A Survey in Space and Time of Dust Lofted by CO_2-sublimation-triggered Mass Wasting on Martian Sand Dunes

M. Kefa, *Nantes Université, Univ Angers, Le Mans Université, CNRS, Laboratoire de Planétologie et Géosciences, LPG UMR 6112, 44000 Nantes, France (mariakefa@yahoo.gr)*, **S. J. Conway,** *Nantes Université, Univ Angers, Le Mans Université, CNRS, Laboratoire de Planétologie et Géosciences, LPG UMR 6112, 44000 Nantes, France (susan.conway@univ-nantes.fr)*, **L. Roelofs**, *Department of Physical Geography, Faculty of Geosciences, Utrecht Univesity, The Netherlands*.

Introduction: Mars' winters are sufficiently cold that carbon dioxide condenses from the atmosphere onto the surface [12]. Its sublimation in the spring can mobilise dust and other sediments and on martian sand dunes can cause mass wasting features [1, e.g., 16]. These mass wasting features come in a variety of forms, including: i) classic gullies – up to kilometre-scale features with a tributary alcove often extending to the dune crest, a somewhat braided and sinuous transport channel and a terminal depositional fan [2, 13, 14], ii) linear gullies - up to kilometre-scale features dominated by a parallel-sided channel with marked levees, which can be extremely sinuous [1, 8, 10, 15]. The alcove is limited to shallow tributary channels near the dune-crest and the termination of the channel is abrupt and rounded often surrounded by individual pits, iii) recurrent diffusing flows (also called perennial rills) – ephemeral hundred-metre scale features with shallow converging and diverging channels of similar depth to the dune ripples, and can have associated pits , and iv) alcove-fan features: hundred-metre scale features characterised by a niche cut into the dune slip face directly connected to a depositional fan at the base of the slope with no visible channel(s) [21]. Features i-iii have only been documented in the southern hemisphere, where the seasonal deposition of CO_2 ice is known to be thicker and more pure [7].

Dinwiddie and Titus [3] were the first to notice that activity in linear dune gullies was accompanied by lofted dust clouds, which then leaves a bright halo around the dark core of the active linear gully. This halo had been noted by previous studies [8, 15], but not connected to lofted dust. Pasquon et al. [13] also noted a similar bright halo around new deposits of classic gullies on dunes. Hence, these halos seem to be a good indicator of recent activity independent of the type of mass wasting process. Therefore, in this study we search for these bright halos in all available orbital imaging data to better understand the influence of the seasonal defrosting on sediment transport within these dune fields.

Approach: To search for halos we use orbital image data from: i) NASA Mars Reconnaissance Orbiter High Resolution Imaging Science Experiment (MRO HiRISE) at 25-50 cm/pix which takes images with a ~5 km wide swath with a central ~0.5-1 km-wide colour strip [11], ii) ESA's Trace Gas Orbiter Colour and Stereo Imaging System (TGO CaSSIS) at 4.5 m/pix which takes colour images with a ~2-8 km wide swath [20], and iii) MRO Context (CTX) monochrome images at 6 m/pix and a ~25 km swath width [9]. Colour images allow us to best identify halos, whereas monochrome images only allow halos to be identified when they form on an ice-free dune surface (the albedo of ice and the halo are very similar). We initially searched dunefields with gullies as listed in [2, 15] and expanded this search to surrounding dunefields. We did not systematically examine every dunefield.

Each halo was mapped with a point feature and associated with the metadata of the image in which it was first observed. To understand the orientation of the duneslopes on which the halos originate, we digitised lines that represent the mean downslope direction where halos are found and associated a line orientation with each halo point.

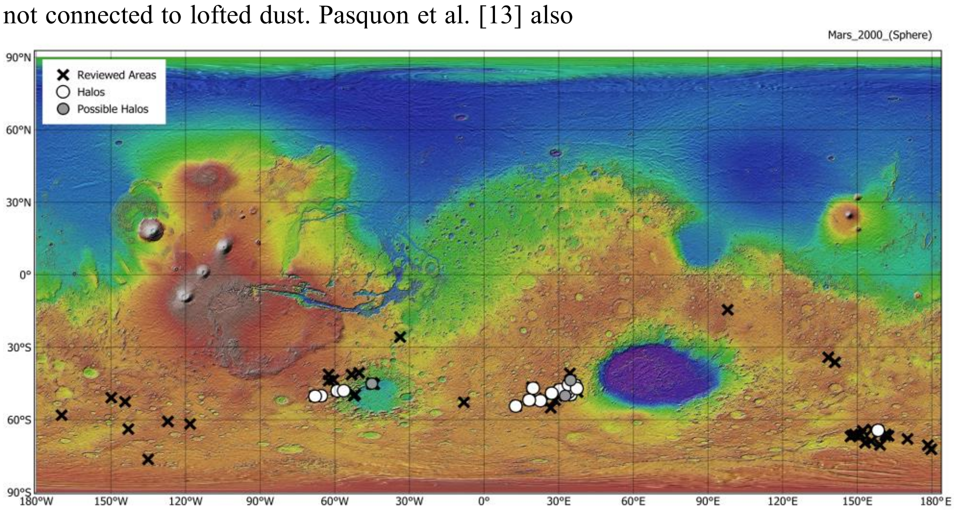

***Figure 1:** Symbols indicate the dunefields examined during this work on a colourised and hillshaded topographic map from MOLA, where red colours indicate high elevation and blue, low elevation.*

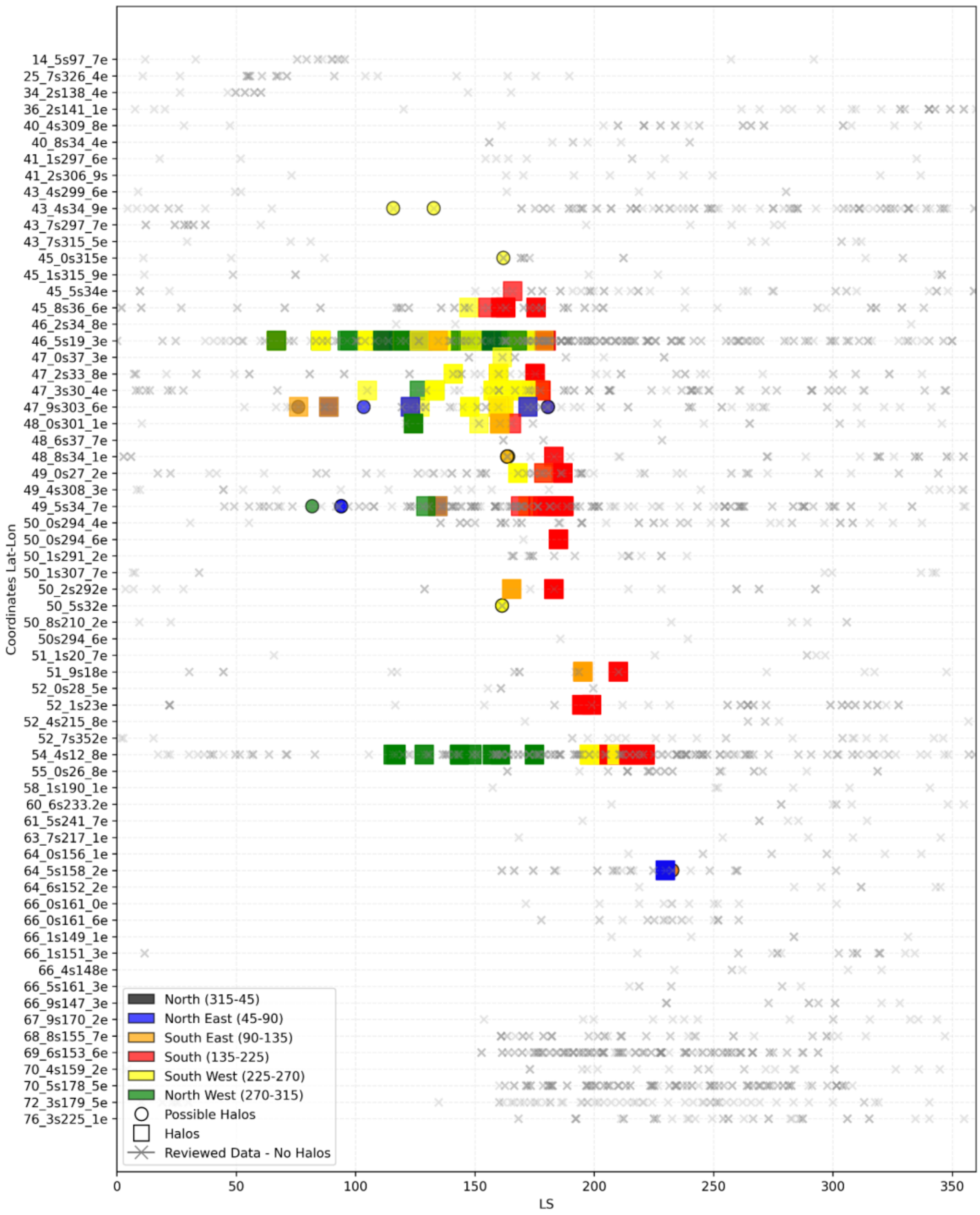

Figure 2: *Distribution in latitude and time (Solar Longitude "LS" in degrees) of the reviewed image data with coloured points indicating the identified halos and the orientation of the duneslope hosting them. Note that the y-axis is ordered by increasing latitude, but the scale is not linear.*

Results: In total, we identified 878 halos across 17 southern hemisphere dune fields, in 197 images: 152 from HiRISE, 37 from CTX, and 8 from CaSSIS (Figure 1). 387 halos are associated with classic dune gullies, 239 with linear dune gullies and 525 with recurrent diffusing flows. Dark pits are found in 65 cases associated with halos, as also found at the classic gully on Kaiser dunefield by Pasquon et al. [13].

The halos are first observed at solar longitude (Ls) 67° and continue to appear until Ls 230° (note that Ls 90° is the spring equinox and 270° is the summer solstice in the southern hemisphere; Figure 2). While the study focused on identifying halos, so not all dune fields were systematically searched, for 46 of the reviewed dunefields halos were not identified, despite images falling within the expected latitude and solar longitude ranges (Ls 50°-250°).

The orientation of the duneslopes on which halos are found varies systematically with solar longitude and also with latitude – south-facing slopes only host halos towards the end of the defrosting season and the lowest latitude sites only have halos on south-facing slopes (Figure 2). North-facing slopes rarely host halos, where the majority of these detections are in Kaiser Crater dunefield. Halos are rare at latitudes equatorward of 45°S and poleward of 55°S.

We find two principal configurations of frosted in and defrosted surfaces in association with halos: i) the top of the duneslope is defrosted and the halo is found superposed on the frosted slope below, ii) only the top of the duneslope has frost and the halo is found on the (mostly or completely) frost-free duneslope below (Figure 3).

Discussion and conclusions: Our study reveals that dusty halos appear annually between Ls 67° and 230° (spring to early summer) on dunefields between

45°S and 55°S with some rare observations outside this latitude range. These latitudinal constraints match with the observed distribution of linear and classic dune gullies as reported in previous studies [2, 15], and the seasonal timing matches with previously reported activity in martian gullies in general [2, 4–6, 15].

Our observations support the hypothesis that halos are a direct result of rapid CO_2 sublimation caused by the contact of defrosted (and relatively hot) sand encountering frosted materials [18]. As the locations of frosted and defrosted surfaces changes during the retreat of the seasonal ices in the spring, so do the locations/orientations of halos (Figures 2 and 3). Halos are associated with a variety of mass wasting processes and importantly occur on dune slopes without any kind of gullies, showing CO_2 sublimation-driven mass wasting processes drive more sediment transport than represented by these landforms.

We suggest that halos are rare poleward of 55°S because the seasonal ice deposits are more continuous [7, 17] and the temporal window during which defrosted and frosted surfaces co-exist in proximity is limited compared to lower latitudes. Another important factor is the availability of steep slopes to drive mass wasting – dunefields located polewards of 55°S have systematically fewer slipfaces (steep slopes) than those at lower latitudes [19].

Equatorward of 45°S, we suggest that CO_2 seasonal ice deposits become too thin and discontinuous to support mass wasting on dunes. This observation is somewhat puzzling because active gullies outside dunefields are found equatorward of 45°S and are thought also to be driven by CO_2 sublimation processes [4–6]. We suggest that the type of seasonal CO_2 ice on dunes may change from continuous portions of slab to more granular frost at this latitude, explaining this disconnect in activity between the two gully-types.

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References cited:

[1] Diniega, S. et al. 2013. A new dry hypothesis for the formation of martian linear gullies. *Icarus*. 225, 1 (Jul. 2013), 526–537. DOI:https://doi.org/10.1016/j.icarus.2013.04.006.

[2] Diniega, S. et al. 2010. Seasonality of present-day Martian dune-gully activity. *Geology*. 38, 11 (Nov. 2010), 1047–1050. DOI:https://doi.org/10.1130/G31287.1.

[3] Dinwiddie, C.L. and Titus, T.N. 2021. Airborne Dust Plumes Lofted by Dislodged Ice Blocks at Russell Crater, Mars. *Geophysical Research Letters*. 48, 6 (Mar. 2021). DOI:https://doi.org/10.1029/2020GL091920.

[4] Dundas, C.M. et al. 2015. Long-Term Monitoring of Martian Gully Formation and Evolution with MRO/HiRISE. *Icarus*. 251, (2015), 244–263. DOI:https://doi.org/10.1016/j.icarus.2014.05.013.

[5] Dundas, C.M. et al. 2010. New and recent gully activity on Mars as seen by HiRISE. *Geophysical Research Letters*. 37, 7 (2010). DOI:https://doi.org/10.1029/2009gl041351.

[6] Dundas, C.M. et al. 2019. The Formation of Gullies on Mars Today. *Geological Society, London, Special Publications*. Martian Gullies and their Earth Analogues, 467 (2019). DOI:https://doi.org/10.1144/SP467.5.

[7] Hansen, C.J. et al. 2024. A comparison of CO_2 seasonal activity in Mars' northern and southern hemispheres. *Icarus*. 419, (Sep. 2024), 115801. DOI:https://doi.org/10.1016/j.icarus.2023.115801.

[8] Jouannic, G. et al. 2019. Morphological characterization of landforms produced by springtime seasonal activity on Russell dune (Mars). *Geological Society, London, Special Publications*. 467, (2019). DOI:https://doi.org/10.1144/SP467.16.

[9] Malin, M.C. et al. 2007. Context Camera Investigation on board the Mars Reconnaissance Orbiter. *J. Geophys. Res.* 112, E5 (mai 2007), E05S04. DOI:https://doi.org/10.1029/2006JE002808.

[10] Mangold, N. 2003. Debris flows over sand dunes on Mars: Evidence for liquid water. *Journal of Geophysical Research*. 108, E4 (2003). DOI:https://doi.org/10.1029/2002JE001958.

[11] McEwen, A.S. et al. 2007. Mars Reconnaissance Orbiter's High Resolution Imaging Science Experiment (HiRISE). *Journal of Geophysical Research: Planets*. 112, E5 (2007), E05S02. DOI:https://doi.org/10.1029/2005JE002605.

[12] Neugebauer, G. et al. 1971. Mariner 1969 Infrared Radiometer Results: Temperatures and Thermal Properties of the Martian Surface. *The Astronomical Journal*. 76, (Oct. 1971), 719. DOI:https://doi.org/10.1086/111189.

[13] Pasquon, K. et al. 2019. Are different Martian gully morphologies due to different processes on the Kaiser dune field? *Geological Society, London, Special Publications*. 467, (2019). DOI:https://doi.org/10.1144/SP467.13.

[14] Pasquon, K. et al. 2019. Present-day development of gully-channel sinuosity by carbon dioxide gas supported flows on Mars. *Icarus*. 329, (Sep. 2019), 296–313. DOI:https://doi.org/10.1016/j.icarus.2019.03.034.

[15] Pasquon, K. et al. 2016. Present-day formation and seasonal evolution of linear dune gullies on Mars. *Icarus*. 274, (août 2016), 195–210. DOI:https://doi.org/10.1016/j.icarus.2016.03.024.

[16] Pilorget, C. and Forget, F. 2016. Formation of gullies on Mars by debris flows triggered by CO_2 sublimation. *Nature Geosci*. 9, (2016), 65–69. DOI:https://doi.org/10.1038/ngeo2619.

[17] Piqueux, S. et al. 2015. Variability of the martian seasonal CO_2 cap extent over eight Mars Years. *Dynamic Mars*. 251, (May 2015), 164–180. DOI:https://doi.org/10.1016/j.icarus.2014.10.045.

[18] Roelofs, L. et al. 2024. How, when and where current mass flows in Martian gullies are driven by CO_2 sublimation. *Communications Earth & Environment*. 5, 1 (Mar. 2024), 125. DOI:https://doi.org/10.1038/s43247-024-01298-7.
[19] Rubanenko, L. et al. 2024. Decreased Dune Slipface Slopes as a Signature of Seasonal Frost on Mars. Mars Polar, Whitehorse, Canada (2024). https://www.hou.usra.edu/meetings/marspolar2024/pdf/6069.pdf
[20] Thomas, N. et al. 2017. The Colour and Stereo Surface Imaging System (CaSSIS) for the ExoMars Trace Gas Orbiter. *Space Science Reviews*. 212, 3–4 (Nov. 2017), 1897–1944. DOI:https://doi.org/10.1007/s11214-017-0421-1.
[21] Diniega, S. et al. 2019. Diniega, Serina, et al. "Dune-slope activity due to frost and wind throughout the north polar erg, Mars. *Geological Society, London, Special Publications*. 467, (2019). DOI:https://doi.org/10.1144/SP467.6

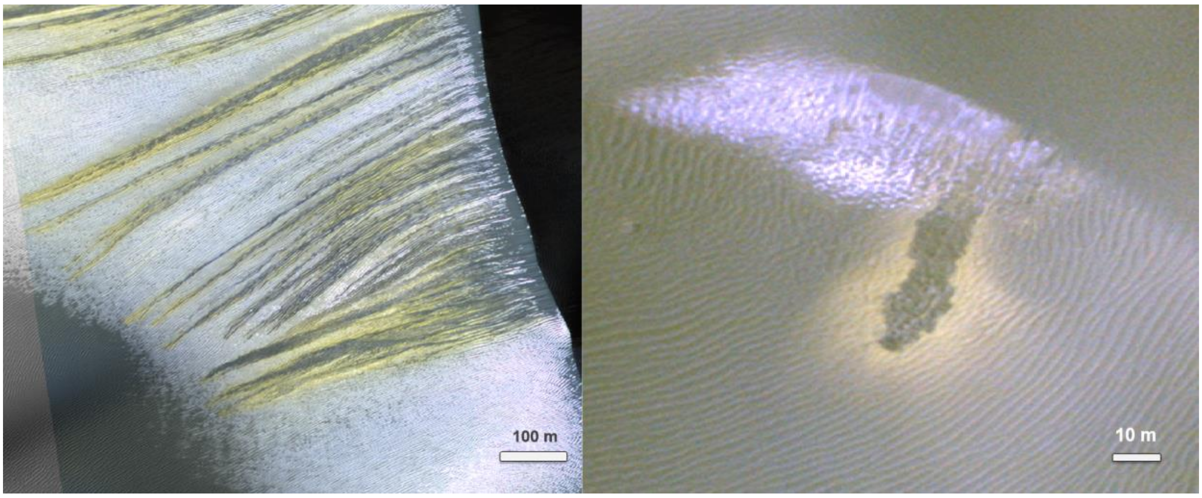

Figure 3: left *west-facing dune slope with halos on frost around dark mass wasting features originating from the defrosted dune crest in HiRISE image ESP_045825_1325 taken at Ls 148° on Kaiser Crater dunfield and* ***right*** *a south-facng slope with a halo around a dark mass wasting feature originating from a dune crest with frost in HiRISE image ESP_073149_1300 taken at Ls 185° on Matara Crater Dunfield.*