THE RELATIONSHIP BETWEEN ICEBERGS AND TSUNAMIS IN ANCIENT OCEANS ON MARS.

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Introduction

It was proposed a quarter century ago that the Martian northern plains, about 1/4 of the planet's surface, were covered by an ocean that existed approximately 3.5 billion years ago. This ocean was likely rimmed by extensive glacier systems [1,2], and could have remained in liquid form due to a large concentration of dissolved solutes [1,3]. Here we propose that the erosion of these glaciers by enormous tsunami waves could have been a major contributor to the iceberg production within freezing-resistant ocean waters.

Methods

Mapping in this investigation was performed using ArcGIS software. The recognitizion and characterization of erosional and depositional relationships, as well as the embayment and overlapping relationships, involved an integrated analysis of (i) visible image data: Mars Reconnaissance Orbiter Context Camera (CTX), 5.15–5.91 m/pixel, and High-Resolution Imaging Science Experiment (HiRISE), 25-32 cm/pixel; (ii) thermal infrared image data: Mars Odyssey's Thermal Emission Imaging System (THEMIS) night-time and day-time infrared image mosaics, 100 m per pixel; and (iii) digital elevation models: Mars Global Surveyor Mars Orbital Laser Altimeter (MOLA), ~460 m/pixel horizontal and ~1 m vertical resolution.

Evidence for icebergs within a Late Hesperian northern plains ocean

We have previously identified three differentiated geomorphologies throughout the northern plains of Mars, as well as within the Hellas basin floor [4], that are informative of the presence of icebergs floating in ancient oceans and/or seas. These morphologies are: (i) scattered scour marks, including curvilinear furrows several km long and some meters deep; (ii) boulders ranging in size from 0.5 m to ~2 m in diameter, distributed forming clusters with sizes from several hundred meters to 1-2 km; and (iii) flat-topped and conical circular fractured mounds (Fig. 1).

The processes described are well documented on Earth and result in distinct morphologies on the ocean floor, which are analogous to features observed in the Martian basins [5]. For example, the association of

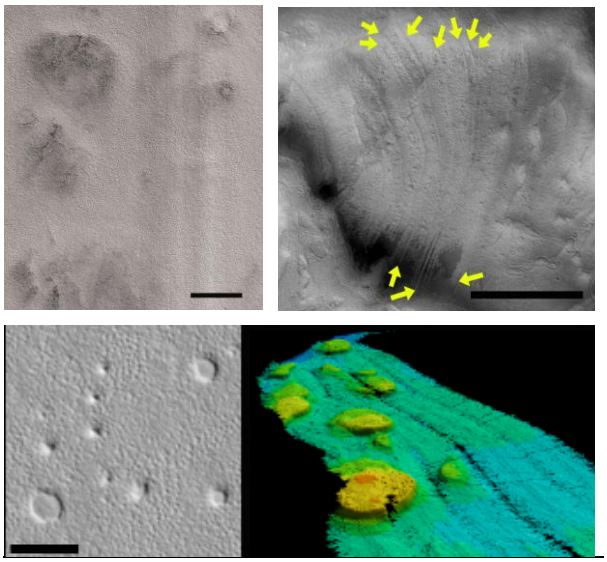

Fig. 1: (Upper left) Portion of the image TRA_000841_2460, showing clusters of boulders northern Utopia Planitia. **(Upper right)** Scour marks (arrows) in Hellas Basin (HiRISE image PSP_009548_1420). **(Lower left)** Roughly circular features with nearly planar tops of varying diameter in Arcadia Planitia, as shown in HiRISE image PSP_006852_2200. Scale bar = 200 m. **(Lower right)** Roughly circular features with nearly planar tops in the Victoria Land Basin, Antarctica, analyzed by multibeam bathymetry data. Features have a diameter of up to 4 km and rise up to 120 m above the surrounding seafloor. Figure modified from Lawver et al. (2007). Scale bars are 1 km, and North is up.

plough marks, clusters of boulders and mounds on the northern plains of Mars can be related to the dual processes of ice keel scouring and ice rafting of both glacial and non-glacial detritus by a floating ice canopy and icebergs [5,6].

Icebergs, glaciers and paleoshorelines

The presence of icebergs floating in cold oceans early in Mars' history imply the occurrence of continental glaciers forming in the highlands and streaming northward towards the lowlands. This hypothesis is further supported by the fact that the iceberg-related features appear mostly spatially restricted to elevated areas of the northern plains near the dichotomy boundary. However, proposed boundary Late Hesperian glacier valley systems [e.g., 1,7] do not generally extend to the proposed paleoshoreline elevation (Fig. 2).

Tsunami waves as a mechanism for iceberg production

The Martian northern boundary plains appear extensively resurfaced by numerous Late Hesperian tsunami waves [8,9]. We are producing a map showing the approximate location of a latitudinal band of glacier systems in northwestern Arabia Terra and the projected incursion distance of the tsunami waves in the region. We find that the glacier valleys would have been likely extensively flooded by the waves (Fig. 2). Reworking of large boulders into bedforms during the backwash retreat phase evidence extremely powerful seaward currents [8] that would have also rafted large volumes of glacial ice, even under cold-based conditions.

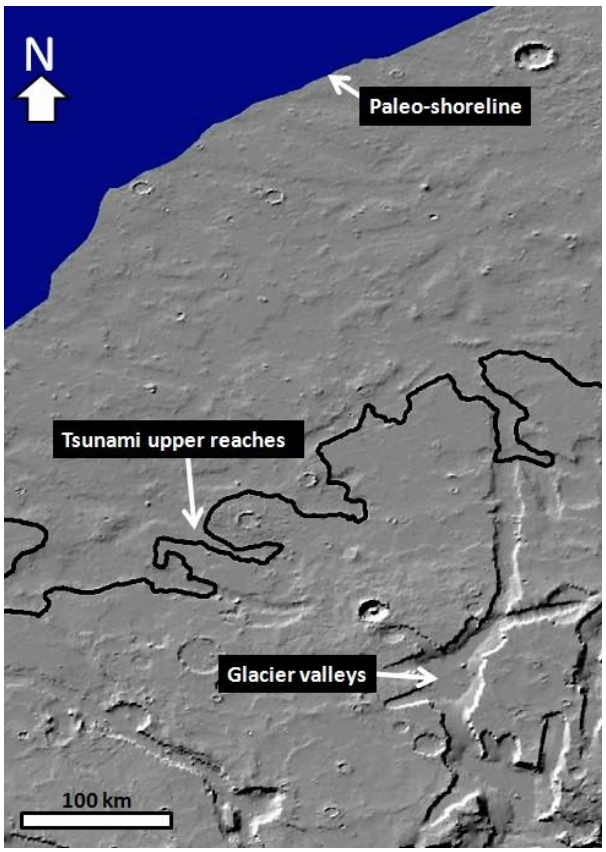

Fig. 2: View of northwestern Arabia Terra showing the locations of (1) canyon systems interpreted as glacier valleys, and their embayment by Late Hesperian tsunami deposits. The paleoshoreline elevation and tsunami margins are close-up views of a map shown in [8]**.** The base of the map is a MOLA shaded relief.

The removal of glacial ice by the tsunami(s) would have generated a peak in iceberg production, which might have been followed by subsequent spikes in productivity if glacial ice was effectively replenished during the intervening time.

Martian icebergs and the northern plains history

Our investigation indicates that Martian icebergs produced landforms similar to terrestrial analogous counterparts. However, we expect that because of the extremely cold climatic conditions that existed on Mars during the Late Hesperian [10], the icebergs could have remained stable for significantly longer than on Earth.

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