



## Martian perched craters and large ejecta volume: Evidence for episodes of deflation in the northern lowlands

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**Abstract**—The northern lowland plains, such as those found in Acidalia and Utopia Planitia, have high percentages of impact craters with fluidized ejecta. In both regions, the analysis of crater geometry from Mars Orbiter Laser Altimeter (MOLA) data has revealed large ejecta volumes, some exceeding the volume of excavation. Moreover, some of the crater cavities and fluidized ejecta blankets of these craters are topographically perched above the surrounding plains. These perched craters are concentrated between 40 and 70°N in the northern plains. The atypical high volumes of the ejecta and the perched craters suggest that the northern lowlands have experienced one or more episodes of resurfacing that involved deposition and erosion. The removal of material, most likely caused by the sublimation of ice in the materials and their subsequent erosion and transport by the wind, is more rapid on the plains than on the ejecta blankets. The thermal inertia difference between the ejecta and the surrounding plains suggests that ejecta, characterized by a lower thermal inertia, protect the underneath terrain from sublimation. This results in a decreased elevation of the plains relative to the ejecta blankets. Sublimation and eolian erosion can be particularly high during periods of high obliquity.

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### INTRODUCTION

Data from the Mars Orbiter Laser Altimeter (MOLA) instrument on board Mars Global Surveyor (MGS) provided a new picture of the topography and morphometry of Martian impact craters. These data allow the study of the geometric characteristics and easier measurements of such crater parameters as depth and ejecta volume. The knowledge of these parameters permits an assessment of formation mechanisms of Martian impact craters and modification processes (i.e., infilling and erosion) that have affected their shapes since their formation. Martian impact craters are commonly surrounded by lobate ejecta morphology that suggests fluidization of the ejecta during its emplacement. This fluidization may have been caused either by entrainment of ejecta in the Martian atmosphere (Schultz and Gault 1979; Schultz 1992) or by the presence of subsurface water or ice (Carr et al. 1977; Gault and Greeley 1978; Mouginiis-Mark 1979; Costard 1989; Barlow and Bradley 1990). Recent observations, such as the discovery of surface ground ice by the neutron spectrometer aboard Mars Odyssey (Boynton

et al. 2002) support the hypothesis that volatiles (water or ice) in the subsurface of Mars are the cause of ejecta fluidization.

The northern lowlands exhibit a concentration of impact craters with fluidized ejecta (Barlow and Bradley 1990; Costard and Kargel 1995), and craters with double-layer ejecta (DLE) morphology are by far the most common (Baratoux et al. 2005; Barlow et al. 2000; Costard 1989, 1994; Barlow and Perez 2003). Costard and Kargel (1995) and Barlow and Perez (2003) have suggested that DLE craters may be formed in areas where the subsurface has a high water content. In addition, a large variety of landforms that suggest the presence of ice in the subsurface, such as polygons and patterned ground (McGill 1985; Lucchitta et al. 1986; Parker et al. 1989; Baker et al. 1991; Kreslavsky and Head 2002a; Head et al. 2003; Mangold et al. 2002; Mangold et al. 2004) and an ice-rich dust mantle (Mustard et al. 2001) (between 30 and 60°), are found poleward of +30°N latitude. These features show that volatiles play an important role in the erosion and resurfacing of the northern lowlands. Moreover, there is considerable evidence for the operation of erosional and depositional processes in this region (Soderblom et al.

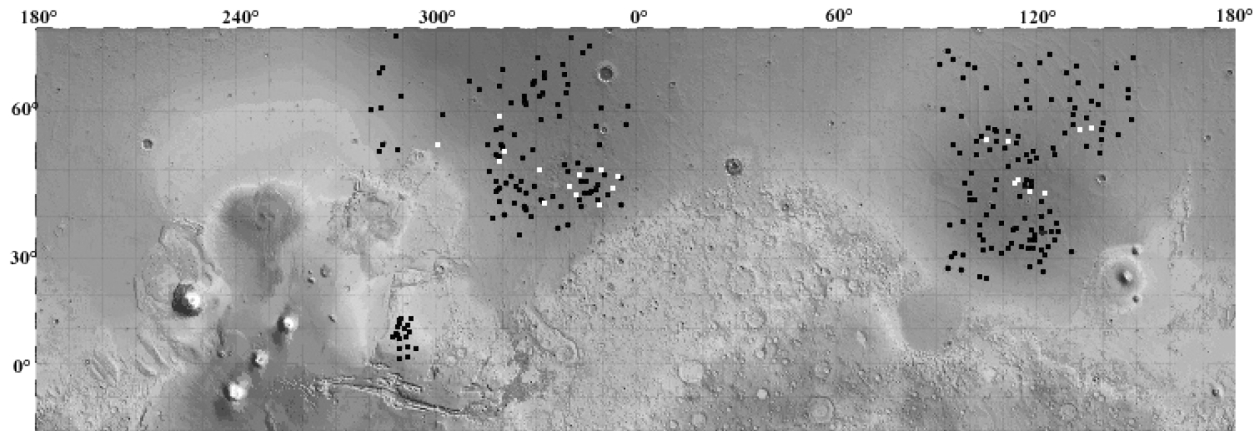


Fig. 1. The location of craters observed in this study. The black points represent the 224 craters studied with the IMPACT program. The white points are perched craters.

1973). Because impact craters form with predictable shapes, changes to those shapes provide an indicator of the type and extent of the process that caused those changes (Garvin and Frawley 1998; Garvin et al. 2000; Boyce et al. 2005). Consequently, a morphometric analysis of impact craters in the northern lowlands provides insight into the degradational history of that region.

In this paper, we focus exclusively on the degradation of craters in the northern lowlands to understand the degradational mechanisms that have operated in this region and their history. In particular, we have used the crater diameter  $D$  and the ejecta volume  $V_{ej}$  as a basis for this study. We have found two principal types of eroded craters in the northern plains: 1) craters that exhibit high  $V_{ej}$  compared to their estimated volume of excavation, and 2) craters called “perched craters” whose morphologic elements (e.g., crater cavity) are topographically above the surrounding terrain (Meresse et al. 2005b). In the next section, we will discuss the evidence provided by these craters for the role of ice sublimation and wind deflation in the development of the northern lowland plains.

## OBSERVATIONS

### Research Areas

There are still many questions concerning the presence and origin of probable volatiles near the surface in the northern lowlands. The existence of large bodies of water during different periods of time on these plains has been previously proposed (McGill 1985; Lucchitta et al. 1986; Parker et al. 1989; Baker et al. 1991; Kreslavsky and Head 2002b; Boyce et al. 2005). Despite uncertainty about the source of water, these authors suggest that bodies of water left a volatile-rich sedimentary residue. The northern lowlands are indeed covered by the distinctive facies of the Late Hesperian Vastitas Borealis Formation (VBF) (Scott and Tanaka 1986; Tanaka

and Scott 1987; Tanaka et al. 2002), a thin sedimentary unit overlying volcanic plains (Head et al. 2002).

In addition, to investigate a subsurface volatile reservoir, many researchers have examined craters with lobate ejecta assuming that fluidized morphology results from impact into subsurface water or ice-rich materials (Gault and Greeley 1978; Mougini-Mark 1979; Costard 1989; Barlow and Bradley 1990; Cave 1993; Barlow and Perez 2003). For example, Mougini-Mark (1979), Costard (1989), and Barlow and Bradley (1990) have suggested that parameters such as the extent of the layered ejecta blankets, defined by the ejecta mobility (EM) ratio, provide information about the concentration of volatiles incorporated into the subsurface. We agree with their suggestion and have extended measurements of layered ejecta blankets into the third dimension to include the volume of their ejecta. In this study, we use altimetric data derived from MOLA digital elevation model (DEM) data and measurement of  $V_{ej}$  of craters to estimate the distribution of subsurface water in the northern lowland plains of Mars.

We have studied two areas in the northern lowland plains, Acidalia Planitia (35–70°N, 300–360°E) and Utopia Planitia (30–60°N, 100–135°E), and one area in Lunae Planum (0–15°N and 285–295°E) (Fig. 1). The two northern lowland regions are located near the mouths of the outflow channels and are largely covered by the Vastitas Borealis Formation. Consequently, these regions are among the most representative of the northern lowlands. Lunae Planum was selected for comparison with the lowland plains test areas because it is thought to be free of subsurface ice (Plescia and Saunders 1980).  $V_{ej}$  has been measured for 224 impact craters, 208 of which are in the northern lowlands ( $D$  ranging from 6 to 47 km) (Meresse et al. 2005a; Boyce et al. 2005), while for comparison 16 craters ( $D$  ranging from 6 to 28 km) (Fig. 1) have been measured in the Lunae Planum region.

The data for the northern lowland plains show a unique type of fluidized ejecta crater distinguished by its small size,

remarkably shallow crater cavity (floor above the surrounding terrain), and a high  $V_{ej}$  that even exceeds the initial volume of the crater cavity. Because of their unique morphology and their implications for the degradational history of the northern lowland plains, we have focused this study on these “perched” craters. Apart from the previous 224 craters measured, we have examined 20 perched craters relatively well preserved among those found in the test areas (Fig. 1). A global search of the MOLA data indicates that this type of crater is most commonly found between 40 and 70°N in the northern plains.

## Methodology

In this study we have measured geometric parameters of craters, such as  $V_{ej}$  and  $D$  of craters in the test areas, using the interactive computer program called IMPACT (Mouginis-Mark et al. 2004) applied to the 1/128th degree MOLA DEM. This program measures Martian crater topography from MOLA DEM data to within  $\sim 10\%$  of topography measured from MOLA profiles for most morphologic parameters, with the exception of rim height, which is much poorer (Boyce, personal communication). The quality of topographic data derived using this program, like most similar programs (e.g., Stewart and Valiant 2006), is mainly limited by the quality of the DEM. For example, the spacing of individual MOLA ground tracks is 1–2 km for the interpolated MOLA DEM and as a result introduces significant measurement errors associated with determining the dimensions of craters and their ejecta smaller than  $\sim 6$  km in diameter (Boyce et al. 2005; Stewart and Valiant 2006). Consequently, to ensure accurate results, only craters larger than 6 km in diameter were used in this study. Moreover, no craters north of 70°N were studied excluding the north polar craterforms and deposits.

## Ejecta Volume

Using IMPACT, we have measured  $D$  and  $V_{ej}$  for the fluidized ejecta of 224 craters selected from the northern plains and Lunae Planum. We have considered without distinction the type of crater, i.e., single-layer ejecta craters or double-layer ejecta craters (Barlow et al. 2000).

The relationship of  $D$  to  $V_{ej}$  is significantly different between Lunae Planum and the northern lowlands (Fig. 3). The observed  $V_{ej}$  for craters in Utopia or Acidalia are commonly greater than those in Lunae Planum (Meresse et al. 2004; Valiant and Stewart 2004; Meresse et al. 2005a). For example, with a crater  $D$  of 15 km,  $V_{ej}$  reaches 394 km<sup>3</sup> in the northern plains compared to only 14 km<sup>3</sup> in Lunae Planum (Fig. 3, black arrows). Head et al. (2002) and Carr and Head (2003) suggest that the substrate of the northern lowlands is similar to the wrinkled ridged materials of Lunae Planum. Consequently, these large discrepancies cannot be related only to differences in the rheology or structural properties of

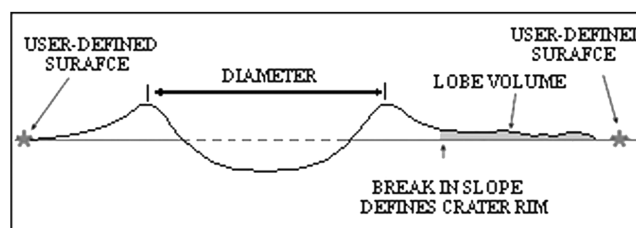


Fig. 2. A diagram showing the parameters measured in this study using the IMPACT program. The “user-defined surface” is the best estimate of the pre-impact surface. Diagram from Mouginis-Mark et al. 2003.

the two terrains (Valiant and Stewart 2004), but instead are most likely related to differences in degradational histories of the two regions.

Moreover, we have compared the measured  $V_{ej}$  with the estimated volume of excavation from the crater cavity from models that predict the relationship of diameter to volume. As a result, excavation volume can be estimated using an equation of the form (Garvin et al. 2000; Melosh 1989)

$$V_{ex} = 0.147D^{2.55} \quad (1)$$

where  $V_{ex}$  is the volume excavation and  $D$  is the rim-crest diameter in kilometers assuming that the diameter of each crater experienced little change since its formation. The ratio of measured ejecta volume to estimated excavation volume ( $V_{ej}/V_{ex}$ ) is expected to be nearly 1 for unmodified fresh craters (ignoring bulking of the ejecta).

Figure 4 is a plot of  $V_{ej}/V_{ex}$  for the 224 craters in the test areas and shows that 1) the  $V_{ej}/V_{ex}$  ratio is always  $< 0.5$  for the craters of Lunae Planum, and 2)  $V_{ej}/V_{ex}$  values for craters in the northern lowland plains exhibit a range of values with some as high as 2.8. In Lunae Planum, the low  $V_{ej}/V_{ex}$  values most likely reflect erosion of the ejecta blanket after crater formation. In the lowlands, the majority of craters have  $V_{ej}/V_{ex}$  values similar to those in Lunae Planum, also suggesting that Utopia and Acidalia craters have undergone erosion. However, about 40 craters also located in the northern lowlands have  $V_{ej}/V_{ex}$  ratios greater than 1. We suggest that the high  $V_{ej}/V_{ex}$  ratios in the northern plains are the result of postimpact modification of the region.

## Perched Craters

Among the different morphologies of craters with lobate ejecta found in the northern lowlands (e.g., SLE or DLE morphology) (Barlow et al. 2000), we have identified an additional type of impact crater (i.e., perched craters). The morphologic nature of perched craters is clearly different from fresh craters (Meresse et al. 2005b), with all the topographic elements of perched crater well above the preexisting surface, even including the floor of the crater cavity. For example, the perched crater in Fig. 6c appears to have undergone a filling up

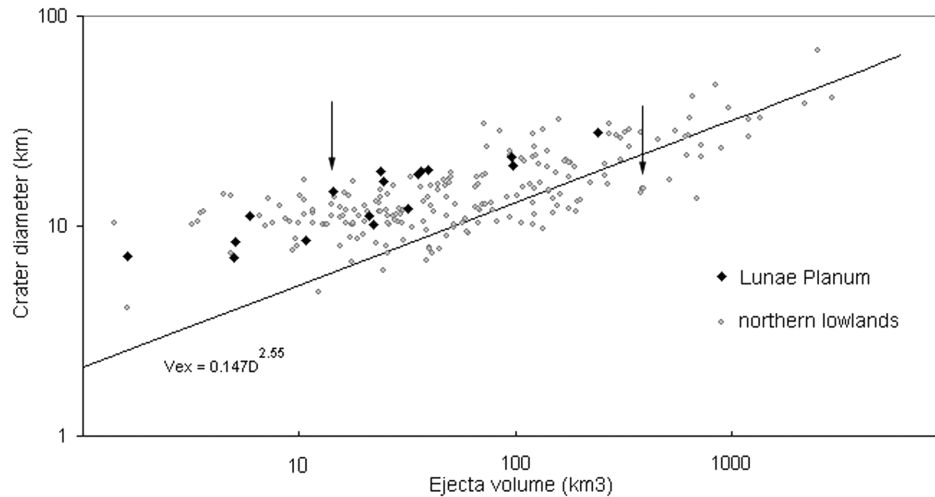


Fig. 3. A logarithmic diagram of ejecta volume versus crater diameter for Lunae Planum and Utopia/Acidalia Planitia. We can see relatively low ejecta-blanket volume for craters in Lunae Planum and a considerable range in the volumes of ejecta of craters in the northern lowlands. The black arrows illustrate the notable difference of ejecta volume observed for a crater of the same diameter in Lunae Planum and the northern lowlands. The black line is a model line that represents where the excavation volume for a given crater diameter equals its ejecta volume. The craters under the line have ejecta volume higher than the volume of their crater cavity.

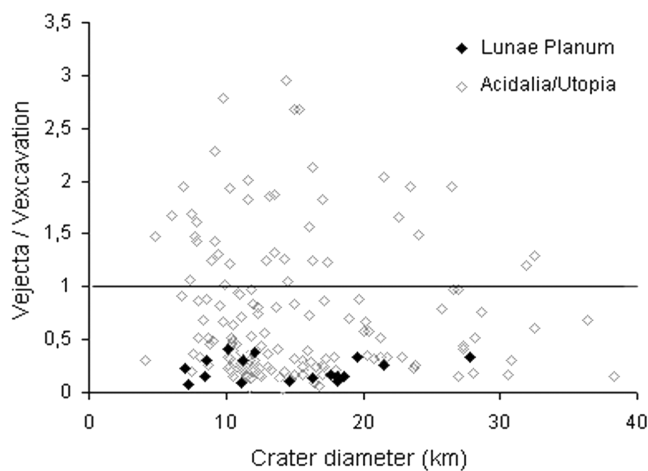


Fig. 4. A scatter plot of the measured ejecta volume plotted against the calculated excavation volume ratio for the craters observed in the northern lowlands and Lunae Planum. The ratio is always smaller than 0.5 for Lunae Planum. The craters with a ratio higher than 1 have excess ejecta volumes.

of its interior by over a hundred meters of material, elevating its floor  $\sim 70$  m above the surrounding surface. All 20 craters studied have diameters between 2.8 and 9.6 km (Fig. 5), so measurements by the IMPACT program is not possible. Furthermore, THEMIS images show that the ejecta blankets and the rim crests are often eroded with deposits on the floors of the cavities and sometimes concentric crater-fill confined within the crater rim (Fig. 7a).

Moreover, perched craters have the same morphology as the type 3 craters described by Boyce et al. (2005) and include all craters whose floors are at or above the elevation of the surrounding terrain. Boyce et al. (2005) have found them

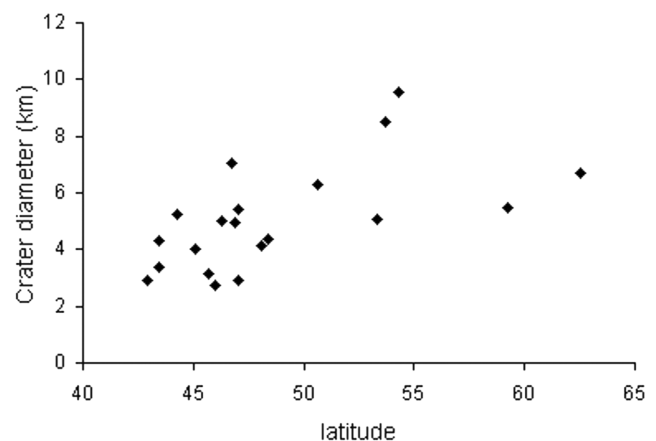


Fig. 5. Latitudes and diameters of the perched craters studied.

mainly north of  $\sim 40^\circ\text{N}$  and below  $-2400$  m, which is in agreement with our observations.

It should also be kept in mind that perched craters and pedestal craters are two distinct morphologic types, although they are sometimes lumped into the same morphologic class. While both are topographically perched (Barlow et al. 2000), only perched craters display DLE morphology (Figs. 6, 7b, and 7d), and have distinctive depth  $d$  versus diameter  $D$  values that are nearly constant whatever the diameter of the crater (Boyce et al. 2005).

We have observed a progression in the degradational state of the perched craters, with the rims and ejecta of some perched craters eroded down to remnants in the shape of cones (Figs. 8b and 8c). Previously, the most modified of these craterforms have been described as volcanic features such as cinder cones (Squyres et al. 1992) or pseudocraters/

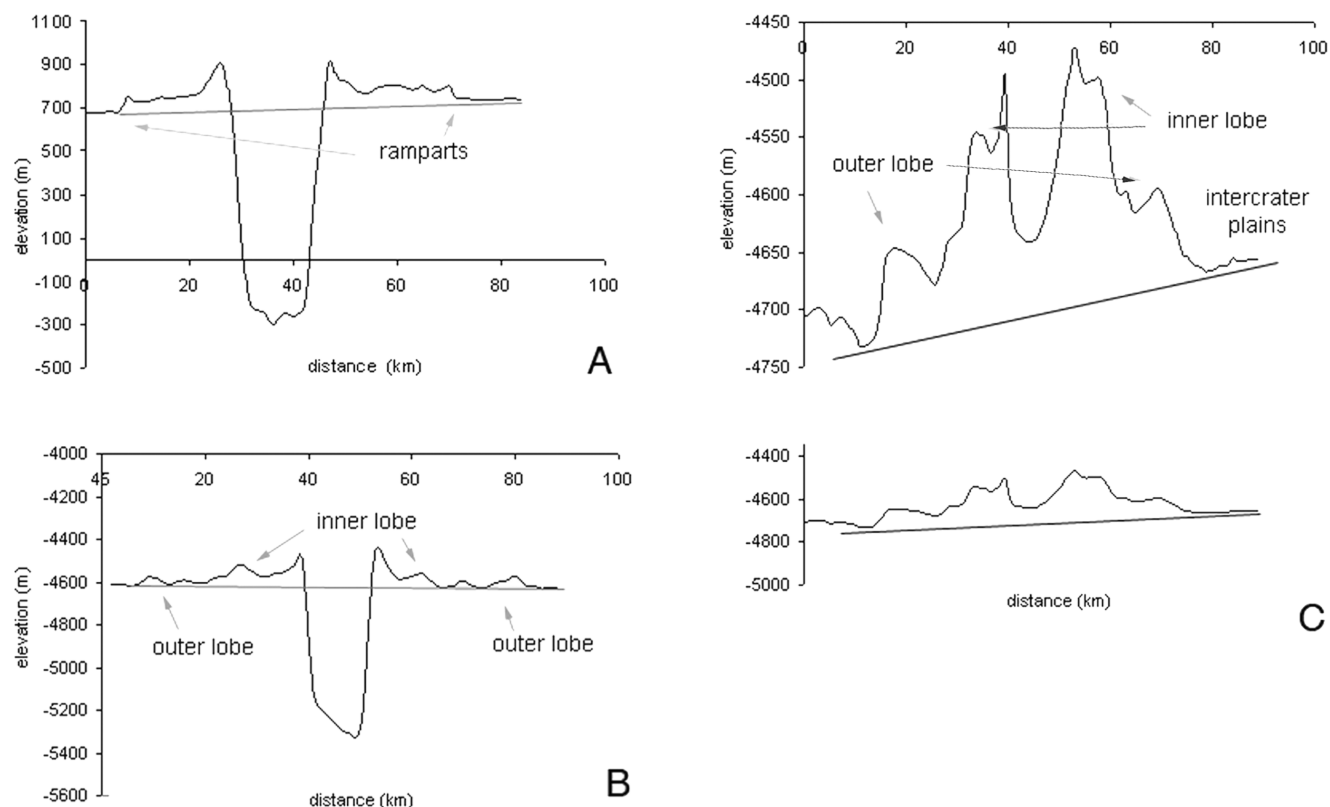


Fig. 6. MOLA cross-sections of three equivalently sized craters ( $D$  between 10 and 15 km). a) An SLE crater in Lunae Planum. b) A DLE crater in Utopia Planitia that is not classified as “high ejecta volume.” c) A perched crater with DLE morphology in Utopia Planitia. The profile at the bottom is reduced at the same scale as (a) and (b). The dark line is the surface used in the ejecta volume measurements. Note that the ramparts at the end of the perched ejecta blanket are very pronounced.

rootless cones (Frey et al. 1979; Frey and Jarosewich 1982; Fagents et al. 2002). Indeed, a field of conical mounds was identified in eastern Acidalia, Utopia, and Isidis, and the mounds were interpreted as pseudocraters resulting from the interaction of lava with surface or near-surface ice (Frey et al. 1979; Frey and Jarosewich 1982) or rootless cones (Fagents et al. 2002). However, we believe that there are major differences between perched craters and volcanic (and ice) features such as cinder cones or pseudocraters. First, perched craters are significantly larger than pseudocraters. The largest pseudocrater cone is <1 km in diameter (with a typical size of 100–700 m) (Frey and Jarosewich 1982; Fagents et al. 2002), while perched crater diameters are principally in the 1–10 km range. Second, the vestiges of distal rampart and DLE morphology around the less-degraded cavities of perched craters (Figs. 8a and 8c) indicate that they are eroded DLE impact craters. Third, perched craters have a random distribution and are not organized into groups like pseudocraters, which tend to be aligned (Squyres et al. 1992) and are concentrated in a zone of magmatic activity. Consequently, perched craters are eroded impact craters that have been subjected to a degradational history that has resulted in lowering of the surrounding terrain around them relative to their ejecta and crater cavity.

To describe the formation of perched craters, we must consider both the cavity-filling event and the events that preserved the ejecta but eroded the intercrater plains. We must also take into account the erosional episode that modified and eroded the ejecta blankets subsequent to the formation of a perched crater.

### Thermal Properties

Diurnal temperature variations at the surface of Mars are regulated by thermal inertia that represents the subsurface ability to store heat during the day and reradiate it during the night (Mellon et al. 2000; Mellon 2001; Putzig et al. 2005) and are in part controlled by grain size (and porosity) on the surface. We used the brightness temperature to compare thermal properties of perched ejecta with the surrounding terrain. The values were gathered from the brightness temperature file provided at the THEMIS web site. The brightness temperature is estimated from band 9. It is the temperature of a black body emitting the same power as the radiance measured with THEMIS for a given surface. The radiance of a body depends on its temperature and on its emissivity. Thus, the actual variations of brightness temperatures can be partially due to variations of emissivity

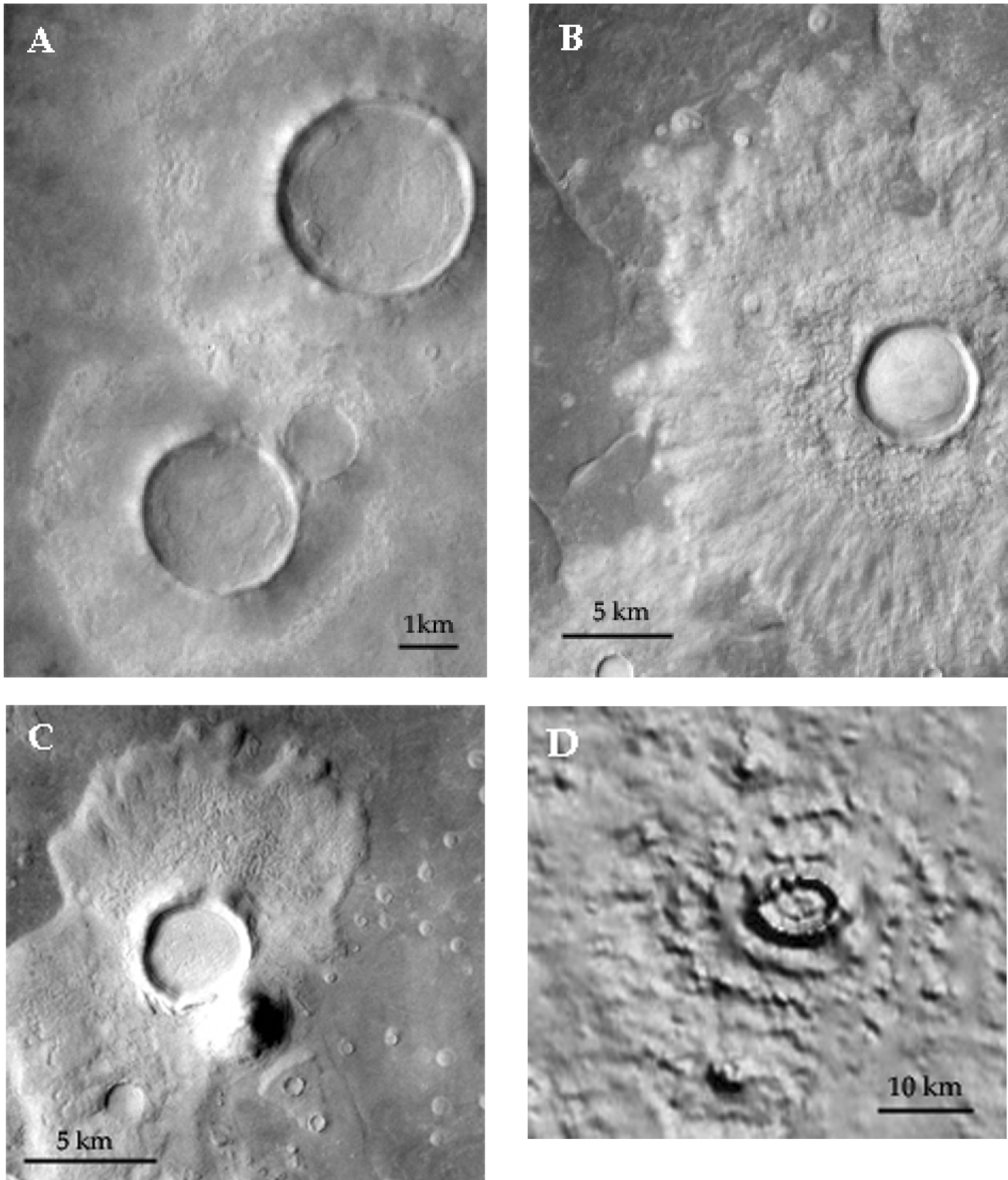


Fig. 7. a) Perched craters located in the Utopia basin ( $55^{\circ}\text{N}$ ,  $130^{\circ}\text{E}$ ). THEMIS image V03753003. Note the near-complete filling of the cavities and traces of concentric crater-fill. b) THEMIS image V03059003 of a perched crater located in Utopia Planitia ( $44.5^{\circ}\text{N}$ ,  $58.5^{\circ}\text{E}$ ). The DLE morphology of these craters is clearly shown. c) A perched crater in Acidalia Planitia ( $46.5^{\circ}\text{N}$ ,  $6.8^{\circ}\text{E}$ ). The high-relief boundaries of the ejecta blanket are very pronounced, suggesting the intercraters' terrains have been degraded relative to the ejecta surface. d) A MOLA shaded relief image of a perched crater with DLE morphology located in Utopia Planitia.

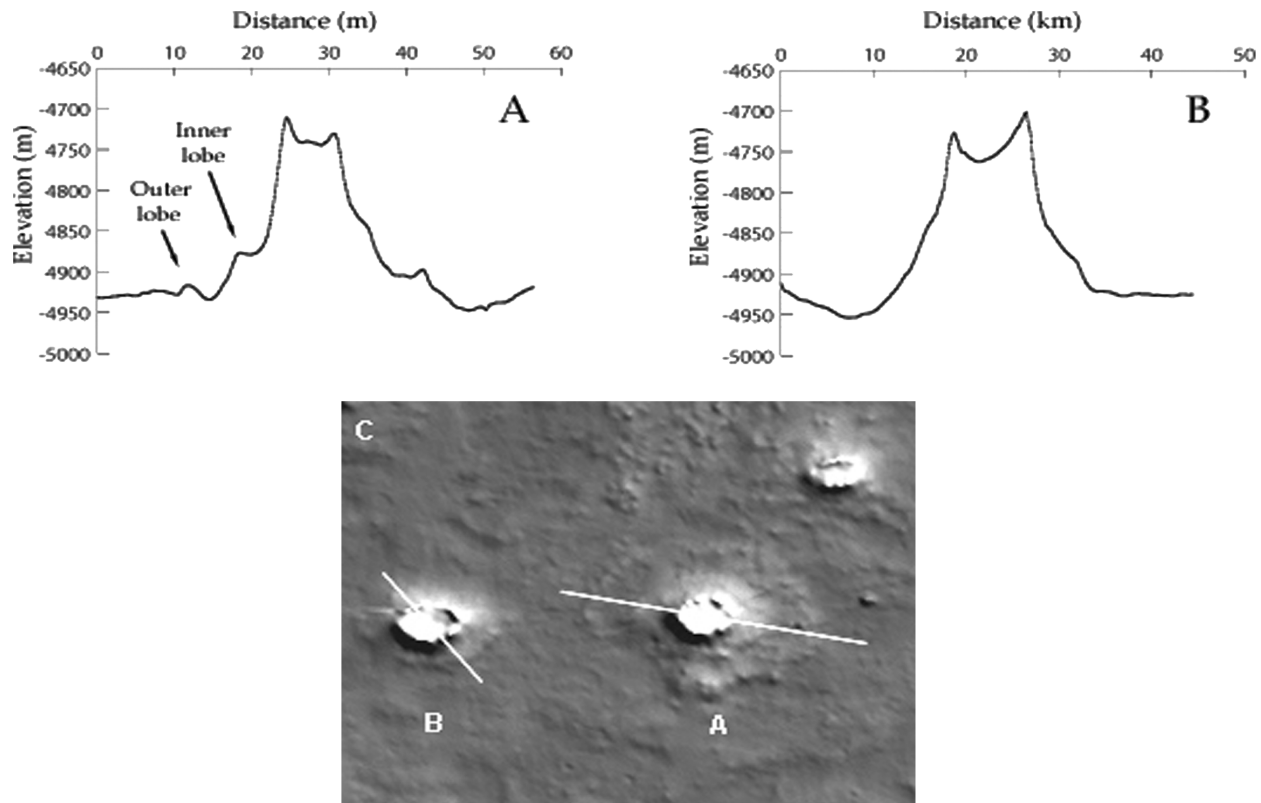


Fig. 8. MOLA shaded relief image (c) of two perched craters surrounded by small, presumably deeply eroded ejecta deposits. Crater A shows vestiges of DLE morphology, including a distal rampart surrounding each layer (black arrows). In the MOLA cross-section, the ejecta blanket of perched crater B appears to be almost completely eroded away. The image is centered at 48.2°N, 114.5°E in Utopia Planitia.

between two types of terrain. However, the observed variations of radiance between the ejecta deposits and the surrounding plains are large compared to possible emissivity variations between rocks of different mineralogical composition. Moreover, the mineralogical composition of the material is expected to be similar between the ejecta and the surrounding terrain since ejecta incorporate a large fraction of near-surface material during their surface flow. Thus, we think that differences in brightness temperature reflect significant differences in surface temperature, and thus differences in thermophysical properties.

At night, the ejecta deposits are darker than the surrounding terrain (Fig. 9a), indicating the relatively lower temperatures of the craters. During the day, the temperature differences are less striking (Fig. 9b), but daytime temperatures are more affected by albedos and local topography and as a result are more difficult to interpret in terms of relative variations of thermal inertia. For each THEMIS image analyzed, we have determined the temperature of an ejecta point and an intercrater plains point. The temperature of each crater and the surrounding intercrater plains are measured both during the day and at night. Figure 10 shows that two distinct clusters of data reveal a major difference in thermal properties between the ejecta and

the surrounding plains. The scattering of the average temperatures is lower than the difference of temperature between night and day, showing that the seasonal effects can be neglected compared to the diurnal effects. The variations of diurnal temperatures are greater for the ejecta suggesting their lower thermal inertia.

Thermal inertia variations are often related to grain-size variations (Mellon et al. 2000; Mellon 2001; Putzig et al. 2005). Indeed, this property of the surface is actually controlled by porosity. The size of the pores of any geological material is influenced by grain size, but may also be affected by processes such as cementation or induration that makes thermal bonds between the grains. Acidalia Planitia has an intermediate-to-high thermal inertia ( $300 \pm 100 \text{ Jm}^{-2}\text{K}^{-1}\text{S}^{-1/2}$ ) consistent with surfaces of coarse and/or indurated material (Putzig et al. 2005). The lower thermal inertia on the ejecta could result from different grain sizes or different degrees of induration and porosity. Fine-grained soil conducts heat less efficiently, resulting in lower thermal inertia. In the same way, induration or cementing of soil grains can dramatically increase thermal conductivity, and therefore thermal inertia (Mellon 2001). The low thermal inertia on the ejecta may imply either the existence of a superficial insulating layer (of a few centimeters) which can protect the terrain underneath

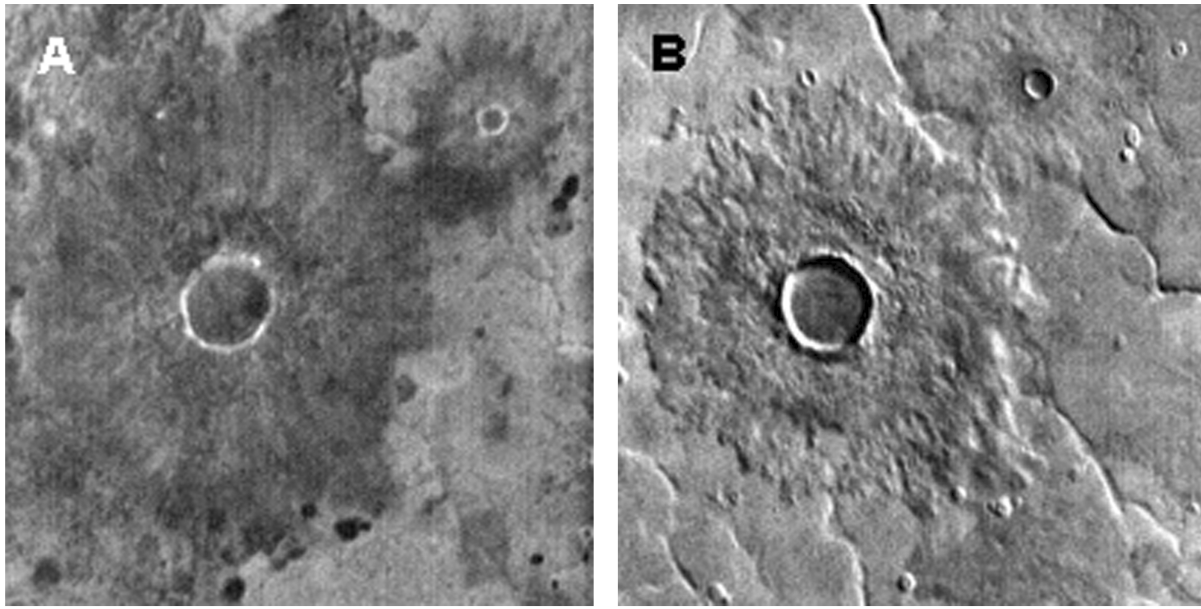


Fig. 9. a) A THEMIS brightness temperature image of a perched crater in Acidalia Planitia (44.3°N, 342.0°E). The ejecta are darker and so colder than the surrounding terrain. Image I05175017. b) A corresponding daytime image (I03059002).

from high temperature variations and slow down a phenomenon such as sublimation, or a relatively high degree of fragmentation of the ejecta themselves. In the first case, this layer might be produced by dust trapped on the ejecta blanket as a result of the high surface roughness of ejecta blankets. This roughness is then a good protection against the wind erosion, and fine materials can remain there over geologically long periods of time. In the second case, ejecta formation can result in a greater proportion of fine material rather than coarse, compared to the northern plains' materials that are not modified by impacts. The ejecta blankets could be composed mainly of fine-grained materials that are slightly larger than the size of particles which can be removed by the wind. At the same time, the northern plains are generally surfaced by the VBF that is cemented by ice (resulting in lower porosity), and their surface appears to have higher thermal inertia than the ejecta blankets. Consequently, ice is expected to be more stable below the ejecta than below the intercraters' plains.

#### DISCUSSION: THE NORTHERN LOWLANDS RESURFACING

The craters studied in the northern plains, and particularly the perched craters, provide important information about the evolution of the surface and modifications of the region. The atypically high ejecta volumes of the northern lowland craters and the elevation of their ejecta and cavities suggest that the northern lowlands have experienced one or more episodes of resurfacing involving deposition and erosion.

#### Crater Infilling Process

THEMIS images of perched craters show deposits on their floors that easily account for their shallowness. The most reasonable origin of this crater infilling is from wind and volatile action. The concentric crater fill (Squyres 1979) visible in some craters (Fig. 7) can be interpreted as resulting from compressive stresses generated by inward flow of ice-rich material from the craters' walls (Squyres et al. 1992). The ice may come from the equatorward extension of stable surface ice deposited during a higher obliquity phase (Mischna et al. 2003). Calculations of the Martian obliquity suggest that it varies chaotically between 0 and 60° (Laskar et al. 2004; Jakosky et al. 1995) on time scales longer than  $10^7$  years. At 35° obliquity, ice is stable in the high mid-latitudes (Mischna et al. 2003) and probably extended to even lower latitudes as suggested by the observation of disaggregating ice-cemented dust in the 30–70°N latitude range (Mustard et al. 2001). The VBF may also have contributed to the crater infilling (Kreslavsky and Head 2002b; Head et al. 2002). The transport of sediment and infilling of craters may have also occurred through eolian activity (Zimelman et al. 1989) that tends to fill crater cavities at a characteristic constant rate (Forsberg-Taylor et al. 2004).

#### Erosional Process

We suggest that the nature of the processes that eroded and removed materials from the northern lowland plains region is responsible for the unusual ejecta volumes and for

the morphology of perched craters. In particular, material around the ejecta blankets may have been selectively eroded and removed, decreasing the elevation of the preexisting surface relative to the ejecta blankets. This decrease in surface elevation is most likely caused by cryokarstic process, like sublimation of ice that may affect the surrounding terrain more than the materials that make up the ejecta blankets. Numerous authors have presented arguments for ice-related erosion of surface materials in this region based on the morphology of the VBF (e.g., Costard and Kargel 1995; Mustard et al. 2001; Kreslavsky and Head 2002b; Head et al. 2002, Costard et al. 2002; Carr and Head 2003; and Boyce et al. 2005) and consequently, it is reasonable to expect that the surface conditions that produced erosion of the VBF must also modify the craters in the same region. This is consistent with the coincidental occurrence of perched craters and VBF in the same region and the occurrence of craters with high ejecta volumes only in the lowland plains where abundant ice is expected. The rate and latitudinal dependence of the sublimation in the VBF is probably amplified during the high obliquities of the planet, which increase the temperature at the high latitude. While under current climatic conditions sublimation cannot occur on northern lowland plains at any seasons, orbital parameters such as eccentricity and obliquity that control insolation and climate at the surface of Mars most likely have changed over time (Laskar et al. 2004).

Eolian activity has also affected the surface of the lowland plains. The wind is indeed a powerful agent of deposition, erosion, and transportation of debris. This is especially true in the northern lowlands where eolian landforms such as dunes and rock outcrops are common (Greeley and Iversen 1987; Armstrong and Leovy 2005) and attest to the erosive power of the wind. Many authors have noted the importance of global-scale topography to eolian activity, suggesting that low regions where the atmospheric density is relatively high (e.g., the northern lowlands) may be a source of dust injection into the Martian atmosphere (Sagan and Bagnold 1975; Armstrong and Leovy 2005). In these places, the wind may excavate the surface causing increased erosion that further removes material (Armstrong and Leovy 2005). Indeed, in low regions of Mars such as in the northern lowland plains, eolian activity would be the dominant mechanism for removal of fines deposits. Moreover, changing orbital conditions influence the rate of wind deflation (Armstrong and Leovy 2005).

The excess material in the ejecta blankets of nonperched and perched craters suggests removal of the volatile-rich materials surrounding the craters (Meresse et al. 2005b; Black and Stewart 2005). Using the cross-sections in Figs. 6b and 6c, we can estimate the minimal thickness of sediment removed by comparing the elevation of the surrounding terrain with that of the average elevation of the surface of the ejecta blanket for the perched and normal (not high ejecta volume) craters. We find that the outer ejecta layer is

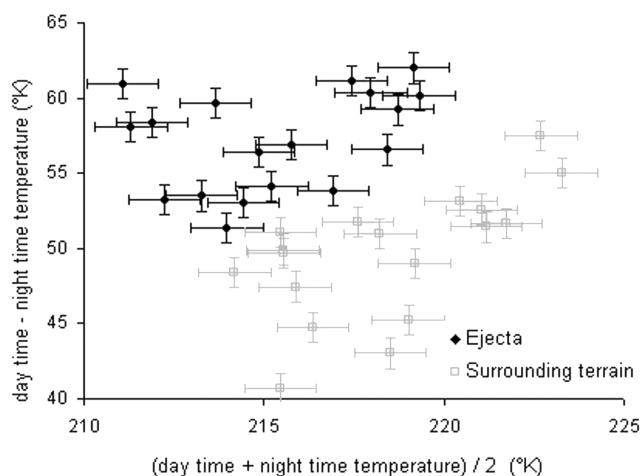


Fig. 10. A scatter diagram showing variations in the average brightness temperature of the ejecta of craters studied and the surrounding terrain. The errors bars represent the temperature difference between two adjacent pixels. The thermal properties of ejecta material are clearly distinct from the thermal properties of the intercraters' plains.

~60–80 m thick for the perched crater and 25–60 m for the normal crater, and the inner ejecta thickness is ~150–200 m for the perched crater and 60–100 m for the normal crater. This would suggest that ~35–140 meters of material has been removed from the terrain around the perched crater compared with the normal DLE crater of equivalent size in Utopia Planitia. The fines removed by this erosion would most likely accumulate in the equatorial regions and far polar regions (Armstrong and Leovy 2005) with the incorporation of sediments into polar ice (Tanaka 2005).

### Proposed Model

Figure 11 summarizes the resurfacing mechanisms and the evolution of the crater morphologies in the northern plains. We suggest that the sublimation of ground ice in the northern lowland plains combined with wind deflation is responsible for both the apparent high ejecta volumes and for the perched craters. Most of the loss of ice occurs during the warmest periods, which may subject materials in the northern lowlands to seasonal mechanical and thermal weathering. As with materials on Earth, such weathering tend to weaken and disaggregate the near-surface materials of the plains, which are exposed to temperature variations. As a result, these weak, disaggregated materials can be removed by the wind and the surface deflated. On the other hand, the ejecta deposits may be protected from thermal erosion and consequently erode slower than the surrounding plains. This protection can be provided by a thin layer of fine-grained material formed by dust capture and accumulation on the ejecta. It can also be linked to the nature of the ejecta which might be composed of preferential fine material. This results in the formation of

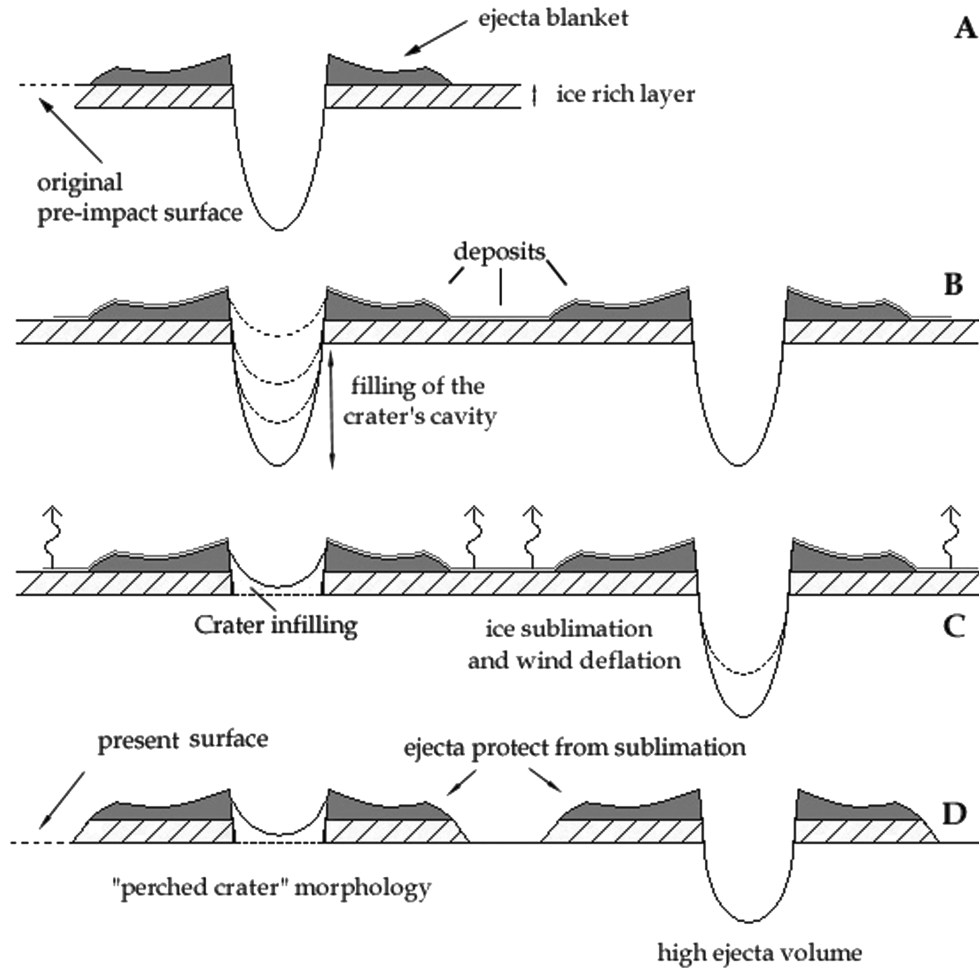


Fig. 11. Synthetic sketch of the proposed model for resurfacing in the northern lowland plains that produced perched craters. a) First is the formation of an impact crater with lobate ejecta in ice-rich ground. b) Second is the formation of a larger impact crater (on the right) and filling of the first crater. The ejecta are also covered by deposits but clearly less than in the cavity. c) Third, ejecta are protected from efficient sublimation and consequent wind deflation. Wind deflation occurs on the intercraters' plains but also on the ejecta. d) Fourth is the erosion of material around the ejecta at a lower rate than removal of materials from the surrounding surface: creation of the perched crater morphology. When the crater diameters are larger than 10 km, the cavities are rarely entirely filled and we only observe craters with high ejecta volume.

perched craters or craters with high ejecta volumes (Fig. 11). As these processes occur, the interiors of the perched craters, like all craters in the region, slowly fill with eolian debris resulting in a nearly complete filling of the smallest craters (<~10 km diameter).

## CONCLUSIONS

The measurements of the ejecta volume have revealed anomalies in the northern lowlands involving postimpact modifications. These data provide evidence that the northern lowlands have experienced one or more episodes of resurfacing requiring the presence of near-surface volatiles and the action of the wind. The resurfacing occurred in the following steps: 1) filling of the crater's cavity, which probably occurred during the entire process, 2) thermal erosion (i.e., weakening and disaggregation of surface

materials caused by sublimation of ice) of the surface materials in the northern plains, but the ejecta blankets are protected from such erosion because of the low thermal inertia of their surfaces, 3) transportation and removal of the fines produced by sublimation and resulting eolian deflation of the plains, and 4) slow eolian erosion of the ejecta. The reason for the low thermal inertia of craters in the northern plains has to be investigated further. We proposed two alternative hypotheses. The impact process results in subsurface material fragmentation and may result in ejecta deposits composed of low-inertia, fine particles. Ejecta also represent a rough surface and may be considered an efficient trap for atmospheric dust. A layer of dust a few centimeters thick can insulate the subsurface material and protect it from erosion. Consequently, the unique morphologies of perched craters result from the differences in rates of erosion between the ejecta and the intercraters plains.

Future experiments such as modeling of sublimation and improved thermal inertia measurements could provide more information about the nature of the ejecta. A global study of the northern plains could also permit an assessment of the total volume of sediment removed.

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