RECENT CLIMATE CHANGE AND PRESENCE OF NEAR-SURFACE ICE DEPOSITS: EVIDENCE FROM INVERTED IMPACT CRATERS LOCATED ON LINEATED VALLEY FILL, ISMENIUS LACUS REGION, MARS. B. S. McConnell[1], H. E. Newsom[1], N. Lanza[1], University of New Mexico, Department of Earth and Planetary Sciences, Albuquerque, NM 87131 bmcconne@unm.edu

Introduction: Lineated valley fill [1] in the Ismenius Lacus region ((0°-180°W; 30°-65°N) is thought to be the result of past glacial activity [2], and resembles the results of terrestrial glacial activity. Located on the lineated valley fill are small circular features, presumably impact craters (20-800 meters in diameter), that have inverted topography, compared to that of fresh bowl-shaped craters. Although fresh appearing bowl-shaped craters are present in the lineated valley fill, they are much less frequent than the inverted impact craters. These inverted impact craters (IIC's) are evidence of episodes of near-surface ice within the past 5-10 Ma, and are results of surface-deflation due to subsequent climate change.

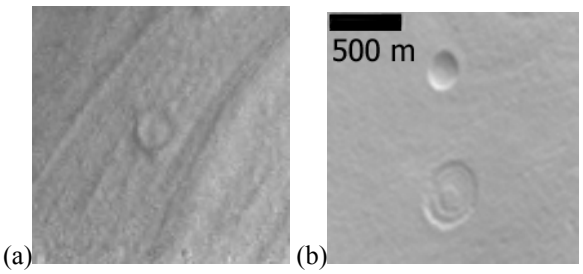

Figure 1 (a) An inverted impact crater imbedded in lineated valley fill. (b) This image shows an inverted impact crater (bottom) compared to a fresh bowl-shaped crater (top). Both craters are located on lineated valley fill in the western region of Ismenius Lacus (scale bar on Fig.1(b) also applies to Fig.1(a)).

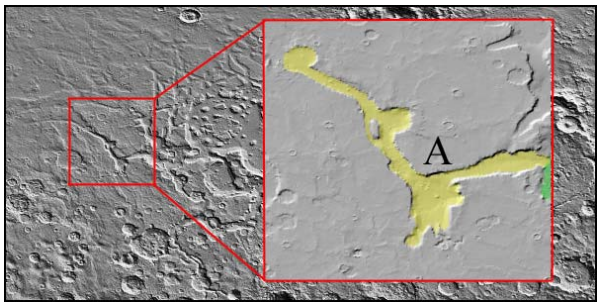

Figure 2 Area A includes the Valley centered at 41.5°N, 12.0°E, on the western edge of Ismenius Lacus. Within this area, approximately 56 potential inverted impact craters were located in the lineated valley fill only. The highest concentration of modified impact craters was located between 41.5°N, 12.4°E, and 41.7°N, 13.3°E. As the valley proceeds north, the valley walls become much less distinct and the frequency of modified impact craters and lineated valley fill decreases and eventually goes to zero.

We investigated the western region of Ismenius Lacus because of the frequent occurrences of lineated valley fill and lobate debris aprons, which are evidence of regional ice accumulations [1]. The inverted impact craters, located only in the lineated valley fill, and not found on lobate debris aprons, have similar morphologies and consist of two different components; a subdued crater rim and a central (layered) deposit.

Observations: We examined approximately 60 high-resolution MOC and THEMIS images of Ismenius Lacus. These images reveal several physical traits related to prior glacial activity. The key observation is the presence of lineated valley fill (Fig.1(a)). The suspect inverted impact craters on these terrains were documented and recorded, and a classification scheme was developed.

Inverted Impact Crater Morphology

Central (Layered) Deposits: The inverted impact craters all contain central deposits that range in shape, size and orientation (Fig.3). These deposits occur within the pit of the structure and are of positive relief. The tops of the deposits vary and can appear convex, concave and flat. Several of the deposits observed boast several layers hence the term, central (layered) deposits.

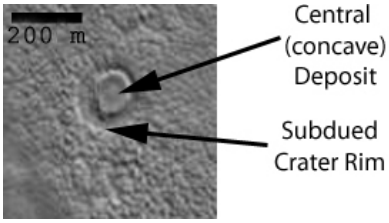

Figure 3 The components of the inverted impact crater, including the central deposit, subdued crater rim. (Note: the crater is located on lineated valley fill).

Subdued Crater Rims: The inverted craters have very indistinct rims (Fig.3). These rims occur around the pit where the central (layered) deposit is located.

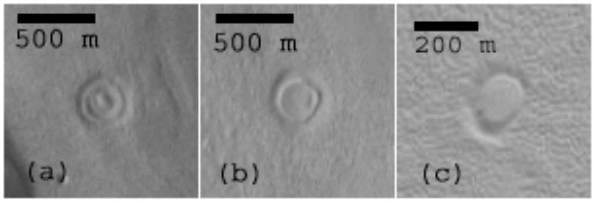

Figure 4 This series of circular features represent the three most common types of inverted impact craters. (a) This Type 3 inverted impact crater shows signs of multiple inner-rings. (b) This is a Type 2 inverted impact crater; note the convex central deposit (c) This is a Type 1 inverted impact crater; note the convex central deposit.

Inverted Crater Classification: Inverted impact craters are restricted to a certain size range and rarely exceed a diameter of 600 meters. Because of resolution constraints on MOC, we believed that these features only occurred as small as 50 meters in diameter. However, the extremely high resolution capabilities of the Hi-Rise camera have lead us to discover that these inverted impact craters occur on such a small scale (<20m diameter) that they were virtually invisible in MOC vis-camera images. We have now observed

these inverted craters to range from 20 to 800 meters in diameter.

The classification of inverted impact craters is size independent and is based on morphologic deviations in the rim, central deposit and moat surrounding the central deposit. The differences observed in these certain components are caused by various amounts of surface deflation due to ablation in the target material as well as the ablation of volatiles in the depositional crater fill, and also the amount of depositional crater fill preceding substantial target-ice melt.

Type 1 Classification: Type 1 inverted impact craters occur most frequently and require the simplest system to produce the end result. They have extremely weathered rims or no rims at all and contain a single shallow moat surrounding the central deposit. The central deposit is plateau-like to convex and occupies most of the crater floor.

Type 2 Classification: Type 2 inverted impact craters deviate from the Type 1 model in that they have concave central deposits.

Type 3 Classification: Type 3 inverted impact craters deviate from the Type 1 model in that they have one or more rings surrounding the central deposit.

Type 4 Classification: Type 4 inverted impact craters deviate the most from the Type 1 model. These impacts are substantially super surface, rarely contain moats and show little evidence of a crater rim.

Origin of Inverted Impact Craters

Numerical Modeling: Numerical modeling simulated crater deformation due to surface deflation in targets once containing ice (Fig. 5). Three phases were simulated in this model. 1) A parabolic crater was formed in a target containing ice. Several trials included targets varying in ice by volume. 2) The next phase in the process included adding several layers of sediment infill to the crater. The deposition amounts ranged from a couple of meters to tens of meters thick. 3) The third phase in this system represents the loss of volatiles. The layers representing the volatile components were partially or completely deleted. Several of the resulting profiles reproduced the characteristics of the inverted impact craters in Ismenius Lacus.

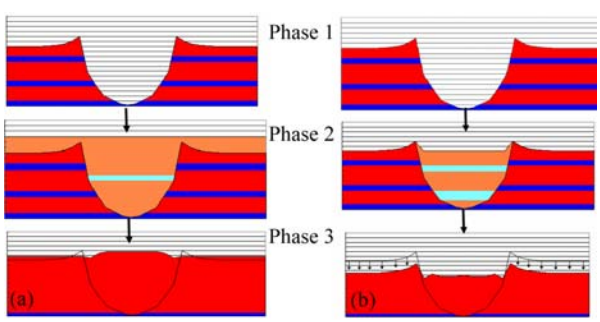

Figure 5 These are two numerical models that show the results that coincide with inverted impact crater impact Types 1 (right) and 2 (left). The red represents non-volatile Martian surface; the blue represents both surface and infill volatiles; the orange represents crater infill. (a) Type 1 (b) Type 2.

Thermal Modeling: The next step in the numerical modeling includes obtaining regional surface insolation rates needed to obtain sublimation rates in the lineated valley fill. This will provide approximate surface deflation amounts, thus helping with quantitative interpretation of the timing and formation of the inverted impact craters.

Discussion: The favored model, resulting in inverted impact craters located on lineated valley fill, coincides with Madeleine's climate change and ice accumulation model. The inverted impact craters provide evidence of episodes of near surface ice in the past 5-10 Ma due to periods of very high obliquity during the Amazonian period, as well as the smaller more recent fluctuations in obliquity over the past 2-5 Ma.

Central (Layered) Deposits: The variation of central (layered) deposit shape and size does not appear to be regional. In many cases, several different variations in shape occur in the same area.

Regional Climate History: The model for inverted impact crater formation outline above is consistent with models for climate-change on Mars. During a period of high obliquity, a thick cloud layer forms of the Northern mid latitudes, causing large ice deposits in the 30°-70°N latitude range.

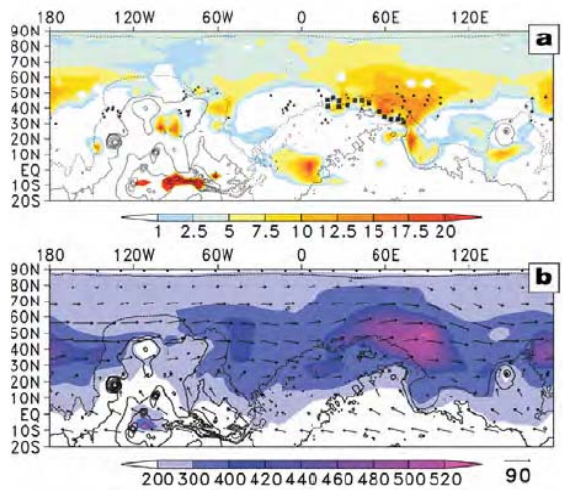

Figure 6 [3] (a) Predicted ice accumulation (mm/yr) superposed on the map by S. Squyres [7]. Squares = lobate debris aprons; Circles = small impact craters with concentric fill. (b) Average cloud ice content (pr-μm) and atmospheric winds for Ls = 270-300°.

The largest ice accumulation occurred in the Deuteronilus-Protonilus Mensae (DPM) region (30-50N 0-70E) (Fig.6) [3]. Adjacent to the DPM region is Ismenius Lacus, where indications of preexisting ice deposits, such as a smoothing of topography, and morphologic features such as polygons, gullies, lobate debris aprons and lineated valley fill [4,5,6] are evident.

Pingo Formation - Although other possibilities were reviewed, positive relief positioned in these small craters can be achieved without the aid of sub-surface liquid water deposits as used in the pingo process (e.g. Sakimoto [8] (Figure7)). Usually pingo altered craters appear on a much larger range whereas the inverted impact craters only occur on a subkilometric scale.

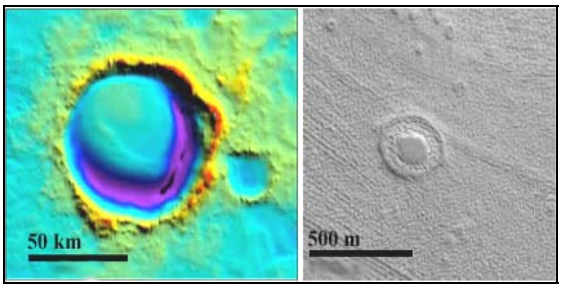

Figure 7 Comparison of possible pingo (left) [8] and inverted impact crater on lineated terrain (right).

Differential Erosion of Layered Deposits – Because of the small size of the impacts, it is less likely that the layered deposits occurring on Type 3 inverted impact craters are a compositional effect. More plausible is a system of depositional ice-melting/refreezing.

Retreating Edges Evidence related to the involvement of ice in crater modification is seen in an example located in the southern hemisphere of Mars. A series of two large craters (≈9 and ≈17 km diameters)(Fig.8) appear to have been filled with ice via glacier. Ice flows are evident as well as lineated terrain but a key trait in identifying sub-surface ice deflation is the presence of retreating edges of the original ice-bearing layer. These edges are interpreted to be the result of ice deflation within the crater fill.

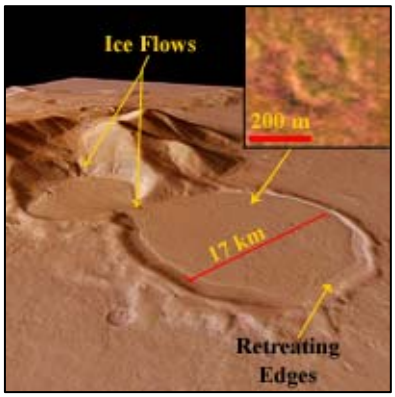

Figure 8 This Mars Express image shows two large ice-filled craters in the 38° southern latitude band. The retreating edges of the floor material are evidence of ice deflation. The floor deposit contains a modified impact crater similar to those in Ismenius Lacus.

Glacial Pits – Although glacial pits are rather common on terrestrial glaciers due to volatile ablation, the regular circularity of these inverted impact craters conflicts with the consistency of circularity in glacial pits.

Lobate Debris Aprons – The lobate debris aprons occurring at the base of escarpments in this region are thought to contain varying concentrations of ice bearing materials [6]. They occur very commonly in the same locations where lineated valley fill is prevalent. The frequency of impact features located on lobate debris aprons is almost zero, and the few observed impact features located on these bodies resemble typical bowl-shaped craters, not Type 1, 2 or 3 inverted impact craters. A couple of different systems could result in this sort of outcome. It is possible that due to a difference in insulation and/or solar exposure, among other variables, lobate debris aprons have a much higher rate of surface devolatilization. This could result in the rapid erosion of impact features in these locations. Another possibility is an age difference between the lobate debris aprons and lineated valley fill. This is quite plausible considering that there is evidence of lobate debris aprons overlapping lineated valley fill, implying that the lobate debris aprons are younger. This evidence discerns that the larger deposits of ice, the lineated valley fill, were formed during periods of high obliquity (>35°) approximately 5-10 Ma, and the lobate debris aprons formed more recently, possibly in the past 2 Ma, when obliquital fluctuations were substantially less severe.

Surface Deflation Due to Target Ice Sublimation – Type 1, 2 and 3 inverted impact craters can occur sub, super or even with the surrounding surface. This depends on the original amount of ice in the target and the extent of it's devolatilization as well as the amount of sediment or icy-sediment depositional crater fill and the extent of it's devolatilization. Also, whether the Type 1, 2 and 3 inverted impact craters have rims is dependent on the amount of local weathering the impact underwent.

Type 4 inverted impact craters are the result of the impact into an extremely icy original target material, followed by substantial depositional crater infill and finally extensive devolatilization of the surrounding surface

Conclusions:

- Lineated valley fill in the western Ismenius Lacus region contains inverted impact craters ranging from ~20m to 800m in diameter.
- Numerical models, assuming crater-fill by dust and sublimation of surrounding ice, match even subtle features observed in the structures such as concave and convex central deposits.
- Numerical models for the crater formation process are consistent with the presence of ice, suggesting that lineated valley fill is the result of preexisting near-surface ice and glacial activity.

Implications: The deformation of the original crater analogues is the result of impacts into targets containing near-surface ice, sometime in the late Amazonian period. The small crater volumes were filled in during this period of high obliquity, when ice accumulations were stable in the mid to high latitudes. As the obliquity reverted back to a more stable and current ~26°, the ice relocated back to the poles, deflating the surface surrounding the craters, and finally leaving the inverted topography.

References

[1] Head J.W. (2005) LPSC XXXVI, Abstract #1257. [2] Marchant D.R. (2006) 4th MPSC, Abstract #8081. [3] Madleine B. (2007) LPSC XXXVIII, Abstract #1778. [4] Kargel J.S. (2003) 3rd MPSC, Abstract #8112. [5] Head J.W. (2007) LPSC XXXVIII, Abstract #1208. [6] Ostrach L.R. (2007) LPSC XXXVIII, Abstract #1100. [7] Squyres (1979) J. Geophys. Res., 84, 8087-8096. [8] Sakimoto S.E.H. (2005) LPSC XXXVI, Abstract # 1273.