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Erosion rate and previous extent of interior layered deposits on Mars revealed by obstructed landslides

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ABSTRACT

We describe interior layered deposits on Mars that have obstructed landslides before undergoing retreat by as much as 2 km. These landslides differ from typical Martian examples in that their toe height increases by as much as 500 m in a distinctive frontal scarp that mimics the shape of the layered deposits. By using crater statistics to constrain the formation ages of the individual landslides to between ca. 200 and 400 Ma, we conclude that the retreat of the interior layered deposits was rapid, requiring erosion rates of between 1200 and 2300 nm yr^{-1}. We suggest that the interior layered deposits are either extremely friable, if eroded strictly by wind, or composed of a material whose degradation has been enhanced by ice sublimation. These erosion rates also confirm that the interior layered deposits have been in a state of net degradation over the past 400 m.y., suggesting that the process that caused net deposition in the past has ceased or slowed substantially on Mars relative to erosion. Our results imply that interior layered deposits with a similar morphology across Mars, including the mound in Gale Crater, have probably undergone similar rapid erosion and retreat, suggesting that their total modern volume underrepresents the depositional record and thus sedimentary history of Mars.

INTRODUCTION

Landslides on Mars typically have runout distances much larger than equivalent features on Earth (Quantin et al., 2004a), and therefore can interact with older landforms that are distal to the failure scarp. Regardless of the exact formation mechanism of these landslides (Soukhovitskaya and Manga, 2006), it is evident that their combined large area and relatively well constrained formation age can be exploited to better understand the evolution of coincident features, particularly if those features have been modified since the landslide event. Mounds of layered deposits, often several kilometers in height, are common in the canyons (Lucchitta et al., 1994) and impact craters (Malin and Edgett, 2000) of Mars. These interior layered deposits (ILDs) are high-priority targets for exploration because they not only preserve long sequences of the stratigraphic record of Mars, but also exhibit evidence for hydrous mineral phases that indicates aqueous activity. Despite their importance, no consensus exists regarding how ILDs form and evolve. Their volumetric contribution to the global sedimentary record is also unknown. In this study we utilize the long runout nature of landslides on Mars and identify a unique region in Ophir Chasma, Valles Marineris, where ILDs have obstructed and diverted landslides. We use the age of the landslides to estimate the erosion rate of the ILDs and discuss the implications for the wider sedimentary history of Mars.

LANDSLIDE MORPHOLOGY

Obstructed Landslides

We used Mars Reconnaissance Orbiter Context Camera (CTX) visible wavelength images (5–6 m/pixel) and stereo-derived digital terrain models (DTMs) at 20 m/pixel to map and characterize the terminal edges of long runout landslides. In one location, where CTX stereo coverage was insufficient, we used a (100 m/pixel) High Resolution Stereo Camera (HRSC) DTM. We produced CTX stereo DTMs using standard methods (Kirk et al., 2008), with the vertical precision of the two DTMs estimated, using previous techniques (see Kirk, 2003), as 7.5 and 3.7 m.

We have identified three major occurrences of landslide deposits in Ophir Chasma (Fig. 1) that are indicative of obstruction and diversion by ILDs that are no longer present. These landslides differ from typical Martian examples in that their toe height increases at the landslide front, an indication that the landslides were obstructed. The elevated toes show distinctive concave scarp faces that are as much as 500 m above the canyon floor and as much as 400 m higher than the immediate upslope region of the landslide. This process of landslide obstruction is demonstrated in Coprates Chasma, where landslides have ridden up between 500 and 800 m in height against bedrock material that has not subsequently been removed (Fig. DR2 in the GSA Data Repository[1]). Typical unobstructed Valles Marineris landslide topographic profiles consist of a steep headwall in the source region (failure scarp), with a long-profile slope that gradually decreases to the landslide toe (Quantin et al., 2004a) (Fig. DR2). Furthermore, by comparison with other landslides in Valles Marineris, it is evident that these frontal scarps have an elevation profile that cannot be accounted for by typical thrust faulting that is caused by deceleration and compression in the toe. The frontal scarps are also unlikely to be remnants of the ILDs because they have a different geomorphic expression and have a surface texture that is clearly continuous with the landslide. The landslide toe scarps in Ophir Chasma mimic the shape of the ILDs, which are currently 1–2 km away from the landslide front (Fig. 1). This indicates that the landslides were obstructed by the ILDs and that the ILDs have since retreated toward the interior of the chasma.

Age of Landslides

The interaction between the landslides and the ILDs provides a unique case on Mars where ILD retreat can be directly linked to a rapid, catastrophic event that provides a distinct time stamp for estimating retreat rates. Previous studies have constrained the formation of the Valles Marineris canyon system to the Late Noachian to Hesperian Epochs (ca. 3.7–3.0 Ga) (Schultz, 1991). ILD formation postdates the opening of the canyons with plausible formation ages that span the Hesperian (Fueten et al., 2008) through the entire Amazonian (Okubo, 2010). Previous studies have also attempted to date individual landslides using impact crater statistics, providing ages for Valles Marineris examples that range from 3.5 Ga to 50 Ma. For the landslides in Ophir Chasma (Quantin et al., 2004b), previous chronology data indicate ages between 1 Ga and 80 Ma. Here we refine the landslide age estimates from crater statistics based on higher resolution CTX imagery.

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[1] GSA Data Repository item 2014287, Figure DR1 (context map), Figure DR2 (typical Valles Marineris landslide profiles), Figure DR3 (perspective view of an obstructed landslide), Figure DR4 (schematic summary diagram), Figure DR5 (crater count result for ILDs), estimate of ILD volume loss, and Table DR1 (results of landslide crater counts), is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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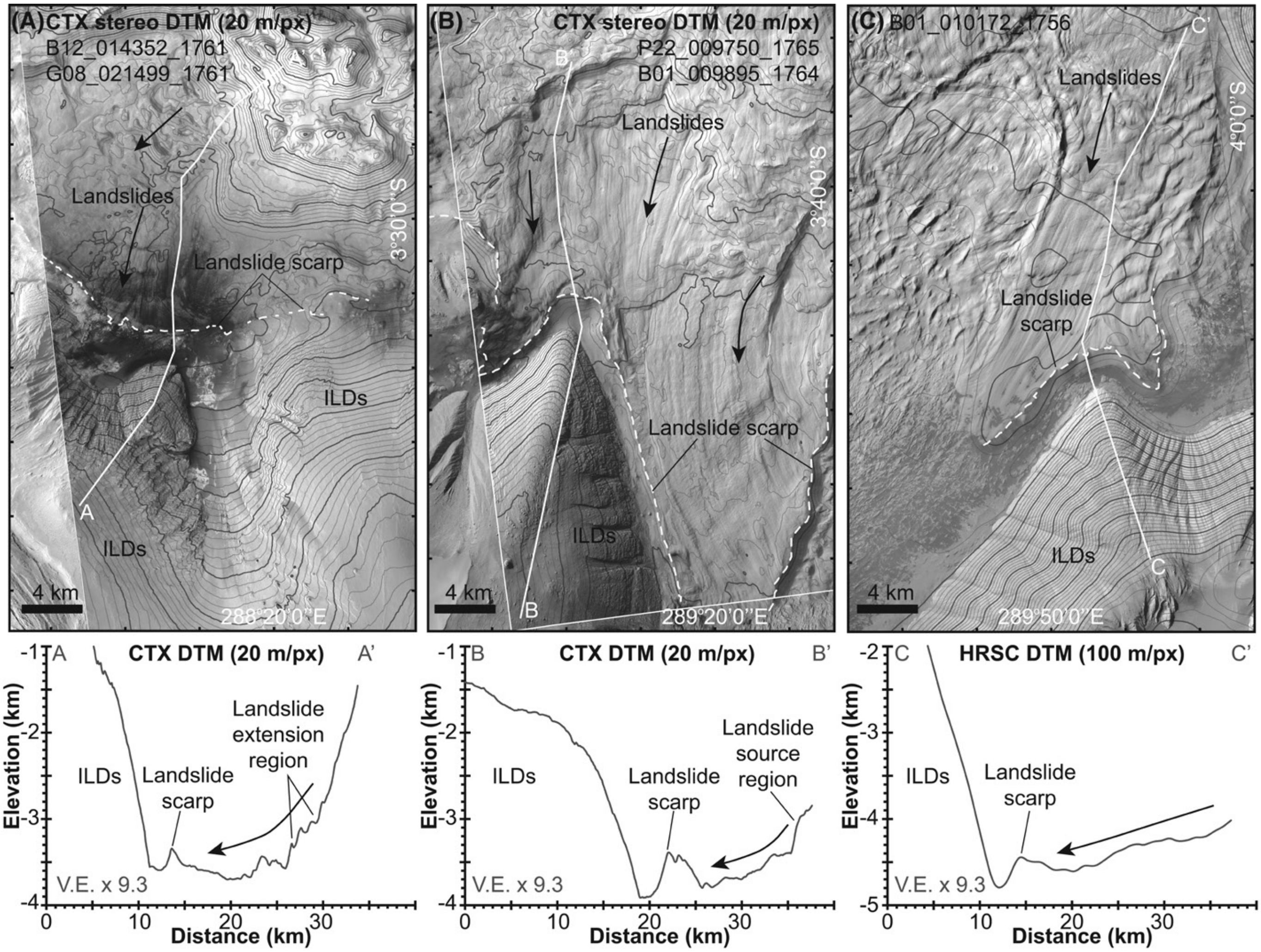

Figure 1. Identification of landslide diversion and obstruction in Ophir Chasma, Valles Marineris, Mars, including Mars Reconnaissance Orbiter Context Camera (CTX) images, digital terrain model (DTM) contour maps, and topographic profiles showing frontal scarps and interior layered deposits (ILDs). Dark contours = 500 m, light contours = 100 m. V.E.—vertical exaggeration; px—pixel. A: Westernmost landslides. B: Central landslides. C: Easternmost landslides.

To determine the relative superposition age of the different landslides we inspected the boundaries between different lobes to identify a relative age. The overlapping nature of the lobes, and the lack of noticeable burial or erosion of the landslide deposits, means that the relative stratigraphic ages can be determined with confidence (Fig. 2). To estimate the absolute age of the different landslides we used CTX images and standard crater counting techniques (Hartmann and Neukum, 2001; Ivanov, 2001; Michael and Neukum, 2010). We counted every crater >100 m in diameter, in units ranging in area from ~160 to 510 km^2. In total, we counted 1122 craters over a landslide area of 1752 km^2. The data suggest, for the central and eastern landslides in our study region, formation ages of 216 (+23/–24) to 423 (+55/–58) Ma (Fig. 2). As confirmation of the crater chronology technique, the absolute model ages for individual landslides are consistent with the relative superposition relationships between different landslide lobes; for example, the topographically lowest landslide lobe has the oldest model age, 423 Ma, and the youngest mapped lobe indicates a 216 Ma age.

INTERIOR LAYERED DEPOSITS

Erosion Rate

The paucity of impact craters on the ILDs in Ophir Chasma, and elsewhere on Mars, is evidence of recent erosion of the ILDs. The ~30 craters >50 m in diameter on the ILDs have a crater size-frequency distribution that does not follow established isochrons, suggesting that craters are being obliterated and a possible crater retention age of ca. 140 Ma (Fig. DR5). However, the combination of well-constrained chronology and the unique circumstance of diverted landslides provides an opportunity to quantify the erosion rate of the ILDs. Because the landslides did not overtop the ILD obstacle, there must have been at least 500 m (depth) of ILD material removed, the mean maximum height of the frontal landslide scarps. Removing 500 m of the ILD mound over the time scales provided by the landslide ages gives an erosion rate between 1200 and 2300 nm yr^{-1}. By comparison, globally averaged erosion rates for Mars (Golombek et al., 2006) have been estimated as 0.02–7700 nm yr^{-1}. The higher rates are derived from only the most ancient, Late Noachian terrains where ubiquitous fluvial and eolian activity modified terrains in the presence of a thicker atmosphere. For Hesperian–Amazonian surfaces of similar age to the ILDs of this study, erosion rates are generally considered to be several orders of magnitude lower. For example, the highest estimated erosion rate for a Hesperian-age surface at the Viking Lander 2 site is 100 nm yr^{-1}. The lowest reported rate at the Mars Pathfinder landing site is 0.02 nm yr^{-1}. All erosion-rate estimates for the Hesperian–Amazonian Epochs on Mars are therefore too low to account for such a rapid loss of material from the ILDs in the time

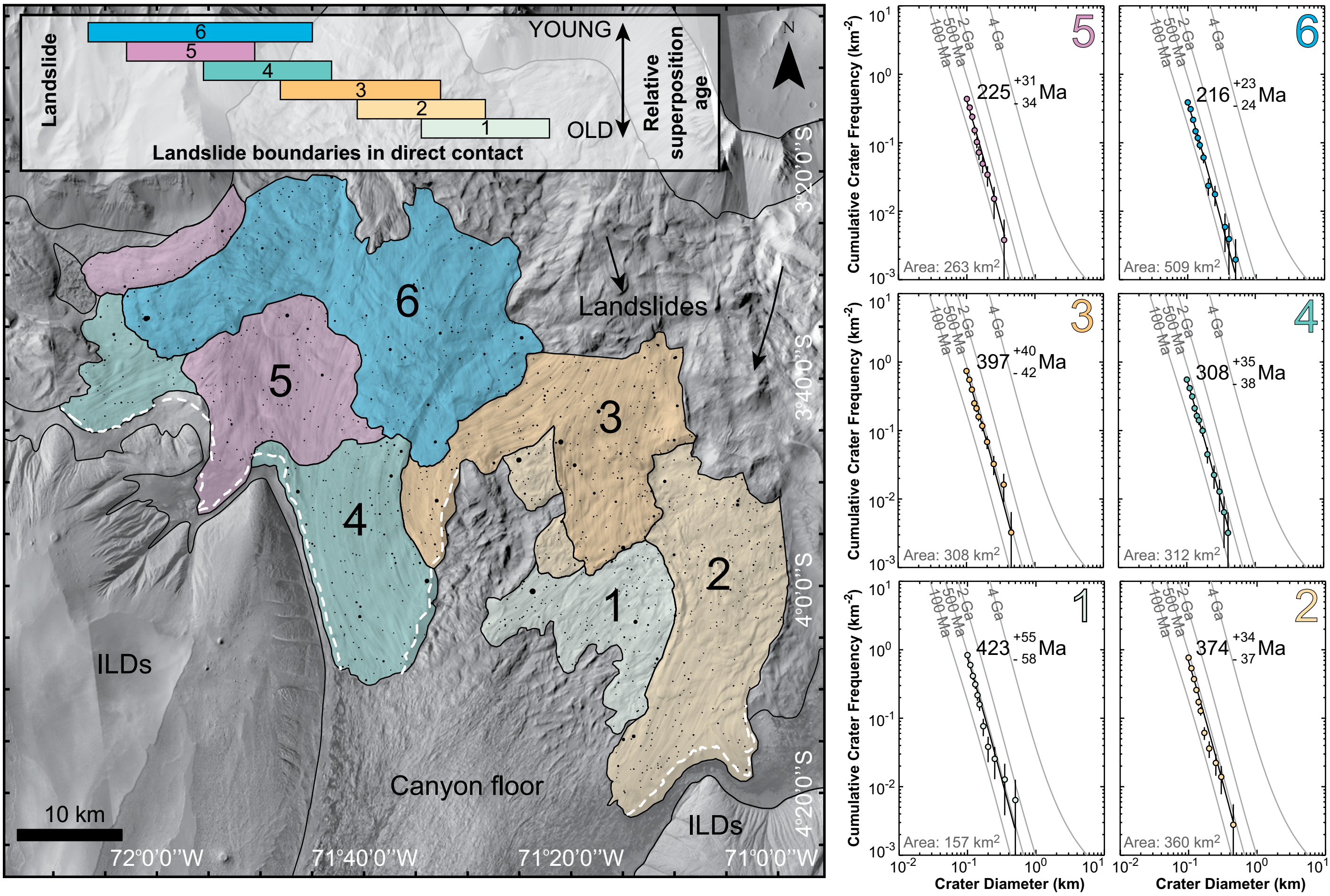

Figure 2. Landslide ages from crater count studies. Left: Mars Reconnaissance Orbiter Context Camera base map showing location of the six landslides dated using crater counting. Numbers represent relative stratigraphic position of the landslide as inferred from superposition relationships. ILDs—interior layered deposits. Inset shows relative stratigraphic age determined from landslide boundaries in direct contact. Right: Binned cumulative crater frequency histograms for each landslide, according to number in left image. Production function is from Ivanov (2001); chronology function is from Hartmann and Neukum (2001).

since the landslides formed. Using the highest Hesperian estimate would require ~5 b.y. to remove 500 m of ILD material. We conclude that the ILDs in Ophir Chasma have undergone degradation by some mechanism at a rate that far exceeds any other surface or material reported for the Amazonian.

EROSION MECHANISM

The rapid erosion of ILDs is likely related to the complex interplay between the mechanism of sediment mobilization and the material properties (composition, compaction, and lithification). We present two possible mechanisms to explain such rapid degradation: (1) eolian modification of poorly lithified materials in the ILD mound, and (2) sublimation of cementing ice and disaggregation. The second mechanism would likely also require an eolian component to mobilize and remove the disaggregated sediment from the region. Importantly, no debris aprons, fans, or large eolian bedforms are present at the base of the ILDs, indicating that there was efficient removal of sediment from the mound.

Eolian Abrasion

A recent study (Bridges et al., 2012) derived mean eolian abrasion rates on Mars of between 4950 and 27,500 nm yr^{-1}, accounting for Martian boundary conditions (e.g., gravity, atmosphere). These abrasion rates could plausibly remove 500 m of ILD material in 18–101 m.y. These accelerated rates are the result of saltation, a process that is capable of eroding friable material in hyperarid deserts on Earth (Rohrmann et al., 2013) at rates that are comparable to fluvial processes in more temperate climates. It is therefore physically plausible on Mars as well as Earth to remove substantial volumes of material by solely eolian processes given a friable substrate and the boundary conditions and grain sizes (sand sized) to support saltation-driven abrasion. For the ILDs of Ophir Chasma, large grooves on some sloping surfaces attest to an abrasive process that may have been triggered by off-mound slope winds (e.g., katabatic winds). These grooves are morphologically similar to yardangs on Earth and elsewhere on Mars and may represent the geomorphic expression of ILD retreat. However, other regions of the mound, including those most proximal to the landslide divergence point where retreat has clearly occurred, do not show evidence for yardang formation. At these locations it is possible that retreat is caused by more uniform abrasion or another process altogether.

Ice Sublimation

An alternative explanation for rapid degradation, and possibly more uniform degradation of the ILDs, requires the disaggregation of ice-cemented sedimentary materials through sublimation. Ice could have been present from the initial formation of the ILDs (Michalski and Niles, 2012), from a previous glacial system in Valles Marineris (Gourronc et al., 2014), or more recent obliquity-driven processes (Madeleine et al., 2009). Sublimation of ice on Mars is a complex process that depends heavily on parameters such as ambient and surface temperature, regolith diffusion properties, and wind (Williams et al., 2008). Here we estimate the likely minimum sublimation rate for the upper bound on the time required to remove 500 m of ice. The likely range of ambient temperatures in Ophir Chasma (Millour et al., 2012) gives rise to sublimation rates (Chittenden et al., 2008) that are as much as five orders of magnitude greater than the globally averaged Hesperian to Amazonian surface erosion rates, resulting in a maximum time of ~57 m.y. to remove 500 m of ice. Although it is unknown whether ice formed a significant volume of the ILDs, the possible rate of ice sublimation is likely always several orders of magnitude greater than the globally averaged erosion rate under a given environmental condition, and so cannot be ruled out as a contributing loss mechanism. Importantly, if the ice sublimation model is correct, it would imply that large ice-rich deposits were present as recently as 400–200 Ma at the equator on Mars.

CONCLUSIONS AND IMPLICATIONS

We conclude that the ILDs of Ophir Mensa have eroded at rates that require the target material to be either friable and easily mobilized through saltation-driven eolian abrasion, or to contain significant cemented ice that has allowed rapid degradation, enhanced by eolian processes. Either scenario has major implications for the origin, evolution, and extent of ILDs across Mars. Both mechanisms imply that ILDs are composed of easily mobilized materials, providing possible predictions for the grain size and cementing characteristics of ILDs elsewhere on Mars, including Aeolis Mons at Gale Crater, a location that will soon be sampled by the Mars Science Laboratory. Our results confirm that not only do ILDs erode quickly, but significant volumes of material have been removed and transported away from the mound. Our retreat rates also confirm that these ILDs have been in a state of net degradation over the past 400 m.y., suggesting that the process that caused net deposition in the past, possibly as late as the Amazonian (Okubo, 2010), has ceased or slowed substantially on Mars relative to erosion. For the Ophir Chasma ILDs, we demonstrate unequivocally that the mound was once more extensive in the past and that its modern form underrepresents the actual volume of material that was once deposited into the canyon, in contrast to previous studies (e.g., Kite et al., 2013). Given the similarity between ILDs in different locations on Mars, it is possible that tectonic canyons and impact craters on Mars could have accommodated large volumes of sedimentary materials (pyroclastic, eolian derived, fluvial, lacustrine) that have since been removed. Because many of the ILD mounds on Mars are associated with sulfur-bearing hydrated minerals (Michalski and Niles, 2012), the question of depositional volume has major implications for the sediment budget of Mars and for the total sulfur budget and the global pervasiveness of aqueous alteration.

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