Evolution of the Imhotep Basin on Comet 67P/Churyumov-Gerasimenko

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Highlights

- **Most of the changes observed by Rosetta on comet 67P occurred within the *smooth terrains*.**
- **Future sample return missions like *CAESAR* will be restricted to sampling the top few centimeters of *current day smooth terrains*.**
- **Therefore, understanding the erosional processes capable of modifying these terrains throughout their lifetime exposed on a cometary surface is necessary for understanding the overall evolution of the comet and to interpret returned samples.**
- **We track the evolution of migrating scarps within the Imhotep basin on comet 67P and apply an existing model of smooth terrain erosion *(Birch et al., 2019)* to explain our observations.**
- **Simultaneous erosion and deposition is observed in Imhotep due to its proximity to the equator.**
- **We create a *sediment budget* for the region to understand the net movement of material.**
- **Re-deposition of material cannot be explained by uniform airfall and *local scale effects play a significant role.***

1. Introduction

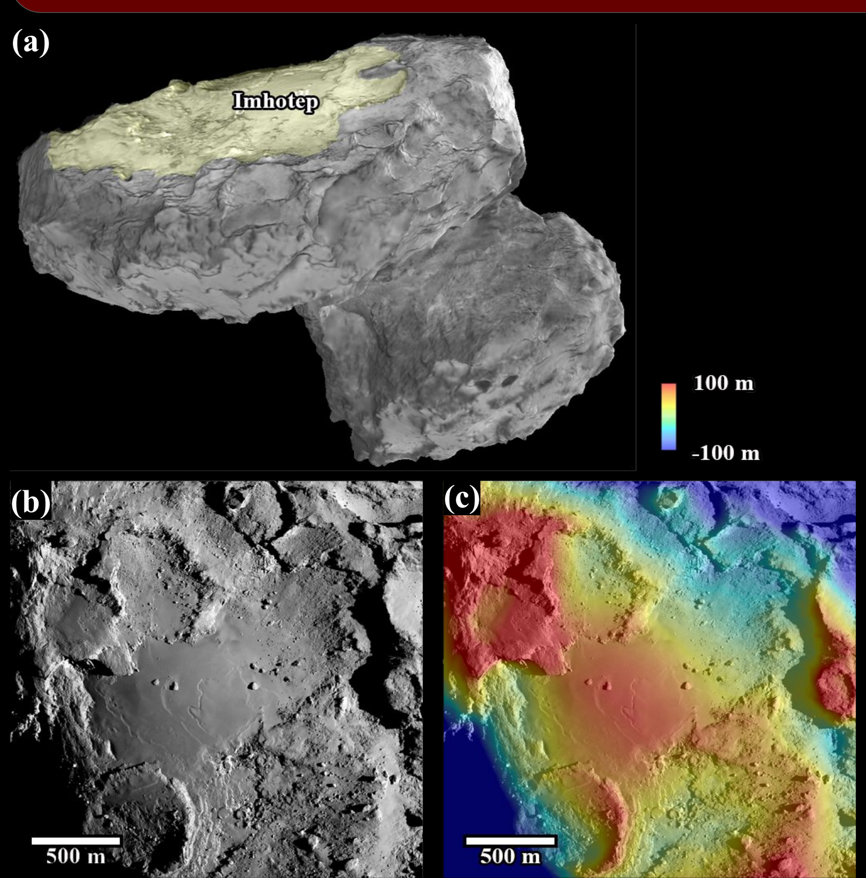

Fig 1: (a) Location of the Imhotep region on the largest lobe of 67P, (b) NAC image taken on September 5th 2014 showing Imhotep, (c) Topography of Imhotep

The smooth terrains of comet 67P/Churyumov- Gerasimenko are primarily formed by centimeter-/decimeter-sized ***air-falling particles*** liberated during erosion of the consolidated nucleus *(Keller et al., 2017; Thomas et al., 2015)*. Covering 36% of the nucleus, the smooth terrains represent sedimentary basins of ice-rich regolith materials *(Birch et al., 2017)*. Over the course of the Rosetta mission, the smooth terrains also exhibited the most drastic transient changes, and so understanding their evolution is paramount to understanding the evolution of 67P's surface in general. We explore the evolution of the ***largest smooth terrain deposit on 67P***, within the Imhotep region, a highly active, and most southern of all smooth terrain basins on 67P *(Auger et al., 2015)*.

Using image data from the Optical, Spectroscopic, and Infrared Remote Imaging System (OSIRIS) narrow-angle camera (NAC) onboard the Rosetta spacecraft, we ***track decameter-scale changes*** and ***measure the depth of erosion and deposition*** across the smooth terrains of the Imhotep basin during the course of the mission.

2. Changes in the Imhotep Basin

We track the temporal evolution of 12 scarps ('a' through 'l') in Imhotep for a period of eight months from May 24th, 2015, to January 23rd, 2016 (*Fig 2*). Rosetta's first image of the Imhotep basin showed a landscape of smooth terrains with several scarps (e.g. scarps labeled 'a', 'b' and 'c') which we interpret as remnants of erosional processes occurring during 67P's previous perihelion passage.

The ***first changes*** in the region are observed on ***June 3rd, 2015***, and the terrain continues to get modified until ***November 29th, 2015***, when ***no more changes*** are detected in this region down to the decimeter scale in the Rosetta data. During our period of observation, the sun rises in the eastern end of Imhotep, with the first light falling upon the cliffs in the western part of the basin.

Most of the scarps we observe move at speeds of the order 10cm/hr - consistent with the predictions from *Birch et al. (2019)* for similar features in Hapi implying similar ice fractions within the regolith. Based on the patterns observed in the movement of the scarps, we have divided the activity in Imhotep into two major parts: (i) The activity that starts before July 1st, 2015, and (ii) The activity that starts after July 1st, 2015.

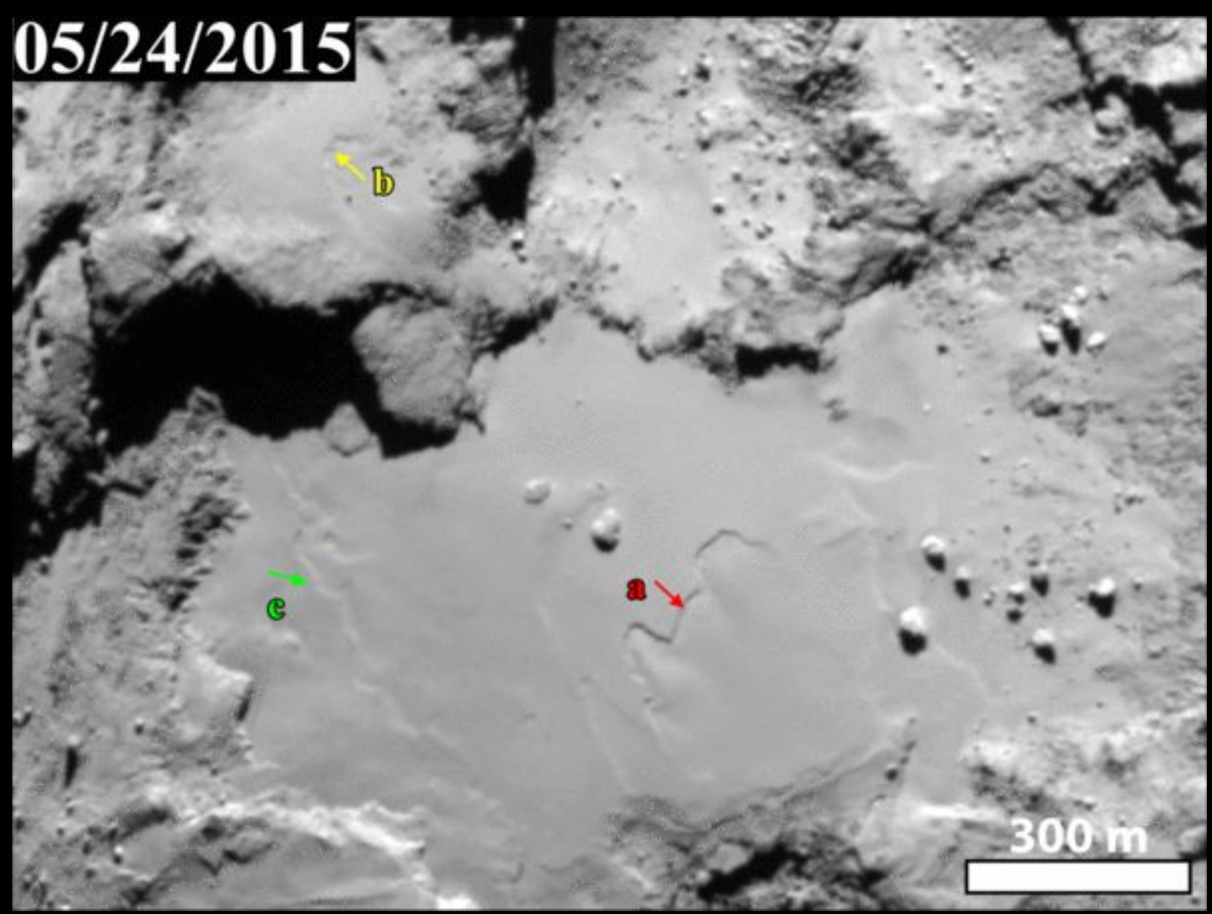

Fig 2: Animation showing changes in the Imhotep region from May 24th, 2015 (shortly before activity begins) until January 23rd, 2016 (shortly after the region turns dormant). All images are NAC images acquired by Rosetta and georeferenced to the first image taken on May 24th, 2015. The date corresponding to each image is shown on the top-left corner and the labels 'a' through 'l' denote the major scarps observed in Imhotep over the course of the Rosetta mission.

Activity starting before July 1st, 2015

- Changes are ***concentrated around the 15°S latitude***, with no discernible changes in surface morphology below 18.5°S (*Fig 3*).
- This is ***coincident with the subsolar latitude at this time***, which moves from 11.8°S to 26°S between June 5th and July 1st.
- All the ***scarps originate from topographic discontinuities***, such as boulders, cliffs, or pre-existing scarps within smooth terrains and are all consistent with ***growth by uniform scarp retreat*** *(Birch et al., 2019)*.

Activity starting after July 1st, 2015

- Just like scarps in the previous cycle, the morphology of the post-July 1st scarps all suggests ***growth via uniform scarp retreat***, where cliff walls and/or boulders serve as seed points.
- The topography of the scarps both pre-July 1 and post-July 1 remain similar, with the largest difference being that ***scarp activity is now distributed all across the basin***.
- We hypothesize that the broader latitudinal range over which changes occur, and the higher migration rates can be attributed to the fact that 67P is rapidly approaching the Sun. With sublimation rates growing exponentially over this later period nearer to perihelion, the surface temperature everywhere is elevated and so activity is more widespread, consistent with previous observations of jet activity (*Vincent et al., 2016*).

After November 29, 2015, all scarp activity ceases and we are left with 4 scarps ('h', 'i', 'j', and 'l') in the central part of the basin which remain unaltered until the end of the Rosetta mission. All other scarps either erode off a complete layer of regolith materials, or they are buried under redeposited material. We hypothesize that ***these leftover scarps will serve as a seed point for activity in the next orbit***.

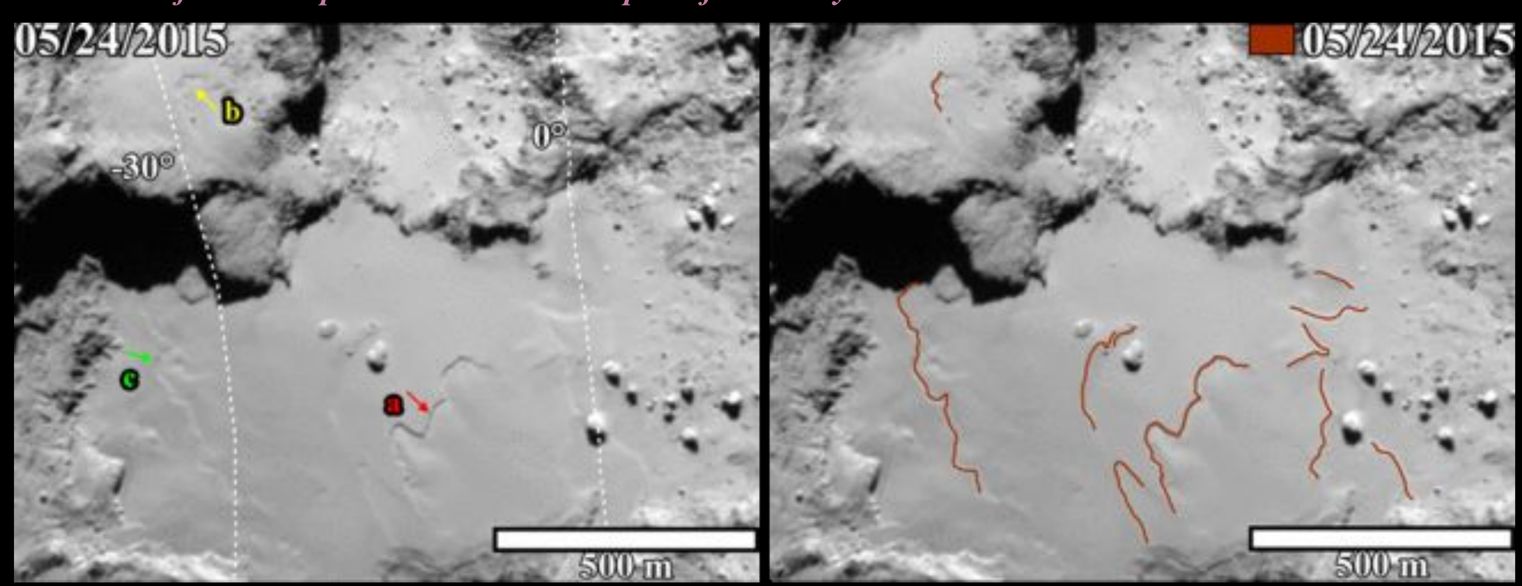

Fig 3: Animation showing a subset of changes shown in Fig 2. The labels in the left panel are the same as Fig 2 and point to the major scarps observed in Imhotep. The panel on the right shows the same image as the left panel and has the boundary of the scarps thus outlined with the position of the scarp on different dates denoted by the colors. For the image on 05/24/2015, all scarp boundaries are outlined , but for every other image, only the boundaries of the scarps that show move after the previous image are outlined. Hence, the scarp outlines are meant to draw attention to the parts of Imhotep that are active at different times.

3. Sediment Budget for Imhotep

We generate ***Digital Terrain Models (DTMs)*** using the ***photoclinometry*** technique described by *Tang et al. (2019)* in order to measure values of net erosion/deposition in different regions of Imhotep and create a *sediment budget*.

- We use ***known landmarks that have a measurable relief*** as a baseline for measuring changes in the thickness of the surface regolith.
- We assume that the ***largest boulders and exposed cliffs are static***, and that smooth terrain material can either erode or deposit around them.
- We choose ***5 subregions within Imhotep*** *(Fig 5)* such that each region encompasses at least two boulders lying in the smooth terrains.
- In order to measure the total erosion/deposition we choose ***two Rosetta images*** containing one of our sub-regions of interest
  - one from ***September 2014*** (the early phase of the mission)
  - another from ***June 2016*** (near the end of the mission).
- We then make DTMs for each of these images, and reference them to one another using a 3D affine transformation applied on boulders that are visible in each image. Once this is done we can draw line profiles along our DTMs and measure the net erosion/deposition *(Fig 4)*.

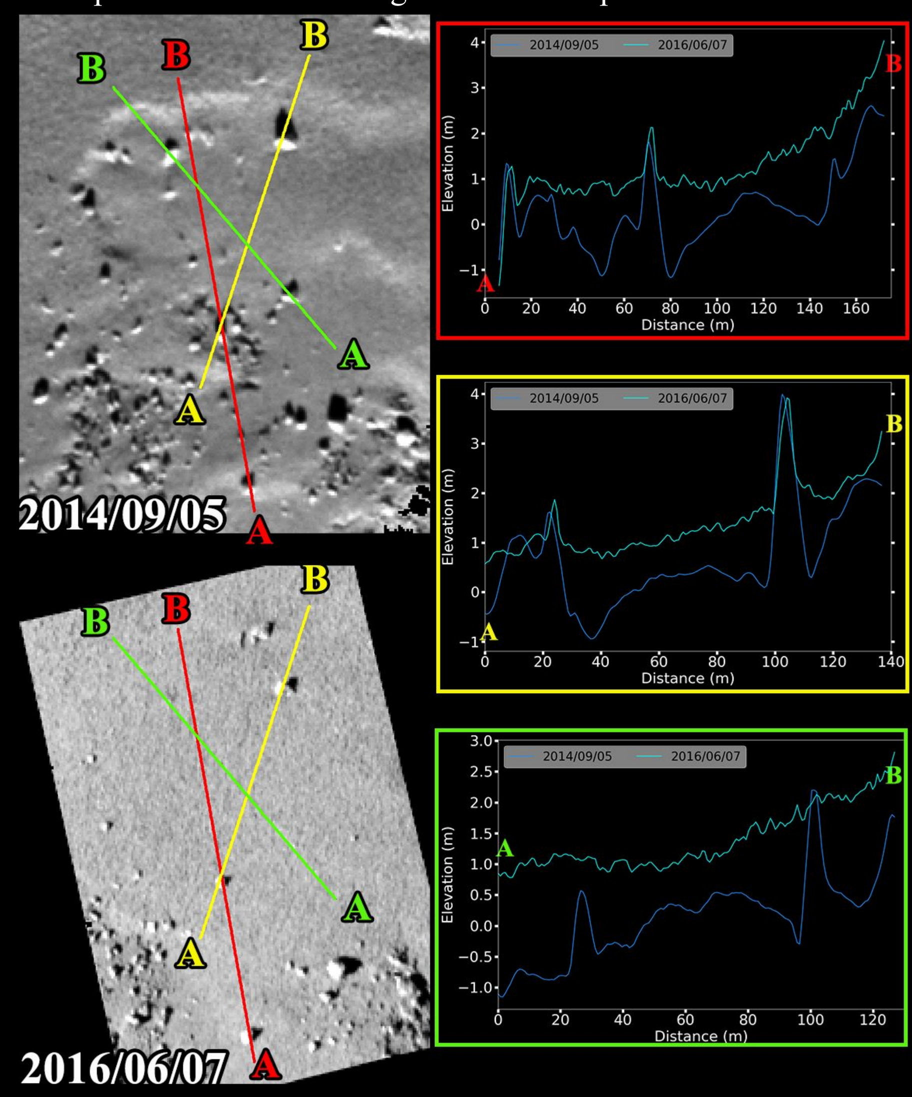

Fig 4: Calculation of the net erosion/deposition in a region. The panels on the left are cropped images (georeferenced) of the same region taken on different dates. The plots on the right show the topography along the line profiles for the two different dates (the outline color of the plot corresponds to the color of the line profile). The top of the boulders line up as expected, while the regolith around the boulders changes in height.

Our results show that regions 'A', 'D' and 'E' each receive a ***net deposition of material*** over the course of the mission, while regions 'B' and 'C' show ***net erosion***. Our DTM generation procedure fails to converge for patch 'C', and even though we are unable to get a total value of erosion, the emergence of buried boulders can still confirm that the region undergoes net erosion.

The significant difference in the total amount of material eroded from or deposited to regions in close proximity (~300m) to one another suggests that ***material transport is significantly affected by local processes***

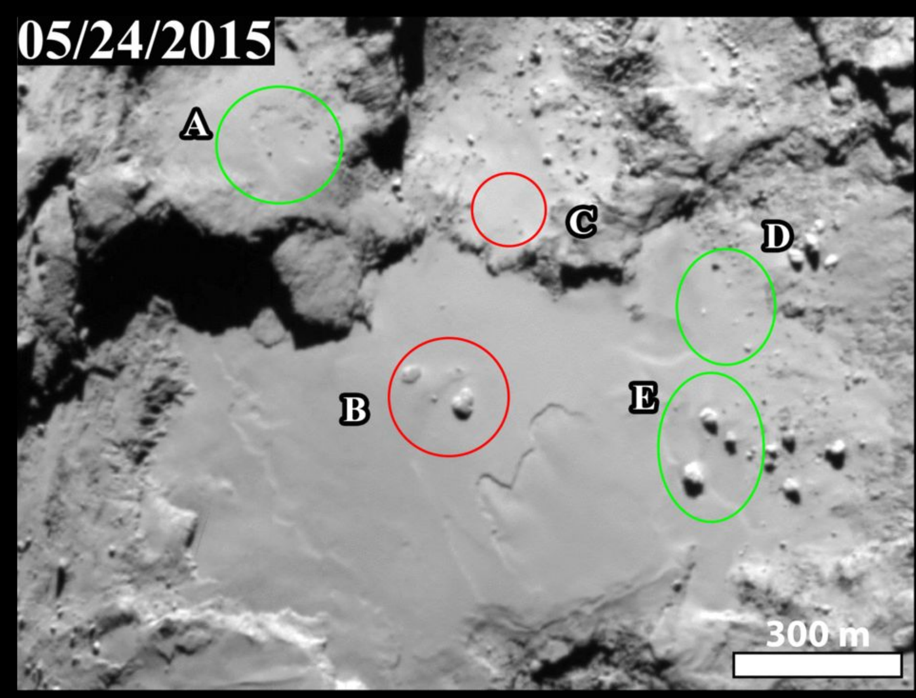

Fig 5: Net erosion (red circles) and deposition (green circles) in different subregions of Imhotep. The values for erosion/deposition are obtained using measurements made on our DTMs as described in Fig 4. Our DTMs fail to converge for patch 'C', but the emergence of new boulders implies erosion.

4. Future Work & Conclusions

- Our observations of scarp migration on 67P suggest that erosion and deposition indeed follow the broad trends predicted by *Keller et al. (2017)* and quantified more precisely by *Davidsson et al. (2021)*, where deposition occurs in the north during perihelion.
- Scarps begin to migrate in the northern region of the basin and then extend across the entire basin as 67P approached perihelion. The migration we observe, and the ice fraction we predict, is strikingly similar to those in Hapi, suggesting a common mechanism that erodes cometary smooth terrains.
- However, models do not predict such localized net erosion and deposition on 67P, as measured by our DTMs, and confirmed by analyses of the images. ***That these five regions, separated by only a few hundred meters, exhibit such different erosion/depositional histories is a surprising finding, one that hints at significant local transport of materials.***

Exactly how such material is transported is left to follow-up studies.

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