MIGRATING SCARPS ON COMET 67P.

S.P.D. Birch[1], A.G. Hayes[1], O.M. Umurhan[2], Y. Tang[1], J-B. Vincent[3], N. Oklay[3], D. Bodewits[4], B. Davidsson[5], R. Marschall[6], J.M. Soderblom[7], J.M. Moore[2], and S.W. Squyres[1], [1]Cornell University (sb2222@cornell.edu), [2]NASA Ames, [3]DLR, [4]University of Maryland, [5]JPL, [6]ISSI, [7]MIT.

Introduction: Early Rosetta observations of comet 67P/Churyumov-Gerasimenko (67P) led to a hypothesis that sublimation-driven erosion of consolidated cliffs plays a major role in shaping cometary surfaces [1]. The remnants of this erosional process are the smooth terrains: large sedimentary deposits of fallback material [2]. Few changes of the cliffs were observed during the Rosetta mission, indicating that this process acts on multi-orbit timescales. Instead, many rapid changes were detected in the smooth terrains [3-5]. We detail a sequence of observations of transient large-scale depressions that began to form in March 2015. Over the following 2 months, the scarps that make up the depression walls migrated at a rate of 3-7 cm/hour in the sunward direction, opposite to the direction of other sublimation-driven erosional features observed across the solar system. Simultaneously, the depressions appear to be a source for dust jets. Together, these observations are consistent with scarp migration driven by re-radiated infrared light from the depression floors onto a shadowed, water-ice rich scarp. We confirm that large volumes of water-ice are embedded within the near surface of the smooth terrains, and that subsequent de-volatilization of these ices drives the shedding of 67P's upper dust mantle via scarp retreat. Consequently, our observations provide a window into a mechanism responsible for processing cometary materials.

Migration Observations: Using image data from the OSIRIS Narrow angle camera (NAC) onboard the Rosetta spacecraft, we find a cluster of large-scale depressions that were first observed on March 5, 2015 (Figure 1b). These features are in the Hapi region, in the comet's 'neck', a gravitational low where the largest volume of fallback materials are expected [2].

The depressions appear as small linear arcs proximal to boulders or cliffs (yellow arrows in Figure 1b). The arcs then enlarge over the subsequent 12 days into quasi-circular, decameter-sized depressions (Figure 1c). The upper boundaries of each depression at this time form scarps that originate from the initial arcs (shown in Figure 1b).

Additional images of this region were acquired over the following ~2.5 months; the final high-resolution image of the depressions in this region was acquired on May 22, 2015. This sequence of observations clearly show that the initial quasi-circular depressions (Figure 1c), evolved into fewer, larger features that span nearly the entire plain (Figure 1d/e).

Simultaneous OSIRIS images throughout this time period also show dust jets emanating from the region, suggesting that, as the depressions form, the finest material is removed directly to the coma.

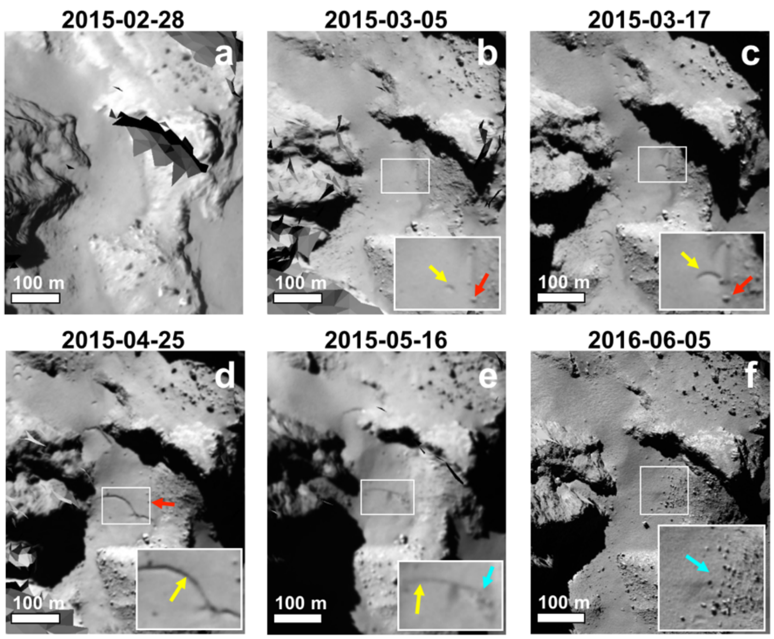

Figure 1 – Arc-shaped depressions (yellow arrows in all panels) began to appear in this region in March 2015 (b/c), and then coalesced into larger features over a 2+ month period (d/e). Images 12 months later (after perihelion; panel f) show a surface similar to prior to depression formation (a), with featureless smooth terrains. Underlying boulders, however, have been abandoned (cyan arrows) as a result of the changes in panels b-e. The red arrows point to the same boulder.

The curvature of the depression scarps, where inward-facing protrusions are sharper than outward-facing promontories, is consistent with growth and agglomeration of numerous small depressions into increasingly large depressions via uniform retreat of the depression scarps. The later-stage morphologies also suggest that an upper layer of regolith is progressively removed during this process, leaving behind only the largest boulders (cyan arrows in Figure 1e/f).

Though the temporal coverage is sparse, we measure a migration rate of the depression scarps of 3-7 cm/hour, with a mean of 4±2 cm/hour. However, from OSIRIS image data alone, we are unable to determine if this rate is constant throughout the 2+ month period, or if the depression scarps retreat in sudden bursts, followed by quiescent periods of no change.

The migration direction of these depression scarps (toward the top of each panel in Figure 1) is very nearly 180° opposite the azimuth of the sun angle at the time of the observations. This implies that the depression scarps are migrating opposite compared to all other known sublimation-formed depressions across the solar system, which all enlarge along a direction near-parallel to the sun azimuth for lower solar elevations.

Water Ice: On April 25, the depressions were imaged with multiple OSIRIS NAC color filters, allowing for a spectrophotometric analysis. Through a decrease of the spectral slope (i.e. a blueing of the surface [6]) we identify significant exposures of water-ice (Figure 2).

The water-ice signature, though already substan-

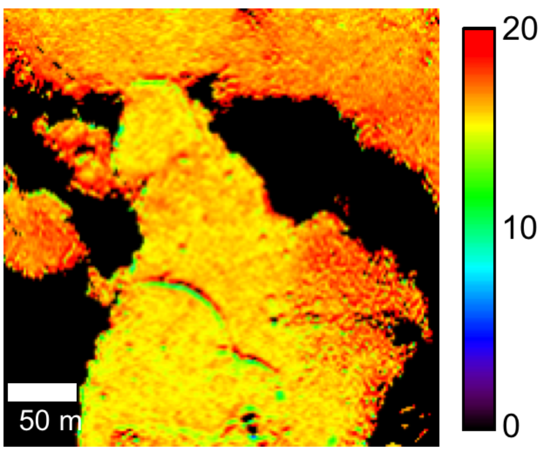

Figure 2 – Color observation of the region of interest. The water ice-rich portion of the scarp appears green in the image

tially higher in Hapi than all other regions of 67P [7], is further enhanced within the depressions, proximal to the scarps (Figure 2). Given the geometry of the depressions and orientation of the scarp relative to the solar azimuth, these scarps/water-ice terrains are shadowed from direct insolation at this time. The surrounding terrain, meanwhile, though more water-ice rich than the bulk nucleus (Figure 2), is uniform in color across the region through which the depressions expand (Figure 2). This implies that the depression scarps are revealing near-surface water-ice that is otherwise buried below the smooth terrains in Hapi.

Model: Based on the observed formation and evolution of these features, as well as the presence of dust jets, the likely geomorphic process driving the scarp retreat is the sublimation of near-surface ices. To model the formation and evolution of these features, we require some simplifying assumptions.

We assume that the regolith in Hapi is like the material that Philae touched down in, consisting of centimeter-sized gravels. While the depth of the regolith layer in Hapi is unknown, it is likely several meters [2], far deeper than the measured depression depths (~1 m). This requires that sublimation of ices must come from

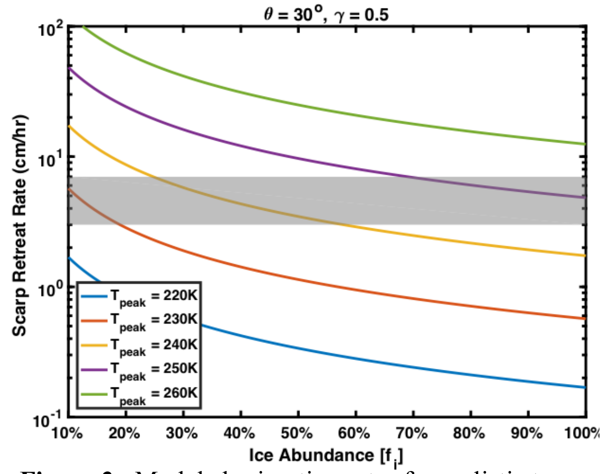

Figure 3 –Modeled migration rates for realistic temperatures. The measured scarp retreat rates in all the OSIRIS images are plotted in the grey box.

within the regolith layer itself, and not from an underlying consolidated layer, implying that dust and ices are well mixed.

Given the geometry of the depressions (Figure 1), and the blue color of the shadowed scarp (Figure 2), we assume that within the scarp itself, there is exposed water-ice (mixed with non-volatile material) that can freely sublimate. The remainder of the surface has less water-ice (<5%), and we assume those surfaces to be relatively inactive. Growth and migration of the scarps, then, is driven by re-radiated infrared radiation from the both the surrounding slopes and the depression floors onto the shadowed scarp (Figure 3). Subsequent sublimation of ices within the regolith ballistically transports surrounding particles out of the scarp. This results in the observed sunward migration direction. Finally, the lack of material at the bottom of the scarp rules out processes such as cracking that have been demonstrated to drive activity elsewhere on 67P.

We assess sublimation rates using the formation developed by Lebofsky [7] and models for both the peak surface temperature and temperature variations throughout a given day. Our modeled and observed scarp migration rates are consistent for temperatures >230 K (Figure 3). Thus, our observations provide evidence as to the two-step process by which 67P seasonally de-volatilizes and sheds material.

References: [1] Vincent J.-B et al. (2016) *A&A, 587*, A14. [2] Thomas N. et al. (2015) *A&A, 583*, A17. [3] Groussin O. et al. (2015) *A&A, 583*, A36. [4] El Maarry M.R. (2017) *Science, 355*, 1392. [5] Hu X. et al. (2017) *A&A, 604*, A114. [6] Oklay N. et al. (2016) *A&A, 586*, A80. [7] Lebofsky L.A. (1975) *Icarus, 25*, 205.