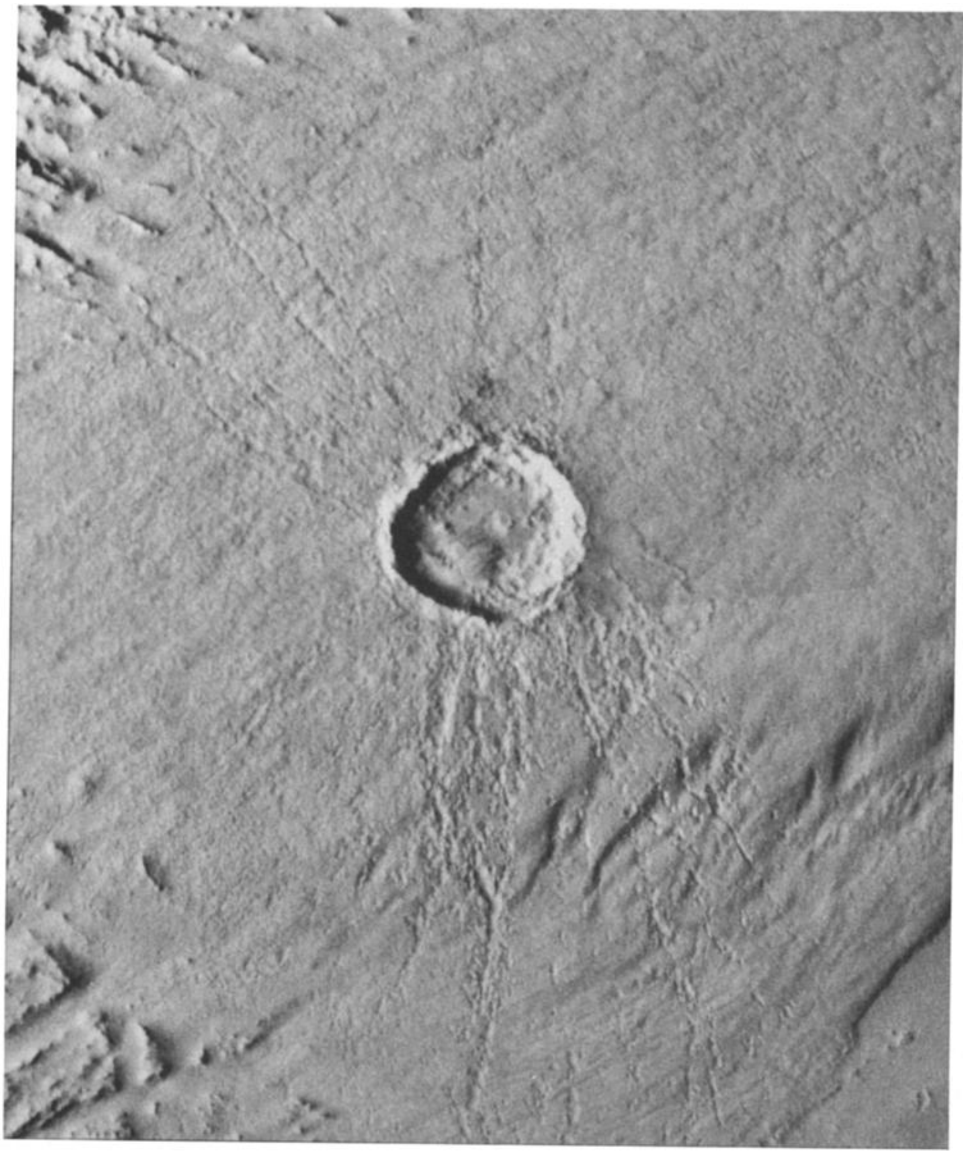

Fig. 4. Crater 2, 29.2 km diameter, located on a segment of the Olympus Mons aureole material. Notice the asymmetric distribution of secondary craters around the crater, which is suggestive of an oblique impact event. Image resolution is 198 m/pixel. This is a composite of Viking Orbiter images 512A45 and 512A46.

(Figure 7). The crater has a prominent butterfly-wing ejecta blanket and well-preserved distal ramparts, and some radial striations can be seen on the ejecta lobes at a resolution of ~200 m/pixel. Parts of the ejecta lobes are emplaced on the lower flank of Ceraunius Tholus, and there is a prominent central ridge in the middle of the crater. As a result of this unusual geometry, this particular crater has been suggested by *Nyquist* [1983] to be a suitable parent crater for the SNCs.

In addition to its unusual geometry, this impact crater probably excavated material from both the flanks of Ceraunius Tholus (perhaps including both extrusives and intrusives) and the surrounding lava plains; it may thus be a good crater for sampling multiple rock types of different ages on Mars, with the possibility that Ceraunius Tholus has an age of 1.3 Ga and the surrounding plains having an age of 180 Ma.

Worst attributes: *Jones* [1985] questioned the relative youth of crater 5, because of the existence of a valley on the northern flank of Ceraunius Tholus that cuts the rim. There is also some material on the floor of the crater that appears to be associated with this valley. While this stratigraphy implies that the crater did not post-date all activity on the volcano, we do not believe that this is sufficient evidence to discount crater 5. The origin of valleys of this type of Martian volcano has been variously attributed to lava flows [*Carr et al.*, 1977], volcanic density currents such as pyroclastic flows [*Reimers and Komar*, 1979], and fluvial erosion [*Mouginis-Mark et al.*, 1982, 1988; *Gulick and Baker*, 1990]. The lack of lava flows and late-stage pyroclastic deposits on Ceraunius Tholus suggests to us that the valley in question is probably fluvial in origin, perhaps initiated by water released as a consequence of the seismic effects of the impact event. No other valleys on Ceraunius Tholus appear to have been active since the surrounding lava plains were emplaced (i.e., all the other channels predate the formation of crater 5). However, we note that other Martian volcanoes that have numerous valleys on their flanks (such

Fig. 5. Crater 3, 14.8 km diameter, which lies close to the summit caldera of Olympus Mons volcano. Note the prominent swirl pattern of material on the floor of this crater, and the ballistically emplaced ejecta blanket. Image resolution is 91 m/pixel. This is Viking Orbiter image 46B13.

as Hecates Tholus [*Mouginis-Mark et al.*, 1982]) may have been volcanically active in the very recent geologic history of Mars, and so late-stage explosive volcanism (with the generation of relatively small pyroclastic flows) may be a characteristic of this type of Martian volcano.

The two implied ages (1.3 Ga for Ceraunius Tholus and 180 Ma for the surrounding plains) also represent problems if crater 5 is the parent crater for the SNCs. *Landheim and Barlow* [1991] interpret the volcano to have formed during the heavy bombardment of Mars about 3.8 x 10^9 years ago, so that the 1.3 Ga age is very young compared to that inferred from the cumulative crater counts. Second, if the plains materials (unit Atm) that embay Ceraunius Tholus are 180 Ma, then many other units within Tharsis such as the younger flows around Ascraeus and Olympus Montes (which both have lower superposed impact crater densities) must have absolute ages of less than 180 Ma. Such an absolute chronology for volcanism in Tharsis is also very different from that inferred from crater counts [*Neukum and Hiller*, 1981].

Crater 6: 33.8 km Diameter, 22.2°N, 98.0°W

Best attributes: Immediately to the south of the volcano Ceraunius Tholus are three craters that have been formed next to each other on a young/medium age target (Figure 7). The largest of these craters (crater 6) is the oldest of the three

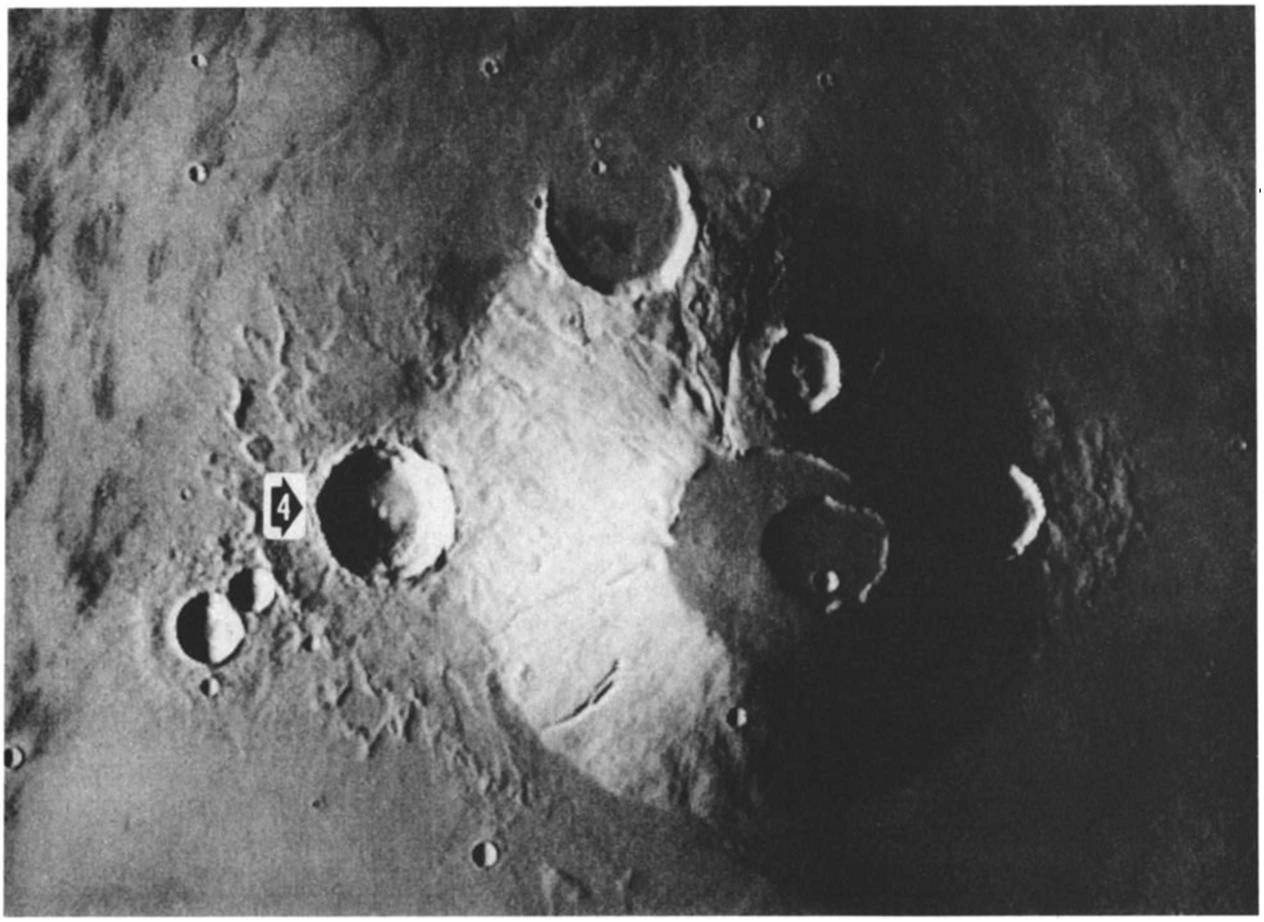

Fig. 6. Crater 4 (arrowed), 13.7 km diameter, formed on the flank of the volcano Uranius Tholus. Image resolution is 200 m/pixel. This is Viking Orbiter image 516A23.

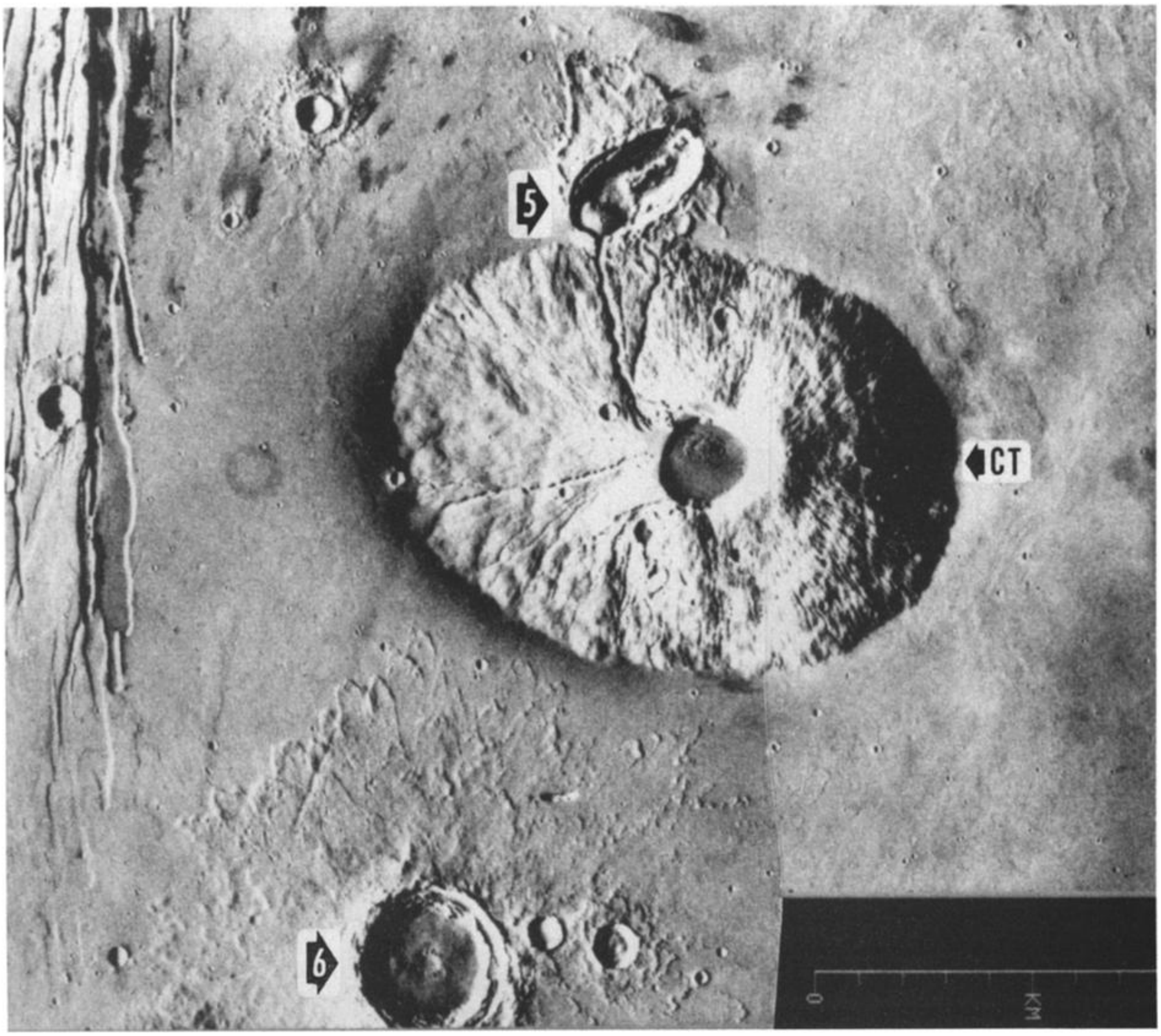

Fig. 7. Crater 5 and crater 6. Crater 5 (34.2 x 18.2 km in diameter) is an elongate impact crater formed on the flanks of the volcano Ceraunius Tholus (arrow labeled "CT"). Note the large channel that originates at the summit of the volcano and cuts the wall of the impact crater, indicating activity (possibly fluvial) on the volcano after the formation of the crater. Crater 6, 33.8 km diameter, is unusual because there are two smaller impact craters superposed on its ejecta blanket ("A" and "B"). Image resolution is 200 m/pixel. This is Viking Orbiter image 516A24.

impact events (based on the superposition of overlapping ejecta blankets) but still possesses a well-preserved lobate ejecta deposit. It has a small central pit rather than a central peak in its interior, and the inner wall has prominent terraces. *Wood et al.* [1978] suggested that central pits may have been produced by the explosive release of subsurface volatiles, making crater 6 somewhat unusual, but fresh craters with central pits are relatively common on Mars [*Wood et al.*, 1978; *Pike*, 1980] so that the formation of a central pit within a crater does not appear to be a likely ejection mechanism. The two smaller craters (7.9 and 10.3 km in diameter) formed in the ejecta blanket of the larger crater, but all three craters are inferred to be young because of the preservation of their ejecta and rim deposits.

Worst attributes: The presence of the two smaller craters on its ejecta blanket implies that crater 6 is not very young. In addition, this crater suffers from the circular crater, single-lava-type problem.

Crater 7: 21.9 km Diameter, 17.8°N, 111.0°W

Best attributes: This crater (Figure 8) is located to the northwest of Ascraeus Mons, just south of Ceraunius Fossae. The crater has a prominent lobate ejecta blanket, a sharp well-defined rim crest, and a small central pit implying that it is a very young crater.

Worst attributes: Most likely, this crater was excavated in a single geological unit and so could not be the source for the petrologically diverse SNCs. The crater suffers from the circular crater, single-lava-type problem.

Crater 8: 18.3 km Diameter, 19.5°N, 99.8°W

Best attributes: This crater (Figure 9) formed to the south of Ceraunius Tholus volcano on the lava flows that extend northeastward from Ascraeus Mons. Its young age is indicated by a well-preserved interior morphology, including a prominent terrace and central pit.

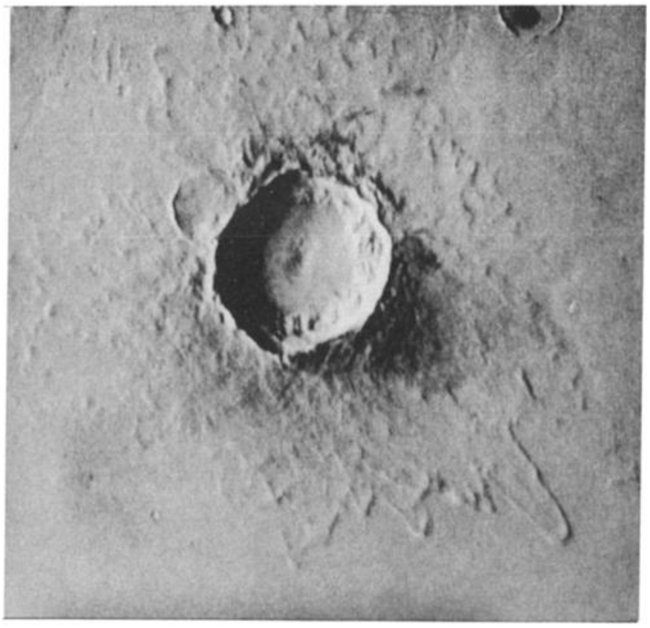

Fig. 8. Crater 7, 21.9 km diameter, located northwest of Ascraeus Mons. This is Viking Orbiter image 516A53.

Fig. 9. Crater 8, 18.3 km diameter, located south of Ceraunius Tholus that formed on lava flows from the northern flanks of Ascraeus Mons. Note the circumferential graben that has cut part of the ejecta blanket. This is Viking Orbiter image 516A45.

Worst attributes: Ejecta on the northern side of the ejecta blanket have been faulted by a circumferential fracture related to Ascraeus Mons, suggesting either recent tectonic deformation of the flank of the volcano or a greater age for the impact crater. In the latter case, this would require tectonic activity to have taken place on Mars since 1.3 Ga. The crater also suffers from the circular crater, single-lava-type problem.

Crater 9: 12.0 km Diameter, 22.7°N, 92.0°W

Best attributes: This crater (Figure 10) formed on the lava plains to the south of the volcano Uranius Patera. At ~250 m/pixel resolution, little detailed information on the morphology of the crater can be gained, although a central pit can be identified.

Worst attributes: Most likely, this crater was excavated in a single geological unit and so could not be the source for the petrologically diverse SNCs. The crater suffers from the circular crater, single-lava-type problem.

DISCUSSION

Number of Potential Parent Craters

One feature that this analysis brings to light is the surprisingly small number of craters which satisfy our constraints for the SNC parent crater. After consideration of the requirements for a large (>10 km diameter), young (i.e., morphologically fresh) crater sampling a young, volcanic terrain, only nine craters satisfy these criteria well. If petrologic diversity is also included as a criterion, six of these nine craters (craters 1, 3, 6, 7, 8, and 9) would also be excluded. Considering the enormous number of craters present on diverse surfaces on Mars, the ability to narrow the number of potential SNC parent crater candidates to these nine (or three) is in itself worthy of note.

A second feature of this analysis is the lack of any craters >100 km in diameter, superposed on young terrain. This size of crater is required in the models of *Vickery and Melosh* [1987], but it is clear that craters of this size simply do not exist on young volcanic regions on Mars. Even if the criteria for identifying a fresh crater (which are necessary to explain the 180 Ma age of the shergottites as either a shock age or crystallization age) are relaxed so that all craters of any degradation state are included in our sample, there are only nine craters (including two that are listed in Table 1)

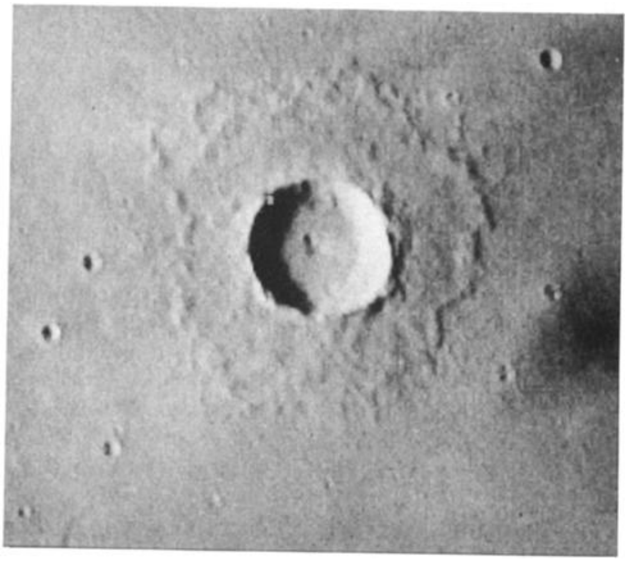

Fig. 10. Crater 9, 12.0 km diameter, south of the volcano Uranius Patera. Note that at an image resolution of 250 m/pixel it is difficult to be confident that this is a very young crater, since texture on the ejecta blanket may be the result of small superposed impact craters that cannot easily be seen. This is Viking Orbiter image 857A48.

that are larger than 30 km in diameter. Only one of these craters, which lies to the north of the volcano Pavonis Mons at 8.5°N, 113.0°W, exceeds 60 km in diameter, and only one other crater is >40 km in diameter. This largest crater has a diameter of 69 km and has had its ejecta blanket extensively modified by the debris aprons on the northern flanks of Pavonis Mons. The rim crest of this crater is still complete, but the removal of the majority of the ejecta lobes (some fragmentary lobes can be seen to the north of the crater) suggests that this crater is older than 180 Ma. In terms of its stratigraphic position relative to other craters listed in Table 1, this crater formed on unit Atm, which is the same geologic unit as that of several other candidate SNC parent craters but is older than than several of the other candidates (Figure 2). It is possible to make the ad hoc assumption that a crater >100 km diameter completely destroyed a young sequence of lava flows in an area that currently shows no morphologic evidence for recent volcanic activity (such as the southern highlands), but the probability of this is so small that we reject this idea. Thus our analysis shows that ejection of material off of the Martian surface has to be achieved during impact events that produce craters significantly smaller than the 100 km threshold proposed by *Vickery and Melosh* [1987].

Which Crater?

We return now to the original question of the parent crater of the SNC meteorites. Although all nine of the most likely candidate craters were initially ranked as having a high probability of being the SNC parent crater, detailed examination suggests that some of these craters are in fact more likely candidates than others. Craters 1, 3, and 7–9 seem to be less likely candidates because they probably sample only one flow unit. Crater 6 offers the potential for ejecting blocks that were originally at depth but that were lying on the surface at the time of impact because they formed part of the ejecta blanket of an earlier crater; however, this geographic setting does not appear to be unique on Mars, and the younger craters superposed on the ejecta blanket are both quite small (~10 km diameter), reducing, we feel, the probability of the ejection of these blocks. This leaves us with craters 2, 4, and 5. Crater 2 formed in a unique geologic setting, on the unconsolidated aureole material of Olympus Mons, and also has an asymmetric ejecta blanket indicative of an oblique impact. Craters 4 and 5 occur on the boundary between the flanks of a volcano and surrounding volcanic plains, consistent with the petrologic diversity of the SNCs. Crater 5, the one originally suggested by *Nyquist* [1983] as the parent crater of the SNCs, has the additional distinction of being highly elongate (probably due to a very oblique impact event), so that an unusual ejection mechanism may be more easily ascribed to this crater. It would be difficult, if not impossible, to unequivocally decide between these craters, and the other six leading craters can certainly not be ruled out. However, these three craters (particularly 2 and 5) have unique features which may explain why they could be the only craters to have delivered to Earth the retrieved Martian samples. On the basis of the reasons stated above, including the uncertainty placed on crater 2 because of the unknown origin of the Olympus Mons aureole material, our preferred choice for the SNC parent crater is crater 5. This choice is consistent with the earlier hypothesis of *Nyquist* [1983]. However, if crater 5 is the SNC parent crater, this places several rigorous constraints on the absolute chronology of Mars (as described above) that are contrary to the chronologies of the area based on the number of superposed impact craters [*Neukum and Hiller*, 1981; *Landheim and Barlow*, 1991].

Shergottite Ages

As mentioned earlier, the crystallization age of the shergottites remains a question of much debate. While the exact age makes little difference in our selection of SNC parent craters, we may be able to use the set of craters selected to constrain the true ages of these rocks. If the crystallization age of the shergottites is really 180 Ma, then the SNC parent crater apparently sampled material that was 180 Ma and 1.3 Ga, with no materials of intermediate age. This of course assumes that all the SNCs were ejected by a single event, which we favor, as discussed above.

Craters 2, 4, and 5 are considered to be the most likely SNC parent craters, and they each sampled at least two distinct lithologies. Crater 2 sampled the Olympus Mons aureole material, which almost certainly comprises a variety of volcanic units that may have been deposited over a long span of time. In this case, it may have been possible for an impact event to randomly sample materials of only 180 Ma and 1.3 Ga, without sampling material of intermediate age.

Craters 4 and 5 each sample two types of material (volcanic plains and the flanks of a volcano) and, potentially, rocks of two different ages. While the exact ages of these surfaces are uncertain, it seems possible that the two surfaces sampled differ in age by 1.1 b.y., even though the young age for the plains unit Atm would assign a very young absolute age to many of the surface units in the Tharsis region.

On the basis of these stratigraphic and absolute chronologies for geologic events on Mars, it seems less likely that the 180 Ma age of the shergottites is the crystallization age. No crater exists to satisfy well the criteria of sampling both a 1.3 Ga surface (nakhlites and Chassigny) and a 180 Ma surface (shergottites) without at the same time imposing significant constraints on the chronology of Mars as inferred from the cumulative crater curves.

Extent of Volcanism

The most intriguing implication of this work is the possibility that volcanic activity has occurred in the recent past within parts of Tharsis other than on Olympus Mons and may even continue until the present. This inference has significant implications for the interpretation of absolute Martian chronologies [e.g., *Neukum and Hiller*, 1981], which would assign ages as old as 3.0 Ga to some of the lava plains in Tharsis. Although crater 1 formed on the youngest units in Tharsis (Figure 2), all the other craters formed on slightly older units. If any of craters 2–9 were the SNC parent crater, volcanic activity continued after the 1.3 Ga crystallization age of the SNCs. For example, craters 4–9 formed on older lava plains (Figure 2), mapped as unit Atm by *Scott et al.* [1981*a*]. Five geologic volcanic units formed after unit Atm, thus implying that volcanic activity occurred on the plains of Tharsis much more recently than 1.3 Ga. If crater 5 is the SNC parent crater, geomorphic activity (in the form of renewed valley formation) must have taken place on Ceraunius Tholus more recently than 1.3 Ga. Since several lava flow units in Tharsis have significantly fewer superposed craters than the target rocks of crater 5, then other areas of Tharsis (such as the lava flows to the south of the summits of Pavonis and Ascraeus Montes and to the south and east of the Olympus Mons escarpment) must be much younger than 1.3 Ga. Recognition of this relative youth for several surface units in Tharsis, based on the age of the SNCs, must therefore be included not only in current interpretations of the relative [e.g., *Barlow*, 1988] and absolute [*Neukum and Hiller*, 1981] crater curves for Mars but also in the thermal models for the evolution of discrete magma sources in Tharsis and the elastic lithosphere of Mars [e.g., *Solomon and Head*, 1990].

CONCLUSIONS

1. Only a few (nine) craters of sufficient size (>10 km diameter) that formed on young terrains in the Tharsis region satisfy the petrologic criteria of the SNCs and the proposed 1.3 Ga crystallization ages of the meteorites and have a pristine morphology that might be expected for a 180 Ma crater. No craters of >100 km diameter exist on young volcanic units on Mars, and only two degraded craters are in the diameter range 40–70 km. This lack of large, fresh impact craters implies that previous theoretical studies of the ejection mechanism for the SNCs need to be reassessed; ejection of material may occur during impact events that form craters a few tens of kilometers in diameter.

2. No crater location can be found where convincing evidence exists for two adjacent geologic surfaces of significantly different ages (180 Ma and 1.3 Ga), while at the same time preserving the general characteristics of cratering chronologies as inferred from the number of superposed craters on different units.

3. Volcanic activity on the plains of the Tharsis region may extend well past 1.3 Ga.

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