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THE ESA ROSETTA MISSION:
A SPACE ARCHAEOLOGY CASE STUDY

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Abstract: After millennia of associative and cultural interaction between human communities and the Cosmos, since the launch of Sputnik in 1957, the first artificial satellite in History, Space has become a natural environment with which today's societies constantly interact for their own economic, scientific, political, and military needs: the development and proliferation of human activities in Space represents one of the shaping and characterizing factors of contemporary society in the 20th and 21st centuries. Space Archaeology emerged in the late 1990s (mostly in the US and Australian academic context), and it examines the contexts of human and robotic Space exploration analysing the relationship between Material Culture, human behaviour and the natural environment, according to the theoretical model of *Cultural Landscape*. This article represents a synthesis of a broader research carried out for the writing of the master's thesis (Forassiepi, 2023): an overview of the general principles and methodological aspects of the discipline is provided, and then developed in the case study related to the ESA's (European Space Agency) Rosetta mission (2004-2016), presenting data and results.

Keywords: Space Archaeology; Cultural Landscape; Space Exploration; Rosetta; Comet.

1. Introduction to space archaeology

Space Archaeology can be defined as "the systematic and scientific study of the non-renewable material remains of human spaceflight history across time and space through the application of modern archaeological method and theory" (Westwood et al., 2017).

This definition embraces a broad view of the discipline's targets, not limited to the study of Material Culture located in Space, but extended to all infrastructures related to the human activity of space exploration (control centres, launch bases, industries, etc.; O'Leary, 2009a), down to any material evidence of its cultural impact in society (space-themed playgrounds, food products, toys, etc. Gorman, 2019). The relationship between spatiality and human behaviour within the International Space Station has also been analysed, representing the first *in situ* study in the discipline (Gorman & Walsh, 2021). The totality of these contexts and artifacts testifies to the development of the historical, social, cultural and political processes of space exploration, a phenomenon of fundamental relevance to Contemporary History, which has transformed the natural environment around our planet: Earth orbit is filled with tons of material for human activities (telecommunications, scientific research, military defence systems, etc.; Gorman, 2014, 2021). The archaeological analysis of the material trace of Space Exploration ensures the transmission of the related heritage of historical and cultural information: as pointed out by several authors (O'Leary, 2009b; Szczepanowska, 2009; Westwood et al., 2017), the frequent gaps in the archival management of space agencies hinder the reconstruction of the technological stages of the aerospace sector development; the artefacts themselves often constitute the only evidence available to us. Elevating the material trace of space exploration to the rank of cultural heritage, favours the definition of management and preservation plans, preferably *in situ*. The risks of disturbance related to Space Economy development, expected in the coming years (spread of orbital services, settlement and mining on the Moon, space tourism; Ghidini, 2021; Holcomb et al., 2023), and the environmental contexts fragility in which the material culture of space exploration is located, make concrete the need to elaborate protocols and legal frameworks for cultural heritage protection, to which the discipline is actively working, despite the difficulties inherent in the international legislation regulating space activities (NASA, 2011; Gorman, 2021; 2023; O'Leary, 2009b; Reynolds, 2014; Stooke, 2008).

Currently, several methodologies are employed for the investigation of space archaeological contexts: high-resolution orbital surveys for contexts located on the surface of a celestial body (O'Leary, 2014; Stooke, 2009), providing information on the evolution of natural formation processes and their interaction with human material culture, the subject of study of Planetary Geoarchaeology, a sub discipline recently introduced and proposed by Holcomb (Holcomb et al., 2023); laser, radar and optical tracking of satellites and orbiting debris (Gorman, 2014); diagnostic analysis on artefacts recovered from Space (Biermann, 2009; Harland & Lorenz, 2005; Szczepanowska, 2014) or on prototypes and engineering models of spacecraft (used for testing in the development phases of a space mission, Szczepanowska, 2009); photography and cataloguing of the daily evolution of an inhabited space context (Gorman & Walsh, 2023). With the exception of the study carried out in 2022 on the International Space Station, the discipline's potential for *in situ* analysis is still held back by the current costs and difficulties in accessing space: however, settlements and mining activities on the Moon, private space initiatives, and Earth-orbiting debris management activities planned for the next few years chart a well-defined path towards more opportunities for interaction with space-based archaeological contexts, giving legitimacy to the delineation of methodologies that are not feasible at the present time, but will be in the near future (Forassiepi, 2023; Gorman, 2009c; 2021; 2023).

The theoretical approach is based on the concept of *Cultural Landscape*, already widespread in archaeological practice and introduced into the discipline by Gorman (2009b). Defined as the "*combined result*" of nature and human beings (UNESCO, 2021), it allows us to overcome the natural-artificial, present-past dichotomies by analysing the relationship between materiality, human behaviour and the natural environment as it unfolds over time, in an integrated manner; it highlights the co-existence of different values and narratives within the same landscape, effective in analysing the role played by human groups that have 'suffered' the developments of space exploration (often forgotten by the space agencies' documentation), such as the Indigenous peoples of French Guiana and Australia, whose territories were subjected to a colonial-style occupation by the infrastructures of the Kourou and Woomera space centres (Gorman, 2005; 2007); it includes all the associative aspects, cultural, religious and social values connected with the landscape in question. In fact, today's space exploration interacts with environments characterized by an enormous stratification of cultural meanings, such as the Moon, planets, comets: every human culture has developed an associative relationship with the night sky and celestial bodies; contemporary space missions become part of this relationship, shaping it and adding new layers of meaning (Gorman, 2009b).

2. The case study: the esa's *rosetta* mission (2004-2016)

Despite the undoubted historical and scientific significance of the mission, Rosetta has not been the subject of in-depth archaeological studies to date. A brief paper by Gorman (2017)[1] identifies the archaeological contexts on comet 67P Churyumov-Gerasimenko and formulates some hypotheses on the related natural formation processes, but without going into detail: after all, the purpose of the article, rather than developing a real case study, seems rather aimed at demonstrating the legitimacy of an archaeological study for contexts located on celestial bodies as extreme and remote as 67P, a principle I fully agree with. This research intends to fill this gap.

The ESA probe was launched in 2004, and after 10 years in space, it reached comet 67P Churyumov-Gerasimenko in August 2014, inserting itself in orbit around it and starting a 26-month scientific observation and analysis campaign. The mission consisted of two elements, the orbiter Rosetta (fig. 1), and a small lander, Philae (fig. 2), which detached from the mother ship on 12 November 2014 and made the first historic landing on the surface of a comet. However, the operation did not go as planned: due to the malfunction of some landing systems (harpoons and ADS, see tab. 1), Philae bounced off the comet's surface 2 times (plus a small collision, see footnote 3), leaving traces[2] in the landscape, and stopping in a dimly lit crevice, a factor that resulted in the impossibility of recharging the batteries with solar panels and consequently, entering into hibernation after 72 hours. In the almost three days of activity on the surface of the nucleus, the lander nevertheless managed to carry out most of the planned scientific experiments and analyses. In more than two years

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[1] Gorman also proposed a reflection on the social and cultural impact of the mission, see Gorman, 2016.

[2] For an ichnological reflection on the traces left by a technical artifact in a space context, referred to as technotraces, see Díaz-Martínez et al., 2021

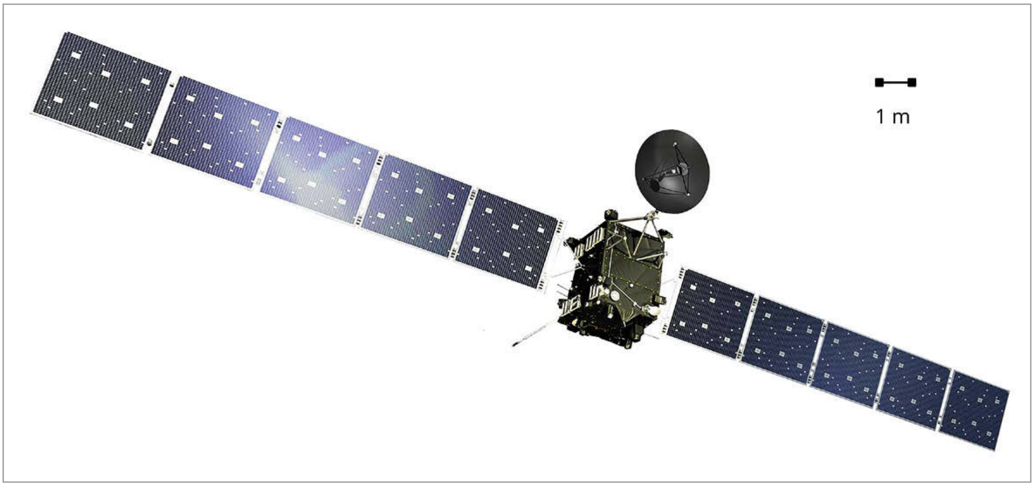

fig. 1. Artist impression of Rosetta, with scale. Credits: ESA/ATG medialab; edited by the author.

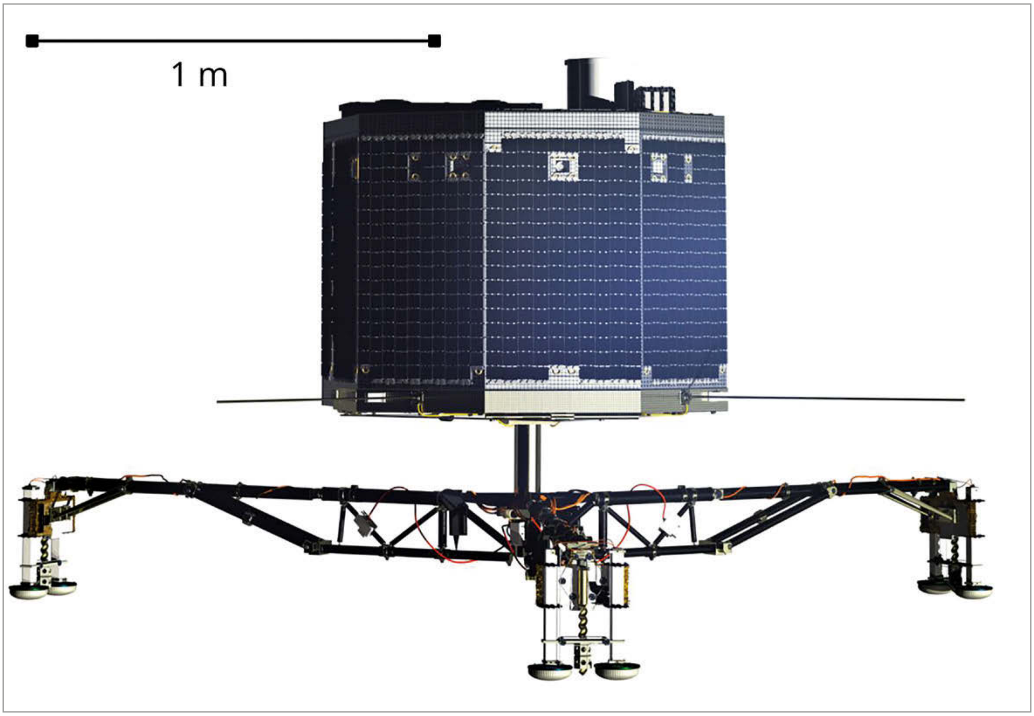

fig. 2. Artist impression of Philae, with scale. Credits: ESA/ATG medialab; edited by the author.

around the comet, Rosetta accumulated a huge amount of data, as well as an important photographic heritage, capturing very high-resolution images of the entire surface of the nucleus and its geological phenomena. Finally, on 30 September 2016, the orbiting Rosetta satellite crash landed on the surface of 67P, bringing the mission to an end (Ferri, 2020).

	Rosetta	**Philae**
Dimensions	*Main structure*: 3,18×2,25×2,56 m *Solar panels* :14×2,2 m; 32,7 m (total length) High Gain Antenna: 2,2 m (diametro)	*Main structure*: 0,8×1×1 m *Landing gear*: 32 cm (height); 1,5 m ca. (legs' length)
Mass	3064 kg at launch (fuel: 1718 - lander: 98 kg)	98 kg
Materials	*Main structure* - aluminium covered in Multi-Layer Insulation (kapton and betacloth); *Solar panels structure* - carbon fibre with aluminium honeycomb core; *High Gain Antenna*: carbon fibre	*Main structure and landing gear*: carbon fibre
Power System	*Solar energy* - Low Intensity, Low Temperature (LILT) solar cells 10LiTHI-ETA3ID (pure silicon); 3 lithium-ion batteries	*Solar energy:* Low Intensity, Low Temperature (LILT) solar cells ASE Silicon 10LITHI-ETA 3/200-3332ID, covering the main body; 2 batteries
Scientific payload	*11 instruments*: ALICE, CONSERT, COSIMA, GIADA, MIDAS, MIRO, OSIRIS, ROSINA, RPC, RSI, VIRTIS	*10 instruments*: APXS, CIVA, CONSERT, COSAC, MUPUS, Ptolemy, ROLIS, ROMAP, SD2, SESAME
Landing systems	none	Damping system (in the central tube of the landing gear); 2 harpoons in the legs; ice screws in the feet; Active Descent System on the top of the main structure (passive hold-on thrust to avoid re-bounces)

tab. 1. Technical overview of Rosetta and Philae (Biele et al., 2009; EADS Astrium GmbH, 2003; Ferri, 2020; European Space Agency, s.d.-a)

2.1 Methodology

Initially, the three types of *Cultural Landscape* indicated by UNESCO (2021) related to the Rosetta mission, have been identified. The *Designed Cultural Landscape* includes all the ground infrastructures involved in the development and management of the mission; however, the research focused on the contexts whose realization is closely linked to the development of Rosetta and Philae. The *Organically Evolved Cultural Landscape* is formed by the contexts of interaction between the Material Culture (Rosetta and Philae), the human behaviour (the scientific research and experiments on the comet) and the natural environment (comet 67P), and their evolution in time. The *Associative Cultural Landscape*, characterized by "*religious, artistic, or cultural associations of the natural element rather than material culture evidence*" (UNESCO, 2021) consists of the set of cultural and social values associated with Rosetta and the cometary environment explored.

With regard to the *Organically Evolved Landscape* and the analysis of the archaeological contexts present on comet 67P, the starting point for the research was the photographic heritage of Rosetta and Philae, and the scientific publications relating to the mission. Hundreds of images taken by Rosetta's OSIRIS (WAC and NAC) and NAVCAM instruments, and by Philae's ROLIS and CIVA, offer a very high level of resolution, allowing for an aerial survey of the studied areas: for NAC, the range is between 2m/pixel up to 0.17m/pixel; the WAC between 12m/pixel and 1m/

Name	Institution	Landing dynamics of Rosetta and Philae	Comet geology, natural formation processes	Environmental effects on materials	Mission history
Andrea Accomazzo	ESA (ESOC) - Rosetta Flight Director	x			x
Paolo Ferri	ESA (ESOC) - (former) Head of the Mission Operations Department	x			x
Vicente Companys	ESA (ESOC) - Rosetta Flight Dynamics Manager	x			
Alessandro Ercolani	ESA (ESOC) - Manager of Science Mission Data Systems	x			x
Ignacio Tanco	ESA (ESOC) - Rosetta Spacecraft Operations Engineer	x			x
Tommaso Ghidini	ESA (ESTEC) - Head of the Structures, Mechanisms and Materials Division			x	
Maurizio Pajola	INAF - Osservatorio Astronomico di Padova		x	x	
Giampaolo Preti	Officine Galileo - Università di Firenze			x	x
Matteo Gemignani	Space Systems Laboratory - Università di Pisa			x	
Giuseppe Cataldi	Space Systems Laboratory - Università di Pisa			x	
Giangregorio Tofanelli	Deimos Engenharia			x	

tab. 2. List of personalities consulted during the research; topics covered during the interviews are indicated.

pixel; the ROLIS camera up to 1 cm per pixel (El-Maarry et al., 2015; Mottola et al., 2015). However, since no probe has returned to 67P after 30 September 2016, the archaeological contexts are photographically documented until this date, no later; this means also that there are no photographs of Rosetta taken after its final landing, as the probe was programmed to deactivate all of its systems upon impact with the surface (Ferri, 2020). These unknowns imply the choice of an inferential approach for reconstructing the scenarios of natural formation processes in the investigated contexts, in line with what Holcomb (Holcomb et al., 2023) proposed in the publication presenting and defining the research typologies of planetary geoarchaeology: in the one used in this study, defined by Holcomb as "*predictive*", the goal is to infer, from scientific observations and investigations, qualitative and/or quantitative estimates of the effects of these phenomena on the human material trace over time. In this regard, the temporal extension of the Rosetta observations offers a considerable advantage for this mode of analysis: the areas of the future archaeological contexts were photographed and analysed several times between 2014 and 2016, making it possible to document the evolution of the natural processes taking place locally and to gather clues about the organic evolution of Cultural Landscapes on 67P. The technical characteristics of Rosetta and Philae materials were researched in ESA and industry archives. On these bases, estimates were formulated and compared with members of the European scientific community to provide them with an adequate scientific ground (tab. 2). To this end, a research visit to the European satellite mission control centre, the ESOC[3] in Darmstadt, Germany, took place in February 2023, during which some of the leading managers and operators of the Rosetta mission were interviewed (see tab. 2; Accomazzo et al., 2023).

It is worth emphasizing the hypothetical nature of the proposed scenarios. Opinions expressed by the experts, regarding what happened after the end of the mission, represent suggestions, sensations and hypotheses formulated on the basis of their professional and scientific experience, but without any claim to objective truth, for which there is a lack of certain data and information: only a return to comet 67P could make a proper survey of the archaeological contexts. This possibility could become reality in the coming years, if the CAESAR[4] mission proposal, which aims at a new observation campaign of 67P and the collection of nucleus samples, would be chosen by the next selection process (NF5) of the NASA *New Frontiers* programme (Max Planck Institute, 2021; Squyres et al., 2018). With regard to the *Designed Cultural Landscape* and the *Associative Cultural Landscape*, the research was based on the ESOC visit, interviews collected and bibliographic research.

2.2 The Designed Cultural Landscape

This category includes all the infrastructures whose construction was stimulated by the development and management needs of the Rosetta mission, the first real example of an interplanetary mission launched by ESA (Ferri, 2020):

Before Rosetta, the European agency had no antennas for communication with deep Space: thus, in 2003 the Deep Space Antenna-1 (DSA-1) was installed in New Norcia, Australia. The geographical location responded to the needs of the Rosetta mission, which in its phase around the comet, was in the southern hemisphere of

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[3] European Space Operations Centre.

[4] Comet Astrobiology Exploration Sample Return.

the sky; furthermore, this choice directly influenced the location of the next two DSA antennas, which had to be 120° apart in longitude (DSA-2 in Spain; DSA-3 in Argentina) to obtain total coverage of the sky (ESA, s.d.-b; Ferri, 2020).

In 2001, a new control room was installed inside the ESOC centre: built primarily for the management of the Rosetta mission, it provided ESA with the necessary tools to manage the flight operations of subsequent interplanetary missions (Ferri, 2020; Accomazzo et al., 2023).

A new control centre, the *Lander Control Centre*, was specially built at the DLR[5] headquarters in Cologne, since the German space agency was responsible for Philae's flight operations: today, it remains a specialized centre for interplanetary landing module operations, collaborating with agencies worldwide[6].

The needs generated by the development and operation of Rosetta and Philae thus provoked an overall upgrade of ESA's capabilities and infrastructures, representing a real turning point in the agency's history: provided with the operational tools and expertise, the European space program finally gained independence from NASA for interplanetary missions (Ferri, 2020). In the case of the DSA antenna network, the operational needs of the mission directly influenced the geographical choice for the installation of the infrastructure, representing an example of the relationship between space exploration activities, materiality and the natural environment in an Earth context, worthy of an archaeological study in its own right.

2.3 The Organically Evolved Cultural Landscape

The archaeological contexts created by the interaction between the Rosetta mission and the surface of 67P are: *Agilkia*, *the 'Skull'*, *Abydos* and *Sais*[7]. After a brief introduction to the general environmental characteristics of comet 67P (fig. 3), a description of the available data for each context will be given and some possible scenarios of their evolution over time, under the action of local natural formation processes, will be outlined.

2.3.1 Introduction to comet 67P Churyumov-Gerasimenko

Comet 67P completes its revolution around the Sun in little more than 6 years (aphelion ca. 5.7 AU[8]; perihelion 1.21 AU[9]; Ferri, 2020). The core consists of 2 lobes, a small one (2.6×2.3×1.8 km) and a large one (4.1×3.3×1.8 km), connected by a tran-

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[5] Deutsches Zentrum für Luft- und Raumfahrt, the German space agency.

[6] https://www.dlr.de/rb/en/desktopdefault.aspx/tabid-9341/

[7] Actually, there is a fifth context of interaction between Philae and the comet's surface: between the first and second bounce on the comet nucleus, Philae impacted slightly, rubbing, against the cliff delimiting the Hathemit depression, on the comet's small lobe, as indicated by on-board instrumentation. However, it is believed that the minimal magnitude of the impact, the approximate localization and the lack of surface markings detectable with the available photographs, prevent any kind of analysis on the evolution of the context and render it vague (Biele et al. 2015).

[8] Astronomical Unit: the basic unit for measuring distances in the Solar System. It corresponds to the average distance between the Earth and the Sun, approximately 150 million km.

[9] Aphelion and perihelion: in an orbit, points of maximum and minimum distance from the Sun.

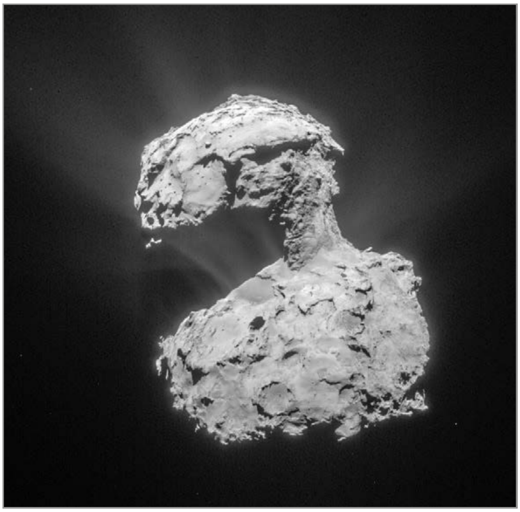

fig. 3. The bilobed shape of comet 67P. The diffuse halo surrounding the nucleus is caused by the emission activity of gas and debris. Credits: ESA/Rosetta/NAVCAM.

sitional region, referred to as the '*neck*'. The core is composed of ice (predominantly H2O, CO, and CO2), minerals, silicates, and carbon compounds, and is characterized by a very low density (about 530 kg/m^3), roughly half the density of water ice on Earth (Borg & Levasseur-Regourd, 2018). Comets are extremely geologically active celestial bodies, shaped by the sublimation activity of the core ices caused by solar irradiation. This outflow of gas, which can take place in a diffuse and homogeneous form, or be concentrated in more intense and potentially 'destructive' events such as jets and outbursts[10] (Borg & Levasseur-Regourd, 2018; Vincent, 2015; 2016), causes the uplift of material, from small grains up to boulders several meters in diameter: the part of the debris that acquires the escape velocity necessary to overcome the weak gravity of the nucleus goes to form the comet's tail; the rest falls back to the surface, albeit in different regions from where it started. This fallout forms a deposit layer, defined *air fall deposit* (Davidsson et al., 2021). The intensity of sublimation in a given area depends on the orbital parameters and the inclination of the comet's rotation axis angle, which create a true seasonality on the comet, cyclically influencing regional illumination patterns. The 'summer' of the southern hemisphere, for example, coincides with the months around the perihelion passage, i.e. the peak of sublimation activity: the resulting erosion causes a large amount of debris to move from the southern to the northern hemisphere (Davidsson et al., 2021). However, local morphology can strongly alter the situation: the shadows of cliffs, reliefs or pits, can decrease the levels of irradiance and thus local sublimation and erosion, compared to the regional and seasonal reference context (Kömle et al., 2017; Pajola, personal communication, 2023). The comet has been divided into 26 regions, named after Egyptian gods (see section 2.4.1; Borg & Levasseur-Regourd, 2018). Coordinates refer to the *Cheops Frame Reference* cartographic system (Preusker et al., 2015).

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[10] In literature, the term denotes the most violent forms of gas and debris emission, capable of concentrating up to 10% of the comet's daily sublimation in a time span of a few tens of minutes (Vincent et al., 2016)

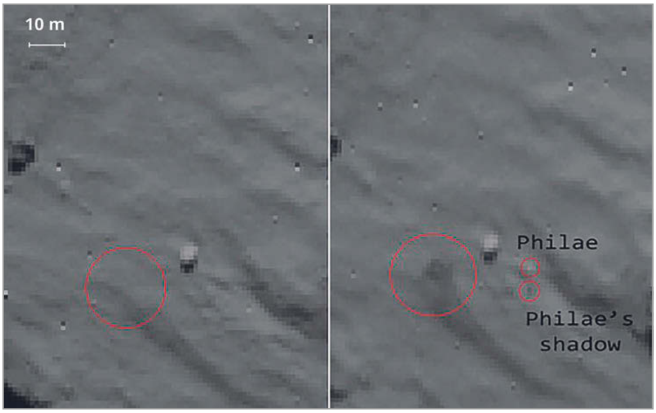

fig. 4. On the left, photograph of *Agilkia* surface before landing; the red circle indicates the area where Philae subsequently impacted; on the right, photograph taken 1.5 minutes after touchdown; one can see Philae just bounced, casting its shadow on the ground; inside the left circle, the cloud of debris raised by the collision is visible. Credits: ESA/Rosetta/NAVCAM, The Telegraph; edited by the author.

fig. 5. Philae's footprints on the surface of *Agilkia*, 10 minutes after impact. Credits: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA. Edited by the author, based on Biele et al., 2015.

2.3.2 Agilkia

The area of Philae's first historic touchdown on the surface of a comet is located in the *Ma'at* region, in the northern hemisphere of the small lobe (lat 12.046° – long 335.866°; Biele et al., 2015). The images capture the scene during the entire contact and bounce phase on the surface. In the centre of fig. 5, we can observe 3 dark areas on the comet's ground. Only features *B* and *C* would constitute depressions, which can be traced back to the sinking of the lander's feet: they measure 2 meters in diameter each, and 10 cm (feature *B*) and 20 cm (feature *C*) deep, respectively. Feature *A* does not show a change in the coefficient of light reflection from the surface: therefore, it would not be a 'cavity', but a small relief, an accumulation of dust, generated by Philae's impact (the cloud of dust lifted by Philae's touchdown is visible in fig. 4; Biele et al., 2015). The landing marks left on November 12, 2014, likely disappeared in the following months, due to the increasing sublimation activity of the area and/or the deposition of debris and dust during the perihelion (August 2015) season (although airfall deposition appears scarce in the area, Davidsson et al., 2021).

2.3.3. The Skull

Philae's second touchdown site is located in the *Wosret* region (lat -6.734°, long 357.547°), on the southern slope of the small lobe, just 30 meters away from *Abydos*,

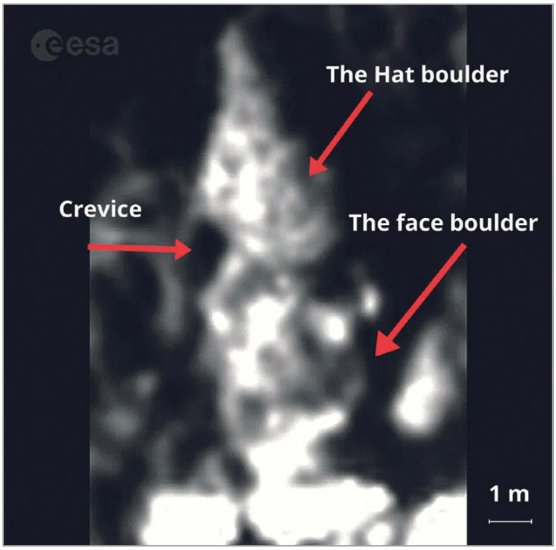

fig. 6. The two boulders (the *hat* and the *face*) of *the Skull* context, engraved by Philae's structures. Credits: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA; edited by the author, based on O'Rourke et al., 2020.

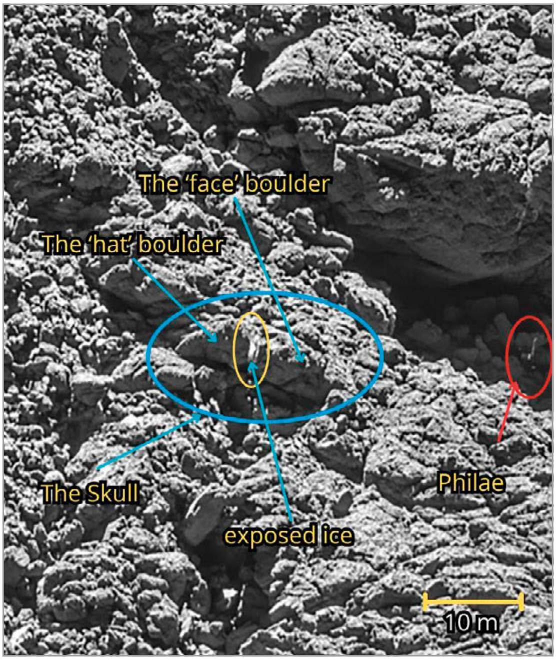

fig. 7. The landscape around the skull (seen here from the side – blue circle). The ice patches exposed by Philae's collisions are visible inside the gap between the 2 boulders. Philae, highlighted by the red circle, is visible in *Abydos*, overhung by a rocky protrusion. The photograph was taken by Rosetta in September 2016, 22 months after the landing of Philae. Credits: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA; edited by the author, based on O'Rourke et al., 2020.

the lander's final landing site (fig. 7). The area is characterized by the presence of a talus deposit, possibly originated after the collapse of a morphological structure: this includes two boulders of about 5-6 meters in diameter, resembling a skull wearing a long hat (fig. 6). The *hat boulder* and the *face boulder* are separated by a fissure about 1-1.5 m wide and 2.5 m long (Lucchetti et al., 2016; O'Rourke et al., 2020): Philae passed through this narrow space in an erratic manner, leaving marks of its passage, including the impression of the skull's left eye and the exposure of some areas of primitive ice, through surface dust layer removal. Photographs taken in August and

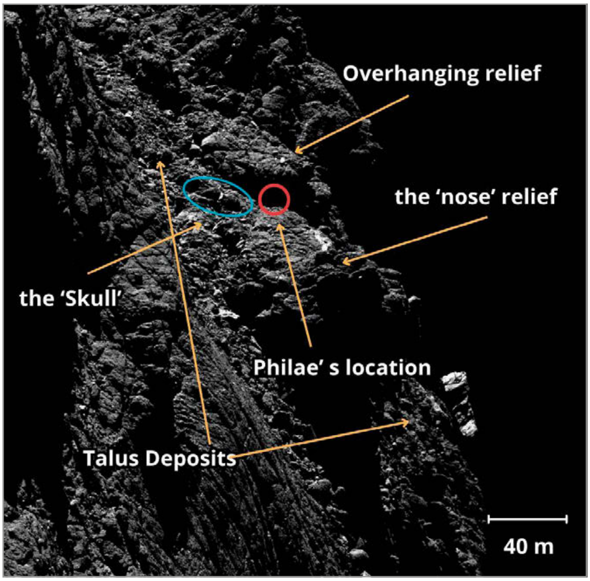

fig. 8. The regional context of Abydos and of the 'Skull'. Note the two reliefs surrounding Philae and the collapse (talus) deposits that characterise the area. Credits: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA, edited by the author, based on O'Rourke et al., 2020.

September 2016 show these ice patches still intact 22 months after landing. The course of exposed ice depends on the lighting characteristics of the area: in a regularly lit region, ice sublimates completely in a few days, or a few weeks at most (O'Rourke et al., 2020; Pajola et al., 2017). The extreme longevity of the Skull ice is due to the particular geometry of the gap between the two boulders, which is only directly affected by the sun 0.21-0.55% of the entire orbital period (O'Rourke, 2020). Thus, it can be assumed that, barring drastic changes in the morphology of the context (collapse, elevation and/or crushing of boulders, etc.), the ice patches exposed by Philae's passage within the fissure remained visible for a long time (and perhaps still are), due to the very low level of illumination and sublimation in this area.

2.3.4 Abydos

Philae's final landing site is located on the border between the *Wosret* and *Bastet* regions (lat -8.04° long -1.60°, see fig. 8, Van Hoang et al., 2020). The area was observed in detail, in the context of the lander's research campaign: however, Rosetta was able to properly capture Philae in its environmental context only once, in September 2016[11]. The area is circumscribed by two small reliefs: one of them overhang Philae, while the other, referred to as the '*nose*' by scientists (for its shape), lies at the lander's feet (Kömle et al., 2017). In fig. 9 (enlargement of fig. 7), the lander is lying on one side of its main structure and on two feet of the landing gear, while the third one points to the overhanging relief's ceiling). Three vertical lines can be seen in the

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[11] Although the approximate area of Philae's final landing had been immediately deduced thanks to the two probes' instrumentation (in particular the CONSERT instrument), observation campaigns in the area failed for almost the entire duration of the mission to track down the small lander, hidden by the shadow of the relief under which it had settled (Ferri, 2020).

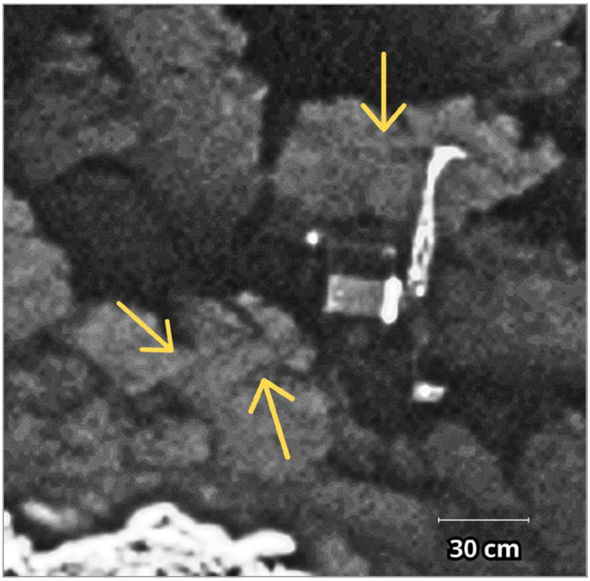

fig. 9 (enlargement of fig. 7). Close-up of Philae in *Abydos*. The arrows indicate the incisions generated by the lander's feet on the surface during the final stages of the landing. Credits: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA, by the author, based on Heinisch et al., 2019.

boulders surrounding the lander. Two lines are parallel to each other, approximately 1.8 meters long, 11 cm thick and separated by 40 cm; a third line, at the top, is 30 cm long. Lines' characteristics seems to be consistent with the rubbing of the lander's feet during touchdown (Heinisch et al., 2019). Apparently, Philae's orientation observable in September 2016 (figs. 7-9), is the same as the one in November 2014, as indicated by the data from the scientific instrumentation and the CIVA (Philae) camera photos. This means that in 22 months, including the peak of cometary activity during perihelion 2015, the lander has not moved substantially (Ferri, 2020; Accomazzo et al., 2023). Moreover, the environmental context of Abydos appears to be relatively stable: sublimation activity in the area appears to be almost absent, due to very low levels of insolation (Borg & Levasseur-Regourd, 2018; Accomazzo et al., 2023; Kömle et al., 2017); jets and mini outbursts have been observed around Abydos but not directly in the area where Philae is located (Van Hoang et al., 2020). In the photo, the lander appears clear of dust or debris deposits: this is consistent with Abydos' location in the southern hemisphere, which tends to be the "source", not the "destination", of air fall deposits (Davidsson, 2021); the hardness of the soil surrounding Philae, measured before perihelion (thus before strong erosion phenomena), seems to indicate the near absence of this type of deposits (Borg & Levasseur-Regourd, 2018). All these considerations suggest the hypothesis that the archaeological context of *Abydos* is relatively stable and the photo taken on 2 September 2016 (figs. 7-9) by Rosetta's OSIRIS camera may roughly represent the current situation. However, another possibility should be considered: as observed in other regions of the comet, a collapse of the relief above Philae is possible, caused by embrittlement phenomena from thermal stress and vibrations caused by jets or outbursts in the vicinity, small impacts or gravitational stresses (Lucchetti et al., 2016; 2019; Pajola, personal communication, 2023; Pajola et al., 2017). In this scenario, Philae would be covered by a collapse deposit, similar to the one where *the Skull* context is located: given the low density of cometary material,

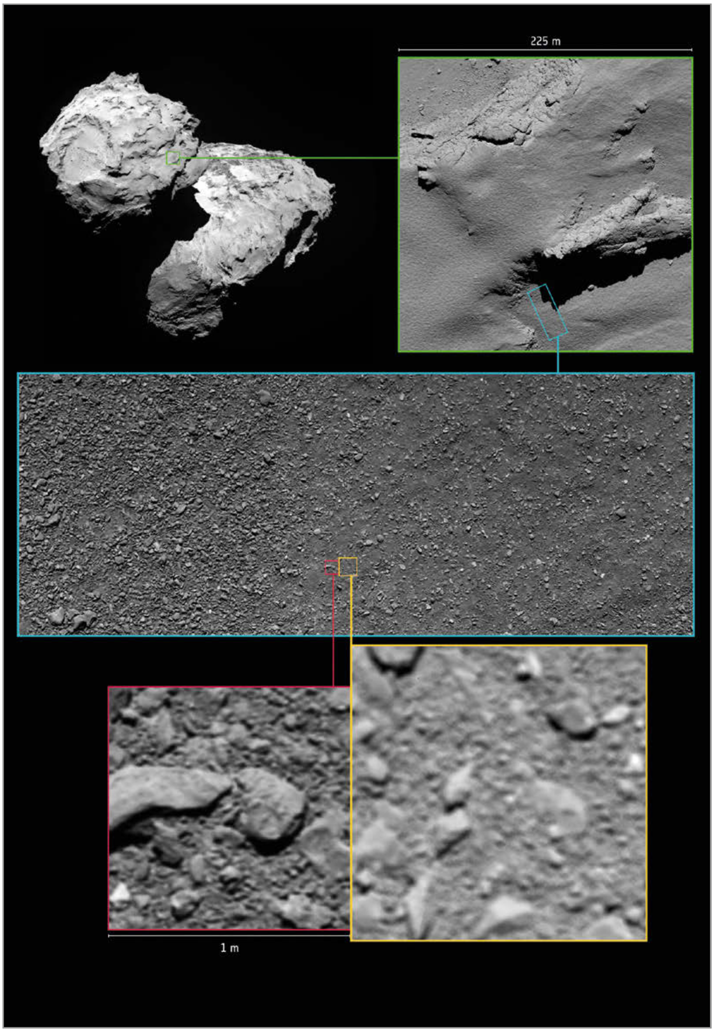

fig. 10. The regional context and location of the *Sais* impact site: top left, the location of *Sais* in the *Ma'at* region, in the northern hemisphere of the comet's small lobe; top right, the position of the impact area on the edge of the *Ma'at 3* pit; center, the morphology of the *Sais* terrain; bottom, details of the surface, taken a few tens of meters away. Credits: ESA/Rosetta/MPS for OSIRIS MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA team

the landslide would not be able to crush and compress Philae's enormously denser and stronger structures (Pajola, personal communication, 2023).

2.3.5 Sais

The Rosetta impact site, named *Sais*, is located in the northern region of *Ma'at*, on the small lobe (fig. 10; lat 35° long 2°; Accomazzo et al., 2017). Rosetta impacted the surface on the outer edges of an inactive pit, named *Ma'at 3* (Vincent et al., 2015). On September 30th, 2016, at 3.8 AU away from the sun (after perihelion), from the photos taken by Rosetta during the final descent, the area appeared mainly consolidated, almost dust-coating-free, with clusters of granular-looking pebbles and boulders. (Pajola et al., 2017).

Since there are no photos of Rosetta after its touchdown, the landing dynamics of the satellite have to be inferred: in order to get some clues about it, the data about Rosetta's impact velocity and structural characteristics were collected and compared

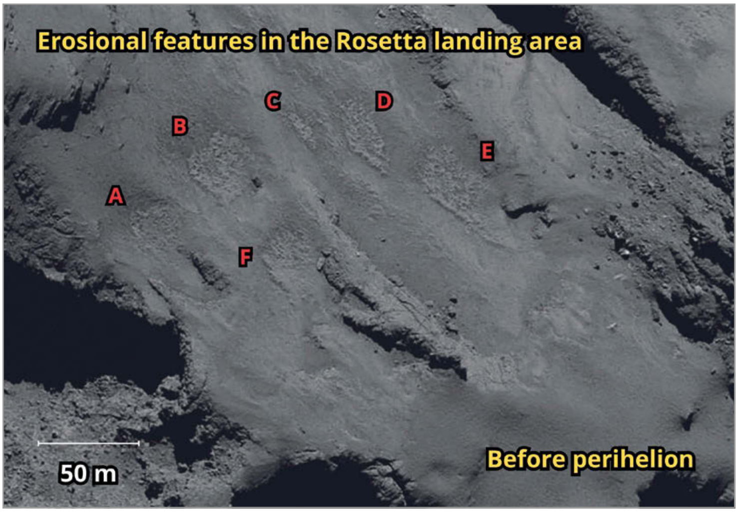

fig. 11. *Sais* context (see *Ma'at 3* pit well in the center) photographed in March 2015, where some areas of surface rippling are visible, due to sublimation activity (Hu et al., 2017). Credits: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA; edited by the author, based on Hu et al., 2017.

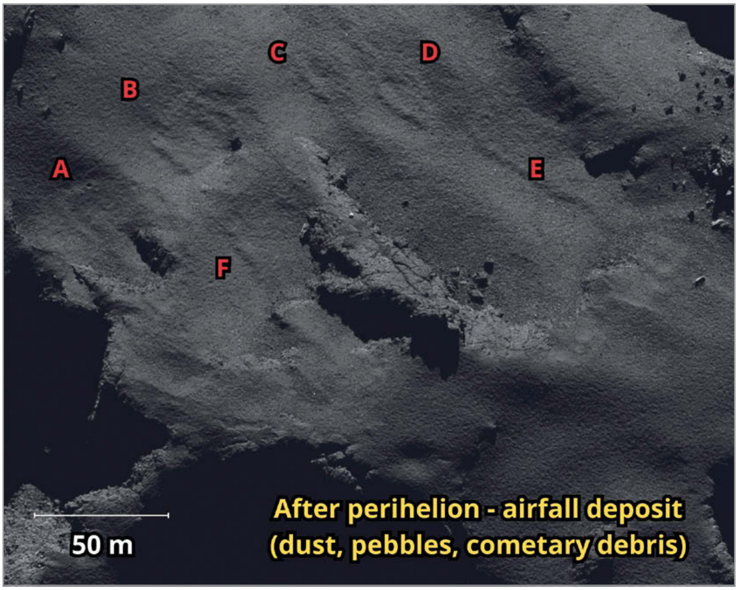

fig. 12. *Sais* context photographed in March 2016, where the rippled areas are less visible due to the deposition of a layer of dust and debris during the perihelion passage in summer 2015 (Hu et al., 2017). Credits: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA; edited by the author, based on Hu et al., 2017.

with a better known case of cometary landing: the Philae's first touchdown at Agilkia and the subsequent two bounces (tab. 3).

The most likely scenario, based on these data, scientific literature and on the advice of Rosetta mission managers and operators (Accomazzo et al., 2023), is the following:

– Given Rosetta's mass and impact velocity; the near absence of dust deposits in Sais that could have dissipated kinetic energy as in the case of Philae in Agilkia; and the absence of landing systems on the orbiter probe, Rosetta is estimated to have ricocheted one or more times off the comet's surface, as its structural characteristics and impact dynamics had a much higher probability of bouncing than Philae's.
– During this bounce(s), Rosetta probably suffered major damage to structures protruding from the main 'body' such as solar panels, antenna, scientific instrumentation,

	Rosetta - *Sais*	**Philae - *Agilkia***
Surface impact velocity	0,86 m/s	1,01 m/s
Mass	1300 kg ca.	98 kg
Landing systems	none	Landing gear with damping system
Kinetic energy dissipated by landing systems (estimated %)	0%	between 10 and 40%
Impact surface morphology	consolidated, almost dust-coating-free surface	Presence of a surface dust layer (the lander's feet have sunk 10 - 20 cm)
Kinetic energy dissipated from the impact surface (estimated %)	0%	between 50 and 80%

tab. 3. Landing dynamics of Rosetta (*Sais*) and Philae (*Agilkia*) compared (Accomazzo et al., 2017; Biele et al. 2015; ESOC, personal communication, 2023; Pajola, Lucchetti et al., 2017).

thrusters; components and debris from these damaged subsystems would have been scattered all along the trajectory of Rosetta's bounce(s), starting from the first impact site.

– Rosetta's main body should have survived the various impacts without any particular damage, although there remains the possibility of greater damage caused by the combustion of the hypergolic propellant in case of fuel leaks caused by the impacts.

– Fuel leaks may have 'contaminated' the surface of 67P in the event of damage to the propulsion system.

– Attempting to speculate on the trajectories of these bounces would be completely arbitrary: however, the structure of the satellite, and the gravitational characteristics of the landing area, lead ESA managers to think that Rosetta's main body should not be too far from the site of the initial touchdown at Sais (Accomazzo et al., 2023).

– With regard to the reconstruction of natural formation processes, the scenario inferred from this '*predictive*' research and from the contribution of Pajola (see tab. 2) on the seasonality of cometary activity in the archaeological context of Sais is as follows:

The satellite and any fragments generated during the rebound(s) of 30 September 2016, are cyclically (about every 6 years) covered by a deposit of debris and dust about 1 m thick, coming from the southern regions, during the comet's perihelion passage (figs. 11-12). This phase lasts only a few weeks, as the insolation of *Sais* rapidly increases again, and at 2.1 AU distance from the Sun, the emission activity of the area exceeds that coming from the southern hemisphere, eroding the layer accumulated in the previous months, until its almost complete elimination: in the Sais area, only bigger pebbles, with a diameter between 0.26 and 0.7 m seems to remain (Pajola et al., 2017; Pajola, personal communication).

Another possibility was suggested by Pajola. He argues that the comet's gravity, about 1/1000th of Earth's, is so weak that Rosetta could be occasionally lifted up again by a cometary jet. This would be consistent with the lifting of huge boulders (7-8 meters in diameter) caused by sublimation activity, observed by Rosetta's cameras during the mission (Pajola, personal communication, 2023; Vincent et al., 2019). In such a scenario, the debris field would be even more substantial and scattered over a much larger area. Rosetta's main body could be anywhere on the comet or even be dispersed in interplanetary space, should the jet's thrust be able to overcome 67P's gravity[12].

2.3.6 The effects of cometary phenomena on the probes' materials:

Finally, issues concerning the state of preservation of the two probes' materials, influenced by cometary phenomena and the space environment, are addressed. Based on the study of reference literature and the contribution of Ghidini (personal communication, 2023) and some other aerospace engineers (tab. 2), the following scenarios are outlined:

– *Debris impacts*: the comet's minimal gravity implies that airfall deposition rates on Rosetta are very low, just a few meters per second (Lisse et al., 2022); this, combined with the low density of the cometary material, suggests that impacts are essentially harmless to the satellite's metal structures; Philae does not appear to be affected by such deposits.
– *Gasses*: the emission of gas and dust from the core has an infinitesimal density, about 8×10-^{2} Pa at surface level (13,000 times less than the intensity of an Earth breeze); the particles of these extremely rarefied gasses hit the materials at low relative velocities; these two factors lead us to rule out the possibility of atomic erosion of organic materials by the hydroxyl radical OH, present in the 67P emissions; the only plausible effects on surfaces could be *adsorption*[13] phenomena of water, CO and CO2 (Ghidini, personal communication, 2023; Heaps, 2009; Lisse et al., 2022; Snodgrass et al., 2017).
– *Outburst*: estimating the emission velocity, 300 m/s, and the mass of debris lifted up observed by Rosetta, such an event, closely hitting the two probes, could crater their surfaces and cover them to a large extent with dust; in addition, there is the possibility to lift Rosetta and Philae off the ground, as suggested by Pajola (Lisse et al., 2022; Pajola, personal communication, 2023).
– *Radiation (cosmic and solar)*: the materials of the two probes were tested to withstand the environmental conditions foreseen by the mission; the solar particle load suffered by the two probes is not particularly high, as 67P spends most of its orbital period at very large distances from the Sun; in the case of Philae, the morphology of the outcrop above the lander may provide additional protection (Ghidini, personal communication, 24 March 2023).
– *Temperature:* the temperatures of *Sais* (min: -200/-210° ca. max: -74° ca.) and *Abydos* (min: -200/-210° ca. max: 65° ca.) are within the ranges for which the materials of the

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[12] The idea of a Rosetta being lifted by a jet has perplexed Accomazzo (tab. 2) who remembered that the surface-to-mass ratios of both Rosetta and Philae are such that it is impossible for cometary activity to move the two probes. However, he emphasized that his opinion is based on what was known about the cometary environment during the mission; he therefore admits the possibility that in later years scientific research may have produced up-to-date models for understanding cometary phenomena that he is unaware of, given his subsequent employment on other space missions. Considering the opinion of Rosetta's flight director to be extremely authoritative on the matter, it was deemed necessary to report it (Accomazzo et al., 2023).

[13] Process whereby a solid surface adsorbs molecules from a gas or liquid with which it comes into contact. The adsorbed layer generally does not exceed the thickness of a molecule (Can & Türk, 2021).

two probes were designed and tested in order to avoid thermal stress and fatigue to the structures (Davidsson et al., 2021; Ghidini, personal communication, 24 March 2023; Kömle et al., 2017; Pajola et al., 2017).

The analysis of these phenomena seems to indicate that the effects on materials are relatively weak and slowed down. Both the extremely low gravity of the comet, unable to 'weigh' on any accumulated mechanical and thermal stresses, and a derisory atmospheric density, too rarefied to cause significant erosion and abrasion on materials, contribute to further weakening these processes. For all these reasons, Ghidini feels able to hypothesize a scenario in which Rosetta and Philae's structures will remain relatively intact for thousands of years (personal communication, 2023).

2.4 The Associative Cultural Landscape:

Central to the set of cultural values associated with Rosetta are the scientific motivations that led to the creation and launch of the mission, namely the understanding of the origins of our Solar System, the oceans and life itself on our planet, processes to which comets would be unique witnesses, as indicated by scientific research in the 19th and 20th centuries (Borg & Levasseur-Regourd, 2018). These underlying reasons underpin both the nomenclature associated with the mission and the interaction between Rosetta and the cultural substrate associated with comets and sedimented throughout history, two elements that have contributed to the mission's great cultural and social impact.

2.4.1 The Rosetta mission and the Rosetta stone

The mission was named *Rosetta* (Latinisation of *Rashid* رشيد) in honour of the city where the famous Egyptian stele from the 2nd century B.C.E. was found, the text of which enabled the decipherment of the hieroglyphic writing system in the early 19th century. In the hopes of the scientific community, the satellite was to be the key to understanding the mysteries surrounding the origins of our planetary system, just as the stele had been for ancient Egyptian writing and culture. As a result, all subsequent nomenclature relating to the comet and the mission followed an Egyptian theme: *Philae, Agilkia, Abydos, Sais* are names linked to the history of the stele and its decipherment; the 26 regions of the comet have been named after Egyptian deities; other geological structures have been associated with Egyptian archaeological sites, such as the *Deir el-Medina* pit, and the reference boulder for the comet's longitudinal system, called *Cheops* (Borg & Levasseur-Regourd, 2018).

But the relationship between the Egyptian stele and the European space mission is not limited to nomenclature: in Rosetta's main structure, beneath the MLI's protective layer[14], there is a small nickel disc, 7.5 cm in diameter, with a life expectancy of at least 10,000 years; microscopically engraved with 6,000 pages of text, it contains the records of some 1,000 idioms, correlated by linguistic, phonetic and grammatical indications. Rosetta's materiality thus preserves a veritable global linguistic back-up

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[14] Multi-Layer Insulation, a lightweight, multilayer protective cover used for thermal management of spacecraft.

on the comet's surface, perhaps enabling future scholars to reconstruct, thousands of years from now, human languages (and related cultures) that would otherwise risk oblivion: the European satellite thus performs the same function as the ancient Egyptian stele, metaphorically closing the circle of meaning and cultural association between these two historic human artefacts (ESA, 2002).

2.4.2 Rosetta and the associative cultural landscape of Comets

The motivations behind Rosetta's scientific mission have also helped shape the cultural associative landscape of comets, in continuity with previous cometary missions (*Giotto, Stardust, Deep Impact*, etc.) and the body of 19th-20th century scientific research. The 67P is in fact only the latest example of a type of natural environment with which human communities have established a deep and culturally, socially and religiously meaningful relationship throughout human history: a problematic relationship, as in almost all global cultures the exceptional occurrence of comets, which interrupts the regularity of the celestial movement of planets and stars, has been interpreted as an inauspicious omen and held directly responsible for the onset of epidemics, famine, social and political unrest, wars and death of the leader/king (Chen & Lü, 2022; Ferri, 2020; Roberts, 1982; Yershova, 2001).

Despite the naturalization of comets following the astronomical discoveries of the modern age, some of these recurring themes have survived into contemporary times, maintaining the same narrative pattern albeit with extremely different forms and cultural paradigms. Among others: the 19th and 20th century theories that attempted (in vain) to scientifically link the passage of comets to the spread of germs and pathogens in the atmosphere (Hoyle & Wickramasinghe, 1980); the 'animistic' narrative underlying the geological theory of coherent catastrophism (Gould, 1987); mass *comet phobia* on the occasion of the passage of 1P Halley in 1910 (Ferri, 2020); the instrumental use of astrological interpretation of comets in the context of power struggles in late 19th and early 20th century China (Chen & Lü, 2022).

A real turning point that began to deposit an unprecedented layer of significance on this millennia-old cultural deposit was the discovery of the presence of water and organic molecules fundamental to basic biotic chemistry on cometary cores, starting with the first spectrographic analyses in the 19th century and continuing with space missions in the 20th-21st centuries (Borg & Levasseur-Regourd, 2018). Beyond the contradictory results of the investigations conducted on the water of 67P and fuelling the scientific debate (Borg & Levasseur-Regourd, 2018), it is believed that the development of space exploration, and the Rosetta mission in particular, has helped to shape a narrative about comets in recent decades that is diametrically opposed to the cultural paradigm that has settled over the millennia: from being harbingers of death and destruction, comets are beginning to be presented as potential vectors for the spread of water and Life in the Universe.

2.4.3 The cultural impact of Rosetta

The rich associative and cultural heritage just mentioned is certainly one of the main factors in the cultural impact of Rosetta, one of the largest in the history of space exploration and by far the most noticeable among European space missions, witnessed by numerous cultural and social expressions, including a cartoon, a short film, paintings, musical compositions, toys, collective participation and media events at mission highlights or for the choice of landing site names (Baldwin et al., 2016; Mignone, 2016).

These events are concrete evidence of an empathetic connection between society and the Rosetta mission, a connection actively sought by the ESA communications team and recognised as one of the main factors in the mission's media success (Baldwin et al., 2016). Moreover, this empathy underscores the collective significance of a space mission as an expression, not only of a society's technological, economic, and scientific level, but also as a cultural expression, in which the spacecraft embodies the set of values and meanings socially associated with it, which vary according to the type of mission and the historical and political context of the human community that carried it out (Gorman, 2016; 2019).

3. Conclusions

With regard to the taphonomic analysis of the archaeological contexts on the comet, one last necessary consideration is given, concerning the possible environmental changes that occurred following a close passage of 67P to Jupiter in the years following the mission, which caused a reduction in the orbital period from 6.42 years to 6.23, observed and measured with precision thanks to the Earth observation campaigns. The possible effects of this 'encounter' between the comet and the gas giant remain unknown: changes in the morphology of the nucleus; modification of the period and axis of rotation, resulting in a change of the comet's seasonality and patterns of insolation and sublimation activity at the regional level (Max Planck Institute, 2021). In short, the environmental data on which the scenarios described and argued in this study were based may have been distorted.

In spite of this unknown, it is believed that, although the possible change in the seasonality of 67P may have 'shuffled' regional and seasonal environmental characteristics, the types of phenomena at work on the comet remain the same, and in the impossibility of knowing whether and how the environmental picture has been altered, it is considered necessary and legitimate to make qualitative geoarchaeological estimates from the available photographic and scientific data.

Obviously, only future *in situ* reconnaissance can shed light on these aspects and confirm or not the predictions of this research work on the taphonomy of the archaeological contexts of 67P. In this regard, it is hoped that the CAESAR mission, if selected and developed by NASA in the coming years, will be able to make these necessary observations: to this end, the predictive analyses of the taphonomic evolution of the various archaeological contexts of 67P, carried out in this study, could provide indications for reconnaissance planning.

In any case, although no mission will return to comet 67P in the future, it is believed that the study approach presented here provides a methodological example of inferential and predictive analysis of the natural formation processes of a space archaeological context, in necessary collaboration with the relevant space agency and the scientific community, and in line with the latest trends in the discipline. (Gorman, personal communication, 2022; Holcomb et al., 2023). In particular, it is believed that this model of analysis can be applied for the geoarchaeological analysis of those space contexts for which the only available data, observations and images have been collected by the probe itself that is the subject of the archaeological enquiry: Mercury, Venus, Titan, the asteroids Eros, Ryugu, Itokawa and comet 9P Tempel 1 host some examples that fall into this typology.

Finally, it is believed that the application of the archaeological method to the study of the Rosetta mission, in accordance with the theoretical principle of the Cultural Landscape, has made it possible to highlight the totality of the relationships between the artefacts (Rosetta and Philae) and the set of contexts connected to them by relationships of necessity and significance, whether they are located on Earth or on comet 67P, including in the analysis the relative associated heritage of human values and behaviour: the archaeological enquire of a space mission thus returns a complete and exhaustive picture of the processes at work in space exploration, encouraging a critical analysis of the choices that human societies have made and are making in taking their first steps off our Planet (Gorman, 2005).

Reference list

Accomazzo, A., Ercolani, A., Ferri P., & Tanco, I. (22/02/2023). Intervista presso L'European Space Operations Centre (ESOC) (Intervista di L. Forassiepi), *ArcheoLogica Data, 4, 2024*.

Accomazzo, A., Ferri, P., Lodiot, S., Pellon-Bailon, J.-L., Hubault, A., Urbanek, J., Kay, R., Eiblmaier, M., & Francisco, T. (2017). The final year of the Rosetta mission. *Acta Astronautica*, *136*, 354-359. https://doi.org/10.1016/j.actaastro.2017.03.027

Baldwin, E., Mignone, C., Scuka, D., Homfeld, A.-M., Celius, K. R., Rolfe, E., Bennett, M., Schepers, A., O'Flaherty, K. S., Bauer, M., & McCaughrean, M. (2016). "Hello, World!" Harnessing Social Media for the Rosetta Mission. *Communicating Astronomy with the Public Journal*, 19, 30-36. https://www.capjournal.org/issues/19/index.php

Biele, J., Ulamec, S., Richter, L., Knollenberg, J., Kührt, E., & Möhlmann, D. (2009). The putative mechanical strength of comet surface material applied to landing on a comet. *Acta Astronautica*, *65*(7-8), 1168-1178. https://doi.org/10.1016/j.actaastro.2009.03.041

Biele, J., Ulamec, S., Maibaum, M., Roll, R., Witte, L., Jurado, E., Muñoz, P., Arnold, W., Auster, H.-U., Casas, C., Faber, C., Fantinati, C., Finke, F., Fischer, H.-H., Geurts, K., Güttler, C., Heinisch, P., Herique, A., Hviid, S., … Spohn, T. (2015a). The landing(s) of Philae and inferences about comet surface mechanical properties. *Science*, *349*(6247), aaa9816. https:// DOI: 10.1126/science.aaa9816

Biermann, P. J. (2009). Studies in aging. In A. Garrison & B. O'Leary (Eds.) *Handbook of space engineering, archaeology, and heritage* (pp. 619-630). CRC Press, Taylor & Francis Group.

Borg, J., & Levasseur-Regourd, A.-C. (2018). *L'exploration cométaire*. Nouveau Monde.

Can, E., & Türk, M. (2021). Thermodynamics and kinetics of adsorption of metal complexes on surfaces from supercritical solutions. In Can E. & Türk, M (Eds.) *Synthesis of Nanostructured Materials in Near and/or Supercritical Fluids Methods, Fundamentals and Modeling* (Vol. 8, pp. 73-127). Elsevier.

Chen, T., & Lü, L. (2022). Astronomical or political: Interpretation of comets in times of crisis in Qing China. *Journal for the History of Astronomy*, *53*(1), 13-26. https://doi.org/10.1177/00218286211070275

Davidsson, B. J. R., Birch, S., Blake, G. A., Bodewits, D., Dworkin, J. P., Glavin, D. P., Furukawa, Y., Lunine, J. I., Mitchell, J. L., Nguyen, A. N., Squyres, S., Takigawa, A., Vincent, J.-B., & Zacny, K. (2021). Airfall on Comet 67P/Churyumov-Gerasimenko. *Icarus*, *354*, 114004. https://doi.org/10.1016/j.icarus.2020.114004

Díaz-Martínez, I., Cónsole-Gonella, C., Citton, P., & De Valais, S. (2021). Half a century after the first bootprint on the lunar surface: The ichnological side of the Moon. *Earth-Science Reviews*, *212*, 103452. https://doi.org/10.1016/j.earscirev.2020.103452

EADS Astrium GmbH (2003). *Rosetta Users Manual.* https://dms.cosmos.esa.int/COSMOS/doc_fetch.php?id=1262617

El-Maarry, M. R., Thomas, N., Giacomini, L., Massironi, M., Pajola, M., Marschall, R., Gracia-Berná, A., Sierks, H., Barbieri, C., Lamy, P. L., Rodrigo, R., Rickman, H., Koschny, D., Keller, H. U., Agarwal, J., A'Hearn, M. F., Auger, A.-T., Barucci, M. A., Bertaux, J.-L., … Vincent, J.-B. (2015). Regional surface morphology of comet 67P/Churyumov-Gerasimenko from Rosetta/OSIRIS images. *Astronomy & Astrophysics*, *583*, A26. https://doi.org/10.1051/0004-6361/201525723

European Space Agency. (2002). *Rosetta disk goes back to the future*. https://sci.esa.int/web/rosetta/-/31242-rosetta-disk-goes-back-to-the-future

European Space Agency. (s.d.-a). *The Rosetta orbiter.* https://www.esa.int/Science_Exploration/Space_Science/Rosetta/The_Rosetta_orbiter

European Space Agency. (s.d.-b). *Estrack ground stations*. https://www.esa.int/Enabling_Support/Operations/ESA_Ground_Stations/Estrack_ground_stations

Ferri, P. (2020). *Il cacciatore di comete*. Laterza & Figli.

Forassiepi, L. (2023). *L'Archeologia dell'Esplorazione Spaziale: Principi, metodologie e il caso di studio della missione Rosetta* [Unpublished thesis]. Università degli Studi di Pisa.

Garrison Darrin, A., & O'Leary, B. L. (2009). *Handbook of space engineering, archaeology, and heritage*. CRC Press, Taylor & Francis Group.

Ghidini, T. (2021). *Homo Caelestis. L'incredibile racconto di come saremo*. Longanesi.

Gorman, A. (2005). The cultural landscape of interplanetary space. *Journal of Social Archaeology*, *5*(1), 85-107. https://doi.org/10.1177/1469605305050148

Gorman, A. (2007). La Terre et l'Espace: Rockets, Prisons, Protests and Heritage in Australia and French Guiana. *Archaeologies*, *3*(2), 153-168. https://doi.org/10.1007/s11759-007-9017-9

Gorman, A. (2009a). Beyond the Space Race: The significance of space sites in a new global context. In Holtorf C. & Piccini A. (Eds.), *Contemporary Archaeologies: Excavating Now* (pp. 161-180). Peter Lang.

Gorman, A. (2009b). Cultural landscape of Space. In A. Garrison & B. O'Leary (Eds.), *Handbook of space engineering, archaeology, and heritage* (pp. 335-346). CRC Press, Taylor & Francis Group.

Gorman, A. (2009c). Heritage of Earth orbit: Orbital debris – Its mitigation and cultural heritage. In A. Garrison & B. O'Leary (Eds.), *Handbook of space engineering, archaeology, and heritage* (pp. 381-398). CRC Press, Taylor & Francis Group.

Gorman, A. (2014). Robot Avatars: The Material Culture of Human Activity in Earth Orbit. In B. O'Leary & P.J. Capelotti (Eds.), *Archaeology and Heritage of the Human Movement into Space* (pp. 29-48). Springer Cham.

Gorman, A. (2016). The death of a spacecraft. Day of Archaeology 2016, Explore Posts, Public Archaeology, Science drspacejunk. https://archaeologydataservice.ac.uk/archiveDS/archiveDownload?t=arch-3016-1/dissemination/pdf/2016/doa_post23695.pdf

Gorman, A. (2017). Comet Quest. *Anthropology News*, *58*(1), e63-e70. https://doi.org/10.1111/AN.283

Gorman, A. (2019). *Dr Space Junk vs the Universe*. MIT Press Ltd.

Gorman, A. (2021). Space Debris, Space Situational Awareness and Cultural Heritage Management in Earth Orbit. In M. De Zwart & S. Henderson (Eds), *Commercial and Military Uses of Outer Space* (pp. 133-151). Springer Singapore. https://doi.org/10.1007/978-981-15-8924-9_10

Gorman, A. (2023). The sustainable management of lunar natural and cultural heritage: Suggested principles and guidelines. *Global Expert Group on Sustainable Lunar Activities*.

Gorman A. and Walsh J.S.P. (2021). A method for space archaeology research: the International Space Station Archaeological Project. *Antiquity, 95*(383), 1331-1343. https://doi.org/10.15184/aqy.2021.114

Gould, S. J. (1987). *The flamingo's smile: Reflections in natural history*. W.W. Norton.

Harland, D. M., & Lorenz, R. D. (2005). Space systems failures: Disasters and rescues of satellites, rockets, and space probes. *Choice Reviews Online*, *43*(03), 43-1585-43-1585. https://doi.org/10.5860/CHOICE.43-1585

Heaps, W. S. (2009). Potential effects: Atmosphere of space bodies and materials. In A. Garrison & B. O'Leary (Eds.), *Handbook of space engineering, archaeology, and heritage* (pp. 573-580). CRC Press, Taylor & Francis Group.

Heinisch, P., Auster, H.-U., Gundlach, B., Blum, J., Güttler, C., Tubiana, C., Sierks, H., Hilchenbach, M., Biele, J., Richter, I., & Glassmeier, K. H. (2019). Compressive strength of comet 67P/Churyumov-Gerasimenko derived from Philae surface contacts. *Astronomy & Astrophysics*, *630*, A2. https://doi.org/10.1051/0004-6361/201833889

Holcomb, J. A., O'Leary, B., Darrin, A. G., Mandel, R. D., Kling, C., & Wegmann, K. W. (2023). Planetary geoarchaeology as a new frontier in archaeological science: Evaluating site formation processes on Earth's Moon. *Geoarchaeology*, *38*(5), 513-533. https://doi.org/10.1002/gea.21966

Hoyle, F., & Wickramasinghe, C. (1980). Diseases from Space. Harper & Row.

Hu, X., Shi, X., Sierks, H., Fulle, M., Blum, J., Keller, H. U., Kührt, E., Davidsson, B., Güttler, C., Gundlach, B., Pajola, M., Bodewits, D., Vincent, J.-B., Oklay, N., Massironi, M., Fornasier, S., Tubiana, C., Groussin, O., Boudreault, S., … Thomas, N. (2017). Seasonal erosion and restoration of the dust cover on comet 67P/Churyumov-Gerasimenko as observed by OSIRIS onboard Rosetta. *Astronomy & Astrophysics*, *604*, A114. https://doi.org/10.1051/0004-6361/201629910

Kömle, N. I., Macher, W., Tiefenbacher, P., Kargl, G., Pelivan, I., Knollenberg, J., Spohn, T., Jorda, L., Capanna, C., Lommatsch, V., Cozzoni, B., & Finke, F. (2017). Three-dimensional illumination and thermal model of the Abydos region on comet 67P/Churyumov-Gerasimenko. *Monthly Notices of the Royal Astronomical Society*, *469*(Suppl_2), S2-S19. https://doi.org/10.1093/mnras/stx561

Mignone, C. (2016). Impressions of Rosetta's legacy. Communication, Outreach and Education Group – Directorate of Science – European Space Agency. https://sci.esa.int/web/rosetta/-/58680-impressions-of-rosetta-s-legacy

Lisse, C. M., Combi, M. R., Farnham, T. L., Russo, N. D., Sandford, S., Cheng, A. F., Fink, U., Harris, W. M., McMahon, J., Scheeres, D. J., Weaver, H. A., & Leary, J. (2022). Operating spacecraft around comets: Evaluation of the near-nucleus environment. *Acta Astronautica*, *195*, 365-378. https://doi.org/10.1016/j.actaastro.2021.11.030

Lucchetti, A., Cremonese, G., Jorda, L., Poulet, F., Bibring, J.-P., Pajola, M., La Forgia, F., Massironi, M., El-Maarry, M. R., Oklay, N., Sierks, H., Barbieri, C., Lamy, P., Rodrigo, R., Koschny, D., Rickman, H., Keller, H. U., Agarwal, J., A'Hearn, M. F., … Vincent, J.-B. (2016). Characterization of the Abydos region through OSIRIS high-resolution images in support of CIVA measurements. *Astronomy & Astrophysics*, *585*, L1. https://doi.org/10.1051/0004-6361/201527330

Lucchetti, A., Penasa, L., Pajola, M., Massironi, M., Brunetti, M. T., Cremonese, G., Oklay, N., Vincent, J., Mottola, S., Fornasier, S., Sierks, H., Naletto, G., Lamy, P. L., Rodrigo, R., Koschny, D., Davidsson, B., Barbieri, C., Barucci, M. A., Bertaux, J., … Tubiana, C. (2019). The

Rocky-Like Behavior of Cometary Landslides on 67P/Churyumov-Gerasimenko. *Geophysical Research Letters*, *46*(24), 14336-14346. https://doi.org/10.1029/2019GL085132

Max Planck Institute (November 23, 2021). *A New Encounter with Rosetta's Comet*. https://www.mps.mpg.de/a-new-encounter-with-rosetta-s-comet

Mottola, S., Arnold, G., Grothues, H.-G., Jaumann, R., Michaelis, H., Neukum, G., Bibring, J.-P., Schröder, S. E., Hamm, M., Otto, K. A., Pelivan, I., Proffe, G., Scholten, F., Tirsch, D., Kreslavsky, M., Remetean, E., Souvannavong, F., & Dolives, B. (2015). The structure of the regolith on 67P/Churyumov-Gerasimenko from ROLIS descent imaging. *Science*, *349*(6247), aab0232. https://doi.org/10.1126/science.aab0232

NASA (2011). *Recommendations to Space-Faring Entities: How To Protect and Preserve the Historic and Scientific Value of U.S. Government Lunar Artifacts*. https://www.nasa.gov/directorates/heo/library/reports/lunar-artifacts.html

O'Leary, B. L. (2009a). Evolution of Space archaeology and heritage. In A. Garrison & B. O'Leary (Eds.), *Handbook of space engineering, archaeology, and heritage* (pp. 29-48). CRC Press, Taylor & Francis Group.

O'Leary, B. L. (2009b). Plan for the future preservation of Space. In A. Garrison & B. O'Leary (Eds.), *Handbook of space engineering, archaeology, and heritage* (pp. 820–834). CRC Press, Taylor & Francis Group.

O'Leary, B. L. (2014). "To boldly go where no man [sic] has gone before:" Approaches in Space Archaeology and heritage. In B. O'Leary & P.J. Capelotti (Eds.) *Archaeology and Heritage of the Human Movement into Space* (pp. 1-12). Springer Cham.

O'Leary, B. L., & Capelotti, P. J. (2014). *Archaeology and Heritage of the Human Movement into Space*. Springer Cham.

O'Rourke, L., Heinisch, P., Blum, J., Fornasier, S., Filacchione, G., Van Hoang, H., Ciarniello, M., Raponi, A., Gundlach, B., Blasco, R. A., Grieger, B., Glassmeier, K.-H., Küppers, M., Rotundi, A., Groussin, O., Bockelée-Morvan, D., Auster, H.-U., Oklay, N., Paar, G., … Sierks, H. (2020). The Philae lander reveals low-strength primitive ice inside cometary boulders. *Nature*, *586*(7831), 697-701. https://doi.org/10.1038/s41586-020-2834-3

Pajola, M., Höfner, S., Vincent, J. B., Oklay, N., Scholten, F., Preusker, F., Mottola, S., Naletto, G., Fornasier, S., Lowry, S., Feller, C., Hasselmann, P. H., Güttler, C., Tubiana, C., Sierks, H., Barbieri, C., Lamy, P., Rodrigo, R., Koschny, D., … Baratti, E. (2017). The pristine interior of comet 67P revealed by the combined Aswan outburst and cliff collapse. *Nature Astronomy*, *1*(5), 0092. https://doi.org/10.1038/s41550-017-0092

Pajola, M., Lucchetti, A., Fulle, M., Mottola, S., Hamm, M., Da Deppo, V., Penasa, L., Kovacs, G., Massironi, M., Shi, X., Tubiana, C., Güttler, C., Oklay, N., Vincent, J. B., Toth, I., Davidsson, B., Naletto, G., Sierks, H., Barbieri, C., … Thomas, N. (2017). The pebbles/boulders size distributions on Sais: Rosetta's final landing site on comet 67P/Churyumov-Gerasimenko. *Monthly Notices of the Royal Astronomical Society*, *469*(Suppl_2), S636-S645. https://doi.org/10.1093/mnras/stx1620

Preusker, F., Scholten, F., Matz, K.-D., Roatsch, T., Willner, K., Hviid, S. F., Knollenberg, J., Jorda, L., Gutiérrez, P. J., Kührt, E., Mottola, S., A'Hearn, M. F., Thomas, N., Sierks, H., Barbieri, C., Lamy, P., Rodrigo, R., Koschny, D., Rickman, H., … Vincent, J.-B. (2015). Shape model, reference system definition, and cartographic mapping standards for comet 67P/Churyumov-Gerasimenko – Stereo-photogrammetric analysis of Rosetta/OSIRIS image data. *Astronomy & Astrophysics*, *583*, A33. https://doi.org/10.1051/0004-6361/201526349

Reynolds, J. (2014). Legal Implications of Protecting Historic Sites in Space. In B. O'Leary & P.J. Capelotti (Eds.) *Archaeology and Heritage of the Human Movement into Space* (pp. 11-129). Springer Cham.

Roberts, A. F. (1982). Comets importing change of Times and States: Ephemerae and process among the Tabwa of Zaire. *American Ethnologist*, *9*(4), 712-729. https://doi.org/10.1525/ae.1982.9.4.02a00060

Snodgrass, C., A'Hearn, M. F., Aceituno, F., Afanasiev, V., Bagnulo, S., Bauer, J., Bergond, G., Besse, S., Biver, N., Bodewits, D., Boehnhardt, H., Bonev, B. P., Borisov, G., Carry, B., Casanova, V., Cochran, A., Conn, B. C., Davidsson, B., Davies, J. K., … Zegmott, T. J. (2017). The 67P/Churyumov-Gerasimenko observation campaign in support of the Rosetta mission. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *375*(2097), 20160249. https://doi.org/10.1098/rsta.2016.0249

Squyres, S. W., Nakamura-Messenger, K., Mitchell, D. F., Moran, V. E., Houghton, M. B., Glavin, D. P., Hayes, A. G., Lauretta, D. S., & CAESAR Project Team. (2018). *THE CAESAR NEW FRONTIERS MISSION: 1. OVERVIEW*. 49th Lunar and Planetary Science Conference 2018 (LPI Contrib. No. 2083), The Woodlands, Texas, USA.

Stooke, P. J. (2009). Lost spacecraft. In A. Garrison & B. O'Leary (Eds.) *Handbook of space engineering, archaeology, and heritage* (pp. 481-496). CRC Press, Taylor & Francis Group.

Stooke, P. J. (2008). *Preserving exploration heritage in the Moon 2.0 era*. NLSI Lunar Science Conference.

Szczepanowska, H. M. (2009). Space technology: Vanguard 1, Explorer 7, and GRAB – Materials and museum concerns. In A. Garrison & B. O'Leary (Eds.), *Handbook of space engineering, archaeology, and heritage* (pp. 633-656). CRC Press, Taylor & Francis Group.

Szczepanowska, H. M. (2014). The Space Shuttle Discovery, its scientific legacy in a museum context. In B. O'Leary & P.J. Capelotti (Eds.) *Archaeology and Heritage of the Human Movement into Space* (pp. 60-73). Springer Cham.

UNESCO, World Heritage Centre. (2021). Operational Guidelines for the Implementation of the World Heritage Convention. https://whc.unesco.org/en/documents/190976

Van Hoang, H., Fornasier, S., Quirico, E., Hasselmann, P. H., Barucci, M. A., Sierks, H., Tubiana, C., & Güttler, C. (2020). Spectrophotometric characterization of the Philae landing site and surroundings with the Rosetta/OSIRIS cameras. *Monthly Notices of the Royal Astronomical Society*, *498*(1), 1221-1238. https://doi.org/10.1093/mnras/staa2278

Vincent, J.-B., A'Hearn, M. F., Lin, Z.-Y., El-Maarry, M. R., Pajola, M., Sierks, H., Barbieri, C., Lamy, P. L., Rodrigo, R., Koschny, D., Rickman, H., Keller, H. U., Agarwal, J., Barucci, M. A., Bertaux, J.-L., Bertini, I., Besse, S., Bodewits, D., Cremonese, G., … Tubiana, C. (2016). Summer fireworks on comet 67P. *Monthly Notices of the Royal Astronomical Society*, *462* (Suppl 1), S184-S194. https://doi.org/10.1093/mnras/stw2409

Vincent, J.-B., Birch, S., Hayes, A., Zacny, K., Oklay, N., & Cambianica, P. (2019). Bouncing boulders on comet 67P. *EPSC Abstracts*. EPSC-DPS Joint Meeting, Geneva, Switerland. https://meetingorganizer.copernicus.org/EPSC-DPS2019/EPSC-DPS2019-502-1.pdf

Vincent, J.-B., Bodewits, D., Besse, S., Sierks, H., Barbieri, C., Lamy, P., Rodrigo, R., Koschny, D., Rickman, H., Keller, H. U., Agarwal, J., A'Hearn, M. F., Auger, A.-T., Barucci, M. A., Bertaux, J.-L., Bertini, I., Capanna, C., Cremonese, G., Da Deppo, V., … Tubiana, C. (2015). Large heterogeneities in comet 67P as revealed by active pits from sinkhole collapse. *Nature*, *523*(7558), 63-66. https://doi.org/10.1038/nature14564

Westwood, L., O'Leary, B. L., & Donaldson, M. W. (2017). *The Final Mission: Preserving NASA's Apollo Sites*. Univ Pr of Florida.

Yershova, G. G. (2001). Comets and meteors in the beliefs of ancient mayas. *Astronomical & Astrophysical Transactions*, *20*(6), 1017-1037. https://doi.org/10.1080/10556790108221607 https://doi.org/10.1002/gea.21966