ORIGIN AND EVOLUTION OF THE LANDSCAPES OF COMET 67P/CHURYUMOV-GERASIMENKO.

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Introduction: Comets are the oldest objects in our solar system and typify the remnant, unprocessed materials from which all the larger planets and moons were constructed. Consequently, they represent a window into the initial conditions that proved favorable for the formation of the Earth and life as we know it. With Rosetta's rendez-vous of comet 67P/Churyumov-Gerasimenko (67P) in the summer of 2014, we now have a dataset that permits access to the spatial scales where the processes relevant to small body evolution can be directly observed. These observations have allowed for detailed analyses of morphologies down to the meter scale across the entire nucleus, and have provided a long temporal data set with which to search for changes on the surface, important observations that have given us the opportunity to watch how a comet erodes.

For instance, changes on the surface are driven by outgassing from sublimation of near-surface volaties, and are expressed on the surface in two forms: large-scale changes to the bulk nucleus via cliff collapse [1], and small-scale changes contained within the smooth terrain regions that blanket much of the northern hemisphere. Large-scale failure of cliffs generates low thermal inertia, volatile-depleted regolith that acts to slow further bedrock sublimation, allowing for the surface of 67P to retain its relatively primitive topographic form to the current day. We have no knowledge, however, of the frequency of mass wasting events and how much material may be expected to be removed in any given event. Small-scale changes are far more frequent [1,2], and so studying a larger sample of changes will aid in better understanding the subsequent evolution of the regolith.

Numerical landscape evolution modeling offers the possibility to tie Rosetta's many observations to the fundamental physics that drives these processes, and ultimately determine whether 67P evolves gradually, through its jets, or stochastically through large outburst events. Specifically, we utilized the MARSSIM landscape evolution model, which accounts for the thermophysical weathering of a bedrock composed of both volatile and non-volatile materials [3] on a low, variable gravity environment like on 67P. Unlike for other planetary bodies, our simulations use realistic inputs as to the volatility and strength of the bedrock, and insolation rates and initial topography as measured by Rosetta.

These simulations, therefore, allow us to constrain the rates of landscape evolution and the total erosional exhumation on 67P, to directly answer the question as to how its surface evolved despite the current apparent low levels of observed activity. Accordingly, we assess the question of whether 67P is primitive or not, and compare directly the erosional processes observed on both 67P, and all other cometary nuclei observed to date. Further, we combine a robust study of transient changes in the smooth regolith terrains, which are expressed as pits, to better constrain both the evolution of this vast smooth regolith cover, and of the volatiles embedded within the near-surface of 67P.

General Evolution: Rosetta observations have shown that the cliffs that dominate the northern hemisphere landscapes are surprisingly stable over a single orbit [1]. Despite their brittle appearance in Rosetta images, with boulder deposits at their base suggestive of mass wasting, there is little evidence of substantial topographic evolution of the cliffs after 67P's perihelion passage [1,4]. Most changes were within the smooth plains deposits [1], with only a few observations of cliff failures [4]. Our simulations are designed to test over what time scale(s) 67P's topography evolves, and in what manner (i.e. does the surface erode gradually through its jets, or are sudden, chaotic events the dominant means by which the topography is formed)?

Ultimately, we seek to understand the dominant process(es) that have shaped 67P's landscapes. The jets, as on 9P/Tempel 1 are well correlated with local sunrise, and are the result of the sublimation of surface ices deposited the previous night [5]. There are no observations of jets effecting the large-scale surface topography (i.e. cliffs), though their daily activity may act to slowly deflate the surface over many orbits. Outbursts have been well documented [6], and are much more violent surface phenomena that have been observed to drive mass wasting of cliff margins [1]. Observations of outbursts are much less common, however, and it is not clear how frequently these comparatively violent sublimation-driven cliff failures occur, and whether the regolith they generate is a significant fraction of the total regolith on 67P.

In this work, we detail the results of numerical simulations using the updated modules of MARSSIM [3] to assess the relative importance of these two processes in shaping the topography of 67P. These simulations are also able to constrain the total erosional exhumation of both the northern and southern hemisphere terrains and provide constraints on the timescales over which these morphologically different terrains evolve. With these constraints, and assuming 67P's orbit does not evolve substantially, we have also extended the length of our simulations to test the timescale to bevel 67P's topography, allowing us to determine how primitive it is. These final simulations allow us to directly compare 67P's landscapes to other cometary nuclei observed in situ, to understand whether the cometary surfaces observed to date are just a function of their cumulative time spent in the inner solar system [7].

Transiet Pit Formation & Evolution: Smooth regolith terrains blanket large portions of the underlying terrains of the northern hemisphere. Boulders and cliffs are often seen outcropping from beneath this regolith cover, indicating that it is relatively thin (~1 meter). Perhaps surprisingly, changes within these terrains became increasingly common as 67P approached perihelion [1, 2], and are the predominant type of change observed on the comet [1].

We have identified a field of pits in the Hapi region, where more than a dozen pits have appeared within the smooth regolith terrains between March 5 and March 17, 2015 (Fig. 1a/c), with a jet having been observed to originate from the region on March 11 (Fig. 1b). Analysis of the region from an OSIRIS narrow angle camera (NAC) image acquired on March 5 (Fig. 1a) shows that at least 17 pits, tens of meters in diameter have since formed some time within the intervening 12 days. We have made DTMs of this region to estimate the volume of these pits (Fig. 1d). Preliminarily results show that they are ~1-meter deep (with <<10% vertical precision), flat-floored depressions, excavating a depth comparable to the thickness of the smooth regolith terrains. Assuming a dust-to-ice ratio of 8.5 [8], regolith porosity of 65% [9], and material density of 535 kg m^{-3} [10], the mass of volatiles released is ~1.2×10^5 kg. While this estimate is early, it is comparable to the mass lost in the Aswan outburst and cliff collapse (1.08×10^5 kg; [4]), suggesting that the smooth regolith terrains of 67P retain large volumes of volatile materials.

This field of pits is just one such example, where more have been observed by Rosetta throughout its mission [1]. We will present on these results and show that the topographic form and planform curvature of all other pits across the nucleus are all consistent with the presence of significant volumes of volatiles in the near subsurface of the smooth regolith terrains, and that growth of these pits is through uniform scarp retreat.

We will then show results from numerical simulations (via MARSSIM) to understand what process drives their formation, and in turn, how often these features form. If their formation is erosional, then it is likely driven by the sublimation of volatiles. What is not clear, however, is whether only water ice is required or, because of the low thermal inertia of the regolith, whether volatiles like CO or CO_2 are necessitated.

Finally, our simulations investigate whether the formation and morphologies of pits are consistent with volatiles embedded within the regolith, or if sublimation is from the underlying bedrock. Since we measure the volume displaced during their formation, their planform curvature, and the frequency at which they occur, we are able to place bounds on the volumes of required volatiles either from within the buried bedrock, or from the re-condensation of volatiles within the upper regolith.

References: [1] El-Maarry M.R. et al. (2017) *Science, 355,* 1392-1395. [2] Hu X. et al. (2017) *A&A, 604*, A114. [3] Umurhan O.M. et al. (2018) *Icarus, in review*. [4] Pajola M. et al. (2017) *Nature Astronomy, 1*. [5] Prialnik M.F. et al. (2008) *MNRAS, 388*, L20. [6] Vincent J.-B. et al. (2016) *MNRAS, 462*, S184-S194. [7] Birch S.P.D. et al. (2017) *MNRAS, 469,* S50-S67. [8] Fulle M. et al. (2016) *MNRAS, 462*, S132-S137. [9] Spohn T. et al. (2015) *Science, 349*(2). [10] Preusker F. et al. (2015) *A&A, 583*, A33.

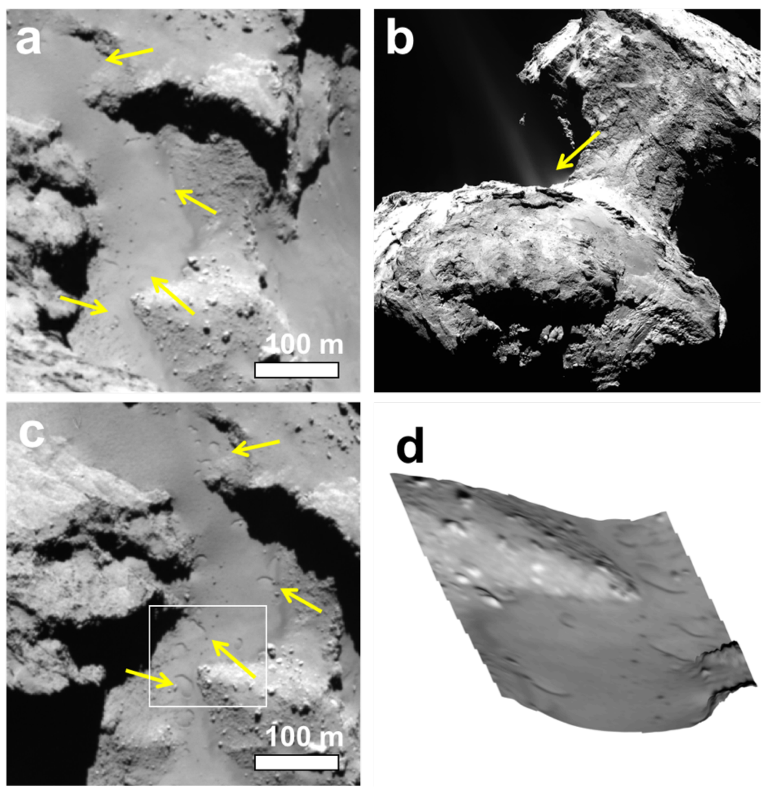

Figure 1: (a) NAC image of the Hapi region acquired on 2015/03/05; (b) NAC image of a jet (yellow arrow) originating from the region of interest acquired on 2015/03/11; (c) NAC image of the Hapi region acquired on 2015/03/17 showing the formation of at least 17 new pits; (d) DTM of the region within the white box of panel c showing pits several pits ~1 meter deep. The overall curvature of the DTM matches the input shape model. Yellow arrows in a/c point to the same feature.