ORIGIN OF LONGITUDINAL RIDGES AND FURROWS ASSOCIATED WITH LONG RUNOUT LANDSLIDES: THE CASE STUDY OF A MARTIAN LANDSLIDE.

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Introduction: Intriguing features that sometimes characterize the deposits of long runout landslides are longitudinal ridges and furrows [1]. On Earth, such features are commonly found in landslides emplaced on glaciers, amongst which is the iconic Sherman Glacier landslide [2]. Consequently, their occurrence in martian landslides is often attributed to the presence of an icy substrate at the time landslides took place. Based on laboratory experiments and field observations, Dufresne and Davies [3] concluded that the formation of longitudinal ridges is the result of the fragmentation of the flowing mass due to failure in extension caused by the material moving faster in the longitudinal flow direction than laterally. Instead, De Blasio [4] suggested that the formation of longitudinal furrows is the consequence of tearing apart of the flowing mass by lateral spreading. Although these two models propose different mechanisms, they both focus on the importance of the nature of the substrate, suggesting a soft terrain that is able to provide strong lubrication, such as snow, ice, and evaporites. However, experimental work and stability analysis on rapid granular flows conducted by Forterre and Pouliquen [5][6] showed the spontaneous formation of longitudinal vortices within the flow. The mechanism proposed to explain the formation of longitudinal vortices is based on density profile inversion. Initially, the strong shear between grains and a rough substrate generates an increase in granular temperature and, consequently, a decrease in density at the base of the flow; the existing density gradient causes the flow to become mechanically unstable; finally, the instability induces the formation of convective longitudinal rolls. Also, it was found that the wavelength of the ridges scales with the thickness of the flow by a factor of ~ 2-3.

Methods: We decided to investigate whether longitudinal ridges and furrows observed on the surface of long runout landslides may have origin from the same mechanism proposed by Forterre & Pouliquen [6]. For this purpose, we conducted morphological and morphometric analysis of a long runout landslide in Coprates Chasma on Mars (Fig. 1) using Context Camera (CTX) and High Resolution Imaging Science Experiment (HiRISE) images. CTX DEMs were created with commercial photogrammetry software SOCET SET.

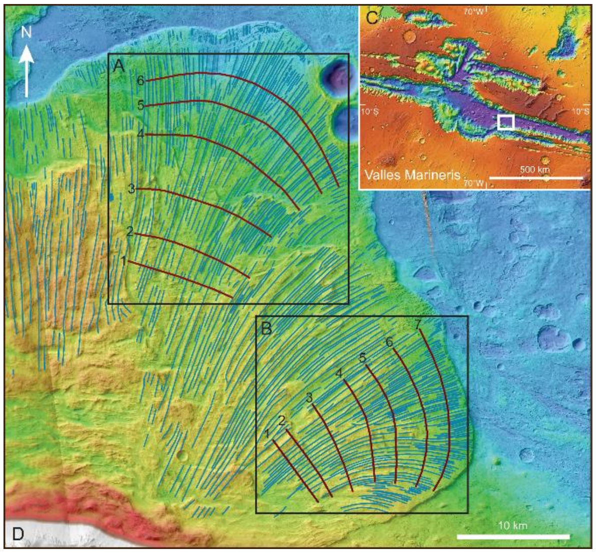

Fig. 1: (C): Valles Marineris, Mars, showing the location of the landslide object of this study in Coprates Chasma (white box). (D): Stereo-derived DEMs using CTX image pairs B21_017688_1685_XN_11S067W /B22_018321_1685_XN_11S068W and P20_008906_1685_XN_11S067W/P22_009763_1690_XN_11S067W. (A) and (B): study areas within which morphological and morphometric characterization was conducted.

Morphological and morphometric analysis: We mapped longitudinal ridges on the surface of the landslide deposit. We chose two areas where to conduct our analysis (A and B in Fig. 1) and traced profiles transver-sal to the flow direction, in order to study how ridges evolve with distance. We measured the spacing between the ridges and counted their number along each profile. Within both areas, from proximal to distal edge of the deposit, we found that ridges diverge while their number increases and their amplitude and wavelength decrease (Fig. 2). Also, we assessed the average thickness of the deposit at each profile and calculated the ratio between the average spacing (S) and average thickness (T). The central area (A in Fig. 1 and Fig. 2) shows a very constant S/T ratio, between 2.55 and 2.99. The right area (B in Fig. 1 and Fig. 2) shows lower values, however still quite constant, between 1.44 and 2.4.

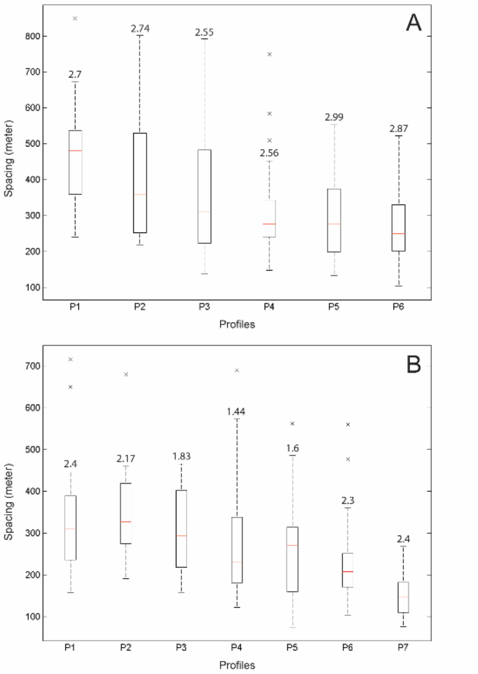

Fig. 2: The plots show how the spacing between longitudinal ridges varies with distance (from proximal to distal areas of the deposit; in the plots, from left to right). A and B letters refer to the study areas as illustrated in Figure 1. The numbers above whiskers represent the ratio between average spacing (S) and average thickness (T) at any given profile.

Discussion: Our results suggest a scaling relationship between the wavelength of ridges and the average thickness of the landslide deposit, as found by Forterre and Pouliquen [5]. Also, Forterre and Pouliquen [5] noticed that the vortices drift in the transverse direction, leading to complex evolution that includes annihilation and creations of ridges. We question whether the appearance of new ridges that we observed derives from this complex mechanism (Fig. 3a and 3b). Close-up inspections allowed us to identify s-shaped linear features superposed on longitudinal ridges that we attributed to a velocity gradient (Fig. 3c and 3d). Their orientation suggests a flow structure with fast-moving regions corresponding to ridges and slow-moving regions corresponding to furrows. Forterre and Pouliquen [5] also reported about a velocity gradient and further experiments and modeling by Borzsonyi et al. [7] identified two opposite flow structures, which depend on whether being in a dilute regime or a dense regime. Our observations match with the flow structure in a dense regime.

Conclusions: We speculate that longitudinal ridges associated with long runout landslides may be expression of an induced instability within the flowing mass that generates the formation of longitudinal vortices, as observed by Forterre and Pouliquen [5] in laboratory experiments on rapid granular flows. Our results and observations could represent the first field evidence of such experimental work and modelling. Although not ruling out the presence of ice and other mineralogical facies as a key factor for the generation of long runout distances, our results suggest that the origin of longitudinal ridges does not necessarily depend on the nature of the substrate, challenging the environmental link proposed to explain the occurrence of such features.

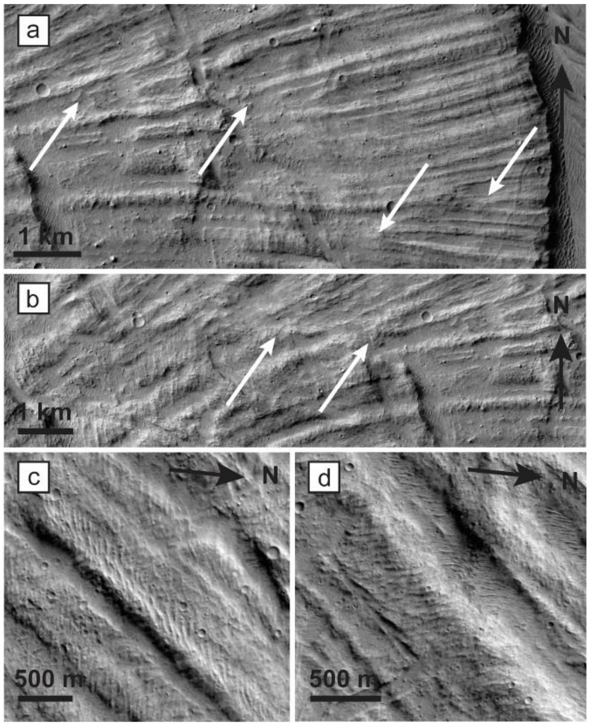

Fig. 3: Images (a) and (b) showing the appearance of new, smaller ridges between diverging ridges, as indicated by white arrows. Images (c) and (d) showing s-shaped linear features superposed on longitudinal ridges.

References: [1] Lucchitta B.K. (1979) *JGR, 84*, 8097-8113. [2] Marangunic C. and Bull C. (1968) *PNAS*, *1603*, 383-394. [3] Dufresne A. and Davies T.R. (2009) *Geomorphology, 105*, 171-181. [4] De Blasio F.V. (2011) *Planet. Space Sci., 59,* 1384-1392. [5] Forterre Y. and Pouliquen O. (2001) *Phys. Rev. Lett., 86,* 5886-5889. [6] Forterre Y. and Pouliquen O. (2002) *J. Fluid Mech., 467,* 361-387. [7] Börzsönyi et al. (2009) *Phys. Rev. Lett., 103*, 178302.