TSUNAMI WAVES EXTENSIVELY RESURFACED THE SHORELINES OF AN EARLY MARTIAN OCEAN.

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Introduction: Viking image-based mapping of a widespread deposit covering most of the northern lowlands of Mars led to the proposal by Parker et al. [1-2] that the deposit represents the vestiges of an enormous ocean that existed ~3.4 Ga. Later identified as the Vastitas Borealis Formation [3], the latest geologic map of Mars [4] identifies this deposit as the Late Hesperian lowland unit (lHl). This deposit is typically bounded by raised lobate margins [5-7]. In addition, some margins have associated rille channels [2], which could have been produced sub-aerially by the backwash of high-energy tsunami waves. Radar-sounding data indicate that the deposit is ice-rich [8]. However, until now, the lack of wave-cut shoreline features and the presence of lobate margins have remained an impediment to the acceptance of the paleo-ocean hypothesis.

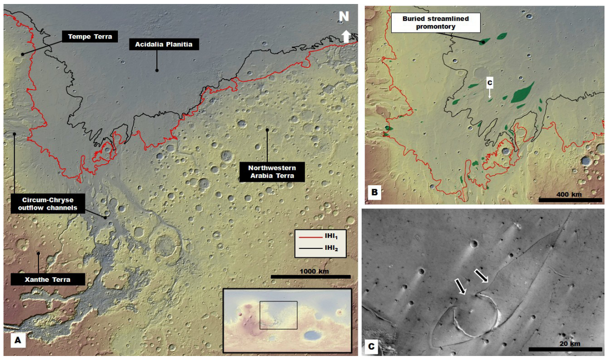

Figure 1 (A) Regional view of sections of circum-Chryse highland-lowland boundary region made up of Chryse and Acidalia Planitiae lowlands and Tempe, Xanthe, and Arabia Terrae highlands; boundary is breached by outflow channels. Red and black lines trace margins of units lHl_1 and lHl_2, respectively. **(B)** Close-up view showing the distribution of streamlined promontories (green) within Chryse Planitia buried by units lHl_1 and lHl_2. (Topography for **A** and **B** from color-coded shaded-relief MOLA digital elevation model (460 m/pixel). **(C)** View of streamlined promontory that is partly buried by a unit lHl_2 lobe. (Part of HRSC image H1436_0000_ND3 (12.5 m/pixel) centered at 30.3°N, 35.9°W.

Here, we present new morphological observations and mapping results based on MRO ConTeXt (CTX), and High Resolution Imaging System Experiment (HiRISE) images and Mars Orbital Laser Altimeter (MOLA) digital elevation data as well as numerical analysis, which indicate that unit lHl's marginal morphologies were generated by two enormous tsunami waves. Our results imply that on early Mars, tsunamis played a major role in generating and resurfacing coastal terrains.

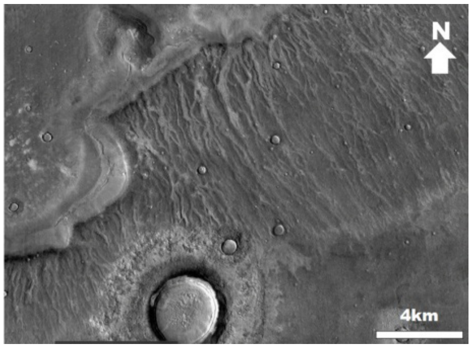

Figure 2 Example of backwash channels in northwestern Arabia Terra displaying streamlined bars (Part of HiRISE image ESP_028537_2270, 25 cm/pixel.)

Morphological characterization of tsunami-related features and spatial relationships: Our new geologic mapping in the Chryse Planitia and northwestern Arabia Terra regions reveals distinct, older and younger members of the Late Hesperian lowland unit (lHl_1 and lHl_2, respectively, Fig. 1A). We find that both members are bounded by south-facing lobes that are typically tens of kilometers in length and width.

However, in Chryse Planitia, these dimensions reach a few hundred kilometers in scale, and typically ascend a few hundred meters between approximately -4100 m and -3200 m of elevation. These deposits embay dozens of streamlined promontories (Fig. 1B and C) scattered over a surface area of ~570,000 km^2. Throughout the eastern part of northwestern Arabia Terra, the marginal parts of unit lHl_1 cover low-slope ramps that are extensively marked by NNW-trending sets of aligned channels proposed to be backwash features (Fig. 2).

These channels were first identified in Viking data [2], but only locally along Arabia Terra in association with their older lowland unit A.

Upslope flows are implied by the highland-facing orientation of the deposits' lobes (Fig. 1B) as well as by their relief gains. These characteristics rule out emplacement by downslope moving gravity-driven flows such as debris flows, floods, glaciers and lavas. Uphill unidirectional winds can generate elongate aeolian deposits known as wind streaks. However, these deposits are mostly composed of sand-sized particles, exhibit surface bedforms, typically cover topographic obstacles along their paths, and mostly have length to width ratios that are more than 1 [e.g., 10]. In contrast, the *lHl* lobes include sediments that range in size up to meter-scale boulders, marginal folds oriented parallel to the flow direction (likely pressure ridges), exhibit flow separation around low-relief knobs, and have length to width ratios that are mostly less than 1 (which is consistent with sideways, and not just uphill unidirectional flow dispersion). Therefore, we propose that the two unit *lHl* members represent successive, highly energetic tsunami wave deposits that resulted from the formation of large bolide impacts into a Late Hesperian paleo-ocean.

Our crater counts statistics show that, while the deposits formed during the Late Hesperian Epoch, their absolute ages could differ as much as several tens of millions of years. The elevation right below the proposed backwash channels is at approximately -3800 m, which provides an upper boundary to the paleoshoreline from which the older tsunami propagated. The lowest margins of the mapped lHl_2 lobes are at approximately -4100 m in elevation, which we have used as a proxy to the paleoshoreline elevation from which the younger tsunami propagated.

Based on our paleo-oceanographic reconstructions we estimate that typical run-up distances are ~190 km and ~210 km for the older and younger tsunami, and their respective maxima reaching ~530 km and ~650 km. Overall the morphometric characterizations of both tsunamis are strikingly similar. The slighter larger dimensions of the younger event is consistent with it extending from a lower shoreline, and therefore, flowing over more boundary plains material. These run-up distances and inundation areas are enormous by terrestrial standards, which explain why the backwash channels exhibit lengths of ~20 km, while terrestrial examples produced by much smaller tsunamis range between ~200 and ~300 m in length [11]. The tsunami forms mostly occur between approximately -4100 m and -3200 m. Consequently, within the study region, tsunami activity associated with a receding Late Hesperian ocean significantly contributed to the typical estimated 1200 m deviation from the shoreline equipotential elevation measured by Head et al. [9].

Tsunami generation and frequency: Numerical simulations show that tsunamis induced by the formation of an impact crater ~30 km in diameter would generate tsunami waves with a typical onshore height of ~50 m and local variations from ~10 m to as much as ~120 m [12]. We estimate that impact craters with a diameter of ~30 km formed at a rate of one every 2.7 million years during the Late Hesperian over the entire ocean's surface. Although we have only identified evidence for two tsunami events in our study area, other regions in the northern plains likely experienced similar tsunami-related coastal resurfacing. Older tsunami deposits may have been completely resurfaced by more recent events with similar run-up distances. Thus, the mapped tsunami margins comprise only the largest magnitude tsunami events located at the highest elevations. Smaller previous tsunamis could have indeed occurred, but their deposits, which would have lower run-up distances, would have been covered or resurfaced by the ones we document in our work.

Climatic implications: The lHl_1 lobes are mostly made up of lithic deposits and exhibit backwash modifications. In contrast, the landward-facing lobate termini of unit lHl_2 lack evidence indicative of a backwash phase subsequent to their emplacement. Like on Earth, the absence of backwash features associated with these flows could have been the result of the waves transitioning into sub-aerial debris-laden slurry flows extending over low gradient surfaces [13, 14]. However, the lHl_2 lobes appear to be mostly composed of water-ice [3,8], suggesting that the transition into slurry likely involved the formation of voluminous bedload made up of ice particles. We propose that these morphologic differences might be linked to colder environmental conditions taking place between the two tsunami events.

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