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The Philae lander mission and science overview

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The Philae lander accomplished the first soft landing and the first scientific experiments of a human-made spacecraft on the surface of a comet. Planned, expected and unexpected activities and events happened during the descent, the touch-downs, the hopping across and the stay and operations on the surface. The key results were obtained during

12–14 November 2014, at 3 AU from the Sun, during the 63 h long period of the descent and of the first science sequence on the surface. Thereafter, Philae went into hibernation, waking up again in late April 2015 with subsequent communication periods with Earth (via the orbiter), too short to enable new scientific activities. The science return of the mission comes from eight of the 10 instruments on-board and focuses on morphological, thermal, mechanical and electrical properties of the surface as well as on the surface composition. It allows a first characterization of the local environment of the touch-down and landing sites. Unique conclusions on the organics in the cometary material, the nucleus interior, the comet formation and evolution became available through measurements of the Philae lander in the context of the Rosetta mission.

This article is part of the themed issue 'Cometary science after Rosetta'.

1. What is Philae?

The Rosetta mission of the European Space Agency (ESA) (see Taylor *et al*. [1]) aims to explore comet 67P/Churyumov–Gerasimenko (abbreviated 67P) with the research goals of improving the scientific understanding of comets and of illuminating their role in the formation of the Solar System. ESA's core mission, represented by the Rosetta orbiter and its scientific instruments, was enhanced by the Philae lander and its instrumentation, which was provided by a consortium of national space agencies and research institutes in Europe (led by the Deutsches Zentrum für Luft- und Raumfahrt (DLR), the Centre National d'Etudes Spatiales (CNES), the Agenzia Spaziale Italiana (ASI) and the Max-Planck Institute for Solar System Research (MPS)). From a technological and operational point of view, Philae had to be considered an ambitious and risky mission: soft landing on and scientific operations at a cometary surface had not been done nor even attempted before Philae.

The Philae lander is equipped with 10 instruments (figure 1), which are listed together with their respective key science investigation in table 1 and are described in greater detail in publications referenced in the last table column. The Philae instruments amount in total to 27 kg of mass and are integrated in the lander spacecraft that has a total mass of about 97.6 kg (111 kg including lander units on-board the orbiter, i.e. for attachment and separation as well as for communication). A description of the Philae lander investigation, i.e. of the spacecraft, the landing concept and the lander operation approach, is presented in Bibring *et al*. [12]. During launch and cruise phase of the Rosetta mission, the lander spacecraft was attached to the orbiter.

The science objectives of the lander mission were the study of: the nucleus interior; the nucleus surface and subsurface composition and structure; the physical surface properties; the nucleus activity; the long-term evolution of the surface and of the cometary environment; as well as the comet–plasma interaction. The science goals were formulated by the Philae Steering Committee and are extracted from the Philae Science Plan in table 2. A relevant scientific aspect for the lander mission was to provide so-called ground-truth information for orbiter instruments [12]. Last, but not least, the lander project was also involved in public relations and public outreach tasks.

2. The landing at 67P

(a) Technical and operational aspects of the Philae landing

The Philae lander is a passive lander, i.e. it is 'thrown' down to the surface and does not contain any guidance, navigation control or propulsion system for trajectory corrections during descent or for impact velocity deceleration before soft landing. Apart from the timing, the only degree of freedom for the lander targeting is the velocity vector (direction and magnitude) at release. Stability of the lander body axis attitude is accomplished through a flywheel and slow rotation around the lander body axis is accepted. Targeting the landing site at the cometary surface is

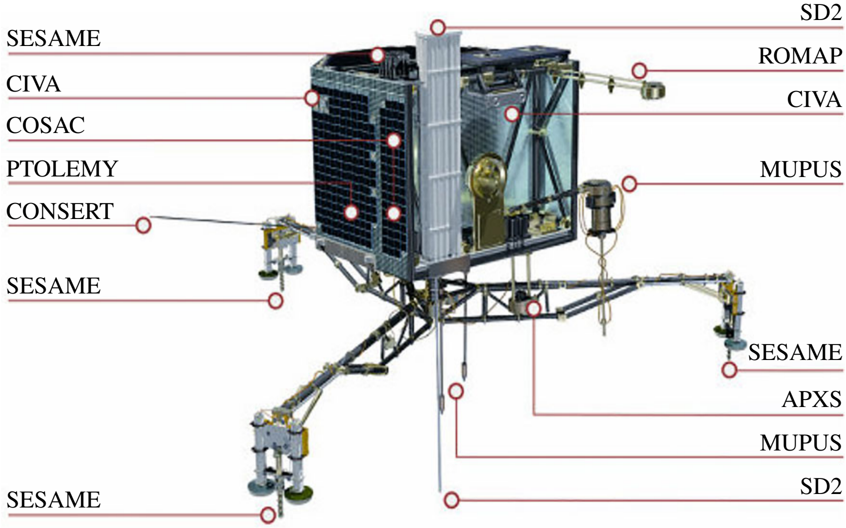

Figure 1. The Philae lander spacecraft with the ensemble of scientific instruments. The location of the various Philae instrument units is indicated. Some instruments (for instance CIVA, MUPUS, SESAME) have different units that are distributed over the lander spacecraft. Other instruments (for instance COSAC, PTOLEMY) are mainly located inside the lander compartment and not visible in the figure. Lander dimensions are about 0.7 × 0.7 × 0.9 m; the distance of the feet of the landing leg tripod is about 2.3 m. (Online version in colour.)

Table 1. The 10 scientific experiments of the Philae lander. References for instrument descriptions are provided in the last column.

instrument	key science investigation	references
APXS	elemental composition of surface material	Klingelhöfer *et al.* [2]
CIVA	panoramic imaging, microscopic imaging (M/V) and analysis of sample composition (M/I)	Bibring *et al.* [3]
CONSERT[a]	internal structure of the nucleus	Kofman *et al.* [4]
COSAC	molecular composition and chirality of samples	Goesmann *et al.* [5]
MUPUS	physical properties (density, porosity, thermal aspects) of the surface and subsurface	Spohn *et al.* [6]
PTOLEMY	isotopic composition of light stable elements in samples	Morse *et al.* [7]
ROLIS	descent and down-looking imaging of the surface	Mottola *et al.* [8]
ROMAP	magnetic and plasma monitoring	Auster *et al.* [9]
SD2	sample acquisition (drill) and transfer	Bernelli-Zazzera *et al.* [10]
SESAME	electric (PP) and acoustic (CASSE) sounding of the surface, dust impact monitoring (DIM)	Seidensticker *et al.* [11]

[a] The CONSERT experiment consists of instrument units on-board both the orbiter and the lander.

done with the combined help of the orbiter and of the lander release mechanism (a subunit of the mechanical support system (MSS) for the lander) on-board Rosetta. The MSS contains two redundant release mechanisms: a belt-driven spindle drive allows preset ejection velocities (between 0.05 and 0.5 $\mathrm{m\,s^{-1}}$) and a spring eject system provides a fixed release velocity of

Table 2. Scientific goals of the Philae lander mission to 67P/Churyumov–Gerasimenko (as defined by the Philae Steering Committee). The goal achievement is evaluated in the last column of the table.

no.	science goal	achieved?
(1)	Study of the composition and structure of the cometary nucleus, reflecting growth processes in the early Solar System	partly achieved
(2)	Determination of the composition of the cometary surface and subsurface matter: bulk elemental abundances, isotopic ratios, minerals, ices, carbonaceous compounds, organics, volatiles—also dependence on time and insulation	partly achieved
(3)	Investigation of the structure and physical properties of the cometary surface: topography, texture, roughness, regolith scales, mechanical, optical and thermal properties, temperatures	achieved
(4)	Investigation of the global internal structure by radio wave sounding, seismometer and magnetometer	partly achieved
(5)	Characterization of the near-surface plasma environment and investigation of the comet–plasma interaction	partly achieved
(6)	Investigation of dynamic processes leading to changes in cometary activity	not achieved
(7)	Study of the physical and thermal properties of the near-surface material, the thermal behaviour as well as the heat and mass transport over many insulation cycles and over a significant variation of insulation intensity (i.e. heliocentric distance) yields information about fractionation processes, i.e. the most volatile components have retreated to the cold interior, while refractory materials are concentrated near the surface. Knowledge about fractionation and ageing processes that occur in the upper surface layers is necessary to draw conclusions on the original cometary material from the measured chemical composition of the present aged surface material	partly achieved
(8)	Long-term *in situ* observations on the surface reveal local erosion of the surface by sublimating ices, modifications of texture and chemical composition of near-surface materials, changes in dust precipitation and heat flux through the surface as well as transient activity phenomena as a function of distance to the Sun	not achieved
(9)	Provision of ground-truth data for orbiter instruments. Close-up panoramic observations can calibrate albedo and topographical features observed by OSIRIS. *In situ* analysis of chemical and mineralogical composition can calibrate brightness at various infrared wavelengths observed by VIRTIS. Measurements of the surface structure on small scale can be compared to the respective findings from orbiter dust experiments. Structural stability of solid-state particles as well as possible alteration processes can be analysed	partly achieved
(10)	Public relations and public outreach tasks	achieved

$0.1874\,\mathrm{m\,s^{-1}}$. The spindle drive is commanded first and it triggers automatically—with a fixed time delay—the spring ejection.

Favouring operational simplicity, namely to plan landing for a single touch-down scenario, it was decided to apply identical ejection velocity settings for both MSS mechanisms at the price of accepting a longer descent duration. The lander was meant to touch down at the targeted landing site with—ideally—zero lateral velocity with respect to ground, although a small non-zero lateral motion of the lander cannot be avoided. Absorption of the dominant vertical kinetic energy and fixation of the lander to the ground involves: (i) the landing gear with the leg tripod and ice screws, pushing the lander head towards the tripod and transforming the mechanical energy into electrical energy by a built-in generator, capable of absorbing up to about 60 J of kinetic energy safely (equivalent to a vertical touch-down speed of $1.1\,\mathrm{m\,s^{-1}}$); (ii) the active descent system (ADS), a cold gas thruster, mounted to the lander top plate and to be fired at touch-down in order to reduce the bouncing motion of the lander by pushing it towards ground; and

(iii) the lander anchor system, two harpoons with cords, connected to the landing gear and shot automatically at touch-down (after the harpoon heads are fixed in the cometary soil, the lander can be pulled back and tightened to the ground via a rope–pulley mechanism). Although the amount of kinetic energy absorbed at touch-down by the non-rigid lander spacecraft body could not be well estimated beforehand, the major unknown for the planning of the Philae landing was the strength of the cometary surface.

Aiming Philae to the landing site involves proper selection of the orbiter trajectory and orientation for the release, proper selection of the separation velocity of the lander spacecraft and proper timing of the lander release. For the choice of the landing site and landing time, spacecraft safety for both the lander (during descent, landing and beyond) and the orbiter (for the pre- and post-release trajectory and manoeuvring) deserves the highest priority. Simulations of descent lander trajectories using the body shape and gravity model of 67P known before landing have shown that not all surface regions of the 67P nucleus (i.e. only 40 per cent of the surface) were within reach for a Philae soft landing.

(b) Landing site selection

Within about two months from mid-August 2014, the landing site selection was performed as a joint effort by the Philae team, the orbiter instrument teams (providing viable information on the nucleus and on surface and environmental properties of the comet) and by ESA (for navigation and mission operations). From a scientific point of view, the key criteria for the landing site selection were: (i) safe descent and landing with the Philae spacecraft and its instruments in full working order after landing, (ii) enabling the performance of the first science sequence (FSS) immediately after landing with measurements of each instrument at least once, at a heliocentric distance of 3 AU, (iii) enabling the performance of the long-term science phase (LTS) of the lander expected for the distance range of the comet from 3 to 2 AU pre-perihelion, and (iv) at least part-time illumination of the landing site by the Sun during the FSS and LTS phases. An important goal, though not a requirement, was to accomplish scientific measurements during descent and in particular close to landing.

The down-selection of the landing sites was done in three steps. First, 10 preliminary candidate sites were selected. Then, five prioritized sites out of the 10 were chosen for a more in-depth analysis. Finally, the primary and a single back-up landing site were selected out of the five, considering scientific, technical and operational criteria of the landing sites and of the overall lander delivery sequence. The landing site selection process for the Philae mission was performed within six weeks and it may represent the fastest one ever done for a space mission, also considering that useful information on the 67P nucleus relevant for the site selection became available only about two weeks before starting the whole selection process. After analysis, ESA confirmed the primary landing site J (later named Agilkia), located at 335.00° longitude and +14.75° latitude (in the ESA flight dynamics reference frame, version 00085, for the nucleus) as proposed by the lander mission project, for lander separation on 12 November 2014, 08.35 UTC at about 22.5 km height above ground. The estimated descent duration was 6 h 59 min, resulting in a relatively large extent of the landing uncertainty ellipse (about 500 m semi-major axis). The planned touch-down velocity was set to 1 m s^{-1}, at the upper bound of the allowed range for proper compensation by the damping mechanism of the Philae landing gear.

(c) Philae descent: the happy part

'Go' for the Philae separation from Rosetta was given by the ESA mission manager early in the morning of 12 November 2014. With a series of orbital manoeuvres Rosetta was injected into the hyperbolic lander delivery orbit. Lander separation started as scheduled and the set ejection speed (0.1874 m s^{-1}) was almost ideally (1% uncertainty) achieved via the MSS spindle drive. The landing legs of the tripod and stowed instrument units (ROMAP sensor arm, CONSERT antennas) unfolded shortly after separation. During the 7 h descent to the surface, the lander had a slow rotation about its body axis and it was in quasi-continuous communication link with the Rosetta orbiter. CONSERT ranging, using the orbiter and lander instrument units, allowed the lander to be followed on its trajectory until about 50 min before touch-down at the surface and was used for the *a posteriori* analysis of the Philae descent trajectory. During the descent, a series of scientific measurements were also executed successfully and fully according to plan. The most critical measurements were the ROLIS landing site imaging from a very short distance above Agilkia ground and the ROMAP magnetometer sensing over the last few metres towards the touch-down.

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(d) Philae landing: the lucky part

On 12 November 2014, 15:34:04 UTC, Philae touched down at Agilkia (335.69° longitude, 12.04° latitude), just 112 m away from the target point for the landing [13]. Already before separation, sensor measurements of the pressure in gas pipes indicated that the gas tank for the ADS thruster did not open, such that firm fixation of the lander to the ground had to rely almost exclusively on a successful firing and performance of the two harpoons on-board. For a still unknown reason and despite nominal set-up and performance of the on-board subunits involved, and despite proper execution of the correct command sequence, the shooting of the harpoons did not happen when the touch-down signal trigger arrived. The lander feet sunk into the soft regolith on the surface, digging five holes into the ground and ejecting a cloud of dust grains over the touch-down area imaged by the OSIRIS [14] and the navigation cameras on-board Rosetta (see for instance fig. 5 in [13] and http://www.esa.int/spaceinimages/Images/2014/11/). After a time span of about 20 s with repeated ground contacts and having absorbed about 10% of the kinetic energy inside the landing gear (estimated from sensor readings of the landing gear generator; see [13,15,16]), Philae bounced back from the surface, starting now an almost 2 h long hopping tour across the surface of the comet. All available orbiter and lander observations and house-keeping data from the Philae touch-down at Agilkia were analysed and permitted the reconstruction of the sequence of events the lander experienced on the ground, and even to derive important physical parameters of the cometary surface at the landing site, like the strength of the cometary material (see [13,15,17]).

The hopping trajectory of the lander after having left Agilkia is only known approximately (see for instance [13]). As concluded from the mismatch of the outgoing hopping direction with that towards Abydos, the final landing location, as seen from Agilkia [13], at least one more—possibly two—short touch-down(s) on the surface must have happened. The lander attitude and rotation motion during the whole landing period (descent, hopping, final landing) are reconstructed by combining magnetometer measurements of ROMAP on-board Philae with those of RPC/MAG on-board Rosetta [18] (for a movie see http://blogs.esa.int/rosetta/2015/11/12/reconstructing-philaes-flight-across-the-comet). The reconstruction showed that a very complex rotational motion resulted for Philae as a consequence of the touch-downs, the terrain properties and the deceleration of the lander flywheel. The third ground contact of Philae very likely happened not too far away from the final landing location.

During the whole hopping period the lander instruments performed the first part of the FSS measurement sequence. The lander subsystems and instruments used during that time operated nominally, according to a planned sequence designed for immediate post-landing activities, assuming Philae being at rest at the Agilkia site. Not surprisingly, some scientific measurements were badly affected (CIVA, SESAME) due to the unexpected hopping of the lander. However, it is noted that also unexpected (successful and very interesting) scientific measurements resulted from this part of the on-comet operation of Philae (for instance for ROMAP, COSAC, PTOLEMY).

On 12 November 2014, 17:31:17 UTC Philae finally came to rest—after the first touch-down and one or even two surface contacts during the hopping phase—at approximately 357.8° longitude and −9.0° latitude [19], a site later named Abydos and located in the Wosret (close to the Hatmehit) region on the nucleus (for the definition of the 67P surface regions, see [20]). The location and attitude of Philae enabled two-way telecommunication with the Rosetta orbiter,

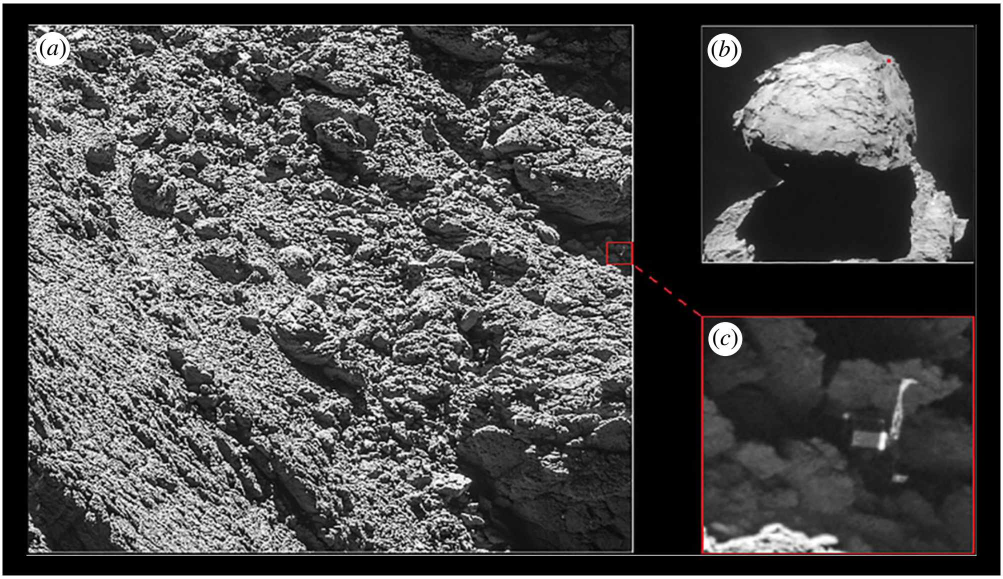

Figure 2. (*a,c*) The Philae lander on the surface of 67P, imaged by the OSIRIS camera. The context of the landing area is depicted in the NAVCAM image (*b*). Copyrights: Osiris images—ESA/Rosetta/MPS for the OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA; Navigation Camera image—ESA/Rosetta/NavCam.

for commanding activities on-board Philae, and for receiving the data acquired and sent back to the orbiter. From ranging measurements, performed by the CONSERT experiment, the lander location during the FSS period was known to within about 22 × 106 m [19,21]. Attempts to identify the exact landing site through landscape imaging during FSS (using CIVA, ROLIS) and through subsequent search campaigns (up to summer 2016) via orbiter imaging (using OSIRIS and the Rosetta navigation camera) were difficult, because the lander landed in a cavity-like surrounding which blocked at least in part illumination by the Sun and visibility from the orbiter. Nonetheless, it resulted in potential detections of the Philae spacecraft on the ground. Only very close to the end of the Rosetta mission, on 2 September 2016, the lander was imaged successfully by the OSIRIS camera (figure 2), and the location of the spacecraft on the nucleus is being determined (preliminary result: 358.45° longitude, −8.15°; uncertain to about 3 m; the location coordinates are to be refined based upon improved digital terrain models that will become available in the future).

(e) Philae operations on the comet

The Philae spacecraft and its instruments survived the descent, touch-downs, hopping and final landing, almost fully intact: only the mounting of a foot at the landing gear tripod was deformed and the entrance window of a ROMAP sensor may have been blocked by soil material (according to available house-keeping and science data). The lander performed—living mostly from battery power—a 56 h 28 min long FSS measurement and operation programme at Abydos and during the hopping phase from Agilkia to its final landing site. It switched into hibernation mode on 15 November 2014 after 00:02:36 UTC (time stamp of last bus voltage reading in Philae house-keeping data), after the last CONSERT ranging signals were exchanged between the respective lander and orbiter instrument units.

During the FSS (and not knowing where and how the lander was on the nucleus), the FSS science programme had to be adapted, reshuffled, modified and complemented by a prepared execution block for emergency situations in almost real time. Fortunately, flexibility had been implemented as a nominal way of operation, given the envisioned predicted Philae configuration at landing. All instruments of the lander (including the SD2 drill for sampling) were operated at least once for scientific measurements during the FSS period, although not with all modes and/or subsystems (for instance, with CIVA the M/V and M/I instrument units for imaging and near-infrared spectroscopy of the drill samples were not activated). However, important measurements of instruments had to be dropped (for MUPUS, PTOLEMY, SESAME) and not all instruments could obtain scientifically useful measurements (for APXS), which—as found out *a posteriori*—was due to unfavourable conditions and circumstances due to the unknown location and environment. For instance, the surface drilling by SD2 and subsequent sample analysis by COSAC as well as the APXS elemental composition scans had no scientific output, because the surface devices of the respective instruments did not reach the ground, although the command execution was performed successfully. For MUPUS, PTOLEMY and SESAME, important measurement sequences had to be shortened or even cancelled completely due to lack of time and/or power.

The overall scientific data package obtained from the Philae landing remained the one collected during descent, hopping and FSS. During later operations phases of the lander no scientific data could be collected and transmitted to Earth. Despite the limitations due to the unique landing sequence, unprecedented results were acquired.

The various technical and operational aspects and issues concerning the Philae landing site selection, the descent trajectory, the lander operations as well as the instrument science operations at the comet are described in: Accomazzo *et al*. [22]—Rosetta mission operations for landing; Ashman *et al*. [23]—Rosetta–Philae science planning after Philae landing; Balazs *et al*. [24]—Philae command and data management system; Di Lizia *et al*. [25]—SD2 operations; Dudal & Loisel [26]—Rosetta–Philae radio-frequency link communication; Geurts *et al*. [27,28]—on-comet operations preparation and planning, and on-comet operations execution; Heinisch *et al*. [18]—attitude reconstruction of Philae; Jurado *et al*. [29,30]—landing site selection and descent trajectory; Knapmeyer *et al*. [31]—SESAME/CASSE instrument listening to the MUPUS PEN insertion; McKenna-Lawlor *et al*. [32]—performance of the mission-critical Electrical Support System (ESS); Morse *et al*. [33]—PTOLEMY operations at the surface; Moussi *et al*. [34–36]—Philae science planning and operations; Remetean *et al*. [37]—locating the lander; Rogez *et al*. [38]—CONSERT operations planning; Roll *et al*. [15,17]—landing performance; Ulamec *et al*. [39–41]—landing and operations on the comet; and Witte *et al*. [16]—landing performance.

3. Scientific results from Philae

(a) Characterization of the cometary surface

Imaging data of CIVA [3,42] and ROLIS [8,43] on-board Philae provide a view of the physical constitution of two sites on the cometary surface, i.e. of Agilkia, the area of the first touch-down, and of Abydos, the final landing site of Philae. Owing to the close distance—the exposures at Agilkia were taken during the last metres of the descent (67.4 to 9 m above the surface [43]) or on the surface at Abydos (about 0.5 m to local horizon)—the images show details that are not discernible in the data from the remote sensing cameras of the orbiter.

(i) Agilkia

ROLIS images of the Agilkia site show a granular surface on centimetre to decimetre scale with embedded boulders up to several decimetres to metres in size. Two terrain types with different surface roughness are distinguished (figure 3), reflected also in the slopes of the particulate differential size distributions (see for instance the log–log plot in fig. 3 of [43]): 2.8 ± 0.2 for the smoother terrain; 3.5 ± 0.3 for boulders larger than 4 dm and 2.2 ± 0.1 for the smaller grains (completeness limit at 4 cm) in the rougher terrain [43]. The upper surface layer at Agilkia appeared to be an air-fall product (particles emitted by cometary activity and falling back to the surface of the comet), as was first proposed by Thomas *et al*. [44] for major regions on the

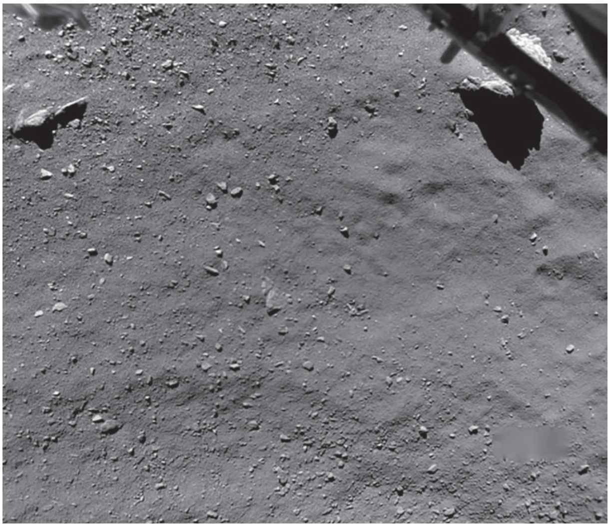

Figure 3. ROLIS image of the Agilkia landing site before touch-down. The image was taken 28.9 m above the surface and covers an area of 31 m across. Two terrain types—smooth and rough—as well as boulders are seen on the ground. The dark structure in the upper right corner shows a part of the landing gear. Copyright: ESA/Rosetta/Philae/ROLIS/DLR.

surface of 67P. The Agilkia terrain as a whole is not fully covered by very fine grains (sizes below 0.4 mm), because the surface granularity does not appear to be uniformly masked by powder-like dust at sub-pixel resolution. This indicates that the particles returning to Agilkia experienced size selection effects; larger grains (mm to cm scale and above) lifted up by cometary activity have fallen back to the surface, while smaller dust particles emitted from the surface mostly with escape velocity and faster were deposited at a much lower rate, or not at all.

Indications for aeolian-like features close to larger surface entities exist, suggesting surface transport of material. In fact, the smooth and rough terrains in the ROLIS images are seen as a clear indication [43] that so far unidentified material transport and sorting processes must be at play on the surface of not only Agilkia, but at many more regions on 67P (see also [44]). Although the air-fall scenario allows the surface regolith to originate from different surface terrains with possibly different physical properties, the surface reflectivity in ROLIS images of Agilkia appears to be rather uniform, which extends a similar finding from orbiter data [45] to a finer order of granularity. No fracture lines are seen in the Agilkia images from ROLIS; if present they may be completely covered by the surface regolith. The analysis of terrain outcrops in the ROLIS images together with the interpretation of digital terrain data of the site provide a first idea about the thickness of the surface regolith at Agilkia, i.e. up to 50 cm in the smooth terrain and 1 to 2 m for the rough terrain [43]. It is noted that underneath the regolith layers the surface may display a different structure across the Agilkia site. This is fully in line with the analysis of the footprint images from the Philae touch-down at Agilkia [13]: an at least 20 cm depth for the shallow excavation holes from the feet and legs was derived for the first lander touch-down. From a finite-element analysis of the touch-down dynamics, combined with measurements of the touch-down from the lander and orbiter, Roll *et al*. [15,17] estimated the strength of the surface regolith at Agilkia; they found for the compressive strength a mean value of 1.5–2 kPa assuming a strength parameter that is constant with penetration depth. A refined value of 3 kPa m^{-1} is found for a compression strength that increases linearly with penetration depth and is considered by the authors as an overall better scenario for the lander touch-down at Agilkia. They also note that according to their modelling the lateral strength of the soil material at Agilkia should not exceed 10 Pa. It is speculated that the lander bouncing at Agilkia may have been accentuated by the presence of a harder surface underneath the top regolith layer [13].

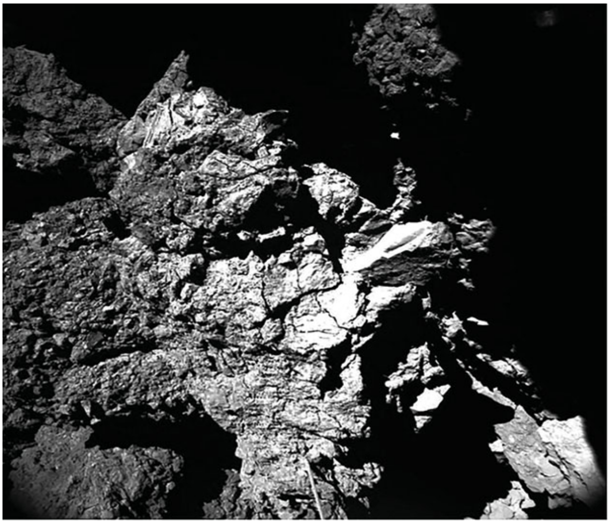

Figure 4. CIVA image of the Abydos landing site. The rough terrain displays pebble-like features, blocks, cliffs and linear cracks on the surface. The bright linear feature at the bottom centre is the tip of one of the two 5 mm thick CONSERT antennas on-board Philae. Planetary Science Archive reference: CIVA_FS3P_141113061443_4_0.IMG (J.-P. Bibring, Y. Langevin, A. Soufflot, M. Berthe, G. Poulleau, B. Gondet, ROSETTA-LANDER 67P CIVA 3 FSS V1.0, RL-C-CIVA-3-FSS-V1.0, ESA Planetary Science Archive and NASA Planetary Data System, 2016). Copyright: ESA/Rosetta/Philae/CIVA.

(ii) Abydos

The CIVA imaging of the final landing site Abydos [42] shows a rugged terrain of cliffs, boulders and pebbles, in this respect complementing the finding from the orbiter imaging for this and several other regions on the nucleus (figure 4). Fractures and cracks—with predominantly linear extension—in the material structure are ubiquitous and appear on different scales. They may be the result of environmental processing, for instance by the thermal stress imposed by daily and ephemeral Sun illumination together with cometary activity. In this respect, the Abydos site is distinctly different from the regolith-covered touch-down area at Agilkia. A further characteristic of Abydos compared to Agilkia is that the material, while on average very dark with albedo of a few per cent (as found for the overall surface of 67P; see [45]), contains embedded regions with much higher reflectivity, clearly above 10%. The latter could be composed of icy and/or salty ingredients, while the abundant dark material may resemble carbon-rich organic compounds [42], which appear to be spread around the entire nucleus surface as exhibited by the VIRTIS remote sensing instrument [46].

Regolith-like surface material is present at Abydos, but is far less abundant than that at the Agilkia site. This may imply that resurfacing by cometary activity has less affected the surface structure at Abydos. Alternatively, though considered less likely, one may also interpret the regolith-depleted surface region at Abydos as being due to an enhanced clean-up of the surface layer from granular material driven by recent gas activity. In this respect, it is noteworthy to mention that signs of local activity, for instance dust grains released from the local surface, are not reported from (direction-sensitive) SESAME-DIM dust impact monitor measurements at Abydos [47,48] despite significantly longer measurement times and a very close surface distance with respect to the SESAME dust detection during the lander descent. The comparison of the surface texture of Agilkia and Abydos suggests that different degrees of physical processing have shaped the surface landscape at both sites, with the material at Abydos being more representative of the less processed nucleus surface.

At Abydos the MUPUS hammer was released to the surface, and for 3 h attempts were made to hammer its sensor head into the ground [49], as is documented by acoustic surface wave signals from the hammering, recorded by the CASSE unit of the SESAME instrument [31]. The resulting house-keeping of the MUPUS instrument suggests that the hammer was not able to enter into the ground deeply, possibly not at all. This in turn constrains the compression strength of the soil at the hammering area to be above 2 MPa, much higher than estimated for the regolith layer at Agilkia. The thermal infrared sensor of the instrument followed the diurnal temperature cycle at the final landing site [49]. The surface temperature varied between 90 and 130 K. The fast increase and decrease shortly before comet mid-day was most likely due to direct Sun illumination of the sensor field of view. Numerical modelling of the MUPUS temperature data versus time led to a best-fit value for the thermal inertia of $85\,\mathrm{J\,m^{-2}\,K^{-1}\,s^{-1/2}}$ [49]. The MUPUS result for the thermal inertia is clearly above that of MIRO (10 to $50\,\mathrm{J\,m^{-2}\,K^{-1}\,s^{-1/2}}$ [50]) which would support a much thinner regolith cover at Abydos compared with the wider average of the cometary surface as represented in the MIRO results. From further modelling (assuming adequate mean values for the density, specific heat and ice-to-dust mixing) the thermal conductivity of the soil at Abydos is constrained to be $0.02–0.06\,\mathrm{W\,m^{-1}\,K^{-1}}$ and the bulk porosity to be 40–55% [49]. The latter value range falls clearly below estimates for the bulk porosity of the nucleus interior ([19]; see also §3b) and suggests processing of the surface material and increased compactness, most likely due to a kind of 'thermal' sintering due to cometary activity at and underneath the surface.

The relative electric permittivity of the first metre into the ground at Abydos was found to be above 2.45 ± 0.2 as measured by the PP permittivity probe of the SESAME experiment [51]. This is much higher than the average value for the cometary interior found by the CONSERT radio sounding experiment (1.27 [21]). The lander results point towards a soft fluffy regolith surface constitution at Agilkia and a more solid, harder and rugged surface structure at Abydos. The visible appearance of surface constitution across the 67P nucleus seems to depend on the relative importance of resurfacing by air-fall and by local activity. In this respect, it is likely that a harder surface structure may exist underneath the surface regolith at Agilkia and other dust-covered locations on the nucleus [51]. Parametric simulations of the CONSERT signal of the surface constitution underneath the Abydos site suggest material properties with continuously decreasing dielectric constants [52]. This may be related to a decreasing compactness of the nucleus material with increasing depth underneath a solid cover layer.

(b) Characterization of the nucleus interior

The radio signals of the CONSERT experiment [4], exchanged between the orbiter and lander units, were meant to penetrate through the cometary nucleus and to sense the constitution of its interior, for instance by the delay and the amplitude of the radio wave, scattered by volumes with different dielectric properties due to composition and/or geometry inside the nucleus [4,21]. Furthermore, the instrument also allowed measurements of the distance between orbiter and lander during the descent and during FSS (in total three epochs on 13 and 14 November 2014). From the latter data, the identification the Philae location at the Abydos site [19] was accomplished with uncertainties of about $22 \times 106\,\mathrm{m}$ (see yellow region in [19]). Owing to the lander hopping and the resulting landing site location (Abydos), and due to the pre-programmed measurement timing [35], the CONSERT sensing of the 67P interior relates mostly to the 'head' of the nucleus body. The measured signal width (figure 5) indicates a uniform constitution of the nucleus interior without voids or volumes of enhanced or reduced mass concentration (mass-cons) with sizes of a few wavelengths (10 m [21]). The relative electric permittivity of the nucleus material is measured to be 1.27, a value much smaller than that of water ice or other solid material. The CONSERT results suggest a dust-to-ice volume mixing ratio of 0.4 to 2.6 and provide evidence for high porosity of the material of the nucleus interior (75 to 85%). Kofman *et al*. [21] also point out that ordinary chondritic-type material is not compatible with the CONSERT results. From a synoptic analysis of data from various instruments Herique *et al*. [53] conclude that the CONSERT results require a relatively high carbonaceous content (75 vol% in volume) and that stratospheric interplanetary dust particles (IDPs) and Antarctic micrometeorites may represent cometary material available in the laboratory. Overall, the 'head' of the 67P nucleus seems to

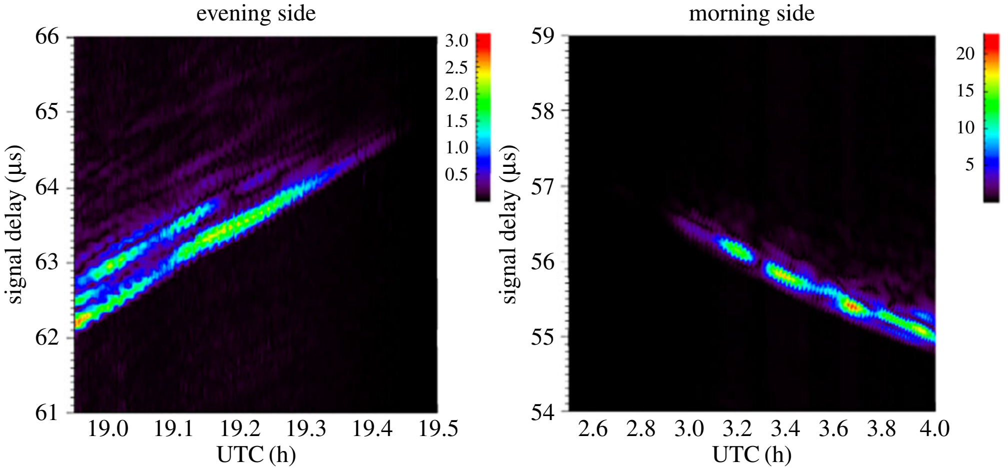

Figure 5. The CONSERT sounding of the 'head' of 67P. The panels display the signal delay (the measured signal travel time between orbiter and lander) versus time with the colour-coded linear amplitude of the sounding signal. The cross-cut profiles of the signal delay pattern are narrow indicating very little dispersive scattering by mass-cons or voids. The two panels show differences in the signal delay pattern: multi-path propagation is seen for the sounding of the evening side, but not on the morning side of the comet 'head' which may indicate variations, e.g. structures, in the electric permittivity of the material and/or reflections of sounding waves. The figure is adapted from Kofman *et al*. [19]. (Online version in colour.)

have a very uniform and homogeneous interior in terms of permittivity, suggesting uniformity also in terms of composition and component sizes on scales of several metres. The findings from the CONSERT measurements, if interpreted as a signature of cometary formation, may not easily be explained by a rubble pile scenario for the growth of the 67P nucleus and would favour a more uniformly structured cometary nucleus, accreted during the planetary formation era (for a more detailed discussion see also [54]). Alternatively, the components of the 67P nucleus body may be seen as a fragment from a larger body that has achieved a differentiated interior. Fragments of more uniform constitution on shorter scales would then be produced by collisions during the post-formation era, a scenario that is described and modelled with respect to the Rosetta results at 67P by Morbidelli & Rickman [55].

(c) Magnetization of surface material and plasma environment

Magnetism of the nucleus and plasma interaction was investigated thanks to the simultaneous measurements at different locations with ROMAP [9] on-board Philae and the RPC/MAG magnetometer on-board Rosetta [56]. The magnetic field measurement during descent and the subsequent bouncing sequence of the lander allowed the exploration of remnant magnetization of the cometary material at the three touch-down locations and at the final landing site [57]. An upper magnetic field magnitude of less than 2 nT at the cometary surface has been measured at all locations, with the upper specific magnetic moment being less than $3 \times 10^{-5}\,\mathrm{A\,m^2\,kg^{-1}}$ for metre-size homogeneous magnetized boulders. The magnetization found in 67P is much too low to enforce alignment of 0.1–10 m and larger cometesimals in a protoplanetary nebula. If comet 67P is representative of cometary nuclei, magnetic forces are unlikely to have played a role in the accumulation of planetary building blocks on scales of larger than 1 m [57].

During the Philae landing period the ROMAP and RPC/MAG magnetometers were operating simultaneously for about 33.5 h (start 12 November 2014 03:35:00 UTC, end 13 November 2014 14:36:39 UTC with intermittent ROMAP switch-off on 13 November 2014 04:05:35 UTC to 06:31:07 UTC). These measurements provided a unique opportunity to analyse the spatial and temporal evolution of low-frequency waves in the magnetic field of the comet boundary region (frequency

Table 3. A possible set of species fitting the mean COSAC mass spectrum from instrument measurements obtained on 12 November 2014 between 16:00:30 and 16:02:50 UTC, when the lander was about 150 m above the surface on its first bounce from Agilkia.

compound	percentage in mass spectrum	compound	percentage in mass spectrum
H_2O	80.92	$HCONH_2$	3.73
CH_4	0.70	$C_2H_5NH_2$	0.72
HCN	1.06	CH_3NCO	3.13
CO	1.09	CH_3COCH_3	1.02
CH_3NH_2	1.19	C_2H_5CHO	0.44
CH_3CN	0.55	CH_3CONH_2	2.20
HNCO	0.47	CH_2OHCHO	0.98
CH_3CHO	1.01	$CH_2(OH)CH_2(OH)$	0.79

20–50 mHz, amplitudes up to approx. 3 nT, estimated wavelength of the order of a few hundred kilometres), first noticed in RPC/MAG data alone [58] and possibly caused by collective plasma structures induced by cometary activity. An initial analysis revealed that neither the amplitude nor the direction of these waves depend on the day–night cycle at the landing site, but rather they do depend on the global out-gassing pattern of the nucleus. Based on minimum-variance analyses two different types of waves could be identified in the comet–solar wind boundary region. These mostly compressional magnetic field oscillations have a propagation direction from the comet tail to the front with a velocity between 2 and 10 km s^{-1} [59].

(d) Nucleus composition

Information on the chemical composition of the nucleus was obtained by the COSAC [5] and the PTOLEMY [7] instruments on-board Philae. Both instruments collected data during the early hopping phase of the lander and after landing at the Abydos site. Detection of species probably released directly from the nucleus (H_2O, CO_2, CO) is reported by PTOLEMY [60] from mass spectra taken during the hopping phase. The instrument could measure these species again after landing at Abydos and found a CO/CO_2 ratio of 0.07 [61]. This ratio is much lower than the one obtained by the ROSINA experiment in the gas coma of 67P [62] and can be seen as an indication of chemical heterogeneity of the cometary nucleus. The majority of the peaks in the measured low-resolution mass spectra in both instruments are due to fragment products partly produced with or after release of the species, but mostly by the ionization process inside the instruments. These fragments are associated with organic species. In this respect, the COSAC data were interpreted [63] as being dominated by gas released from one (or more) cometary dust particle(s) that was (were) possibly unintentionally collected via the instrument gas exhaust pipe [5] from the dust cloud produced by the lander touch-down at Agilkia. Apart from H_2O, a mixture of 15 compounds (table 3) from the chemical groups of alcohols, carbonyls, amines, nitriles, amides and isocyanates were used to fit the COSAC spectra from the hopping phase. Sulfur compounds, if any, are below the detection limits for both the COSAC and PTOLEMY instruments [60,63].

Some species used to explain the COSAC mass spectrum were not previously detected by ROSINA. This can be seen as an indication of either chemical heterogeneity of the cometary nucleus, or a distinct composition of the coma gas species and the 'dust' grains measured by COSAC. The organic species used for the fits of the COSAC data are chemically relatively simple compounds and can be formed in space by radiation-triggered and/or radiolysis reactions in ices. Clear signatures of more complex species, even of biological relevance, are not found in the COSAC spectra. The interpretation of the mass spectra peaks measured with PTOLEMY [60] suggests a fractionation pattern that might be related to chain-forming species. Short-chained polyoxymethylenes, first proposed to explain ion mass spectra during the Giotto flyby at comet 1P/Halley [64], are considered possible candidates that might also explain the PTOLEMY measurements. Aromatic species seem to be less abundant as are nitrogen-bearing compounds.

4. The end of the Philae mission

After descent, landing and the FSS the lander batteries were out of power and, as not enough electric power could be generated by the solar cells of the lander compartment at the landing site, the spacecraft went—undamaged—into hibernation. An automatic wake-up mode remained active on-board that would allow spacecraft operation again, provided sufficient power would be available and the operational temperature level would be reached due to increased solar illumination when the comet moved towards perihelion.

As reconstructed from house-keeping data of the Philae spacecraft, wake-up conditions were achieved again by the lander during the last week of April 2015 and, from that time on, almost every cometary day at the Abydos landing site. Since March 2015, the Rosetta orbiter tried repeatedly and as of May 2015 continuously to trigger a communication contact with Philae. This contact happened first on 13 June 2015 with the reception of a short package of house-keeping data under very unstable radio link conditions. Subsequent contacts of similar nature (short and unstable) happened in an irregular pattern. A last—uniquely long and stable—communication contact with the lander was achieved on 9 July 2015, insufficient though to enable scientific operations to be initiated. The available house-keeping data of the lander provided information on the lander wake-up after hibernation and indicated that important lander subsystems like solar cells, battery and computer were in good shape despite having experienced likely temperatures of −100°C or less during hibernation, in any case much below the operation and survival limits the lander and its instruments were designed for. The house-keeping information also suggests that an earlier contact with the orbiter (than around mid-June 2015) should have been possible; however, no clear reason for the late and finally unstable link between Philae and the orbiter was identified. Clearly, the operational conditions, namely the communication links, were insufficient to implement new scientific operational sequences on-board for successful execution by the lander.

Even during perihelion passage of the comet when, for safety reasons, Rosetta had to keep a large distance (300 km and more) from the nucleus, the communication trigger and listening for lander signals on-board the orbiter were continued despite the expected signal strength of the lander being at detectability limits. An analysis of the post-hibernation experience with the lander was performed and new recovery attempts— including active commanding and on-board movement activities (flywheel turn-on)—were prepared for the post-perihelion communication windows with the lander at the Abydos site. Up to the end of January 2016 no signal from the lander was received nor was any other indication obtained that the lander was operational at the surface. Three possible scenarios were proposed for the unsuccessful communication with the lander at Abydos since summer 2015: (i) the communication equipment of the lander is damaged and can no longer receive or send signals from or to the orbiter; (ii) the power situation of the lander does not allow operation any more, for instance due to a permanent coverage of the solar cells by redeposition of absorbing dust due to cometary activity; and (iii) the communication conditions for the lander have changed, i.e. Philae may have turned or even changed location such that the lander antennas point into a direction unfavourable for communication with the orbiter. After the detection of the lander in the OSIRIS image, taken of the Abydos site on 2 September 2016, and the on-going evaluation of the image information on location, attitude and lander status being completed, a new appraisal of the scenarios has to be done, in particular for scenarios (ii) and (iii). In addition, the terrain geometry will be reanalysed for its impact on the communication link between orbiter and lander. The respective results will be published in the future.

On the basis of this information and based upon the revised terrain model of the Abydos site, scientific measurements of the lander instruments will be re-evaluated, for instance: for CONSERT the importance of surface layer reflections of the radio signal, for MUPUS the surface illumination by the Sun, and for SESAME the acoustic reflections of the MUPUS hammering signal in the surface layers. Data from other instruments (CIVA and ROLIS for details of the lander surrounding) will work towards clarification of the detailed terrain morphology of the landing site.

Despite the fact that the prospects for lander operations at Abydos after January 2016 were not promising (because the comet retreated from the Sun and thus the environmental conditions for Philae were expected to turn towards hibernation level again), it was decided to keep the lander telecommunication unit on-board Rosetta switched on and to continue sending the communication trigger to the surface of the comet, listening for a reply by Philae. The unit was finally switched off on 27 July 2016 10:00 UTC, which marks the end of the Philae mission to comet 67P.

With the descent and landing of the orbiter on 30 September 2016 the Rosetta mission was terminated, and, with the orbiter, the 'key' for contacting the lander was deposited on the comet. The lander itself was left behind in its autonomous wake-up mode under hibernation conditions. Provided the lander survives, Philae start-ups may occur again during future returns of the comet to the Sun; however, the lander will remain 'quiet', because it waits for the Rosetta communication trigger before sending signals again. While reception of the lander carrier signal on Earth may be possible under favourable conditions (for instance for close distances to Earth), contacting Philae directly from Earth is far beyond the capabilities of existing radio telescope facilities.

5. Has Philae achieved its science mission goals?

The pioneering landing on a comet that Philae performed has revealed unprecedented and, in large part, unpredicted properties of the nucleus. Although designed 25 years ago, with systems and instruments of challenging specifications and requirements, the mission accomplished many goals. The spacecraft had a close to perfect descent, and it soft-landed on 67P in good shape to perform science on the comet. During the descent and the FSS phase on the comet, all 10 instruments on-board the lander were operated (table 4), and indeed eight instruments could collect scientific data for evaluation on Earth (as the instruments did not reach ground contact, the measurements of APXS and SD2 were found to be of no scientific value). The science return from Philae (13.88 Mbyte of data, table 4) as described in §3 addresses key characteristics of 67P, i.e. the interior (science goals (1) and (4) in table 2), the surface constitution (science goal (3)), the comet composition including the detection of organics (science goal (2)), and the physical parameters of the surface and subsurface (science goal (7)). Some of the findings from the Philae experiments support existing scientific concepts on cometary nuclei by either supporting them like for the surface constitution, or clarifying issues of the nucleus formation like the irrelevance of magnetic fields. The latter and in particular the result of a rather homogeneous interior of the '67P head' certainly challenge aspects of the planetesimal formation in the framework of the processes involved in the formation of the planetary system as a whole—and maybe beyond. After Rosetta, and with the contribution from Philae experiments, there is no doubt that a significant variety of organics exists in 67P, although a synoptic picture still has to be worked out. Organic 'dust' grains have a composition in part distinct from the coma volatile species.

Unfortunately, because the scientific measurements foreseen for the LTS could not be implemented, valuable results of the refractory constituents of the soil (parts of science goal (2)) were not obtained (infrared spectra as well as mass spectra and gas chromatograms through stepwise heating of samples; an assessment of the chirality of the compounds). The LTS measurements were meant to address cometary physics and evolution at much greater depth than during the few days of measurements during descent and the FSS after landing (science goals (6) and (8)). The LTS could not be implemented due to a lack of reliable lander communication with the orbiter. The lander location after hopping resulted in Philae hibernation and a shift in

Table 4. The Philae experiments science return in terms of operations time and data volume. The table lists for each Philae instrument the duration of science operation (in hh:mm:ss) and the data volume (in Mbyte) retrieved. All science operations and the respective data were obtained during the descent (SDL) to the surface and during the phase of the first science operations (FSS).

Philae instrument	SDL+FSS operations (hh:mm:ss)	SDL+FSS science data (Mbyte)
APXS	06:51:19	0.06348
CIVA	01:50:28	2.337996
CONSERT	16:41:08	2.63028
COSAC	02:07:31	0.27738
MUPUS	37:20:24	0.346656
PTOLEMY	01:08:40	0.10212
ROLIS	01:44:23	3.877524
ROMAP	32:33:02	1.268496
SD2	02:48:00	0.045264
SESAME	15:17:27	2.930016

solar distance and time for the LTS as compared to the original planning for Agilkia (where a hibernation break was not predicted). Whether this time shift would have been supportive for the achievement of Philae science goals remains an unanswered question.

It is also difficult to quantify the degree of achievements for the 10 individual science goals defined for the Philae mission—nonetheless, we gave it a try by providing an evaluation for the individual science goals of the Philae mission as listed in table 2. The majority of the science goals were addressed by the Philae scientific experiments and they were partly achieved (as indicated in table 2), meaning that they returned scientifically useful data that provided new results and a new understanding of the comet properties. More would have been possible, in particular, during the LTS phase. Obviously, also science goals related to long-term changes in the lander environment (science goals (6) and (8) in table 2) could not adequately be assessed through lander experiments. No doubt, successful drilling and analysis of surface and subsurface samples would have been an additional asset for the science return of the Philae spacecraft. It should be noted that science goals (3) and (5) benefited from the unsuccessful landing at Agilkia, by the collection of scientific data on two sites and during the hopping phase, respectively, something not foreseen in the original science planning of the mission.

Nevertheless, the Philae mission has undoubtedly paved the way for Solar System exploration in a unique fashion, and it made the public aware and excited about it.

Authors' contribution. H.B. is a lead scientist of the Philae mission. He contributed to the scientific operations and the interpretation of the scientific measurements at the comet. He compiled the paper manuscript based upon the information provided by the co-authors. J.-P.B. is a lead scientist of the Philae mission and principal investigator of the CIVA instrument on-board the Philae lander. He contributed to the hardware design and provision, the scientific operations, and the data analysis and interpretation of the instrument measurements at the comet. I.A. is responsible for the ROMAP plasma experiment and for building the SESAME-DIM unit. He contributed to the hardware design and provision, the scientific operations, and the data analysis and interpretation of the instrument measurements at the comet. H.U.A. is the principal investigator of the ROMAP instrument on-board the Philae lander, and also responsible for the ROMAP magnetometer experiment. He contributed to the hardware design and provision, the scientific operations, and the data analysis and interpretation of the instrument measurements at the comet. A.E.F. is the principal investigator of the SD2 instrument on-board the Philae lander and she contributed to the hardware design and provision, the scientific operations, and the data analysis and interpretation of the instrument measurements at the comet.

F.G. is the principal investigator of the COSAC instrument on-board the Philae lander and contributed to the hardware design and provision, the scientific operations, and the data analysis and interpretation of the instrument measurements at the comet. G.K. is the principal investigator of the APXS instrument on-board the Philae lander and contributed to the hardware design and provision, the scientific operations, and the data analysis and interpretation of the instrument measurements at the comet. M.K. is, since August 2016, the principal investigator of the SESAME experiment on-board the Philae lander, and also responsible for the SESAME-CASSE instrument. He contributed to the software design, the scientific operations, and the data analysis and interpretation of the instrument measurements at the comet. W.K. is the principal investigator of the CONSERT instrument units on-board the Philae lander and the Rosetta orbiter. He contributed to the hardware design and provision, the scientific operations, and the data analysis and interpretation of the instrument measurements at the comet. H.K. is responsible for the SESAME DIM in-flight experiment and contributed to instrument calibration, the scientific operations, and the data analysis and interpretation of the instrument measurements at the comet. S.M. is the principal investigator of the ROLIS instrument on-board the Philae lander and contributed to the hardware design and provision, the scientific operations, and the data analysis and interpretation of the instrument measurements at the comet. W.S. is responsible for the SESAME PP experiment and contributed to the hardware design and provision, the scientific operations, and the data analysis and interpretation of the instrument measurements at the comet. K.S. was, until July 2016, the principal investigator of the SESAME experiment on-board the Philae lander, and also responsible for the SESAME CASSE instrument. He contributed to the hardware design and provision, the scientific operations, and the data analysis and interpretation of the instrument measurements at the comet. T.S. is the principal investigator of the MUPUS instrument on-board the Philae lander and contributed to the hardware design and provision, the scientific operations, and the data analysis and interpretation of the instrument measurements at the comet. I.W. is the principal investigator of the PTOLEMY instrument on-board the Philae lander and contributed to the hardware design and provision, the scientific operations, and the data analysis and interpretation of the instrument measurements at the comet. All authors drafted parts of the manuscript and critically reviewed the paper.

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