“Cyroclasticflows” on Mars – granular flows driven by the sublimation of ices and their implications for Martian surface processes in the Late Amazonian

L. Roelofs[1], S.J. Conway[2], T. de Haas[1], [1]*Department of Physical Geography, Faculty of Geosciences, Utrecht University, Utrecht, The Netherlands,* [2]*Laboratoire de Planétologie et Géosciences, Nantes Université, University Angers, Le Mans Université, CNRS, LPG UMR 6112, Nantes, France*

Introduction:

Martian gullies are alcove-channel-fan systems that are undistinguishable from debris-flow systems on Earth (Figure 1.a)[1]. Therefore, they have long been hypothesised to be formed by the action of liquid water and brines[1,2]. However, over the past decade, the formation hypothesis of these landforms has shifted away from a water-driven process and towards a CO_2-driven process, related to the seasonal sublimation of CO_2 ice[3,4]. Over the last years, we have conducted three experimental campaigns (at the Open University, UK, and Aarhus University, Denmark) at varying scales to explore the feasibility of the CO_2-driven granular flow hypothesis. More recently, we have also investigated if the sublimation of water ice can also promote sediment mobility along a slope under Martian conditions. The rationale behind this campaign is the existence of pseudo gullies (Figure 1.b) around the equatorial latitudes on Mars[5]. The formation of these underdeveloped gully systems cannot be explained by a CO_2-driven process due to the absence of CO_2 ice at these latitudes. However, H_2O ice is observed around these latitudes, even in close proximity to the pseudo gullies.

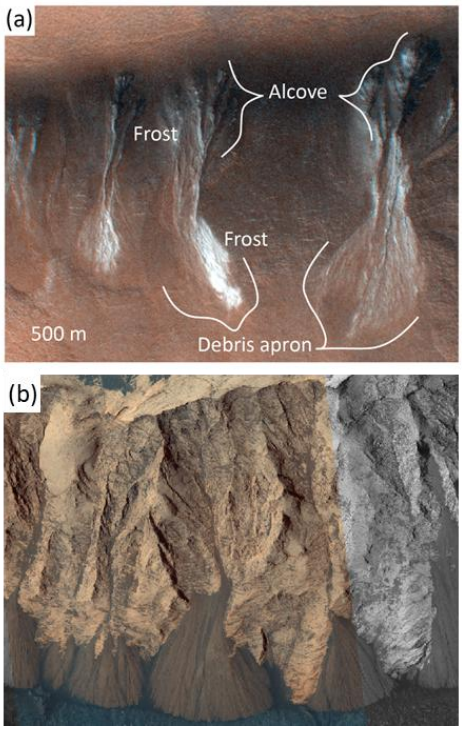


Figure 1: (a) Mid-lattitude gullies on Mars (CaSSIS MY37_023207 _118_0), (b) equatorial “pseudo”-gullies on Mars (HiRISE ESP_032324 _1715)

Granular flows driven by the sublimation of CO_2 ice: From our experimental results with CO_2-driven granular flows we can conclude that these types of granular flows can occur on Mars under a range of specific environmental conditions, that the sublimation of small amounts of CO_2 ice very efficiently fluidizes sediment (Figure 2)[6,7], that the flow dynamics of these flows are akin to terrestrial water-driven debris flows and pyroclastic density currents[7], and that these CO_2-driven granular flows are effective erosive agents (Figure 2.b)[8], likely even more efficient than terrestrial water-driven debris flows. These results combined, advocate for the possibility that CO_2-driven granular flows have been the dominant force in the evolution of Martian gullies in the past 5 million years[9]. However, if either granular flows driven by liquid water, or CO_2-driven granular flows have played the dominant role in Martian gully formation can only be resolved by carefully assessing where, and under which specific micro-climatic conditions on Mars these processes occur.

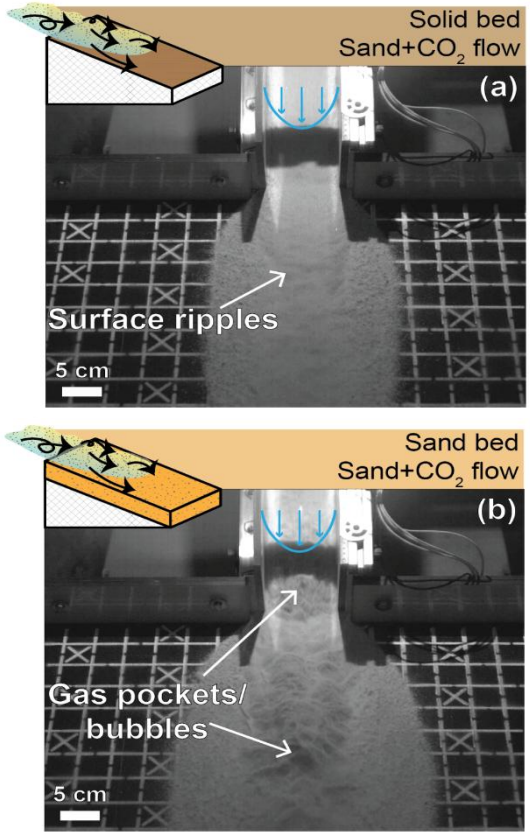


Figure 2: Stills of high-speed footage of experimental CO_2-driven flows under Martian atmospheric conditions. Without (a) and with erosion of an erodible sand bed (b).[8]

The power of H_2O sublimation: Our experiments under Martian atmospheric pressure (5.5 mbar) show that the sublimation of very small amounts of H_2O ice (5 grams) within a granular mixture (1.2 kg of sand) can severely increase the mobility of the granular material on a steep slope (27 degrees) (Figure 3). The more H_2O is present in the granular mixture, the more mobile the material becomes.

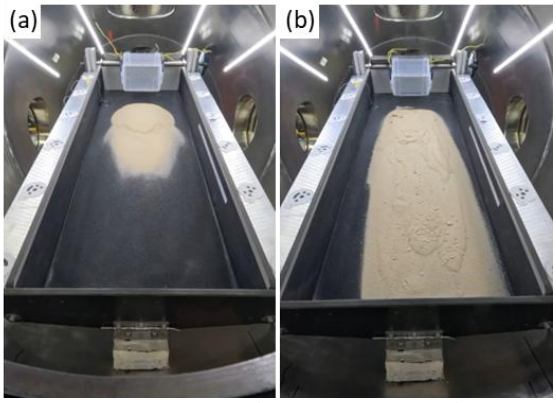


Figure 3: Resulting deposit after releasing 1.2 kg of sand under Martian atmospheric pressure (5.5mbar) on a slope of 27°, with zero H_2O ice on the left (a), and 5 grams of granular H_2O ice mixed into the sand on the right (b).

Food-for-thought: Determining the relative role of liquid water-driven debris flows, H_2O sublimation induced granular transport, and CO_2-driven granular flows in the long-term formation of all Martian gullies is only possible by carefully assessing where, and under which specific micro-climatic conditions on Mars these processes occur.

These "windows of opportunity" for either water-driven or CO_2-driven gully formation than need to be mapped over Martian climate cycles during the Late Amazonian. Although this exercise is beyond the scope of our current research, we present some food-for-thought hypotheses (Figure 4) and hope to inspire discussion within the Martian climate and surface processes community; *when and where are/were these processes active, do/did they interact with other cryospheric processes on Mars, and if so; how?*

Bibliography:

[1]Malin, M. C., & Edgett, K. S. (2000). Evidence for recent groundwater seepage and surface runoff on Mars. *Science*, *288*(5475), 2330-2335. https://doi.org/10.1126/science.288.5475.2330

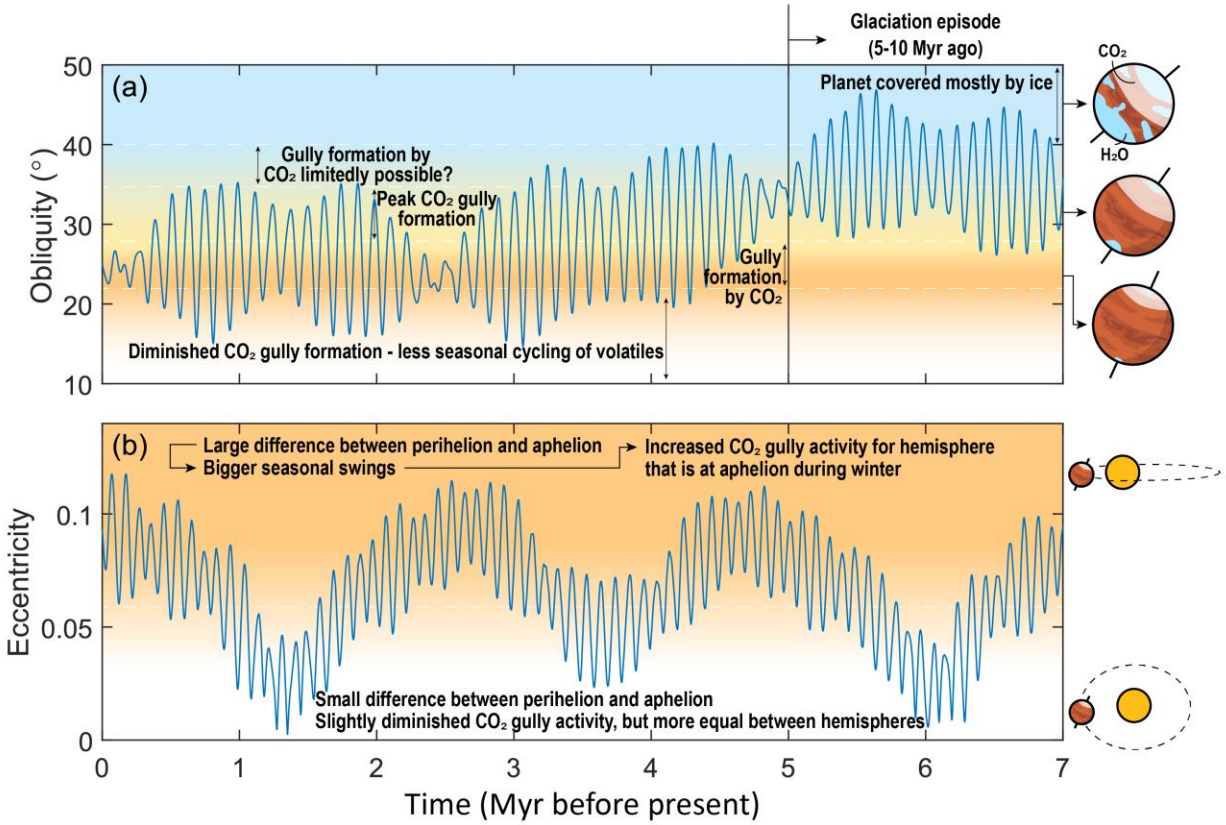
[2]Costard, F., Forget, F., Mangold, N., & Peulvast, J. P. (2002). Formation of recent Martian debris flows by melting of near-surface ground ice at high obliquity. *Science*, *295*(5552), 110-113. https://doi.org/10.1126/science.1066698

[3]Diniega, S., Hansen, C. J., McElwaine, J. N., Hugenholtz, C. H., Dundas, C. M., McEwen, A. S., & Bourke, M. C. (2013). A new dry hypothesis for the formation of Martian linear gullies. *Icarus*, *225*(1), 526-537. https://doi.org/10.1016/j.icarus.2013.04.006

[4]Pilorget, C., & Forget, F. (2016). Formation of gullies on Mars by debris flows triggered by CO2 sublimation. *Nature Geoscience*, *9*(1), 65-69. https://doi.org/10.1038/ngeo2619

[5]Conway, S. J., de Haas, T., & Harrison, T. N. (2019). Martian gullies: A comprehensive review of observations, mechanisms and insights from Earth analogues. https://doi.org/10.1144/SP467.14

Figure 4: Hypotheses on the occurrence and influence of CO_2-driven gully formation processes during the Late Amazonian.[9] ↓



[6]Roelofs, L., Conway, S. J., de Haas, T., Dundas, C., Lewis, S. R., McElwaine, J., ... & Patel, M. R. (2024). How, when and where current mass flows in Martian gullies are driven by CO2 sublimation. *Communications Earth & Environment*, *5*(1), 125. https://doi.org/10.1038/s43247-024-01298-7

[7]Roelofs, L., Conway, S. J., van Dam, B., van Eijk, A., Merrison, J. P., Iversen, J. J., ... & de Haas, T. (2024). The dynamics of CO2-driven granular flows in gullies on Mars. *Journal of Geophysical Research: Planets*, *129*(6), e2024JE008319. https://doi.org/10.1029/2024JE008319

[8] Roelofs, L.,Conway, S.J., van Eijk, A., Merrison, J. P., Iversen, J. J., ... & de Haas, T.. Flow dynamics and volume growth during erosion of different substrates by CO2-driven granular flows in gullies on Mars. *ESS Open Archive* . February 21, 2025. 10.22541/essoar.174017734.45340918/v1

[9] Roelofs, L. (2025). PhD-thesis: Dynamic planetary hillslopes: Granular flows and gullies on Earth and Mars. https://doi.org/10.33540/2902