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Formation of gullies on Mars by debris flows triggered by CO_2 sublimation

C. Pilorget and F. Forget

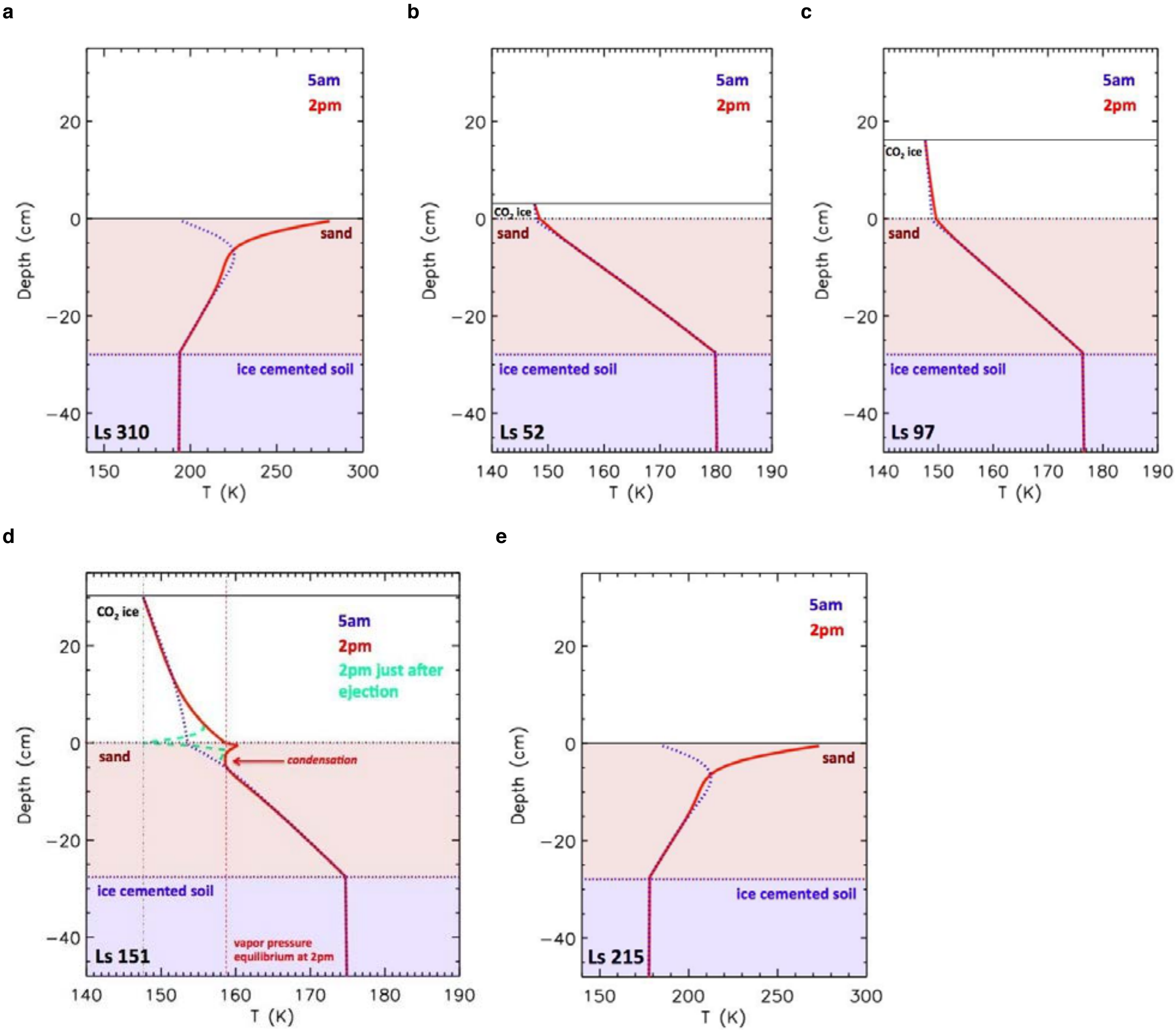

Figure S1: Temperatures profiles on the Russell crater megadune at various times of the year: summer (Ls=310°), fall (Ls=52°), winter (Ls=97° and Ls=151°) and spring (Ls=215°) [Simulation parameters are available in the Table S1]. When CO_2 ice seasonal ice is present at the surface, solar rays can penetrate in the ice layer, down to the regolith which warms up. When the temperature in the regolith reaches the CO_2 condensation temperature, CO_2 ice forms in the pores (***d,*** at 2pm). If the cryostatic pressure is reached, the ice layer lifts up and cracks. Gas is ejected and depressurization down to the surface pressure leads to a quick cooling of the CO_2 ice slab base (***d,*** at 2pm just after the ejection).

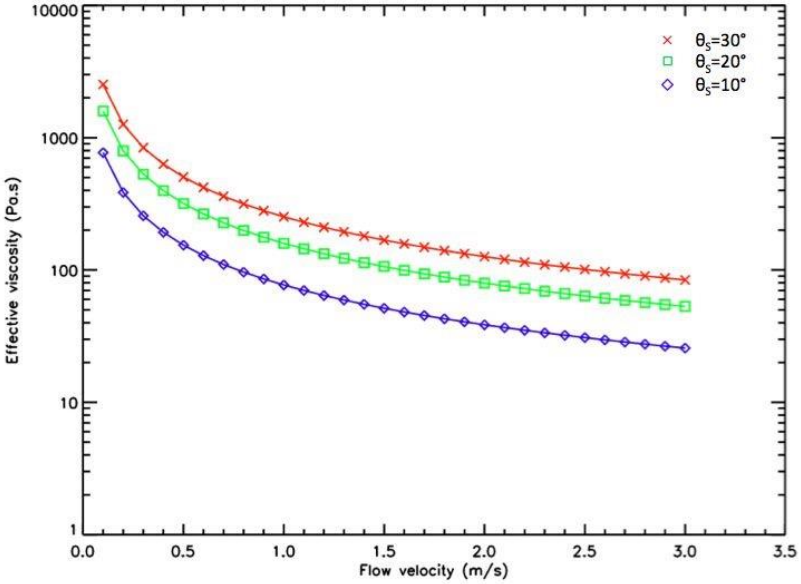

Figure S2: Effective viscosity of a granular flow for various flow velocities and effective repose angles θ_S. The material height is set at 0.28 m, the density of the granular material at 1500 kg.m^{-3} (porosity=0.5) and the gravity is taken at 3.72 m.s^{-2}. Typical flow velocities can be found in [27]. While angles of repose are typically around 30° or above [44], the action of CO_2 gas can reduce this angle. This can explain the formation of fluidized debris flows with viscosities down to a few tens of Pa.s on low-angle slopes like on Russell Crater dunes.

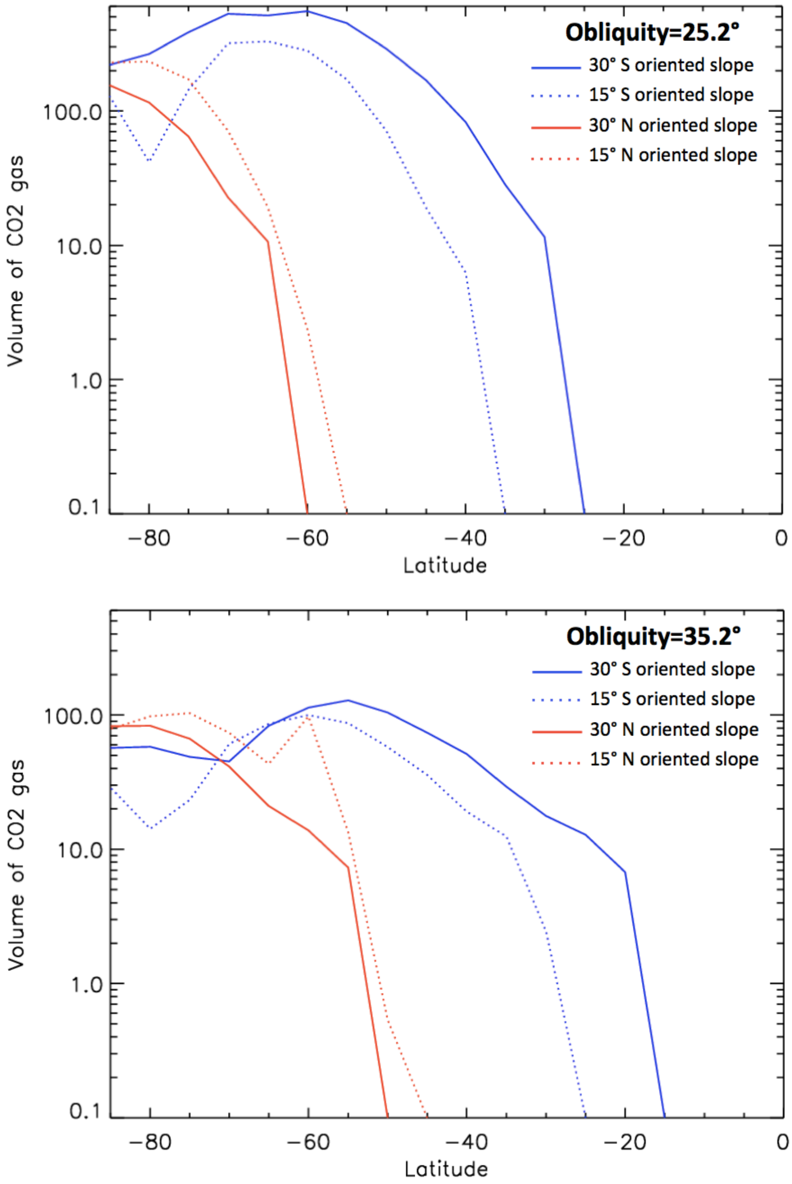

Figure S3: Total amount of CO_2 gas (m^3 per year, calculated as in Figure 2) predicted to diffuse upward through the soil pores below the seasonal CO_2 ice layer, as a function of latitude for obliquities of 25.2° (like today) and 35° (like 860,000 years ago). Simulation parameters are summarized in the Table S1.

Figure S4: An example of deposits left by terrestrial gas-fluidized dense pyroclastic flows produced by the 1993 eruption of the Lascar volcano (Chile). The physical understanding of the dynamics of such flows is still an open question, but it is believed that gases play a negligible role after initiation [24]. While the exact process at work probably differ from the Martian gullies, such deposits illustrate that gas-triggered dense debris flows can carry relatively large blocks over kilometers and create high lateral levees [47]. Figure from [24].

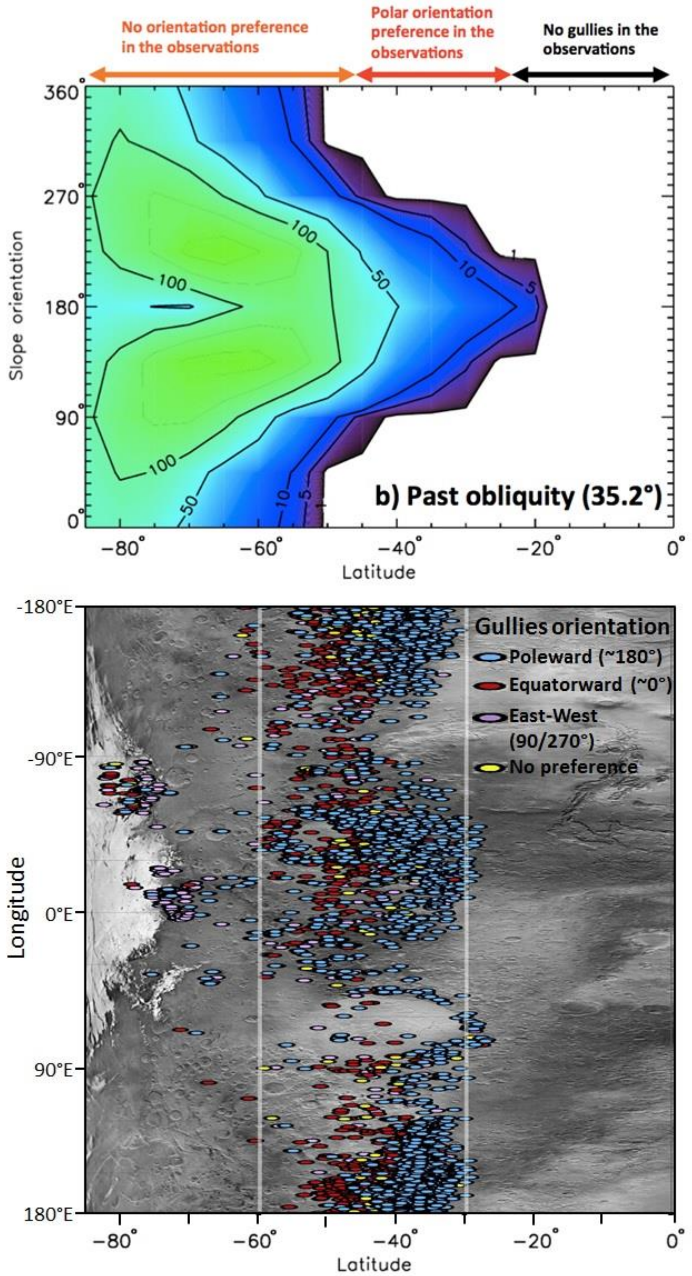

Figure S5: (**Top**) Predicted latitudinal distribution and orientation of "gullies activity" as in Figure 4b (i.e. modeled amount of CO_2 gas diffusing upward through the soil pores, in m^3 per year, assuming a 35.2° obliquity), compared to **(Bottom)** a map of the observed gullies and their orientation preference obtained using CTX data by [7]. Figure adapted from [7].

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Mars parameters	**Value**
Mars gravity	3.72 m.s^{-2}
Mars solar day	88775. s
Obliquity	25.2° (35.2° for high obliquity scenarios)
Orbit eccentricity	0.0934
Solar longitude of perihelion	251.°
Geothermal heat flow	0.03 W.m^{-2}
CO_2 ice parameters	
CO_2 ice thermal conductivity @144K	0.65202 W.m^{-1}.K^{-1} (Kieffer 2007)
CO_2 ice specific heat	1000. J.K^{-1}.kg^{-1}
CO_2 ice latent heat of condensation	5.9e+05 J.kg^{-1}
CO_2 solid density	1606. kg.m^{-3} (Kieffer 2007)
Permafrost parameters	
Permafrost thermal inertia	2000. J.m^{-2}.s$^{-1/2}$.K^{-1}
Parameters adopted in Russell megadune's simulations	
Slope and orientation	15° oriented 210° (SSW) for the upper part of the megadune, 10° oriented 210° for the lower part (from HiRISE DTM DTEEC_007018_1255_007229_1255_A01)
Surface pressure	590. Pa (LMD Mars Climate Database, Reiss and Jaumann 2003)
Surface visible albedo (dune material)	0.1 (Reiss and Jaumann 2003)
Surface IR emissivity	0.95
Thermal inertia of dune material	200. J.m^{-2}.s$^{-1/2}$.K^{-1}
Soil porosity	0.5
Ice table depth	28 cm N.B. This value is consistent with both ice stability model prediction (Aharonson and Schorghofer 2006) and allows the model to accurately predict the dates of first CO_2 ice formation in late fall and final sublimation in spring.
Parameters adopted in other simulations	
Surface pressure	600. Pa Atmospheric pressure could have been higher in the recent past (Phillips et al. 2011), maybe up to ~1200 Pa. Such conditions would tend to slightly amplify the process described here since the pressure in the soil needed to trigger the seasonal ice lift up and breaking would be higher, which would in particular increase the amount of CO_2 gas in the soil and the CO_2 condensation.
Surface visible albedo	0.25
Surface IR emissivity	0.95
Thermal inertia of soil	200. J.m^{-2}.s$^{-1/2}$.K^{-1}
Soil porosity	0.5
Ice table depth	20 cm

Table S1: Parameters adopted in the model