

Rosetta images of Comet 67P/Churyumov–Gerasimenko 1: Near-surface icy terrain similar to comet Tempel-1

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Abstract

The first 3 months of the Rosetta mission have given us remarkable pictures of comet 67P both from the orbiter and recently from the Philae lander in its brief days before running out of power. Though its crust is very black, four indicators of underlying icy morphology are evident. 67P has smooth, planar 'seas' (the largest 600 x 800m) and flat-bottomed craters, both features on comet Tempel-1. 67P's surface is peppered with mega-boulders (10-70km) like comet Hartley-2, while parallel furrowed terrain is a new ice feature. The largest sea ('Cheops' sea, 600 x 800m) curves around one lobe of the 4km diameter comet and the crater lakes up to ~150m across are re-frozen water with organic-rich debris covered by sublimation lag of order 10-cm thick plus impact regolith. The parallel furrows relate to flexing of the asymmetric and spinning two-lobe body, which generates fractures in an underlying body of ice. The mega-boulders are hypothesised to arise from bolide impacts into ice: in the very low gravity, boulders ejected at a fraction of 1m/s would readily reach ~100m from the impact crater and could land perched on elevated surfaces. Where they stand proud, they indicate stronger refrozen terrain or that the surface they land on (and crush) sublimates more quickly. Outgassing due to ice-sublimation was already evident in September at 3.3AU, with surface temperature peaks of 220-230K, which implies impure ice mixtures with less strongly-bound H₂O. Increasing sublimation as Rosetta follows comet 67P around its 1.3 AU perihelion will further reveal the nature and prevalence of near-surface ices.

Keywords: Comets, Rosetta mission, Comet 67P, Churyumov-Gerasimenko, comet Tempel-1, cometary ice

Introduction

The old comet model of frozen elementary gases maybe combined with H₂O in clathrates and condensed in the early solar system, has not been tenable since the 1986 missions to comet Halley. Comets evidently have high fractions of carbonaceous and mineral solids, and are well-processed bodies, with a geology that reflects their past and particularly any of their orbits within the inner solar system. They cannot be viewed as an onion, with layer by layer peeling off on perihelion passes when solar heating sets in, but suffer meteorite impacts and develop surface crusts that severely restrict gas escape. We have previously discussed evidence for carbonaceous-crust covered bulk ice in cometary images, including possible remnants of an early refrozen centre and refrozen near-surface lakes (Wallis and Wickramasinghe 2007, 2011). Like comet Tempel-1 in 2005, comet 67P/Churyumov–Gerasimenko (for short '67P') shows the latter features. The evidence and potential for icy habitats harbouring primitive life is left to a companion paper (Wickramasinghe and Wallis 2014).

Re-frozen Seas

Similar to earlier cometary nuclei, comet 67P has very low albedo, characteristic of largely carbonaceous surfaces and regolith. It has a large smooth area like a 'sea' surrounded by elevated rugged terrain, resembling local seas on Mars (Fig. 1, left image). Like the Elysium sea (Murray et al. 2005) those are thought to be the result of water flooding from below the surface, freezing over and developing a protective regolith. We refer to comet 67P's sea as the Cheops sea, because the largest

of the cluster of boulders (~45m) in its upper part has been named Cheops. Debris shed from a cliff bordering the Cheops sea (top left of Fig.1) spreads onto the 'sea' with the Cheops boulder marking its maximum extent.

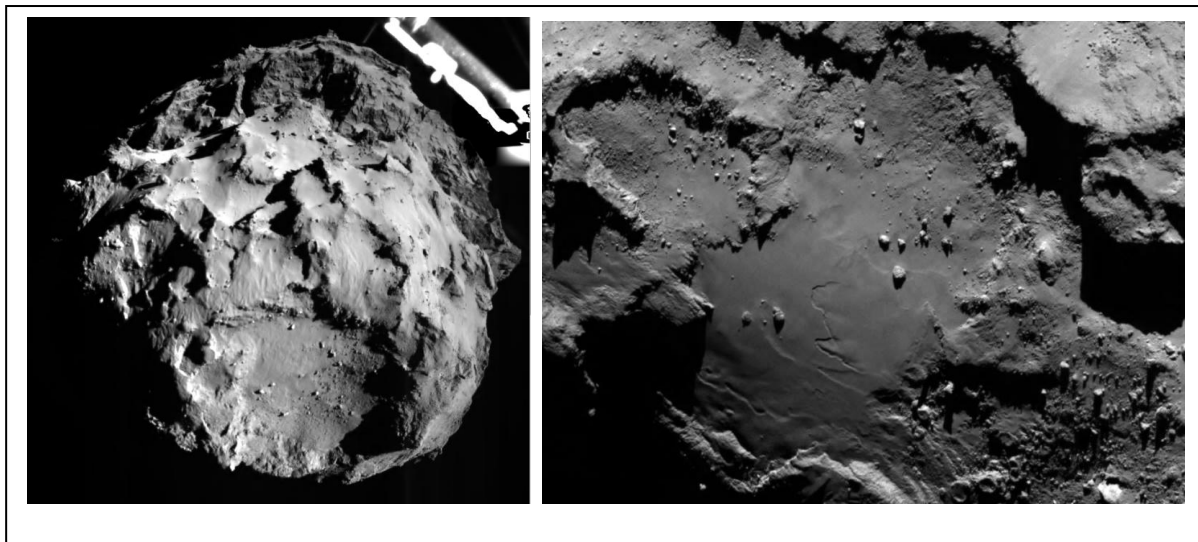
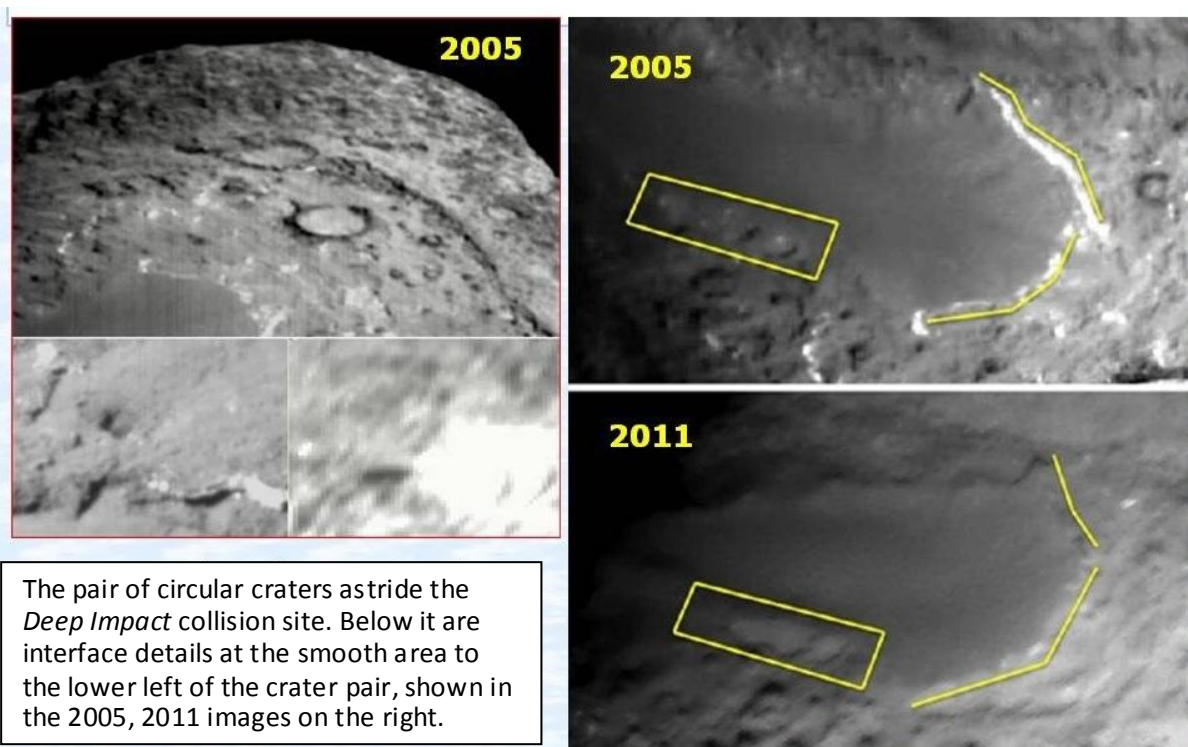


Fig. 1 Large planar 600 x 800m Cheops 'sea' on comet 67P, lower centre in the left image. Note also the near circular depression to the left of the 'sea', resembling an eroded crater. (ROLIS descent image from 3km. ESA/Rosetta/Philae/ROLIS/DLR). The image at higher resolution on the right shows the sea curving away into shadow approaching the terminator at bottom left. The plateau at the top right corner (semi-circular) is a few 100m higher than the sea and appears to have shed debris at the cliff-foot. (ESA/Rosetta/MPS for OSIRIS Team)

Comet Tempel-1 showed two analogous seas: Fig. 2 shows the larger tadpole-shaped 'sea', a smooth flat plateau, curving away into the shadow. The plain would be covered by sublimation regolith of order 10-cm thick, with strength of a cold-welded carbonaceous crust (Wallis et al, 2007, 2009; Wickramasinghe et al. 2009). Between its first imaging in 2005 and second in 2011, changes are identified that indicate active erosion processes. Note in particular an advance of the escarpment shown by the yellow lines and the merging of crater-features in the yellow box.



The pair of circular craters astride the *Deep Impact* collision site. Below it are interface details at the smooth area to the lower left of the crater pair, shown in the 2005, 2011 images on the right.

Fig 2 Images of Comet Tempel-1; upper left shows two flat-bottomed 300m craters above the head end of the 'tadpole sea' shown on the right. The pair of images on the right shows fuller extent of the smooth sea-like area, bending around the body of the comet to the left, into the shadow. The yellow lines mark an escarpment bordering the sea on the right, the 'sea' being a raised plateau at that end. Differences between the 2005 and 2011 images are interpreted as retreat of the sea's margin (by up to 30m) and merging of pits (in the rectangular box).

Large boulders

Large boulders standing proud on the surface and 10s of metres in size are widely scattered over much of comet 67P. This characteristic resembles the 'spotty' distribution on comet Hartley-2 (Fig. 3), whose neck-area is devoid of boulders and craters. Fig.1 shows boulders up to 70m in size on comet 67P near and adjacent to the Cheops sea. Most boulders on 67P are not associated with eroding cliffs or craters. They don't show any layering, but an irregular surface judging by the resolved picture of the one 5-m boulder (Fig. 4).



Fig. 3 Comet *Hartley-2* NASA News Release 4 Nov.2010: size ~2km long with 0.4km wide 'neck'. The 'spotty' appearance is due to 20-50m-sized hillocks or boulders and their shadows. Note the 400m long ravine (left end).

We suggest these boulders originated as ejecta from large meteorites impacting compact frozen terrain. In the very low gravity, boulders ejected at a fraction of the escape speed of 1m/s readily reach ~100m from the impact crater and could land perched on elevated surfaces, if the surface material is crushable (like aged snow) to absorb energy. That they stand proud indicates strong underlying terrain such as compact ice, or that the surface they land on (and crush) sublimates away. Dirty ice-boulders develop dark protective sublimation crusts so have a long lifetime on 87P's distant orbit. Some brighter boulders (Fig. 1, right) and brighter pixels on them at higher resolution (*Comet on 11 Nov*, Rosetta NavCam 3 image, CC BY-SA IGO 3.0) suggest an optically-active crystalline component in the surface material; the boulders may be sublimating slowly while sublimation of the open 'sea' is currently suppressed. This is aged crust plus cm-sized dust (Fig. 4).



Fig. 4. Comet from 40 metres, taken by Philae's down-looking descent ROLIS imager when it was about 40 m above the surface of comet 67P/Churyumov-Gerasimenko (credit ESA/Rosetta/Philae/ROLIS/DLR). The large block in the top right corner is 5 m in size.

Flat-bottomed craters

The prototype pictures are the two flat-bottomed craters near Deep Impact's impact position on comet Tempel-1, pictured on the upper left part of Fig.1. A similar pair of examples are seen in Fig.5 at the upper left 130-150m across. These craters lack ramparts, from impact material displaced laterally, which may not be universal but dependent on the impacted material. Other possible larger crater-examples on the upper lobe of Fig. 5 are unclear, due to probable debris from degraded crater ramparts. Several smaller (30-40km) such craters are visible in comet 67P in the 18th October image of the top right corner of the Cheops sea (see companion paper, Wickramasinghe and Wallis 2014). Of the cluster of 6 craters, 5 have rampart walls, resembling a well, while the sixth is a pedestal crater with practically no ramparts like those in Fig.4.

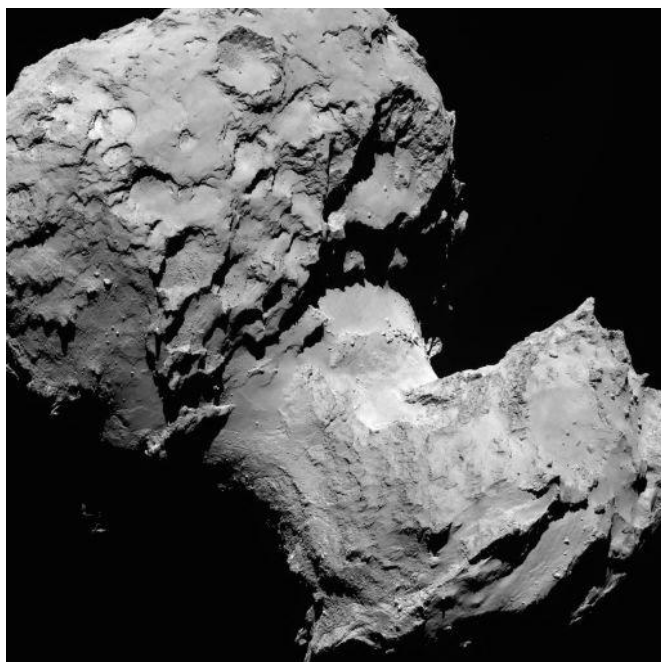


Fig.5 Cratered appearance of the larger lobe (OSIRIS image on 16 August, illumination from top; ~3km square). Note the pair of smaller circular craters to the upper left, flat hollows in low adjacent terrain. This image was used for identifying candidate landing sites, the reserve site C being the featureless area to the right of this crater-pair. (Credits: ESA/Rosetta/MPS for OSIRIS Team)

The craters are thought to be generated by large meteorite or small comet impacts, but clearly different from similar impacts on the Moon and rocky asteroids. On icy terrain, bolide impacts eject some material as solid particles and gases, leaving behind transient lakes that quickly freeze over. As the H₂O-ice covering the lake thickens, with evaporative loss of H₂O from its surface, a sublimation lag accumulates into a surface insulating crust (Wickramasinghe et al. 2009).

Parallel furrowed terrain

Fig.6 shows striking terrain to the right of a largely smooth area, with rocky terrain on both sides. The dark furrows are aligned rather close (20 deg) to the solar direction and appear metres-deep, so may penetrate the protective crust into underlying ice. Their position on the 'neck' suggests that the system of cracks and furrows above them are generated by flexing of the two lobes as the comet rotates. They are reminiscent of cracks on Europa, generated by tidal flexing of that icy satellite which provide energy for ice cracking and convection. Though comet 67P lacks Europa's internal ocean (Kargel et al, 2000; Greenberg, 2008), the furrows would still be sites for active outgassing and jet emissions from subsurface liquid domains. Their higher sublimation rates make them advantageous habitats for ice-living microbes, including algae, cyanobacteria and many other gram-positive bacteria have lipoteichoic acid in their cell walls that induces localized melting of the water-ice if the temperature exceeds 230K (Wickramasinghe, 2004; Hoover and Pikuta, 2010).

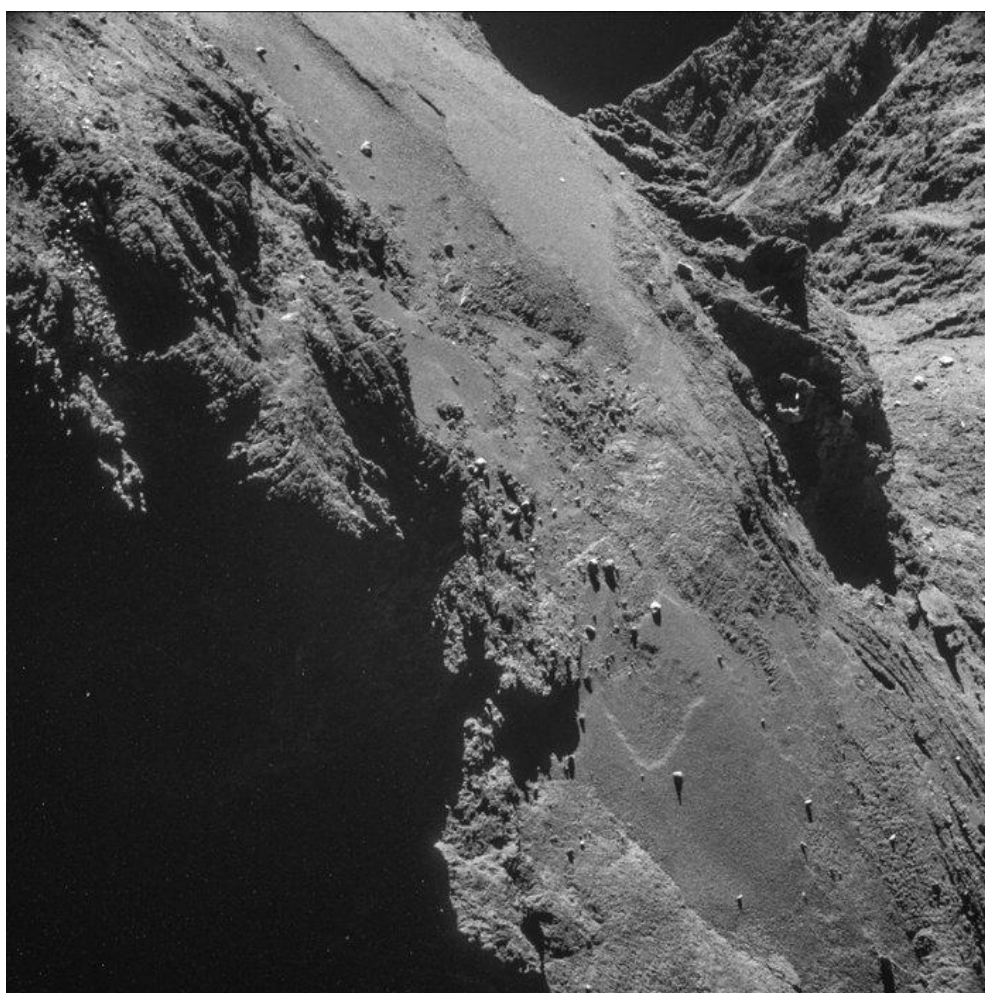


Fig.6 Terrain close to the 'neck' between the two comet lobes (see Fig. 5); the smaller lobe rises in the background. The parallel furrows with 5-10m spacing give the appearance of flexing or compression. (NAVCAM top 10 at 10 km, no. 9 ESA/Rosetta/ NAVCAM – CC BY-SA IGO 3.0; full image size 857m square).

Conclusion

We have previously discussed indications of near-surface icy morphology in comets (Wallis and Wickramasinghe 2007, 2011), like 67P's Cheops sea (Fig. 1), a plain curving around the body of the comet, and flat-bottomed craters (Fig. 2). Comet 67P's furrowed terrain (Fig. 5) is close to another smooth plain, 200m scale with scattered, proud-standing boulders. An icy plain would develop a protective sublimation regolith of order 10-cm thick, with strength of a cold-welded carbonaceous crust (Wickramasinghe et al. 2009). The boulders up to 70m in size, seen also on comet Hartley-2 (Fig. 3), are not associated with eroding cliffs or craters, but may be ejecta generated by large meteorites impacting compact frozen terrain. In the very low gravity, boulders ejected at a fraction of 1m/s would readily reach ~100m from the impact crater, and could land perched on elevated surfaces as seen in these images. Most of the terrain would be too weak to allow them to roll further, giving little accumulation in valleys. Those that stand proud indicate stronger refrozen terrain or that the surface they land on (and crush) sublimates more quickly. Dirty ice-boulders develop dark protective sublimation crusts so have a long lifetime on 67P's distant orbit. Brighter pixels atop some boulders (mid Fig. 2) suggest optically-active crystalline component in the surface material, so the boulders may be sublimating slowly while older regolith suppresses sublimation of the open plain.

Quiescent outgassing such as from 67P in July 2014 at a heliocentric distance of 3.9 AU is evidence of near-surface ice under a crust that has been weathered by micrometeorite impacts during the comet's travels around aphelion. However, outbursts of H₂O outgassing from comets like 67P's in Nov 2007 when the comet was at a heliocentric distance of 4.3AU may be such a bolide impact, but the low probability and the tendency for repetitive outbursts (eg. of Hale-Bopp at 6.5AU – paper 2) indicate most have another cause. Chemoautotrophic microorganisms released into the transient lakes laden with organics would rapidly metabolise and replicate, releasing heat that might increase the initial melt volume by a factor of 10-30. Methane or carbon dioxide produced by bacteria can then build up to be eventually released through fissures in the overlying ices or at the lake edges, in the furrows, cracks in ice (sea or craters) or at the feet of exposed rocks/boulders. In Paper 2 we argue that most of the features described in this paper have a ready explanation on the basis of recurrent biological activity close to the exposed surface of the comet.

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