Rosetta Images of Comet 67P/Churyumov – Gerasimenko: Inferences from Its Terrain and Structure

Wallis MK* and Wickramasinghe NC1,2

1Buckingham Centre for Astrobiology (BCAB), Buckingham University, UK
2Institute for the Study of Panspermia and Astroeconomics, Gifu, Japan

Abstract
The Rosetta mission has given us remarkable images of comet 67P/C-G both from the orbiter, and recently from the Philae lander during its brief days before running out of power. Though its crust is very black, there are several indicators of an underlying icy morphology. Comet 67P displays smooth, planar ‘seas’ (the largest 600 m x 800 m) that flat-bottomed craters, both features seen also on comet Tempel-1. Comet 67P’s surface is peppered with mega-boulders (10-70 km) like comet Hartley-2, while parallel furrowed terrain appears as a new ice feature. The largest sea (‘Cheops’ Sea, 600 x 800 m) curves around one lobe of the 4 km diameter comet, and the crater lakes extending to ~150 m across are re-frozen bodies of water overlain with organic-rich debris (sublimation lag) of order 10 cm. 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 1 m/s would readily reach ~100 m from the impact crater and could land perched on elevated surfaces. Where they stand proud, they indicate stronger refrozen terrain or show 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 220-230 K, which imples impure ice mixtures with less strongly-bound H2O. Increasing rates of 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; Cometary lakes

Introduction
The old comet model of frozen elementary gases, perhaps 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 history and particularly their orbits within the inner solar system. They cannot be viewed as an “onion”, with a layer by layer peeling off on perihelion passages when solar heating sets in; rather they suffer meteorite impacts 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 220-230 K, which impiles impure ice mixtures with less strongly-bound H2O. Increasing rates of sublimation as Rosetta follows comet 67P around its 1.3 AU perihelion will further reveal the nature and prevalence of near-surface ices.

The mapping of comet 67P/C-G has thus far revealed a number of distinct types of region. These have been grouped by Thomas et al. [4], into five categories: dust covered terrain, regions exhibiting brittle surface material with pits and circular structures, large-scale depressions, and smooth exposed surfaces resembling the Cheops Sea. Such features are not consistent with the Whipple dirty snowball model of a comet, but indicative of composition high in carbonaceous material with models of icy material under organic crusts that we have developed over four decades [1,5-7].

Re-frozen Seas
Similar to earlier cometary nuclei, comet 67P/Churyumov–Gerasimenko has very a low albedo of 0.06 [8]. This is indicative of a largely carbonaceous surface and regolith, a fact that is also borne out by infrared reflectance spectroscopy [3,8]. Comet 67P has a large smooth area like a ‘sea’ surrounded by an elevated rugged terrain, resembling local seas on Mars (Figure 1, left image). Like the Elysium sea [9], such seas 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 (~45 m) in its upper part has been named Cheops. Debris shed from a cliff bordering the Cheops sea (top left of Figure 1) spreads onto the ‘sea’ with the Cheops boulder marking its maximum extent.

Comet Tempel-1 showed two analogous seas: Figure 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 [1,9,10]. Between its first imaging in 2005 and second in 2011, changes are identified that indicate the operation of 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.

Giant Boulders
Large boulders standing proud on the surface and tens of metres in size are widely scattered over much of comet 67P [4]. This feature leads
to the ‘spotty’ appearance of comet Hartley-2 (Figure 3), whose neck-area is devoid of boulders and craters. Figure 1 shows boulders up to 70 m in size on comet 67P near and adjacent to the Cheops sea. Most boulders on comet 67P are not associated with any eroding cliffs or craters. Nor do they show any layering, but an irregular surface judging by the resolved picture of the one 5-m boulder (Figure 4).

We suggest these boulders originated as ejecta from large meteorites impacting a compact frozen terrain. In the very low gravity, boulders ejected at a fraction of the escape speed of 1 m/s readily reach ~100 m from the impact crater and could land perched high on elevated surfaces, provided the surface material is sufficiently crushable (like aged snow) to absorb energy. The fact that they stand proud on slopes indicates strong underlying terrain such as compact ice, or that the surface they land on (and crush) sublimates away. Dirty ice-boulders (laden with organics) develop dark protective sublimation crusts so have a long lifetime on comet 69P's distant orbit. 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 Figure 4.

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 boulders may be sublimating slowly while sublimation of the open ‘sea’ is currently suppressed. This is interpreted as aged crust overlain with centimetre-sized dust (Figure 4).

**Flat-bottomed Craters**

The prototype pictures for comparison are the two flat-bottomed craters near Deep Impact’s impact position on Comet Tempel-1, pictured on the upper left part of Figure 2. A similar pair of examples is seen at the upper left of Figure 5, some130-150 m across. These craters lack ramparts, from impact material displaced laterally, which may not be universal but dependent on the nature of the impacted material. Other possible larger crater-examples on the upper lobe of Figure 5 are unclear, due to probable debris from degraded crater ramps. Several smaller (30-40 km) such craters are visible in comet 67P in the 18th October image of the top right corner of the Cheops sea [3]. 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 Figure 4.

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 boulders may be sublimating slowly while sublimation of the open ‘sea’ is currently suppressed. This is interpreted as aged crust overlain with centimetre-sized dust (Figure 4).
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 to form a surface-insulating crust [11]. Sierls et al. [12], find outflow of gas from the base of an active pit (Figure 6), which would be a relatively fresh crater, still developing its crust. The formation of crust explains the low albedo and the dominance of complex organics observed in the comet 67P/C-G [8].

**Parallel Furrowed Terrain**

Figure 7 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°) to the solar direction and appear metres-deep, so may penetrate the protective crust well 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. Sierls et al. draw attention to an isolated crack in a nearby debris-strewn region which may overlie a further furrow. The aligned furrows are reminiscent of cracks on Europa, generated by tidal flexing of that icy satellite, driving ice cracking, creep and convection. Though comet 67P lacks Europa’s internal ocean [13,14], its furrows would still be sites for active outgassing and jet emissions as seen is the OSIRIS image of 10 Sept. 2014 [3]. Their higher sublimation rates make them advantageous habitats for ice-living microbes, including algae, cyanobacteria and many other gram-positive bacteria that have lipoteichoic acid in their cell walls to induce localized melting of the water-ice whenever the temperature exceeds 230 K [15].

**Conclusion**

We have previously discussed indications of near-surface icy morphology of comets, such as 67P’s Cheops sea in Figure 1, a plain curving around the body of the comet, and flat-bottomed craters as in Figure 2, [1,2]. Comet 67P’s furrowed terrain (Figure 5) is close to another smooth plain, 200 m-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 [11]. The boulders up to 70 m in size, seen also on Comet Hartley-2 (Figure 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 on a comet, boulders ejected at a fraction of 1 m/s would readily reach ~100 m from an impact crater, and could easily land perched on elevated surfaces as seen in these images [4]. Most of the terrain would be too weak to allow boulders to roll further, giving little accumulation in valleys. Those that stand proud indicate stronger refrozen terrain or show that the surface they land on (and crush) sublimates more quickly. Dirty ice-boulders develop dark protective sublimation crusts and so have a long lifetime on 67P’s distant orbit. Brighter pixels atop some boulders (mid Figure 2) suggest an 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 seen from Comet 67P in July 2014 at 3.9AU from the Sun is evidence of near-surface ice under a crust that has been weathered by micrometeorite impacts during the comet’s transits around aphelion. More distant episodes of H₂O outgassing from comets, like comet 67P/C-G in Nov 2007 when it was at a heliocentric distance of 4.3AU, may be due to larger bolide impacts; but the low probability of such an event and the observed tendency for repetitive outbursts (e.g. of Hale-Bopp at 6.5AU) point strongly to
another cause [3]. 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 to 30. Methane or carbon dioxide produced by bacteria as metabolic products 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), bottoms of crater pits, or at the feet of exposed rocks/boulders. In our companion paper [3], we argue that most of the features described in this communication and others described by Thomas et al. [4] have a ready explanation on the basis of recurrent biological activity close to the exposed surface of the comet.

References