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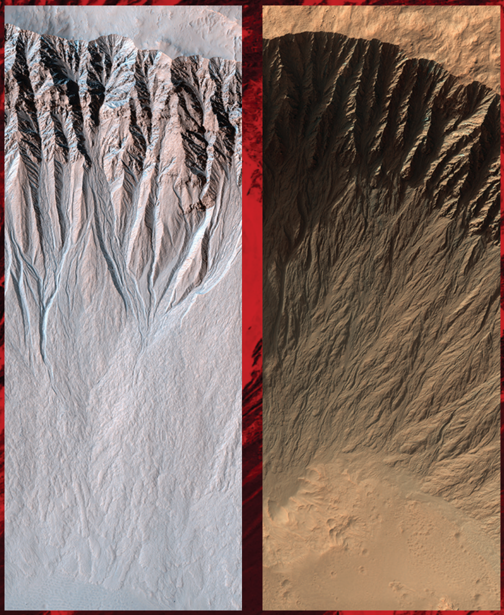
Martian Gullies and their Earth Analogues



20-21 June 2016

The Geological Society, Burlington House

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Martian Gullies and their Earth Analogues

Oral Programme

Monday 20 June 2016	
08.30	**Registration & tea, coffee**
Session 1: Water and gullies at high obliquity	
09.30	**Welcome Address** Susan Conway
09.45	**Recent (Late Amazonian) enhanced backweathering rates on Mars: paracratering evidence from gully-alcoves?** Tjalling de Haas, Utrecht University
10.00	**Liquid H_2O in martian gullies as a function of obliquity on Late Amazonian Mars** James Dickson, Brown University (presented by Erica Jawin)
10.15	**On the possibility of melting water ice on Martian slopes at higher obliquity** Margaux Vals, Laboratoire de Météorologie Dynamique (LMD)
10.30	**Formation and degradation of mid-latitude Martian gullies: Wind and dust** Allan Treiman, Lunar and Planetary Institute
10.45	**Tea & coffee break**
Session 2: Earth analogues	
11.15	**KEYNOTE: Gullies caused by water runoff: a view from Earth** William E. Dietrich, UC Berkeley
11.45	**Gullies in Ladakh, India: potential analogues for Martian gullies** Rishitosh Sinha, Physical Research Laboratory
12.00	**Gullies and debris flows in continental Antarctica: analogues for recent aqueous processes on Mars** Ernst Hauber
12.15	**Lunch**
Session 3: Gullies, volatiles - CO_2 and ices	
13.15	**Frost or wind or something else: investigating present-day gully formation within the north polar erg** Serina Dinega, Jet Propulsion Laboratory
13.30	**Volatiles and minerals composition at active Mars gullies** Mathieu Vincendon, Université Paris-Sud
13.45	**Controls on sediment the transport capacity of carbon dioxide sublimation under Martian conditions: experimental results** Matthew Sylvest, University of Arkansas (Presented by Susan Conway)
14.00	**The instigation of dry-gully morphology by CO_2 block movement across dark basaltic dunes, Arizona** Mary Bourke, Planetary Science Institute

14.15	**Tea & coffee break**
Session 4: CO_2 gully processes and experiments	
14.45	**Formation of gullies on Mars by debris flows triggered by CO_2 sublimation** Cedric Pilorget, Laboratoire de Météorologie Dynamique (LMD)
15.00	**Deep incision of the latitude dependent mantle in Martian gullies formed by CO_2 sublimation processes** Francois Forget, Laboratoire de Météorologie Dynamique (LMD)
15.15	**The unexpected geomorphological impact of metastable boiling water on Mars** Marion Massé, Université de Nantes
15.30	**Implications of a Non-Salt-Recharge RSL Mechanism for Martian Gullies as Remnants of an Earlier Wetter Period.** Samuel Kounaves, Tufts University, & Imperial College London
15.45	**Experimental simulation of Martian gully formation: a debris flow framework** John Dixon, University of Arkansas
16.00	**Discussion**
17.00	**Wine reception**

Tuesday 21 June 2016

09.15	**Registration & tea, coffee**
Session 5: Earth analogues	
09.45	**New insights into processes influencing submarine gully morphology** Jenny Gales, National Oceanography Centre
10.00	**Debris flow recurrence intervals on an alluvial fan in Hanaskogdalen (Svalbard)** Dennis Reiss, Westfälische Wilhelms-Universität
10.15	**Descending dunes observations for Dakhla Oasis, Egypt and Russel Crater, Mars** Krzysztof Skocki, Institute of Aviation
10.30	**Tea & coffee break**
Session 6: Present-day activity	
11.00	**Small Martian gullies associated with recurring slope lineae (RSL)** Alfred McEwan, University of Arizona
11.30	**An active gully on Mars: accumulation and seasonal mobilisation of material** Kelly Pasquon, Université Paris-Sud
11.45	**Recent and present-day activity of Martian gullies** Jan Raack, The Open University
12.00	**Monitoring Martian gullies: Implications for formation and evolution** Colin Dundas, U.S. Geological Survey
12.15	**Lunch**

Session 7: Periglacial gullies	
13.15	**Gullies, mantled terrain, thermokarst and small-scale polygons in the Argyre region, Mars: a critical discussion of their spatial-association** Richard Soare, Dawson College
13.30	**Patterns of Martian deglaciation: assessing the distribution of paraglacial features in mid-latitude craters** Erica Jawin, Brown University
13.45	**Thermal inertia of gully fans as an indicator of gully activity** Tanya Harrison, University of Western Ontario
14.00	**Tea & coffee break**
Session 8: Granular, numerical and software	
14.30	**KEYNOTE: Simulation and detection of granular flows using numerical modelling and seismic data** Anne Mangeney, IPGP
15.00	**Examination of origins of lobate landforms with gullies on Mars from an inverse analysis of debris-flow deposits** Hajime Naruse
15.15	**Automatic detection of changes in Martian gullies from co-registered high-resolution visible images** Panagiotis Sidiropoulos, University College London
15.30	**Discussion & closing remarks**
17.00	**Close of conference**

Poster Programme

An Experimental Investigation of the Interaction Between Sublimating Carbon Dioxide and Porous Substrate
Lauren McKeown

Oral Presentation Abstracts (in programme order)

Recent (Late Amazonian) enhanced backweathering rates on Mars: paracratering evidence from gully-alcoves?

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Mars is believed to have been exposed to low planet-wide weathering and denudation since the Noachian. However, the widespread occurrence of alcoves at the rim of pristine impact craters suggests that recent backweathering rates can be relatively high. Here we present measurements of Late Amazonian backweathering rates from gullied and non-gullied alcoves of 10 young equatorial and mid-latitude craters.

Late Amazonian Martian backweathering rates (10^{-4} – 10^{-1} mm yr^{-1}) are approximately one order of magnitude higher than previously reported erosion rates, and are similar to terrestrial rates inferred from Meteor crater and various Arctic and Alpine rock faces. Alcoves on initially highly fractured and oversteepened crater rims following impact show enhanced backweathering rates that decline over at least 10^1 - 10^2 Myr as the crater wall stabilizes. This “paracratering” backweathering decline with time is analogous to the paraglacial effect observed in rock slopes after deglaciation.

The backweathering rates on the gullied pole-facing alcoves of the studied mid-latitude craters are much higher (2 - 60 times) than those on slopes with other azimuths and those in equatorial craters. The enhanced backweathering rates on gullied crater slopes probably results from liquid water acting as a catalyst for backweathering. The decrease in backweathering rates over time might explain the similar size of gullies in young (<1 Ma) and much older craters, as alcove growth and sediment supply decrease to low background rates over time. This would suggest that gully activity decreases with the age of the host crater.

NOTES

Liquid H_2O in martian gullies as a function of obliquity on Late Amazonian Mars

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Gullies on Mars [1] are globally correlated [2] and locally associated [3] with the latitude dependent mantle (LDM), an H_2O ice-rich unit draping the mid- to high-latitudes [4]. Contemporary erosion of gullies is consistent with loss of CO_2 ice [5-10], while CRISM data show that some modification of gullies occurs when CO_2 is absent but H_2O is present [11]. Stratigraphic evidence shows that some gullies required conditions different than what is observed today to form [3]. Thus, evaluating phase changes of both H_2O and CO_2 over the last ~1 million years is required to provide an end-to-end model for the formation and evolution of gullies.

We performed Global Climate Model (GCM) simulations of pressure/temperature conditions for Mars during its most recent high-obliquity period (ε = 35°, 625 Kyr), when liberated CO_2 ice nearly doubled the density of the atmosphere [12] and H_2O-ice is predicted to have accumulated in the mid-latitudes [4]. These results were integrated in a GIS with mapped gully locations [3], providing a direct comparison between model predictions and empirical mapping. The same model was run using present-day conditions, in addition to an intermediate phase with ε = 30° and pressure of 8 mb. Triple point conditions for H_2O were used to provide a test of whether minimum conditions for melting of the LDM could be met.

Consistent with present-day observations [5-9], H_2O-ice at mid-latitude locations will sublimate instead of melt everywhere that gullies have been mapped except for the margins of the Hellas and Argyre impact basins. While temperatures surpass 273K at all locations, pressure remains below the triple point. Thus, including brines in models for liquid water is likely to have no effect at most gully locations. At high-obliquity, peak conditions are sufficient at all gully locations to permit transient liquid water, including polar gullies and gullies at high elevation in southern Thaumasia. This is temporally consistent with Late Amazonian periods of predicted H_2O-ice accumulation in the mid-latitudes [4].

The recent observations of Vincendon [11] show that any model for gully formation that does not include the activity of both H_2O and CO_2 is insufficient. Our results indicate that gully locations have been inhospitable to liquid H_2O for the last ~625 Kyr, at which point it was a more viable candidate for contributing to gully formation. This record may be preserved in buried and inverted gully systems [3].

[1] Malin and Edgett, 2000, *Science*, 288, 2330. [2] Milliken et al., 2003, *JGR*, 108, 10.1029/2002JE002005. [3] Dickson et al., 2015, *Icarus*, 252, 83-94. [4] Head et al., 2003, *Nature*, 426, 797. [5] Dundas et al., 2010, *GRL*, 10.1029/2009GL041351. [6] Diniega et al., 2010, *Geology*, 38, 1047. [7] Dundas et al., 2014, *Icarus*, 10.1016/j.icarus.2014.05.013. [8] Raack et al., 2014, *Icarus*, 10.1016/ j.icarus.2014.03.040. [9] Dundas et al., 2015, *Icarus*, 251, 244-263. [10] Pilorget and Forget (2016) *Nature Geosci.* 9, 65. [11] Vincendon, 2015, *JGR*, 120, 1859-1879. [12] Phillips et al., 2011, *Science*, 332, 838.

NOTES

On the possibility of melting water ice on Martian slopes at higher obliquity

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On present-day Mars, liquid water is very unlikely to form since, wherever the conditions of pressure and temperature suitable for liquid water are met, the conditions are so arid that all water has always completely sublimed. Moreover, outside the polar regions, water ice is unstable for more than a few weeks on the Martian surface.

Things were different in the past thousands / million years, notably when the obliquity was significantly higher than today. Then, Global Climate numerical simulations have shown that water ice could accumulate in a variety of locations at low and mid latitudes. In particular, it has been found that water ice clouds could have completely changed the Martian environments and allow both warmer temperatures and ice accumulations. At obliquity higher than 35°, poleward facing slopes at mid and high latitudes can be both the coldest places on an annual average sense (a condition which favors the accumulation of water ice), and the warmest during summer, both in the seasonal and instantaneous sense. However, the latent heat cooling of any exposed water tends to limit the summertime increase of temperatures.

We will review our understanding of water ice accumulation and melting at obliquity larger than today, and show new results from simulations combining Global Climate simulations and local calculations to model the environment and water budget on Martian slopes.

NOTES

Formation and Degradation of Mid-Latitude Martian Gullies: Wind and Dust.

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Martian gullies are landforms consisting of sediment deposits sourced in a channel which ‘drains’ an alcove in a steep wall. Gullies in circum-polar regions formed without liquids, by movement of dust and. However, liquids (aqueous solutions) are commonly invoked for gully formation at mid-latitudes. Here, I show that the local geology of gullies in Terra Cimmera is consistent with the actions of wind and wind-blown dust alone.

Gullies in ‘crater 1302’ (35.4°S 152.5°E, 4 km diam.) are exemplary of those across Cimmeria (MOC S1000476, E0101585; HiRISE ESP_016401_1445, ESP_020871_1440). Regional winds are N⇒S, consistent with landforms in and outside the crater. The crater’s northern interior slopes are covered by multiple mantles of fine-grained material, which have been stripped off locally. These slopes show many ‘fresh’ gullies, with channels that eroded and deposits that overlie older gully deposits; i.e., there have been many episodes of gully formation. There are no channels below the gully deposits, nor high-albedo surfaces around them. The oldest gully deposits (and undivided mantling material) are cut by normal faults perpendicular to the local slope. Alcoves of most young gullies expose broken bedrock, but at varying elevations. Very few rocks are present in the gully deposits and mantles (HiRISE resolution), and most deposits are eroded (pockmarked and stripped) by wind.

These data give no support for involvement of liquids in gully formation at 1302. Bedrock on the crater walls is broken, and alcove scarps appear at many elevations, which are inconsistent with liquid from an aquifer. No gully deposits source fluival channels, which should be apparent from compaction and dewatering of a liquid-rich flow. And there is no indication in albedo of salt deposits associated with gullies, as might be expected from martian groundwater.

On the other hand, wind has had a major influence on the morphology of the crater – erosion and stripping of deposits, and formation of local landforms. Wind from the north would form turbulent eddies as it crossed the northern crater walls, and drop dust on there. Dust would accumulate in ‘alcoves,’ and accumulate to the point of instability, and cascade down as dense granular flows. The flow deposits, being originall eolian dust, would be easily eroded again by the wind and transported south. Thus, the geomorphology of crater 1302 (and by extension elsewhere in Cimmeria) can be explained solely by wind and dust, without invoking a liquid.

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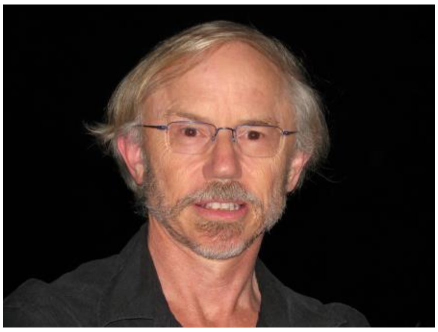

Gullies caused by water runoff: a view from Earth

William E. Dietrich

UC Berkeley

Given the relative accessibility of Earth compared to Mars, one might expect that the mechanisms of steep channel sediment transport and topographic evolution here are well known. Instead, in fluvial geomorphology, steep channel processes are a frontier area of field research. In hilly and mountainous landscapes, a significant fraction of the entire channel network is likely swept and cut by debris flows, yet we lack a general theory for this geomorphic process. The rare occurrence of sediment transport events, the steep and often hazardous setting of these channels, the exceptionally coarse sediment typically transported, and the failure of hydraulics and sediment transport theory present many challenges. Here I will build upon field studies, some based on monitoring, others based on reconstruction of events, and some supported with laboratory experiments and theory, to explore how water runoff can lead to channel incision and to (perhaps) distinctive landforms. Meteor Crater (Arizona, USA) provides an opportunity to explore steep channel processes whilst also providing a topographic setting similar to that pervasive on Mars. Since the impact ~50,000 years ago, the 1.2 km diameter crater wall has been dissected by about 75 gullies that extend from the exposed bedrock upper wall to fans that in the Late Pleistocene bordered a lake. Characteristic boulder lined levees and lobate terminal deposits composed of matrix-supported gravel indicate the primary role of debris flows in cutting the gullies and building debris fans. Gullies typically originate in bedrock alcoves on slopes greater than 30 degrees, levee bounded flow paths start at about 20 degrees and continue with decreasing frequency to about 5 degrees, and then fluvial channels (many emanating from the levee bound debris deposits) extend to 2 degrees and spread and terminate in the crater floor. We propose that runoff (either from rain or snow melt) from the steep bedrock alcoves progressively entrained sediment downslope and transformed into the self-confining debris flows. Laboratory experiments suggest that a critical amount of fines is necessary to sustain mobilization on the gentler slopes. The amount of water needed to transport and deposit the debris flows is trivial compared even to current annual rainfall. Cosmogenic exposure age dating shows that the debris flow activity ceased upon Holocene climate warming and drying. Currently modest fluvial sediment transport is active in the lower reaches. Recent theory and experimental observations may enable us to calculate a minimum runoff for debris flow initiation. This analysis differs greatly from the case where steep channel transport and scour are driven by hillslope landslides that mobilize as debris flows and progressively bulk-up downslope.

NOTES

Gullies in Ladakh, India: Potential Analogs for Martian Gullies

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Ladakh Himalaya, being situated in the rain shadow zone of the Great Himalayan Range [1], hence is derived from the Indian Summer Monsoon (ISM) [2]. Therefore, the terrain is characterized by cold-arid desert landscape having rainfall <100 mm and low temperatures (below freezing point during winters). Due to paucity of moisture, glaciers in the Ladakh Range are hanging type cirques typically <4.5 km long [3]. There are multiple, episodic gullies and channels carved on the glacial and paraglacial sediments such as moraines, alluvial fan and debris flow. Despite being benefitted by the geographical location, its regional elevation (relative relief of 1000-2000 m, with few peaks >7000 m) [3], and insolation conditions that elucidate well its contemporary arid to hyper-arid climate, Ladakh gullies, to our knowledge, have not been assessed to explore their relative importance in understanding Martian gullies.

In this study, we have carried out field investigation of morphology of terrestrial gully analogs from Ladakh Range to provide some insights on the origin of Martian gullies, using field data measurements, ground level photography, and orbital imagery. From analysis of field photographs of Ladakh gullies, the noteworthy morphological element was observation of lobate debris-flow deposits on the wall of cliffs flowing downslope from the top. We noticed that there were (i) individual lobate flow deposits; (ii) gully-channel through lobate deposits with clearly defined levée deposits; (iii) fresh gully-channel systems that flow individually and/or merge/superimpose with the pre-existing gullies; and (iv) lobate deposits through the pre-existing gully. From the orbital imagery (MRO HiRISE) of selected Martian gullies for comparison, we noticed several gullies associated with lobate debris flow deposits. Multiple studies in the past have reported similar geological associations (e.g. Savalbard, French Alps, USA etc.) [4-7]. The foundation of such an interpretation is dependent upon the dominance of wet debris flow features in places where gullies have formed.

Our observation although preliminary in nature indicate that (i) sublimation of CO_2 frost and the trapped gas, rather than liquid water, can explain the Martian gullies needs revision and (ii) the debris-flow processes and gully-channel formation in cold-arid desert-like environment of Ladakh can well demonstrate and elucidate formation of Martian gullies. We believe Ladakh could be a potential Earth-analog for understanding Martian gully systems. Ladakh gullies await exploration in this direction, we hope that from our continued efforts, and future global collaboration, the key aspects involved in gully formation on Mars could be decoded.

References: [1] Juyal N. (2014) *Springer Netherlands, 115-124*. [2] Gasse F. et al. (1996) *Paleoecology, 120, 79-92*. [3] Dortch J.M. et al. (2010) *Quaternary Research, 74, 132-144*. [4] Reiss D. et al. (2011) *GSA 483, 165-175*. [5] Levy J.S. et al. (2010) *Earth Pla. Sci. Lett. 294, 368-377*. [6] Lanza N.L. et al. (2010) *ICARUS 205, 103-112*. [7] Johnsson A. et al. (2014) *ICARUS 235, 37-54*.

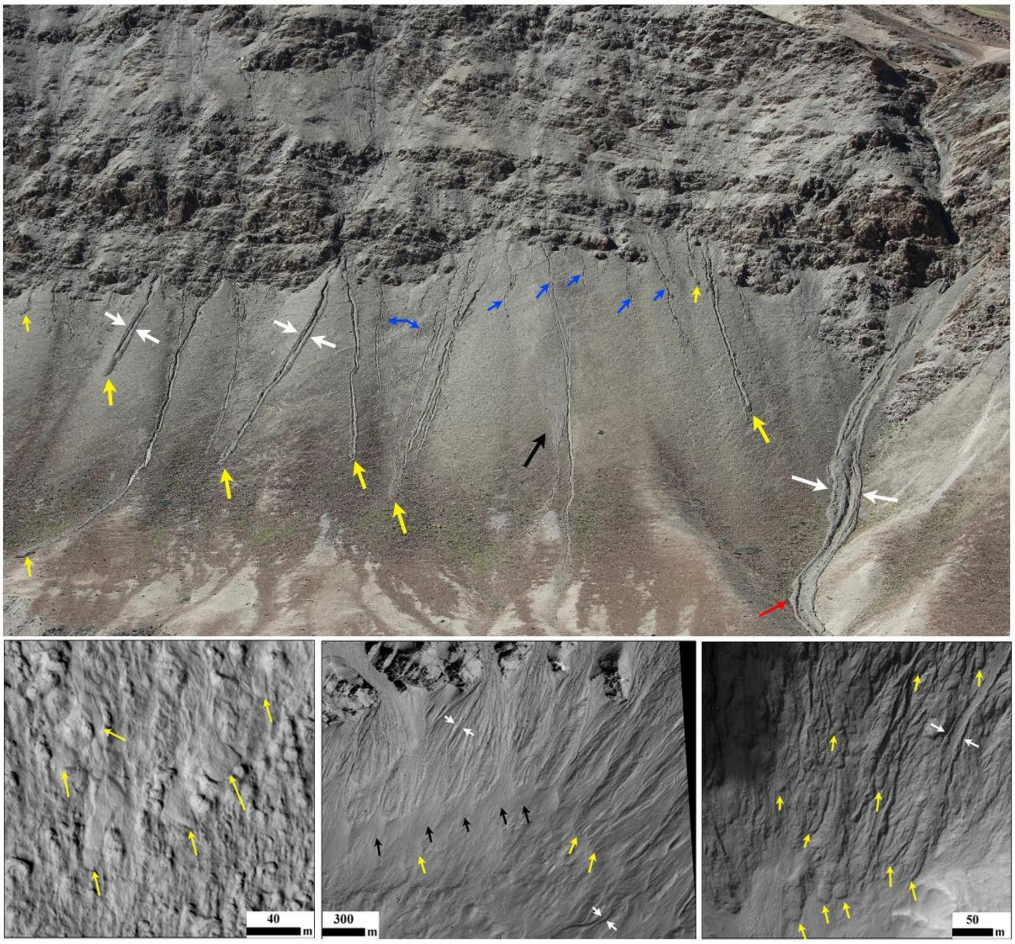

Figure: (**Top**) An example of gully system from Ladakh Range presenting debris flow lobe and gully-channel relationships. (**Bottom**) Example images of Martian gullies to represent features analogousto Ladakh gully [4-7]. The colors represent: 'Yellow' arrows- individual lobate flow deposits with gully-channels formed through them; 'White' arrows- clearly defined levée deposits; 'Black' arrows- pre-existing gully fan crosscut by younger gullies; 'Blue' arrows- relatively fresh gully channels; 'Red' arrow- lobate deposits through the pre-existing gully.

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Gullies and debris flows in continental Antarctica: Analogues for recent aqueous processes on Mars

E. Hauber, J.-P. de Vera, N. Schmitz, D. Reiss, A. Johnsson, H. Hiesinger

It is debated whether recent gullies on Mars were formed by aqueous processes such as debris flows or by dry granular flows. To better understand the range of terrestrial sites displaying gully morphologies analogous to those on Mars, we studied gullies and nearby aqueous pathways in continental East Antarctica, one of the coldest and driest environments on Earth. Our study site is located in the Transantarctic Mountains in Northern Victoria Land (near 71°48.27'S/162°00.8'E). The study area is bordered to the west by the De Goes Cliff, a steep, ~400 m-high scarp of bedrock and talus, and to the east by the Rennick Glacier. In between, a flat-lying, mostly ice- and snow-free area hosts several small lakes that are partly ice-free in the austral summer. The De Goes Cliff is incised by gullies that display alcoves, leveed channels, and small depositional fans. Channel sinuosity is low, channel widths are typically 1 to 3 m, and levee widths and heights are up to 1 m and up to 40 cm, respectively. These characteristics together with weakly developed imbricated layering of clasts in the poorly sorted levees and a well-developed elongated flow tongue with a lobate margin (in plan view) strongly suggest a significant contribution to gully and fan formation by debris flow activity. On a relatively warm and sunny day (20 Jan. 2016) we observed limited meltwater runoff (estimated to be <<0.1 l/s) from snowbanks in the gully channels. A first phase of wettening and darkening of the regolith was followed by limited overland flow. This process started in the early afternoon and began with a propagation rate of the wettening/darkening of ~2m/h, sharply accelerating to >10 m/h at ~5 p.m. Surface evidence for flow intermittently disappeared for up to a few meters, before water emerged again at the surface. Evidence for melting of snow and ice was also found locally in other nearby places, although the produced meltwater volumes were always small. No significant precipitation was observed in January 2016, but drifting snow was frequently deposited and removed by strong winds. Morphologically very similar landforms on Svalbard (Arctic) were unambiguously formed by debris flows, most likely during unusually strong rainfall events. Our observations of debris flow gullies in very dry conditions with no rainfall and extremely limited availability of liquid water demonstrate that rainfall is not a prerequisite of debris flow formation, and snowmelt can provide sufficient water.

NOTES

Frost or Wind or something else: Investigating present-day gully formation within the north polar erg

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Analyses of high-resolution observations have shown that the dunes within the martian North Polar Erg (Olympia Undae) are currently very active on seasonal and yearly timescales, with dune brinks that erode with small alcoves that generally feed into a depositional fan (i.e., "gullies") and dune margin movement. Previous studies have proposed either a general aeolian [1] or seasonal frost driver [2,3] for the gully formation process, based on estimates of gully formation timing. However, these estimates are difficult as HiRISE images are not generally acquired during the formation of the polar hood in the fall and the darkness of winter, and the presence of frost in the spring can affect visibility of shallow gully features [3]. Thus, very careful image comparisons are needed to determine when a gully first appears. Additionally, as we generally cannot constrain the timing well, analysis of trends and variations in gully size, morphology, orientation, and location are needed for additional indications of a seasonal (or other) control. One can also investigate trends relative to latitude and dune type, size, and orientation, if multiple dune fields are studied.

To conclusively determine the gully formation drivers, we are surveying several dune fields and measuring the items outlined above, over multiple Mars years. So far, new gullies that appeared over one Mars year (identified through comparison of frost-free images) have been measured within four dune fields. Current analysis shows that most gully activity can only be constrained to the autumn-early spring period. However, a few gullies had activity that could be constrained to a short period (each ~2-4 weeks), right at the edges of the seasons when imaging is possible. (Further analysis is needed to see if those gullies are any different from other new gullies.) And no gully activity has occurred during late spring through mid-summer, so their formation is not consistent with a purely wind-related origin.

We also will estimate gully activity rates, to determine how large a role this mass-wasting process may play in evolving and migrating the dunes. Within these fields, 20-60% of the dunes had new gullies eroded. Based alcove length and width measurements, we will estimate the average amount of down-slope sand transport that occurs through gully activity every year, and look for interannual and interfield variations. (Additionally, the Arrakis dune field study area contained only a handful of gullies – we will investigate why this field has much less activity.)

[1] Horgan and Bell, 2012, Seasonally active slipface avalanches in the north polar sand sea of Mars: Evidence for a wind-related origin, *Geophys. Res. Lett.* **39**, L09201.
[2] Hansen et al., 2011, Seasonal Erosion and Restoration of Mars' Northern Polar Dunes, *Science* **331**, 575-578.
[3] Hansen et al., 2015, Agents of change on Mars' northern dunes: CO2 ice and wind, *Icarus* **251**, 264-267.

NOTES

Volatiles & minerals composition at active Mars gullies

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Current gully activity occurs preferentially during winter times on mid-latitude pole facing slopes where bright seasonal ice is observed. The condensation-sublimation cycle of the largely dominant atmospheric component, CO_2, is thus though to be the driver of this activity. However, both water and CO_2 ice condense on Mars, with distinct spatial and time distribution. Gully activity includes formation of new channels and lengthening/widening of ancient gullies, but also persistent, ice–free deposits with color or brightness differences compared to ambient surface materials. The relative contributions of texture versus mineralogy changes to these tone modifications remain undetermined.

We analyze reflectance spectroscopy observations of active sites to constrain composition of both seasonal ice and underlying ground. We observe that CO_2 ice form where and – if timing information is available – when formation of new channels and erosion of pre-existing channels occur. This supports the idea that CO_2 is the main agent responsible for current gully formation. We also observe that some minor activities such as formation of new deposits are poorly compatible with CO_2 ice while being observed in association with water ice. This suggests that other mechanisms involving water ice could also be at work. We have started to analyze the mineralogy associated with active sites and found robust spectral evidence for hydrous minerals, likely hydrated (opaline) silica and/or hydrated sulfates, associated with bright deposits observed at the base of active linear gullies of the Russell megadune. These hydrated deposits could be there by coincidence, or could have been formed independently while being transported by the downslope movements associated with gully activity, or could be related to the mechanism responsible for activity. Ongoing analyses at other sites will provide additional constraints to understand which of these possibilities is most likely.

NOTES

Controls on sediment the transport capacity of carbon dioxide sublimation under Martian conditions: experimental results

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Ongoing satellite observations of Martian gullies reveal contemporary geomorphological alteration, including formation of new gully channels. The timing and locations of this activity suggests a relationship with the seasonal deposition and sublimation of CO2 frost over the Martian high to mid latitudes. Here we present the results of the first ever laboratory simulations of this process under Martian conditions, showing that significant quantities of loose sediment can be transported, and examine the influence of slope and regolith grain size as process controls. We performed 25 experimental runs at initial slope angles from 10° – 30°, with coarse sand, fine sand, and JSC Mars-1 Martian regolith simulant. The runs were conducted in the 1m diameter, 2m long Mars simulation chamber, housed at The Open University, UK, allowing control of the atmospheric composition and pressure. The model slopes were formed inside a box, ~30 cm long, 23 cm wide by 12 cm deep, constructed of coiled, copper tubing, allowing cooling by liquid nitrogen. After cooling each slope in a dry N2 atmosphere, CO2 gas was introduced over the slope, condensing CO2 frost on the surface. Finally, the chamber pressure was reduced to ~5 mbar and the slope heated radiantly from above. Stereo video of surface activity was recorded for photogrammetric analysis, allowing determination of slope-angles, displacement volumes, and rates. Both slope angle and grain size influenced the degree of surface activity, the volumes of regolith transported, and the nature of any morphological changes. JSC Mars-1 was the most active substrate, which we believe is caused by the presence of fines, which inhibit gas-escape during sublimation, and with its greater porosity, coarse sand was the least active. In terms of slope angle, although activity significantly decreased between 30° and 20°, some substrate was still mobilised even at slopes as low as 10° – 15°.

NOTES

The instigation of dry-gully morphology by CO_2 block movement across dark basaltic dunes, Arizona.

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We present the results of a set of field experiments that were undertaken at Grand Falls Canyon, Arizona to quantify the geomorphology of CO_2 ice block movement over aeolian dune slopes (Diniega et al, 2013). These are sister experiments to those undertaken elsewhere at Grand Falls, (Bourke et al, 2016a) and in Utah (Bourke et al., 2016b). The experiments were undertaken on an 8 m long falling dune slope (32.3°). Ambient air temperature was 44°C and relative humidity was 12%; sand surface temperatures were 66-74°C.

Two CO_2 ice blocks (25 x 105 x 210 mm and 50 x 90 x 215 mm) were placed on the upper surface of the falling dune, and with a gentle nudge they moved downslope. The dynamics of the block movement were recorded using a pair of high resolution video cameras. Geomorphological observations were noted and topographic change was quantified using a Leica P20 terrestrial laser scanner (TLS) with a resolution of 0.8 mm at 10 m, and change detection limits less than 3 mm. Both blocks were launched from the same location 19 times, over 65 minutes. Similar block dynamics were observed to our other sites (blocks moved straight, swiveled and bounced downslope).

The block runs occupied different tracks. Cumulatively, these still led to the formation of a single feature, with distinctive alcove- track and depositional fan. The response of the slope differed from our other sites in three ways. First, the transit of ice blocks triggered grainflows; this mode of movement formed a larger component of sediment transport than at other sites. Second, a depositional fan formed. Third, the morphology generated by the block (distinctive track, sometimes with levee formation) was rapidly subsumed by grainflows that moved at a slower rate downslope.

These data show that sublimating blocks of CO_2 ice leave signatures of transport paths and are capable of eroding and transporting sediment. However, the results differ from earlier experiments where transit morphologies bore resemblance to features noted on Martian dunes (e.g., sinuous leveed channels). Here we show that the movement of ice blocks over granular sloped surfaces can trigger grain flows. These flows mute the morphological signature of the CO_2 block. The resultant geomorphology is similar to dry granular flows on aeolian dunes. This highlights issues of equifinality where gully morphology assigned to dry or wet flows, may in fact be the result of the transit of sublimating CO_2 blocks.

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Bourke, M.C., Nield, J.M., Diniega, S., Hansen, C.J., McElwain, J.N., 2016. A field study of the geomorphic effects of sublimating CO_2 blocks on dune slopes at Coral Pink Dunes, Utah, EGU.

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, 526-537.

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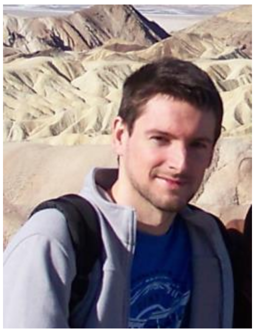

Formation of gullies on Mars by debris flows triggered by CO_2 sublimation

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Since their discovery by the Mars Observer Camera, Martian gullies have attracted considerable attention because they resemble terrestrial debris flows formed by the action of liquid water. This interpretation is now questioned by the discovery of ongoing gully formation occurring in conditions much too cold for liquid water, but with seasonal CO_2 frost present and defrosting. However, how a relatively thin seasonal dry ice cover could trigger the formation of decameter large debris flows exhibiting levees and sinuosities as if they were liquid-rich remained mysterious.

We have developed an innovative thermo-physical model of the Martian soil able to compute the seasonal evolution of a column composed of an underlying regolith, a CO_2 ice layer, and the atmosphere above. Below the surface, in the CO_2 ice layer (when present) and in the regolith, the model simultaneously solves the heat conduction, the radiative transfer through the ice as well as the diffusion, condensation and sublimation of CO_2 and the related latent heat exchanges.

We have found that, during the defrosting season, the pores below the seasonal ice layer can be filled with CO_2 ice, and subject to extreme pressure variations. The subsequent gas fluxes can lower the theoretical angle of repose and destabilize the soil, creating gas-lubricated debris flows with the observed geomorphological characteristics of the Martian gullies. This process can lead to significant material transport, possibly of large boulders, and the formation of entirely new channels, as emphasized in recent observations

We also performed model calculations for a wide range of latitudes and slope orientations. These simulations reveal that high-pressure CO_2 gas trapping in the subsurface and the subsequent formation of ice within the regolith pores are predicted at latitudes and slope orientations where gullies are observed and not elsewhere. Assuming present-day Mars obliquity and orbit, this includes all reported spots where new channels have formed in the past few years. The model can also explain why gullies are observed only on pole-facing slopes between 30° and 45° latitude, and with less clear orientation preference above 45° latitude.

Reference: Pilorget C., Forget F., Formation of gullies on Mars by debris flows triggered by CO_2 sublimation, *Nature Geoscience*, 2016, 9, 65-69, DOI: 10.1038/ngeo2619

NOTES

Deep incision of the Latitude Dependent Mantle in Martian Gullies formed by CO_2 Sublimation processes.

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In recent years, frequent monitoring of the Martian gullies by the Hirise camera has revealed that gully formation is ongoing on present-day Mars, and that CO2 condensation-sublimation processes are likely involved in their formation [1]. Pilorget and Forget (see companion abstract, this issue, and [2]), suggested that the debris flows could be triggered and fluidized by the gas fluxes flowing in the porous subsurface when surface CO2 ice is subliming.

It is striking that gullies often incise deeply the H_2O ice-rich latitude dependant mantle which is pasted on many of the slopes where gullies are found. The V-shaped incision can be several tens of meters deep [3]. Can CO_2 ice processes do that? In reality these processes are expected to trigger debris flows that only remove part or all of the dry grains or debris that are above the ice-table (which is usually stabilized by water vapor-subsurface exchange a few centimeters below the surface). However, each removal of the dry sediments above the water ice table induces sublimation of the unburied of less-buried ice, and the relocation of the local ice table at greater depth. In the long term, a repetition of this process will deeply incise the icy latitude-dependant mantle. At the workshop, we will present a modeling of this process using a model of the Martian environment designed to represent the diffusion of water vapor through the subsurface and its condensation/sublimation on Martian slopes. Such simulations are useful to estimate the timescale involved and understand the shape of the gullies-induced incision in the latitude-dependant ice mantle.

[1] See Dundas et al., *Icarus* 251, 244-263 (2015), and reference therein
[2] Pilorget and Forget, *Nature Geoscience* 9, 65–69 (2016).
[3] Conway and Balme, *Geophys. Res. Lett.* 41, 5402–5409 (2014).

NOTES

The unexpected geomorphological impact of metastable boiling water on Mars

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The low atmospheric pressure at the surface of Mars means that liquid water is metastable, evaporating, boiling and/or freezing and therefore is thought to play a minimal role in present-day surface geomorphological processes on Mars. One of the more surprising recent observations, therefore, has been of metre- to kilometre-scale dark downslope flows, termed “RSL” (Recurring Slope Lineae) on the martian surface. They are observed to both appear and elongate between orbital images taken days to months apart, then fade and reform in subsequent years with a seasonal cycle. RSL have been linked to water because they occur on relatively warm slopes, grow incrementally, fade rapidly (weeks) when inactive, and are associated with hydrated salts. A second surprising observation is that of recent morphological changes in martian gullies, including channel creation and appearance of new deposits. Although most of these gully-modifications can be linked with sublimation of seasonal CO_2 deposits, some occur on slopes without obvious CO_2 and could therefore been linked to sublimation or melting of thin seasonal water ice deposits.

In both cases an important stumbling block for the liquid water explanation is the low quantity of water available on Mars. There is very little knowledge on how small volumes of metastable water interacts with sloping sediments and therefore what morphologies we should expect to observe. In order to begin to address these issues we have performed novel experimental simulations of fluid propagation and sediment transport at martian pressure. We find two processes that have not been previously reported: 1) grain saltation induced by boiling, which can initiate grainflows and 2) for brines, violent ejection of small masses of saturated material, which can extend well beyond the boundaries of the flow. We find that metastable water and brines have a disproportionately high transport capacity, even under low flow rates, compared to the same experiments under terrestrial conditions. Therefore the action of metastable liquid water/brine could be more widespread on Mars than currently considered possible. This new hybrid mechanism involving both wet and dry processes also extends the suite of processes that could be responsible for currently active features on Mars, such as Recurrent Slope Lineae or some recent modifications of gullies.

NOTES

Implications of a Non-Salt-Recharge RSL Mechanism for Martian Gullies as Remnants of an Earlier Wetter Period.

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Among the various hypotheses proposed for gully formation on Mars, the resulting debate as to whether flowing melt-water or a totally non-aqueous process is required for their production, has significant implications in our understanding of Mars' water budget and its potential for current day habitability. In close proximity with the majority of martian gullies, dark downslope flow-like features have been observed that occur annually during spring and summer, especially on steep, equator-facing, southern slopes. Several mechanisms have been proposed to explain the occurrence of these *Recurring Slope Lineae* (RSL), ranging from dry granular flows to effects caused by rapid heating of nocturnal frost. The best current hypotheses for their formation involve either the melting of frozen brines, the seasonal discharge of a local aquifer, or via deliquescence of salts dispersed in the soil. We have recently shown that the darkening of the soil comprising the RSL on Mars can be reproduced by the deliquescent wetting of a perchlorate- and/or chloride-containing martian simulant soil. Our laboratory studies have also shown that this process appears to require longer timescales than previously assumed to produce liquid water in the form of either bulk or droplets.

Our results imply that RSL would not necessarily need the presence of flowing water/brine. Thus, in turn, it is possible that their association with gullies, and the gullies themselves, may not be the result of recent flowing water, but remnants of an earlier period when Mars may have supported a wetter environment that allowed for the melting of subsurface ice at exposed outcrops and/or the flow of water and subsequent precipitation of perchlorate or chloride salts on evaporation. This process would have been most effective on the warmer equator-facing slopes of the craters and dunes, where RSLs are found today. The steep slopes of these formations may have also impeded new dry soil from covering the salt deposits. Our findings and hypothesis are consistent with the latest spectral evidence for hydrated salts in the RSL and do not require a flowing bulk water salt-recharge mechanism, since thin-films of liquid water would be formed in place by the previously deposited salts from an earlier flow. The association of RSL, produced via such a mechanism, with the gullies would imply that the gullies themselves may also be remnants of an earlier wetter period or a seasonal dry-formation mechanism such as ice-sublimation or sediment flow.

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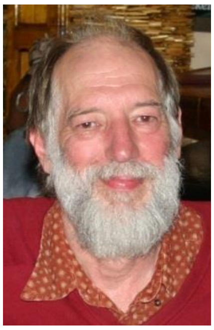

Experimental Simulation of Martian Gully Formation: A Debris flow Framework

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In an attempt to understand the applicability of a slush/water-based origin for the gully forms on Mars, we undertook a series of flume experiments at Earth surface temperatures and pressures and subsequently scaled for Martian conditions. Our objectives were to investigate the potential for gully-like forms to develop as a result of slush-rich fluids running down slopes similar to those observed on Mars. Experiments were conducted in a 3 m x 0.5 m hinged flume filled with medium grain-size sand. The experiments were run over a slope angle range of 10° - 30°, corresponding to the slope range for gullies observed on Mars. Water/ice slush was flowed through a 19 mm diameter silicone hose and released onto the surface at the top of the slope. A variety of morphometric parameters were measured on each gully form produced in the flume. Gully forms displayed development of the fundamental morphological components observed on Mars: alcove, channel and apron, with a diversity of planimetric forms. Strong positive relationships were measured between morphological components and slush flow rates, as well as between slope angle and morphological component. Our results compared favorably with previous experiments using liquid water. The forms produced during simulations compared favorably to those produced by slush-dominated debris flows in terrestrial arctic climates and thus lend support to suggestions that some Martian gullies may be the result of slush-rich debris flows.

NOTES

New insights into processes influencing submarine gully morphology

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Submarine gullies are pervasive features of continental margins and are described as the first features to develop on continental slopes. They influence sediment transport and deposition down-slope, have a key role in continental margin evolution and contribute to sediment deposits on the continental slope and rise. Gullies occur on both active and passive margins, on submarine volcanic flanks, deep-sea sediment drifts, and ocean ridges and persistently across all latitudes. Some show striking similarities to their terrestrial and Martian counterparts. The processes influencing submarine gully morphology remain poorly constrained, with suggested mechanisms including turbidity currents, debris flows, slides, slumps and oceanographic processes such as dense water overflows and contour currents. In this study we identify distinct gully types from quantitative analysis of geophysical data and attempt to link morphology with formation mechanisms. This includes new data collected by a fleet of marine robotics, providing cm-scale resolution geophysical data, targeted sediment cores from gully flanks and axis, and in-situ video footage showing fine-scale gully-morphology. We find that processes influencing gully morphology vary with local slope character and regional factors such as presence of fans, sediment type and yield, and ice-sheet history. Analysis of gully parameters and spatial distribution patterns together with environmentally derived parameters, such as slope gradient and geometry, provide a step forward in constraining processes operating on continental margins and environmental controls influencing gully morphology. We show that gullies are fundamental in contributing to the evolution of continental margins, are active systems today and highlight their importance compared to well-documented down-slope processes. Understanding how these mechanisms differ is fundamental in understanding seafloor erosion patterns, ice-dynamic histories, continental margin and canyon evolution and factors influencing slope instability.

NOTES

Debris flow recurrence intervals on an alluvial fan in Hanaskogdalen (Svalbard)

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As part of a larger project investigating terrestrial analogs on Svalbard for cold-climate landforms on Mars [e.g., 1-3], we analyzed debris flow recurrence intervals on an alluvial fan in Hanaskogdalen, Svalbard. Mass wasting processes including debris flows are common processes on the archipelago of Svalbard. Debris flows are suggested to be triggered mainly by heavy rainfalls or sometimes snowmelt [e.g., 4]. Previous studies based on lichenometric dating of debris flow deposits estimated that major episodes of debris flow recurrence intervals on Svalbard are in the range of 80 to 500 years [4, 5]. This is in broad agreement with comparisons of historic photos with recent photographs by [6] who found no changes on fans in Tempelfjorden in a time span of 90 years. We used multi-temporal air and satellite images and climate data from 1960-2014 complemented by field work in 2008, 2009, 2011, 2012, and 2014, as well as lichenometric dating to narrow down the debris flow changes and activity periods on an alluvial fan in Hanaskogdalen. Our analysis includes three air images from 1961, 1990, and 2008 with a resolution of 20-50 cm/pxl to track morphological changes. These images were complemented with high to medium satellite imagery, by Keyhole-9 (1976), SPOT 1-7 (1986-2014), and DigitalGlobe (2011-2014) data. High-resolution climate data collected near the study area, including precipitation, snow cover, and air temperatures, were obtained through "e-klima" of the Norwegian Meteorological Institute. Based on the observed changes, we measured lichen sizes on individual debris flows estimating/narrowing down their activity period using the lichen growth rates of the same species from Svalbard [7, 8]. Our analyses imply that recurrence intervals of debris flows in the last ~65 years are much shorter (~10-15 years) than cited in literature. We also find that the observed new debris flows are mostly triggered by heavy rainstorm events or the cumulated precipitation quantities in unusually wet years.

Acknowledgements: This work was supported by ESA through project ID 14850 and by the DigitalGlobe Foundation (www.digitalglobe.com).

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NOTES

Descending Dunes Observation for Dakhla Oasis, Egypt and Russell Crater, Mars

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Among plenty of the Martian data, observations of the surface sediments covering the planet are definitely the most common, and all the planet is covered with mid- or even hi-resolution image data, panchromatic, multi- or hyperspectral. Desert landscapes, with windblown sands and dunes are typical for Martian surface, and detailed studies related to dunes can be made with easy on the basis on both orbiter and surface observations. Flat sandy fields as well as much more interesting hilly landscapes covered with eolian sediments can be observed.

Martian dunes have the same shape variability like their terrestrial counterparts: there are linear, star and barchanoid forms. Genesis should also been the same, however the material building the forms is subject to discussion. The big dunes and megadunes apart from polar regions of Mars looks to be quite different than these forming polar regions. Thus, both populations are discussed separately. In this research, only southern dunes population is discussed in detail due to their location inside morphologically complex terrain, and the presence of descending dunes.

In this research, dune field located inside Russell Crater, Mars, was analyzed. The barchan-shaped dunes have classic form, but there are also elongated descending dunes directed by wide gullies (couloirs) and overall terrain morphology. Additionally, linear gullies are observed on the slopes of megadunes present in the crater. The variability of gullies forms enable preliminary characterization of gullies with use of common analyses on the base of sedimentology, geomorphology, mineralogy and climate tools.

Similar environment, with descending dunes on the steep slopes, can be observed and analyzed in Dakhla Oasis, Western Desert, Egypt. These forms are close to their Martian counterparts, in the terms of size, spacing and shape. This enable to use a comparable study for both of these populations.

Presented research summarizes observations for Mars and Earth descending dunes, discusses the similarities and differences and makes the first step to analyze genesis, sediments present, current state and activity of dunes. Interesting features and processes observed, like linear gullies on the dune slopes in site and in the vicinity, are discussed, too. Preliminary analyses of MOC imagery are supported by THEMIS and HRSC data to make a comprehensive analyses possible. Sediments and geomorphologic position of dune field is discussed and possible climatic/meteorological influences and factors are analyzed.

NOTES

Small Martian Gullies Associated with Recurring Slope Lineae (RSL)

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Although classic Martian gullies are concentrated in the mid-latitudes, small channels are often found with RSL in other regions. A gully is defined as "*A small channel with steep sides caused by erosion and cut in unconsolidated materials by concentrated but intermittent flow of water... and too deep (e.g., > 0.5 m) to be obliterated by ordinary tillage*." [1]. The channels (1-20 m wide, >0.5 m deep) associated with many RSL [2-3] fit this definition in terms of size. However, classic martian gullies are much larger, so we call the RSL-related landforms "small gullies" even though they are the size of typical gullies on Earth. The largest RSL gullies are in Valles Marineris (VM), although a recent global CTX-image survey excluded them [4]. Debate continues on whether the mid- latitude gullies are due to the flow of water, wet debris flows, or dry debris flows fluidized by seasonal CO_2. Were the small channels associated with RSL caused by aqueous erosion? Here, too, there are ongoing debates about how RSL form, and whether or not they created the small gullies. In some cases in the southern middle latitudes, the present-day RSL are much smaller and shorter than the gullies they follow, so either the gullies were caused by a different process or much greater past RSL activity. In other places, especially in VM, the RSL precisely fit the small gullies and extend out to the downhill margins of the gully fans. Unless a remarkable coincidence, this suggests that the RSL activity produced the gully topography. There are a few cases where we see topographic changes associated with active RSL [5], but in most cases either the RSL gradually erode and deposit sediment too slowly to detect with HiRISE (~30 cm/pixel) over several Mars years, or the topography changes episodically. Laboratory experiments under martian conditions provide insight into how small water flows may change the geomorphology [6]. In this presentation we will review observations of RSL, models for how they form, and implications for the geomorphology.

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NOTES

An active gully on Mars: accumulation and seasonal mobilisation of material

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Since their first observation by Malin and Edgett (2000) [1], martian gullies have been abundantly studied, but their formation mechanism is still under debate [e.g. 2, 3, 4, 5, 6]. Gullies are generally composed of an alcove, a channel and an apron [1, 7] and some of them are active today [8]. Here, we present our study of one specific gully, which is located on sand dune in the southern hemisphere. This study was performed using HiRISE images at 25-30 cm/pix and 1 m/pix HiRISE elevation data. We found that this gully has been extremely active over the last 4 martian years. Each year, we observe an accumulation of material in the alcove and then its subsequent mobilisation - causing meander growth, extension of the channel, and growth of the debris apron. Over one martian year the debris apron expanded by almost 150 meters from an initial size of 900 meters. Two different pulses of activity are observed: 1) in the middle of winter when CO_2 frost is still present and 2) at the beginning of spring when the seasonal defrosting is coming to an end. This phenomenon is observed on a moderate east-facing slope (~13°). A correlation between seasonal frost and this gully could be consistent with its development timing. Laboratory experiments will be performed to better constrain the potential range of processes involved in such seasonal mobilisation of material on Mars.

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NOTES

Recent and present-day activity of martian gullies

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In this study geologically recent and present-day active gullies in the southern hemisphere of Mars are presented. Gullies in two prominent regions (Argyre impact basin and the polar pits of Sisyphi Cavi) were analyzed with several visible image, hyperspectral and thermal datasets[1,2].

Gullies in the Argyre basin show two different morphological types, with more degraded gullies on equator-facing and more pristine gullies on poleward-facing slopes. The general orientation of gullies in this region is towards the equator, also proposed by e.g. [3,4,5]. The more pristine gullies were formed by the removal/erosion of the volatile-rich dust-ice mantle, which has an age of about 20 Ma determined with crater size-frequency distribution measurements [1]. Some of these gullies superpose ~500 ka old transverse aeolian ridges. Hence, gullies in the northwestern Argyre basin show a general formation age of about 20 Ma, following by a last recent activity of younger gullies less than <~500 ka ago [1]. This is at the end of the last proposed ice age on Mars [6].

Present-day activity of one specific gully was observed at an equator-facing slope of a polar pit within Sisyphi Cavi in the south polar region [2,7,8]. With multi-temporal High Resolution Imaging Science Experiment (HiRISE) images it was possible to identify ongoing activity of dark flow-like features within this gully in the Martian Years (MY) 29 and 31. Activity in MY 30 could not be detected due to the lack of multi-temporal HiRISE-images [2]. The activity occurred in mid-spring, when sublimation of the CO_2 surface cover begins and was only limited to one single gully and not to adjacent gullies, which share the same morphologies, dimensions, orientations, and slope angles (~15°) [2]. With shadow measurements and a HiRISE digital terrain model, the volume of the new deposit in MY 31 was estimated to be approximately 300-600 m^3 [2]. The general proposed formation model for the observed activity is the mobilization of dry material (sand) by CO_2 sublimation [2]. Here, the ongoing sublimation of the CO_2 slab ice cover, which was detected with hyperspectral images in the study region, could support the mobilization of dry material in the interior of the gully channel/alcove leading to the formation of new deposits [2].

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NOTES

Monitoring Martian Gullies: Implications for Formation and Evolution

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Martian gully activity was first reported in 2006 [1]. We are conducting a long-term monitoring campaign with High Resolution Imaging Science Experiment (HiRISE) data [2-5], with repeat imaging now covering nearly 500 gully locations. This enables us to assess the rate and effects of activity and provides insights into the processes that drive gully growth in the present climate. To date, we have seen changes at >50 dune and non-dune gully locations, concentrated in the southern hemisphere, with some sites active repeatedly. We will present current and previous results from this campaign.

We have observed significant changes in gully morphology. These include alcove slumping, new channel segments, abandonment of channels, emplacement of lobate deposits, and formation of terraces. Changes in the morphology of dune gullies are among the most dramatic, including major incision and development of channel sinuosity. “Linear” dune gullies may form differently [6]; however, many active dune gullies have morphologies similar to classic non-dune gullies. Dune gullies are frequently active, probably because of the lack of cohesion of sand.

Nearly all gully activity is correlated with, or consistent with, the timing of seasonal frost [3-7]. Moreover, the orientation distribution of large “gullies” [8] is similar to that of seasonal frost [5]. Most seasonal frost is CO_2, likely the main cause of current activity. Some small-scale activity cannot be definitively tied to CO_2 but may be related to water frost [7]. The abundance of water frost is generally low [9], and is unlikely to produce any significant amount of liquid.

Gullies could have formed in the past due to aqueous processes. However, current activity is sufficiently common that older gullies have probably seen channel erosion and deposition since the last high-obliquity epoch. Moreover, current activity is most consistent with ongoing gully formation by seasonal frost processes, likely involving little or no liquid water. Despite their appearance, gullies may not be aqueous features.

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NOTES

Gullies, mantled terrain, thermokarst and small-scale polygons in the Argyre region, Mars: a critical discussion of their spatial-association.

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Although the Argyre impact-basin and rim-materials on Mars are ancient, having been formed ~3.9 Gya, the regional surface and near-surface exhibit evidence for widespread modification by relatively recent periglacial, glacial, and fluvial processes. Keynote amongst these revisions are stratigraphically distinct “ice-rich” and “icy” mantles, (putative periglacial and glacial) thermokarst, and thermal-contraction (possibly ice-wedge) polygons. Antecedently, we have found that these landforms occur in close spatial-association. This suggests two things: a) the presence and volatilization of liquid water at or near the surface, as each of these landforms originate and evolve only in the presence of water, be it frozen, unfrozen or in a transitive state; and, b) the possibility that some of these landforms are related genetically.

Here, we present three key, albeit preliminary, findings of a study that comprised all available HiRISE images (*n*=815) of the Argyre region (35-65^{0}S; 295-345^{0}E). Gullies have been added to the list of landforms observed in close spatial-association. Ninety-six sites in the study region comprised of 136 HiRISE images have been catalogued and evaluated.

1). Typically, gullies at latitudes ≤~44^{0}S are ensconced in, and surrounded by, an icy (and unpolygonised) mantle that invariably exhibits (glacial-like) thermokarstic depressions and pits. At higher latitudes the polygonised terrain dominates, although where the polygonised terrain and the glacial mantle are observed together, the former underlies the latter; this points to at least one episode of periglacialism predating a more recent period of glaciation.
2). Polygonised terrain, inclusive of gully alcoves, channels and aprons, is observed almost exclusively at and above 44^{0}S, as are periglacial-like thermokarstic depressions and pits.
3). Where polygonised terrain is observed conjointly with gullies at relatively low-latitudes (i.e., ~34^{0}S), as it is within the Hale Crater rim-region, this occurs only on gully alcoves and channels and not on adjacent crater-wall terrain, rim or ejecta. However, thermokarstic depressions and pits associated with possible glacial-processes are observed commonly. Depressions and pits associated with possible periglacial processes are absent. This is consistent with the findings of earlier work suggesting that the latter occur if and only if the surface terrain is polygonised.

NOTES

Patterns of Martian Deglaciation: Assessing the Distribution of Paraglacial FEATURES in Mid-Latitude Craters.

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Extensive evidence of non-polar ice exists on Mars predominantly as debris-covered glaciers in the mid-latitudes, many occurring in craters in the form of concentric crater fill (CCF). In terrestrial glacial regions, the period directly following deglaciation is referred to as the *paraglacial period*, in which the environment returns to “equilibrium” or interglacial conditions. Paraglacial modification often exhibits a specific suite of geomorphic features that form in response to the loss of ice and instabilities introduced into the system by deglaciation.

Recently, a paraglacial period has been identified on Mars in CCF-bearing craters which contain a suite of geomorphic features similar to terrestrial paraglacial settings. As in terrestrial settings, these features are believed to be indicative of deglaciation. One such paraglacial feature that is diagnostic of paraglacial modification is gullies. Other features include washboard terrain, spatulate depressions, and crater wall polygons. This work seeks to determine the degree of variability in paraglacial reworking within the martian mid-latitudes by assessing the distribution of certain paraglacial features in CCF-bearing craters including gullies, washboard terrain, spatulate depressions, broad pits, and crater wall polygons. The variations seen in this analysis will aid in assessing patterns of accumulation and ablation during recent glacial periods on Mars.

The analysis of mid-latitude glaciated craters showed that the degree of paraglacial reworking is variable across the planet. Other observations include: **(1)** ~70% glaciated craters contain some evidence of paraglacial reworking. **(2)** Many more paraglaciated craters are present in the southern hemisphere than in the northern, and proportionally there are more paraglaciated craters in the south than in the north: 89% and 44%, respectively. **(3)** The distribution of paraglacial features is not ubiquitous across all craters. **(4)** The highest concentrations of paraglacial features in the southern hemisphere are located in regions that have been predicted to experience melting conditions at higher obliquities in the last few hundred million years.

The variations in paraglacial reworking suggest that accumulation and ablation are not completely dependent on latitude; primarily, regional circulation patterns will affect the distribution of precipitation throughout the mid-latitudes. The preponderance of paraglacial features in regions that experienced melting conditions in the recent past is evident in the presence of geomorphic features that are expected to form (or be accelerated in their formation) through the presence of liquid water, such as gullies, and potentially washboard terrain.

NOTES

Thermal Inertia of Gully Fans as an Indicator of Gully Activity

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Hundreds of gullied locales are monitored by the Mars Reconnaissance Orbiter Context Camera (CTX) [1] and High Resolution Imaging Science Experiment (HiRISE) [e.g., 2,3] to look for signs of activity. Out of these, ~60 incidents of present-day gully activity have been observed ranging from new flows [e.g., 1–4] down to the movement of a few boulders [e.g., 1–3]. This monitoring effort is a tedious process involving manually examining overlapping images to look for changes between successive images. Thus, the ability to detect changes is limited by the availability of repeat coverage of a given location. Other flows that appear to be new, but lack images by which to date them, have also been observed [e.g., 4].

We present another method that may prove useful in identifying locations of geologically recent gully activity within individual craters: measuring relative differences in thermal inertia between gully fans and/or lobes within fans. Weathering and erosion of inactive fan surfaces leading to denudation and decrease in particle size [5], combined with atmospheric dust deposition, should result in a decrease in thermal inertia of the fan over time. This effect is well illustrated in craters such as Gasa, Galap, and Triolet, which possess large gully fans comprised of multiple distinct lobes. Younger lobes within fans in Gasa crater typically display thermal inertia values in the range of 380–440 $J/m^2K/s^{1/2}$, while the underlying older lobes range from ~280–315 $J/m^2K/s^{1/2}$. Galap displays younger lobes in the ~300–315 $J/m^2K/s^{1/2}$ range, while older lobes are typically between ~270–280 $J/m^2K/s^{1/2}$. Triolet's youngest gully fan portions display thermal inertia values in the ~325–340 $J/m^2K/s^{1/2}$ range, whereas the underlying older portions of the fan range from ~230–250 $J/m^2K/s^{1/2}$. Therefore, looking for relative thermal inertia differences between gully fan lobes may aid in identifying locations where gullies have been active in the recent past beyond the changes that have been directly observed in the past decade.

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NOTES

Simulation and detection of granular flows using numerical modelling and seismic data

Anne Mangeney

IPGP

Gravitational flows play a key role in erosion processes on the surface of the Earth and Mars. They are also closely related to volcanic, seismic and climatic activity and thus represent potential precursors or proxies for the time change of these activities.

Despite the large amount of work devoted to this problem, the mechanisms that govern flow dynamics and deposition in a natural environment are still unclear and key questions remain unanswered, such as the origin of the high mobility of some natural flows or of the sinuous shape of debris flows and gullies. Two severe limitations prevent a full understanding of the physical processes involved in granular flow dynamics and the development of tools for detection of instabilities and prediction of their velocity and extent. First, numerical models do not take into account complex natural phenomena such as the static/flowing transition in granular flows or the co-existence and interaction of fluid (water, gas) and solid phases within the flowing mass, although both play a key role in natural instabilities. Secondly, field measurements relevant to the dynamics of natural landslides are scarce due to the unpredictability and destructive power of such events, making it nearly impossible to validate an unambiguous theoretical description of the modelled physical processes. In this context, the analysis of the seismic signal generated by natural instabilities (i.e. landquakes) provides a unique tool to recover information on flow dynamics and thus validate flow models.

First, I will present new numerical models that deal with the static/flowing transition in granular flows and with the presence of a fluid phase. Then I will describe how seismic waves generated by the flows can be used to extract information on the flow dynamics and on the physical processes involved. Application to gravitational flows on the Earth and Mars will be discussed, showing the open issues raised by combining observation, seismic recording and simulation of these flows.

NOTES

Examination of Origins of Lobate Landforms with Gullies on Mars from an Inverse Analysis of Debris-flow Deposits

Hjime Naruse

Gullies and lobate deposits that commonly occur on the flanks of craters and dune foresets on Mars are often interpreted to have been formed by debris-flow processes. Debris-flow processes suggest the existence of liquid water on the surface of Mars, which is believed to have an extremely cold and dry environment. Debris flows occur when masses of poorly sorted sediment, agitated and saturated with water, surge down slopes in response to gravitational attraction. Thus, recent activities of debris flows imply the existence of liquid water phase materials on the Martian surface. However, the dry granular flow caused by a slope avalanche can also form gullies and lobate deposits, which resemble debris-flow deposits, so there are still uncertainties over the occurrence and origins of liquid water on the modern Martian surface. This study proposes a method for estimating debris-flow properties, in order to distinguish debris-flow processes on Mars. In this method, one-phase rheological model of non-newtonian fluid is employed here as the forward model, and flow parameters such as yield strength and flow viscosity required for the forward model are optimized to reconstruct geomorphological features of Martian lobate deposits. Genetic algorithm is used for this parametric optimization. Results of the inverse analysis suggested that a lobate deposit on Mars can be formed by a debris flow that shows flow properties similar to water-saturated debris flows on the Earth. If rheological parameters of the flows can be determined from the surface morphology of lobate deposits, it would be helpful for distinguishing debris-flow processes from dry-granular flows. The inverse analysis method proposed here with future field surveys and experimental studies will provide quantitative criteria for identifying debris flows from geomorphological features of lobate deposits.

NOTES

Automatic detection of changes on Martian gullies from co-registered high-resolution visible images

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It is estimated that between 1976 and 2014 orbiter missions acquired more than 400,000 high-resolution visible images of the Martian surface, covering an area larger than 5 times the overall area of Mars. While this data abundance generates great opportunities for new scientific discoveries, the community seems to struggle to catch up with the technological achievements, largely due to a number of unresolved issues that the automatic planetary data analysis presents. As a matter of fact, the paradigm for processing Mars data is still the one-at-a-time processing of incoming products by expert scientists, who are more or less forced to use sophisticated software in order to extract input information for their research from raw data, even though they are not data scientists themselves.

A main goal of our work, conducted within EU FP7 iMars project and STFC consolidated grant "Planetary Surface Data Mining", is to create sophisticated software that would automatise as much as possible the required data processing, leaving expert scientists to do (if possible) only the final analysis and interpretation. Our current research has two main objectives:

- To project all available high-resolution images of Mars onto a common coordinate system, thus removing from planetary scientists the need to co-register or orthorectify them.

- To use the co-registered imagery to automatically detect changes on the Martian surface at a global scale, thus releasing to the planetary community a large number of case studies to include in their research.

Currently the software that is required for the first task is completed and tested on the high-resolution images of MC11-E quadrangle, while the automatic change detection software is going to be completed during the next weeks.

After the change detection software is finalized, it will process as much of the Martian high-resolution orbital imagery as possible. In order to follow the planetary community interests we have prioritized areas that are known to be related with dynamic features of Mars, such as gullies, RSLs, impact craters, polar spiders and slope streaks. Note that the examination of gully-related areas is one of our top priorities.

In this presentation we are going to present the features, capabilities and limitations of our developed software. Moreover, we will present the first results of our automatic change detection software to gully-related areas, which hopefully will include some unnoticed so far incidents of gully-related changes.

NOTES

Poster Presentation Abstract

An Experimental Investigation of the Interaction between Sublimating Carbon Dioxide and Porous Substrate

Mc Keown, L. , McElwaine, J. and Bourke, M.C.

Martian gullies were first identified by Malin and Edgett, (2000) from high resolution images taken by the Mars Orbiter Camera. Predominantly located in the southern hemisphere, these features are present in the vicinity of craters, south polar pits and valleys. Gullies are generally characterised by a “theatre-shaped” alcove, sharply – incised channel and depositional apron. A sub-group of gullies exist on polar facing aeolian dune slopes. These active *linear* gullies (Dundas et al. 2012, Védie et al.,2008) are distinguished from those comparable with terrestrial gullies, by terminal pits in place of aprons. Many hypotheses are proposed regarding the formation of linear gullies. These include a wet debris flow, dry granular flow and sublimating carbon dioxide, among others.

The sublimating carbon dioxide hypothesis (Diniega et al. 2013) is consistent with the morphology, location and current activity of linear gullies on Mars. This hypothesis proposes that CO2 ice blocks break off and fall from over – steepened cornices and then slide onto dune slopes in the spring, carving channel paths along their trajectories and sublimating at termini to form pits. We conducted a series of laboratory experiments at the Planetary Science Institute, Tucson, Az in August 2015 to test this hypothesis that sublimating carbon dioxide ice blocks could achieve geomorphic work and initiate sediment transport. Temperature and pressure profiles within glass ballotini beds of discrete grain sizes were recorded and compared with the output of our numerical model. The geomorphic response of the bed in each case was recorded.

Our preliminary results show that a sublimating CO2 ice block of mass 1.9 kg was capable of displacing ballotini beads within a diameter range of 0.044 - 0.088 mm and navigating downwards within the bed to form a pit feature comparable in morphology to those observed on Mars. Refining our experiments and extrapolating our results to Martian conditions will allow us to determine whether carbon dioxide ice blocks may be responsible for the formation of Martian linear gullies.

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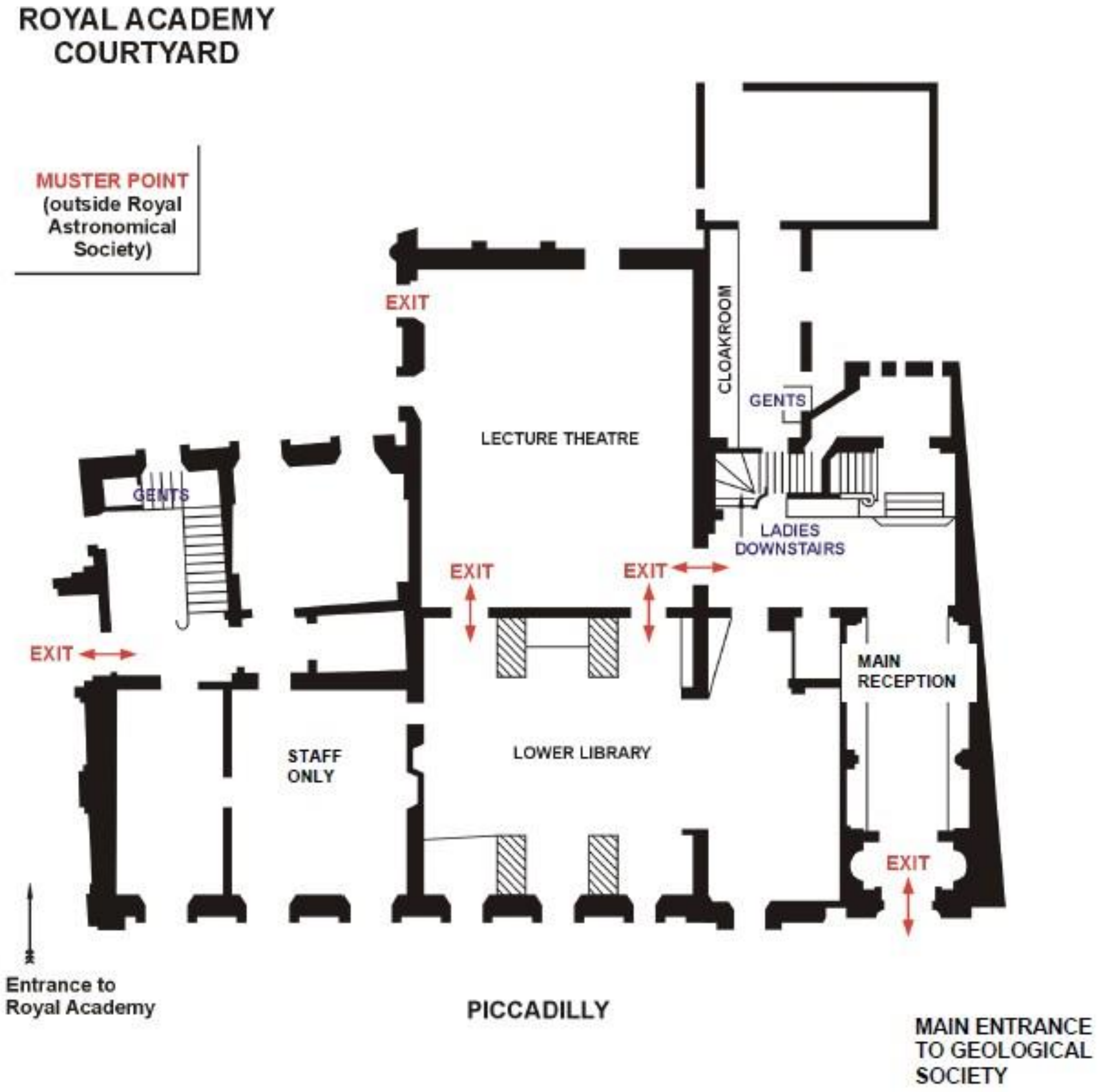
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