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# Estimating the volume of glacial ice on Mars: Geographic and geometric constraints on concentric crater fill, lineated valley fill, and lobate debris aprons along the Martian dichotomy boundary

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## Abstract

Landforms inferred to have formed from glacial processes are abundant on Mars and include features such as concentric crater fill (CCF), lobate debris aprons (LDA), and lineated valley fill (LVF). Here, we present new mapping of the spatial extent of these landforms derived from CTX and THEMIS VIS image data, and new geometric constraints on the volume of glaciogenic fill material present in concentric crater fill deposits.

## 1. Introduction

Debris-covered glacial landforms such as CCF, LVF, and LDA are widespread on Mars and have been long inferred to represent locations of abundant ground ice preserved at mid-latitude locations [1-12]. Here, we present new mapping and geometric calculations aimed at determining the volume of non-polar glacial ice on Mars and its implications for global martian water budgets.

## 2. Methods

LDA, LVF, and CCF were manually mapped using mosaics of CTX and THEMIS VIS image data sampled at 18 m/pixel and viewed at ~1:250k scale between latitudes 30-50˚ N. Criteria used to identify LDA, CCF, and LVF include the presence of parallel/concentric lineations and the presence of "brain terrain" [12] surface textures or subsequent mantling on topographically convex near-surface lobate features (in addition to the range of geomorphic criteria established by [2,7,11]). Results of the mapping are shown in Figure 1.

Once the spatial extent of these features was established, we are using geometric tools to infer the volumetric extent of glacial landforms. For example, for CCF, several morphometric properties were extracted from catalogues of northern hemisphere crater morphologies [13] including: crater diameter, **d** and measured crater depth, $\mathbf{D_m}$. CCF fill radius, $\mathbf{r_f}$ is measured from CTX images of the crater, measured along two orthogonal profiles that span the spatial limit of "brain terrain" surface texture or concentric surface lineations.

Using these quantities measured from MOLA and CTX data, relationships between fresh-crater depths and diameters on Mars [14], coupled with elementary calculus (solids of rotation), permit us to make quantitative estimates of CCF fill volume (note: this method does not distinguish between prior fill and CCF ice-related fill). The functional relationship between crater diameter (d) and crater depth (D) was quantified by *Garvin et al.*

$$d = wD^y \qquad (1)$$

where w and y are constants that depend on d (all constants reported by [14] vary as a function of d for simple craters, 1-7 km in diameter, complex craters, 7-100 km in diameter, or large craters, >100 km in diameter). The topographic profile of a crater wall follows a similar power-law relationship: here, in Cartesian coordinates of height (y) and radial distance (x): $y = kx^n$ (again, with k and n depending on d) [14]. These simple geometric relationships make it possible to calculate the volume of a CCF deposit, assuming an axially symmetric CCF deposit, by integrating a solid of rotation defined by

$$y = kx^n \qquad (2)$$

about the y-axis, and integrating from 0 to x = $\mathbf{r_f}$. The volumes of individual CCF deposits were totalled up to calculate the volume of the CCF reservoir in the mid-latitude study region, and were transformed into minimum and maximum ice masses, by multiplying by 30% and 90% ice volume fractions (rock glacier and debris-covered glacier, respectively) and by assuming negligible ice densification from compaction.

## 3. Results

As shown in Figure 1, mapping efforts have led to a preliminary estimation that glacial landforms cover ~5.8 x $10^5$ $km^2$ of the martian surface between 30-50˚. This glacial landform area consists of ~3.5 x $10^5$ $km^2$ of LDA, ~1.6 x $10^5$ $km^2$ of CCF, and ~0.8 x $10^5$ $km^2$ of LVF. For comparison, the north polar cap has an area of ~$10^6$ $km^2$ [15].

Of the 200 largest craters in the northern hemisphere, 100 are located in the study range, and 18 contain CCF deposits. The combined volume of these crater fill deposits is estimated at ~2 x $10^3$ $km^3$, or 1.8 x $10^3$ $km^2$ assuming a nearly pure ice content [16,17], or 0.6 x $10^3$ $km^3$ of ice, assuming ice only fills CCF pore spaces. This constitutes a global equivalent layer ~1 cm thick. Because many smaller craters are nearly fully-filled with CCF deposits, this CCF volume total is expected to rise dramatically when smaller deposits are measured.

## 4. Conclusions

Glacial ice deposits on Mars are spatially extensive, and, through new volumetric measurements, are being shown to be heterogeneous in volume. Non-glacial ice on Mars represents a major ice reservoir on Mars and is a major indicator of paleo-atmospheric conditions.

## 5. References

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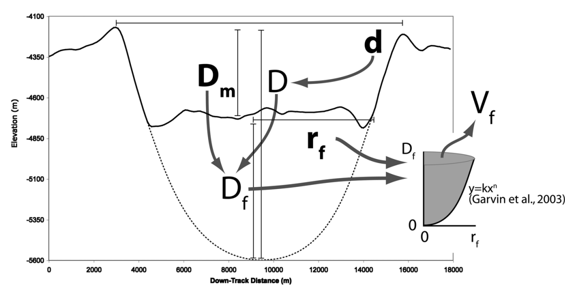


**Figure 2.** Schematic illustration of CCF volume calculations.

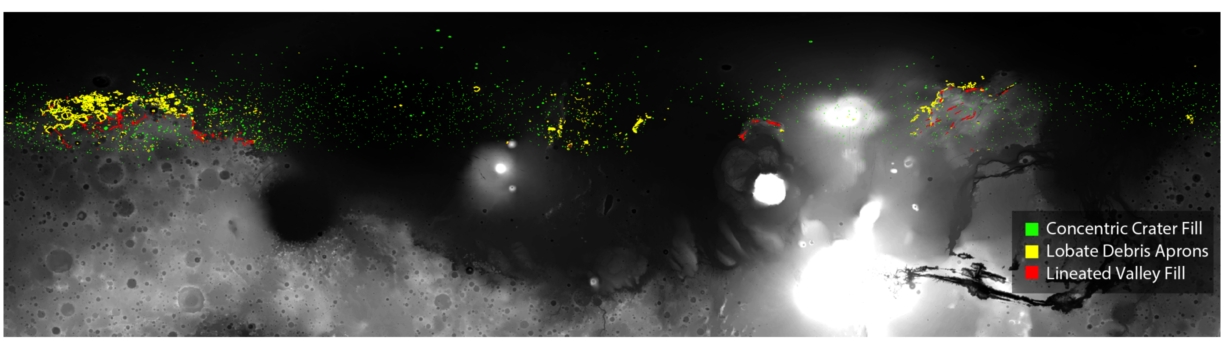


**Figure 1.** Map showing the distribution of CCF, LDA, and LVF based on CTX and THEMIS-VIS mapping in the northern hemisphere. Base map is MOLA elevation. The mapped band spans 30-50˚N.