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Radar and Geomorphic Evidence of the Occurrence of Massive Ground Ice in the Martian Northern Plains.

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Introduction: The possibility that a large ocean or massive ice-sheet once occupied the Martian northern plains has been proposed based on the interpretive identification of various landforms, including sedimentary deposits [1, 2], outwash plains [3] and possible paleoshorelines – the latter based largely on the work of Parker et al. [4-7], who identified evidence of a series of nested levels, which they interpreted as shorelines, located along the highland/lowland boundary. The combination of high-resolution orbiter images with MOLA gridded topography has enabled the compilation of regional and global maps of the proposed shorelines. The highest and oldest of these is called the 'Arabian Level' and is believed to date back to the Late Noachian. In the much higher resolution (~0.2 - 20 m/pixel) MOC, HiRISE and HRSC images, the Arabian Level exhibits evidence of terracing (potentially indicative of wave-cut erosion); however, the topographically lower/younger 'shore-lines' do not. The interior plains encompassed by these lower levels include vast expanses of cold-climate landforms, such as polygonal ground and scalloped depressions [8], a relationship that is consistent with either an initially warm, but progressively cooling, aqueous environment – or initial conditions that were cold from the outset. In either case, the flow-front-like morphologies associated with the lower levels may have resulted from ice-shoving due to short-lived transgresssive events caused by later episodes of outflow channel activity around the northern plains [6].

Apparent discrepancies between the absolute elevation of the Arabian Level with the perimeter of an equipotential surface have been cited as potential serious weaknesses of the paleoocean hypothesis [2]. However, improved shoreline maps, based on the recent influx of new, higher-resolution images, combined with recognition of the potential effect of true polar wander on the post-ocean/ice-sheet deformation of shorelines [9] have helped resolve much of this disagreement.

New Evidence of a Former Ocean/Ice-Sheet: Persuasive new support for the ocean/ice-sheet hypothesis comes from several lines of evidence. First, recent studies of the geographic distribution of Martian valley networks, appear most consistent with a major source of atmospheric water in the northern plains at the time the networks formed [10, 11].

Second, much of the northern plains, and especially the Vastitas Borealis Formation (VBF, the most extensive geologic unit in the northern plains, which is widely interpreted to be a sublimation lag deposit, left by Late Hesperian/Early Amazonian fluvial activity) is characterized by unexpectedly weak radar surface reflectivity – as determined from the strength of the first reflection of selected radar pulses from the MARSIS orbital radar sounder on Mars Express [12]. The low reflectivity of the VBF is consistent with a surface permittivity of ~4.6±0.5, indicative of either a high-porosity (~35%) or ice-rich (~60%) sedimentary layer at least ~60-80 m-deep, assuming dielectric properties averaged over a depth of one MARSIS radar wavelength. It is important to note that the VBF is essentially coextensive with the region interior to the most recent (Deuteronilus Level) of the Parker shorelines [12], suggesting that a frozen relic of a former ocean, ice-sheet, or outflow channel activity, still survives beneath the northern plains.

The survival of a relic of an ancient ocean/ice-sheet is an expected consequence of its progressive freezing in response to a cold early climate and its subsequent burial by volcanics and eolian and fluvial sediments, that may have preserved a remnant of this ice to the present day [1, 3, 8]. While sublimation may have depleted some of the initial inventory of this ice, replenishment by later episodes of outflow channel activity, continued mantling by volcanics and sediments, combined with the potential geothermal redistribution of ground ice from depth (possibly offsetting much of the expected sublimative loss, [14]), is expected to have led to the development of a complex stratigraphy of massive ground ice, frozen sediments, and volcanics, throughout the northern plains [7] (Figure 1).

Finally, and most persuasively, the existence of a former northern ocean/ice-sheet is supported by the high geographic correlation between the areas of weak surface reflectivity/low permittivity and the distribution of double lobate ejecta (DLE) craters, whose distinctive fluidized ejecta morphology (Figure 2) is thought to result from an impact into the complex volatile stratigraphy of an ice-rich target [13] (e.g., Figure 1).

The DLE craters exhibiting the highest ratios of ejecta mobility (lobate ejecta diameter/crater diameter) occur at a latitudes >40°N, where deep ground-ice, if present, will remain stable against sublimative loss. This includes the regions of Utopia and Acidalia Planitiae, which have elevations < –4000 m and occur at the confluence of several major outflow channels [3].

Conclusion: Considered together, the low permittivities that characterize the Martian northern plains and their close geographic agreement with the distribution of DLE craters [13] (Figure 3), and other cold-climate landforms [1, 3, 8] – all within the region interior to Parker's proposed ocean shorelines – provides persuasive evidence of an association with ground ice, most plausibly related to a surviving remnant of a former ocean/ice-sheet and/or the frozen discharge of the outflow channels

A more detailed analysis to test and better constrain these results, is currently in preparation.

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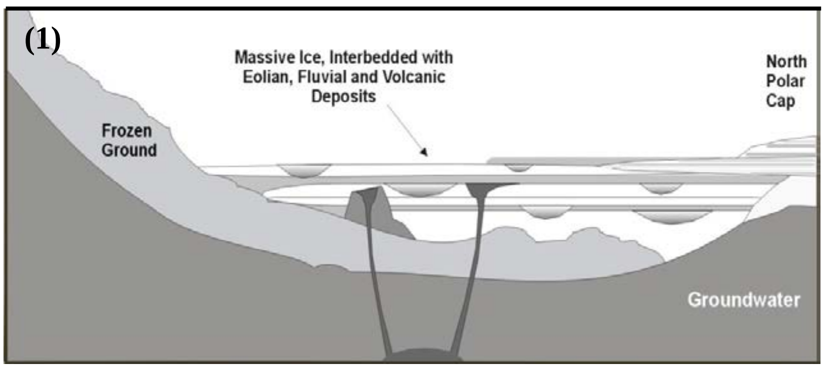

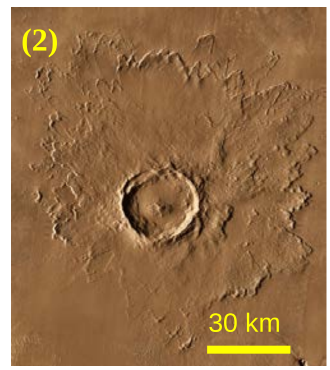

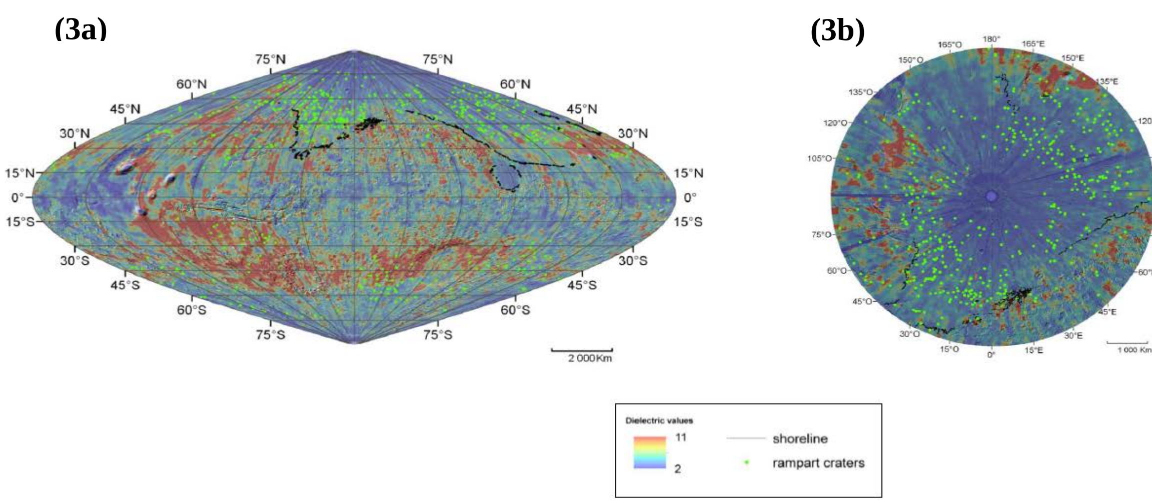

gure 1. An illustration of the potential complex volatile, sedimentary, and volcanic stratigraphy of the northern plains [from Clifford and Parker [7]). **Figure 2.** Tooting Crater (23.4°N, 207.5°E), an example of a 27 km diameter DLE crater in the northern plains. **Figure 3.** MARSIS radar-derived (a) global and (b) northern hemisphere surface permittivity maps [12] on which the distribution of Costard's Type 2 [13] DLE craters (neon green dots) and T. Parker's 'Arabian Level/Shoreline' [4-7] (black line) are also shown. Note that low surface permittivities/weak surface reflections (indicative of high-porosity or ice-rich sediment) are indicated by dark blue and high surface permittivities/strong surface reflections (indicative of coherent rock, like low-porosity basalt) are indicated by dark brown.