Evidence from the Mars Express High Resolution Stereo Camera for a frozen sea close to Mars' equator

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It is thought that the Cerberus Fossae fissures on Mars were the source of both lava and water floods[1,2–4] two to ten million years ago[1,2,5]. Evidence for the resulting lava plains has been identified in eastern Elysium[1,2,4,6–8], but seas and lakes from these fissures and previous water flooding events were presumed to have evaporated and sublimed away[9–11]. Here we present High Resolution Stereo Camera images from the European Space Agency Mars Express spacecraft that indicate that such lakes may still exist. We infer that the evidence is consistent with a frozen body of water, with surface pack-ice, around 5° north latitude and 150° east longitude in southern Elysium. The frozen lake measures about 800 × 900 km in lateral extent and may be up to 45 metres deep—similar in size and depth to the North Sea. From crater counts, we determined its age to be 5 ± 2 million years old. If our interpretation is confirmed, this is a place that might preserve evidence of primitive life, if it has ever developed on Mars.

Extensive fields of large fractured plate-like features on a horizontal surface are visible near the south end of the High Resolution Stereo Camera (HRSC) imaging strip taken on 19 January 2004 (Fig. 1). This area has previously been covered by NASA high-resolution Mars Orbiter Camera (MOC) imagery at pixel sizes down to 1.8 m (Fig. 2). The latter images show fractured plates at a smaller scale. Individual plates are of all sizes from 30 m up to >30 km, with clear signs of break-up, rotation (Fig. 1c) and horizontal drift for distances of several kilometres. The plates show characteristic differences from plate-like features elsewhere on Mars and in the east of Elysium Planitia. The latter features have been interpreted to be rafts of solidified lava floating on the surface of large flood basalts[6], but several observations indicate that this cannot be the case in this area.

Surface ages were determined[12,13] from the size-frequency distribution of 66 impact craters on HRSC images, which suggest a resurfacing event about 5 million years (Myr) ago. Counts of 268 craters on MOC images show that the plates are older than the brighter inter-plate areas (Fig. 3). The statistical errors of the two data sets (counts on plates and inter-plate areas) indicate that they are almost coincident in age, but the whole inter-plate size-frequency distribution falls consistently below that for the plates. This is an indication that the inter-plate areas are really younger than the plates, but within the error limits the age difference could be from a few hundred thousand years up to 2 Myr, with a most likely value of 1 Myr. This age difference is independent of any systematic error in the cratering chronology model used[12,13]. Basalt lava flows 50 m deep can remain partially molten at the centre for only about 5 yr (ref. 14), so these plates cannot be the result of surges and break-outs of lava carrying previously solidified crust, as occurred over timescales of a week or so during the 1783–84 Laki Fissure eruption, Iceland, which is the closest terrestrial analogue to martian flood lavas[6].

Lava break-outs entail build-up and failure of inflating lava to create the plate-like morphology[6], but there are no signs of the inflation that occurs on terrestrial basalts and in other areas of Mars. The Mars Orbiting Laser Altimeter (MOLA) topographic profiles across the area show a remarkably flat surface with broad topography varying by <5 m over more than 60 km, that is, a slope of <0.005°. This compares to a slope of about 0.2° for terrestrial flood basalts.

Furthermore, a drop in surface level occurred after flooding of 18 to 85 m (equivalent to about 9% to 16% of the depth before flooding) within flooded impact craters (Fig. 4). If this had been lava, such a drop would be impossible in these ponded enclosures, because thermal contraction of ponded lava would amount to less than 1% (ref. 15).

Other features in the HRSC image show unique features that provide a clue to their origin. Where the plates have drifted into obstacles, straight or curved lanes have formed downstream within the plates themselves ('L' and 'I' in Fig. 1c). These are not found within lava rafts. Also, the plates are one to two orders of magnitude larger than the largest-known terrestrial basalt rafts. Both these observations, together with the horizontal surface (<0.005°, corresponding to terrestrial tidal sea surface slopes in some estuarine situations) imply an extremely mobile fluid, with characteristics similar to those of water.

Other observations indicate the strong resemblance of these plates to pack-ice. Where pre-existing small topographic highs protrude through the plates to form islands, plate drift has caused rubble piles with pressure ridges on the upstream side (Figs 1c and 2a). Where the highs are craters, these ridges show a superficial resemblance to fluidized ejecta, but unlike the latter, the ridges are subconcentric to the rim and form on one side of the crater only (always the upstream side), show no lobate overlaps or signs of radial movement, have up to 20 subparallel ridges instead of one to three, and show no broad smoother areas proximal to the crater that indicate ejecta flow. Figure 2a shows pressure ridges (denoted 'R') within the rubble pile on the right with wavelengths between 10 and 70 m, which appear to have extended outward from the crater edge as the liquid level dropped and the frozen surface was grounded progressively further down the outer slopes of the crater. These are strikingly similar to rubble piles of sea ice that form around islands in the Arctic and Antarctic (Fig. 2b). The sagging and consequent surface cracking 'C' within the crater itself as the level dropped are also visible. One plate 'F' has drifted into the crater when the level was higher through the gap in the rim 'G', but then become grounded in its present position as the surface lowered, draping it over the northeast rim.

These craters and islands have acted in a similar manner to ice-breakers as the plates drifted past them, leaving straight or curved leads downstream with uniform width (Fig. 1c). The high-resolution MOC image in Fig. 2a shows that these lanes are still very smooth at the 10-m scale, as are similar features in pack-ice on Earth. In places the plates have moved in channels between zones of more stable ice, and overall the direction of drift is towards the west or southwest.

Combinations of processes are unlikely, and have no terrestrial counterparts. Lava plates rafted on mud are not possible because basalt has a density >70% greater than mud. Lava on ice would create pseudocraters, melting and consequent sagging of the raft centres, none of which is observed in this area, and mud rafts floating on mudflows would sink, solid mud having a density 10% greater than fluid mud.

On the basis of this analysis, we interpret the structures and textures to be due to pack-ice formed as a moving and fracturing thermal boundary layer on top of ponded aqueous floodwater that later froze. An early drop in water level occurred while the ice was still drifting (Fig. 2a), mainly owing to evaporation/sublimation, or perhaps seepage of liquid water into the substratum.

Reasonable estimates of the depth can be made by using the rim height to diameter ratios of submerged impact craters. Mean values for simple martian craters are given by: $H = 0.04D^{0.31}$, where H is exterior rim height and D is crater diameter[16]. The impact crater 'I' (Fig. 1c) is 1.1 km in diameter and has only the highest part of the rim exposed, suggesting an initial water depth of about 42 m at that point. Fourteen other crater rims have been identified from their traces partially above or just below the ice as the surface has lowered, yielding initial water depths of between 31 and 53 m, with an average at 45 m. The true depth may be less than these values, as some suspended sediment transported in the early stages would have settled out before freezing. The MOLA profiles across three flooded craters indicate that low parts of the rim are still 0 to 30 m above the mean ice level, suggesting that the evaporation, sublimation and seepage sagging referred to above may have lowered the ice thickness to a present mean depth of around 30 m.

The area lies at the foot of the Athabasca Valles system, where sinuous ridges within the complex of valleys have been likened to those of pack-ice, and plate-like structures there have been proposed to be casts of sediment-rich ice deposited by an ice-rich debris flow, the ice having later sublimed away[17]. Fluvial bedforms also indicate that the Athabasca Valles contained water channels, perhaps fed by a large over-pressured subsurface aquifer[18] giving rise to high

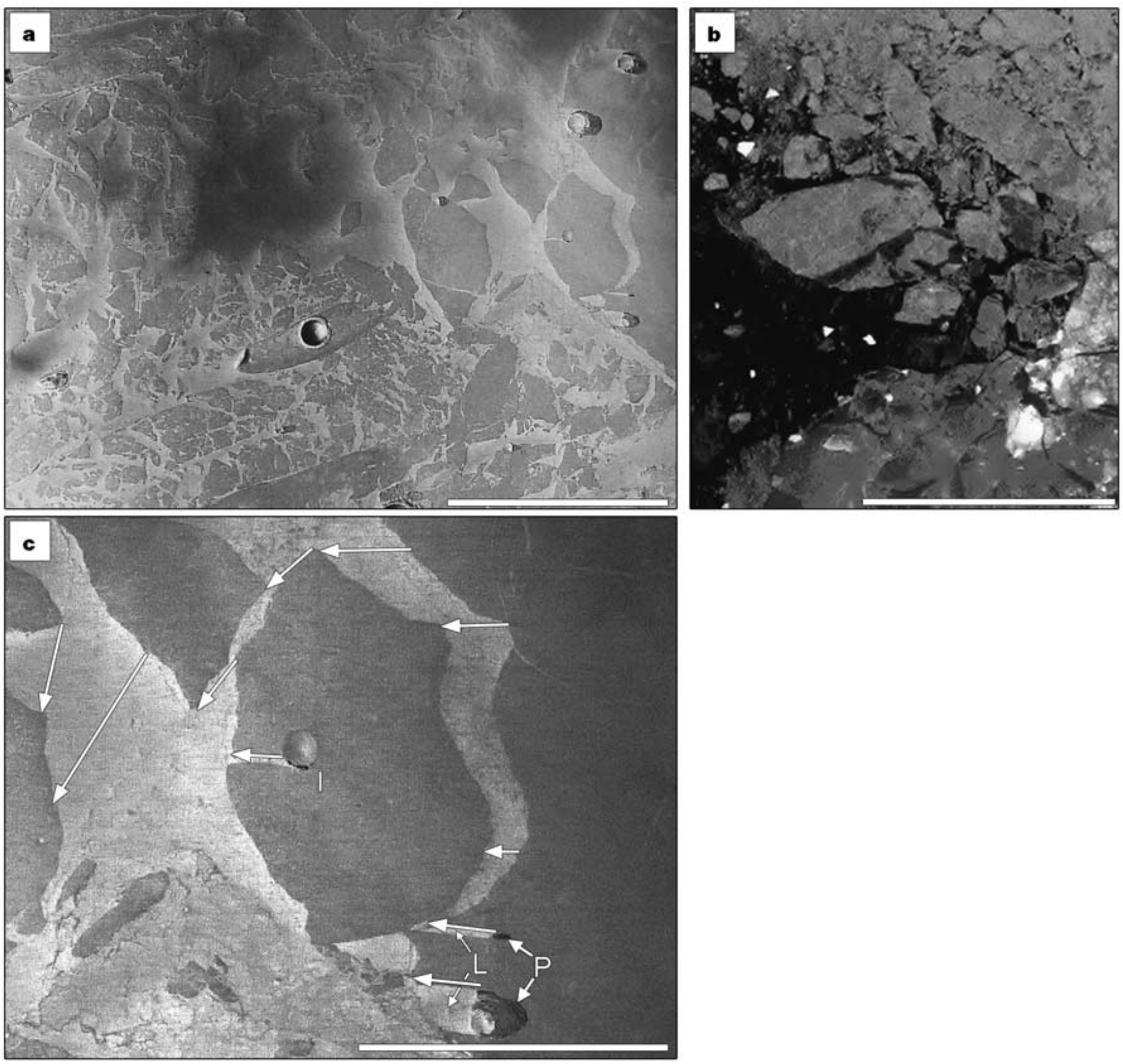

Figure 1 Views of plate-like terrain on Mars, and pack-ice on Earth. **a**, Part of an HRSC image of Mars from orbit 32, with a resolution of 13.7 m per pixel, centred at 5.5° north latitude and 150.4° east longitude, showing plate-like deposits with signs of break-up, rotation and lateral movement to the west-southwest in the lower part of the image. Scale bar is 25 km. **b**, Synthetic Aperture Radar image of pack-ice in the Weddell Sea, Antarctica. Scale bar is 25 km. (ESA image, processed by H. Rott.) **c**, Enlarged view of raft 7 × 12 km showing 8° rotation anticlockwise, causing the clear lane downstream of island 'I' to be curved. Leads 'L' downstream of the crater and small island at lower right are almost straight, indicating unidirectional drift slightly north of westward. Note pressure ridges 'P' upstream of islands. Arrows show relative motion vectors of individual plates. Scale bar is 10 km.

discharge rates[3] of the order of $10^6\,m^3\,s^2$, causing a flood rich in suspended sediment of all sizes.

Water evaporation would be rapid under present Mars conditions[19], but early work[9] indicated that freezing rates at the surface of martian lakes would be of the order of 10^{-5} to $10^{-4}\,cm\,s^{-1}$, and that surface ice will grow to a thickness of 5–10 m after 1 yr. Freezing will continue until a depth of 50 m is frozen solid in 5–10 yr. Recent work emphasizes that the water should have high concentrations of dissolved salts[20,21], and if it originates from magmatic intrusion, could be several degrees to tens of degrees above freezing on emergence[3]. These factors could produce longer timescales for complete freezing to occur[10], and rapid surface heat loss could cause intense convection that would prevent surface ice formation in the early stages, but allow slush to form.

Ice is unstable at the surface of Mars at present owing to sublimation in the 6-mbar atmosphere, but it is thought that huge volumes of volcanic ash also erupted from Cerberus Fossae[6], which—if contemporaneous with water emission—would have formed a substantial protective layer[22] on the ice. Depending on the porosity and thermal properties of this layer, the subsequent lowering of the floe surfaces could be very slow[23]. Subliming water vapour migrating through the pores will help over time to sinter and chemically bind the particles to form a stronger sublimation lag. To account for the 1-Myr age difference between the plates (pack-ice floes) and the younger lanes in between, we suggest the following sequence of events: first, pack-ice formation with a volcanic ash covering, second, remobilization, break-up and drift of pack-ice, with cessation of volcanic activity, third, freezing of the entire body of water, and finally, the sublimation of the unprotected ice between the ash-covered ice-floes, gradually exposing the suspended sediment at the surface to form a protective layer[22] with a younger age than the floes. Alternatively, the latest Athabasca volcanic activity may be as young as 3 Myr[5], which may have scattered ash that prevented further sublimation of inter-floe areas at this later time. This interpretation is supported by the MOLA profiles, which show them to be up to 3 m lower than the floes.

We do not know whether the frozen body of water is still there, or whether the visible floes are preserved in a sublimation residue draped over the substrate. Two observations suggest that it is still there:

(1) MOLA profiles show that three submerged or partially submerged craters 1.8 to 4.8 km in diameter have depths 2% to 3% of their diameter (Fig. 4), whereas the mean depth of a martian crater of this size range is about 20% of its diameter[16], suggesting that most of the ice is still within the crater, though up to 15% by volume of the crater filling may be suspended sediment. Other submerged craters appear to have similar depths. This point depends on the craters being fresh rather than degraded before

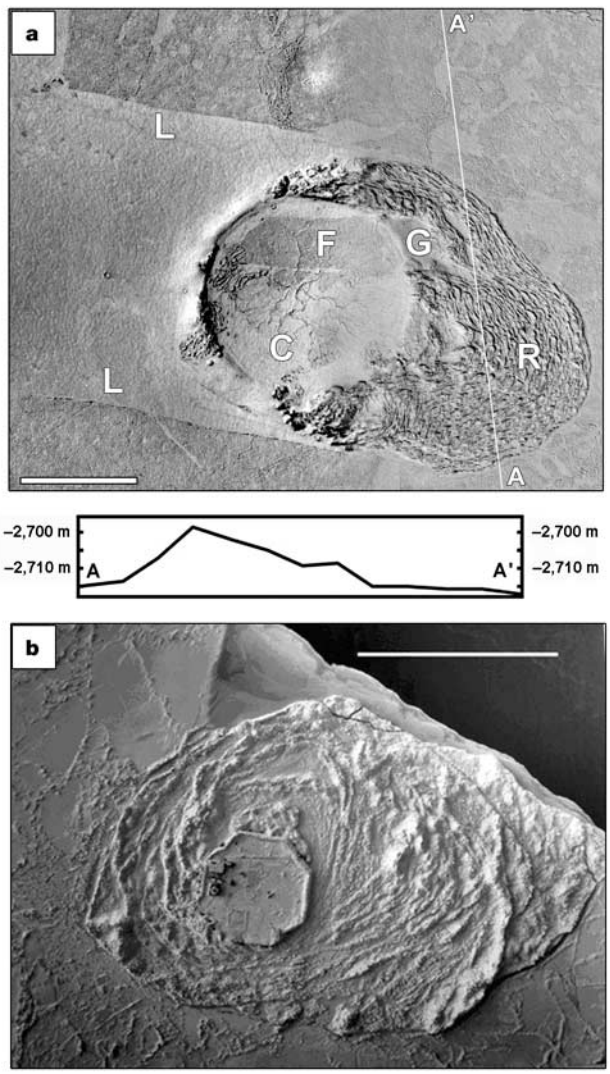

Figure 2 Pressure ridges on Mars, and those caused on Earth by pack-ice drift against obstacles. **a**, High-resolution MOC images E2100112 and R0900475 of an impact crater seen in Fig. 1a. The sides 'L' of the downstream lane are smooth at the 10-m scale, and parallel. The line on the right indicates the MOLA track 19960 crossing the pressure ridges, which are up to 16 m above the surrounding level. The MOLA topographic profile (values in metres) is shown below the image (×60 vertical exaggeration). Scale bar is 1 km. **b**, Air photo of Tarsiut Island, an artificial island in the Beaufort Sea, surrounded by first-year sea ice 1 to 1.5 m thick in the winter of 1983. We note 5-m-high concentric pressure ridging with wavelengths of 2 to 30 m caused by pack-ice rubble becoming grounded on the sloping flanks of the island during winds from different directions. Scale bar is 100 m. (Gulf Canada Resources photo courtesy of T.J.O. Sanderson.) 'C', surface cracking; 'F', a plate that has drifted through a gap 'G' in the rim; 'R', pressure ridges.

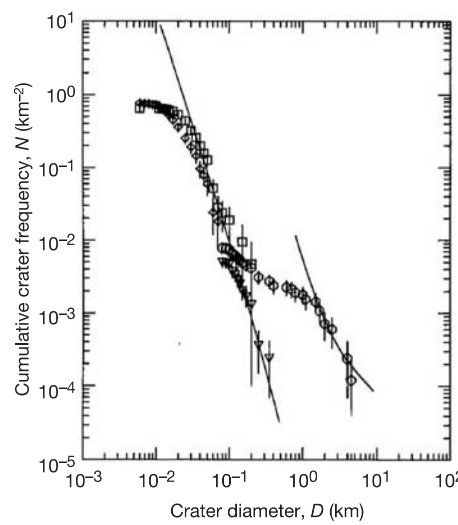

Figure 3 Age dating by crater counting[12,13] on the pack-ice surface using HRSC (triangles) and MOC imagery over a total area of 380 km^2 (squares and diamonds), including those craters that protrude through the surface from the substratum (circles). Whereas the HRSC data indicate a single re-surfacing event about 5 ± 2 million years ago, counts on MOC images show consistently lower numbers for the brighter inter-plate terrain (diamonds) than the darker plate-like terrain (squares) interpreted as ice floes. The lower frequency occurs at all sizes systematically, indicating an age difference of about 1 Myr. The derived age of the substrate before flooding is 3.66 ± 0.05 billion years.

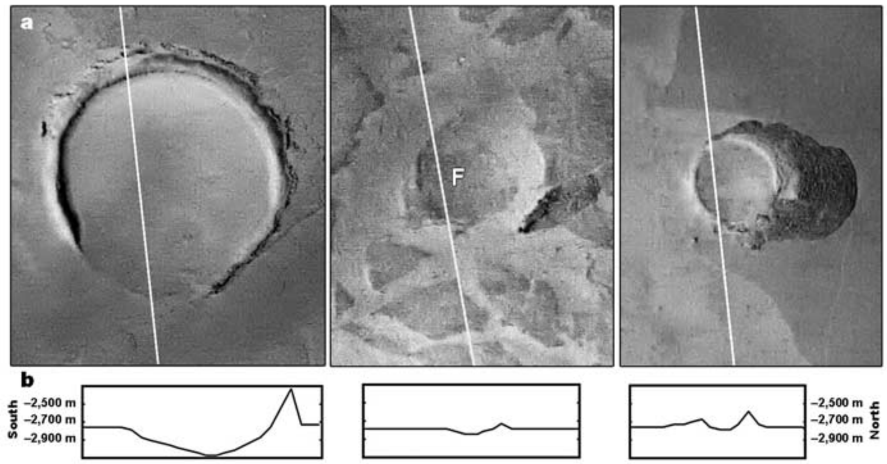

Figure 4 Evidence of ice surface lowering and draping of plate-like features over partly submerged impact craters. MOLA tracks (**a**) and MOLA topographic profiles with 10 × vertical exaggeration (**b**) across three flooded or partially flooded craters 4.8, 2.3 and 1.8 km in diameter from left to right. Values are in metres. Note that the floor sags at least 85, 18 and 25 m respectively, suggesting that 89% to 96% of the proposed ice fill is still within the crater. Note also the raft 'F' draped over the rim and floor of the centre crater. See text for further details.

flooding, but in this area most of the unflooded craters of similar size appear to be fresh with bowl-shaped interiors.

(2) MOLA profiles show a virtually horizontal surface, whereas the ice depth estimates above indicate that the substrate varies in altitude by 55 m. If the ice had been lost, sediment draped over this should have resulted in considerable surface height variation.

Recent work[24,25] has shown that Mars' obliquity, with oscillations of 5° to 10° amplitude and periods of 10^5 yr, was 37° ± 7° between 5 and 10 Myr ago. Global climate model simulations indicate that this would produce a substantially different climate from that of today, with higher dust transport and an atmosphere of higher temperature and pressure[26]. The extremely young age of 5 Myr for the flood suggests that catastrophic flood events from a proposed sub-cryospheric aquifer[20,21] are continuing to happen, as they have done throughout the known history of Mars' surface. The continuous presence of warm water beneath the cryosphere over several billion years might provide more opportunities for life to develop than was once thought. Microorganisms found within deep-sea hydrothermal vent communities[27] are common ancestors to many forms of life on Earth, and the possibility of life developing at similar places elsewhere in the Solar System has been postulated[28]. □

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Discovery of a flank caldera and very young glacial activity at Hecates Tholus, Mars

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The majority of volcanic products on Mars are thought to be mafic and effusive[1,2]. Explosive eruptions of basic to ultrabasic chemistry are expected to be common[3,4], but evidence for them is rare and mostly confined to very old surface features[5]. Here we present new image and topographic data from the High Resolution Stereo Camera that reveal previously unknown traces of an explosive eruption at 30° N and 149° E on the northwestern flank of the shield volcano Hecates Tholus. The eruption created a large, 10-km-diameter caldera ~350 million years ago. We interpret these observations to mean that large-scale explosive volcanism on Mars was not confined to the planet's early evolution. We also show that glacial deposits partly fill the caldera and an adjacent depression. Their age, derived from crater counts, is about 5 to 24 million years. Climate models predict that near-surface ice is not stable at mid-latitudes today[6], assuming a thermo-dynamic steady state. Therefore, the discovery of very young glacial features at Hecates Tholus suggests recent climate changes. We show that the absolute ages of these very recent glacial deposits correspond very well to a period of increased obliquity of the planet's rotational axis[7].

The ESA Mars Express mission, an orbiter carrying seven experiments, was inserted into Mars orbit on 25 December 2003. On 19 January 2004, the multiple line scanner instrument, the High Resolution Stereo Camera (HRSC)[8], imaged the volcano Hecates Tholus in the Elysium region. Our study focuses on two overlapping depressions at the northwestern base of Hecates Tholus (Fig. 1) that were mentioned before[9], but without an explanation for their origin. The HRSC image resolution of that area (~26 m per pixel) is better than that of previous images from the Viking Orbiter camera (~40 m per pixel) and from the THEMIS thermal infrared imager (~100 m per pixel). Several very high-resolution images from the Mars Orbiter Camera (MOC) cover small parts of the depressions with 3 to 4 m per pixel. We use digital photogrammetric techniques[10] to derive stereo information with a mean relative point accuracy of ~30 m from the HRSC's multiple line sensors, which observe the surface under different viewing angles.

The smaller of the two depressions (here referred to as 'depression A') has an area of ~12 km × 10 km (Fig. 2a) and a depth between 1,000 and 1,500 m. The northwestern part of its rim is missing where it overlaps with the larger depression (here named 'depression B'). The remaining rim has an elevation between 800 and 1,800 m. The floor is terraced, with an elevation difference of 200–300 m between the two levels. Owing to the incomplete rim, it is difficult to determine its volume. Our best estimate, based on a reconstructed rim, is ~80 km^3. On the flanks of the volcano, an unusual hilly and knobby deposit can be distinguished adjacent to depression A. Its surface is rougher than the rest of the flank's surface, and it extends outward from the rim to a maximum distance of about 15 km.

We favour a volcanic over an impact origin of depression A for four reasons. First, the morphology of the depression, including the two different levels of its floor, is remarkably similar to part of the caldera complex at the shield volcano Ascraeus Mons in the Tharsis region (Fig. 2b), and also to the summit caldera of Hecates Tholus itself (Fig. 2c); impact craters on Hecates Tholus have a distinctly different appearance (Fig. 2d). Second, the stereo information indicates that the walls slope at an average angle of about ~30°, which is steeper than the walls of most martian impact craters[11]. Third, there is no elevated crater rim, which would be expected if depression A were an impact crater. Fourth, the remaining parts of the rim are distinctly not circular, owing to a promontory at the topographically highest part of the rim.

Hence, the cumulative evidence of these independent observations suggests that depression A is volcanic rather than impact-related. There is no evidence for effusive eruptions, for example, lava flows, near depression A. Instead, we interpret the rough material near depression A as the proximal part of pyroclastic materials from an explosive eruption. Relative to the other parts of the flanks, an area between depression A and the summit caldera displays a lack of impact craters and a generally smooth surface texture at the scale of the Viking and HRSC image resolution. It has been interpreted to be a mantling deposit from an explosive eruption at the summit[9]. However, it may as easily have been produced by an explosion at depression A. Indeed, the isolines of the crater density on the western flank of Hecates Tholus (figure 7 in ref. 9) are roughly