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Research Paper

Pyroduct: A novel parametric software for the simulation of terrestrial, lunar, and Martian lava tubes

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ABSTRACT

Lava tubes, also known as“pyroducts”, are caves found on terrestrial volcanoes and on analogue terrains on the Moon and Mars. Their morphometry is the expression of genetic parameters, which are often not well understood, like lava effusion rates and rheology, and cooling rates. Lunar and Martian tubes could offer protection from radiation, micrometeorites, and extreme temperatures, making them promising candidates for future extraterrestrial habitats. Models used in planetary geology and space architectural studies rely on a few terrestrial examples and notional geometries. This paper introduces Pyroduct, the first fully parametric 3D lava tube generator, developed as a free plug-in for Grasshopper in Rhinoceros 3D. Based on a wide catalog of terrestrial lava tube cross-sections, Pyroduct enables the simulation of realistic cave environments for planetary research. It also supports terrestrial applications, offering a cost-effective method for reconstructing lava tubes' 3D geometries for the evaluation of volcanic hazard and creation of VR models.

1. Introduction

Nomenclature

NASA	National Aeronautics and Space Administration
LiDAR	Laser Imaging Detection and Ranging
MGC3	Mars Global Cave Candidate Catalog
INGV	Istituto Italiano di Geofisica e Vulcanologia
VPL	Visual Programming Language
SSI	Italian Speleological Society
PDC	Pyroduct Digital Catalog
.DXF	Drawing Exchange Format (file format)
.CSV	Comma-Separated-Values (file format)
CSE	Centro Speleologico Etneo
RS	Remote Sensing
DTM	Digital Terrain Model
JMARS	Java Mission-planning and Analysis for Remote Sensing
GIS	Geographic Information System
NURBS	Non-Uniform Rational B-Spline
PPG	Pyroduct Point Generator
ESA	European Space Agency
FELA	Finite Element Limit Analysis
YAC	Young Architects Competition
CAD	Computer-Aided Design

A lava tube, also known by its historical name “pyroduct” (Coan, 1844), is a specific kind of volcanic cave that is defined as a “roofed conduit of flowing lava, either active, drained, or plugged” (Halliday, 2004a, p. 1624).

Since prehistoric times, human populations worldwide have recognised and utilized lava tubes (Romio and Lobosco, 2025). While their overall uses were often similar, they displayed local variations shaped by specific cultural practices (Fig. 1). Throughout the 18th and 19th centuries, travellers and naturalists began to discover, document, and survey several of these structures worldwide. The first examples include the Surtshellir lava tube in Iceland, surveyed by Eggert Ólafsson and Bjarni Pálsson in 1772 (Ólafsson and Pálsson, 1772). Another example is the Grotta delle Palombe on Mt. Etna, Sicily, surveyed by August Sartorius von Waltershausen, which is considered the first survey of a volcanic cave in Italy (Sartorius Von Waltershausen, 1880; Puglisi and Santi, 1999). Since these first experiences, scientists and explorers started to

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Fig. 1. Jean Houel depicts the use of lava tubes for the storage and commerce of ice in 1792 in Sicily (Houel, 1782).

wonder about the processes that led to the formation of such caves and provided some first hypotheses that could explain this phenomenon. In particular, von Troil (1779) and Henderson, in describing the above-mentioned Surtshellir lava tube in Iceland, were ones of the first to propose, respectively in 1772 and 1818, that lava tubes formed due to the crusting-over of an active lava flow within a lava channel (Mills and Wood, 1972; Kempe, 2009; Stefánsson and Stefánsdóttr, 2016) with later observations of active lava tubes in Hawaii, by scientists such as Jaggar (1921), Wentworth and Macdonald (1953), and Greeley (1971a). However, due to the great variety of observed shapes and structural features, it became evident that lava tubes formation couldn't be always accountable only to the above mentioned processes of crusting-over, but that other mechanisms existed, which can lead to different internal forms and shapes (Ollier and Brown, 1965; Mills and Wood, 1972; Calvari and Pinkerton, 1998; Hon et al., 1994; Calvari and Pinkerton, 1999; Kempe, 2009).

Today, thanks to the development of vulcanospeleological research worldwide, and the vast documentation of several lava tube caves that has occurred during the last centuries (Halliday, 2004b), we know that these volcanic caves can form in two main ways (channel crusting-over of and inflation processes), producing a wide range of morphologies depending on several petrological and environmental parameters (Sauro et al., 2020; Hon et al., 1994; Calvari and Pinkerton, 1998, 1999).

1.1. Discovery and challenges for the future exploration of lunar and Martian pyroducts

During the late 60's and early 70's, thanks to the images acquired first by the Ranger and then the Lunar Orbiter probes between 1964 and 67 (Greeley, 1994), scientists started to notice that some river channel-like lunar volcanic features, known as "sinuous rilles" had striking similarities with terrestrial lava channels and partly collapsed lava tubes, making the hypothesis that similar structures existed on the Moon (Kuiper et al., 1966; Greeley, 1971b; Oberbeck et al., 1969).

From that moment, NASA funded various studies aimed at understanding terrestrial lava tubes, to possibly understand lunar ones and their mechanisms of formation and shapes (Hatheway and Herring, 1970; Greeley, 1971a, 1971c; Greeley and Hyde, 1972). Today, after the discovery of the firsts Martian and lunar cave accesses, "pits" in 2007 and 2009 (Cushing et al., 2007; Haruyama et al., 2009), more than 1062 and 278 accesses to the underground have been identified respectively for Mars and the Moon, which are available in two separate databases: the Mars Global Cave Candidate Catalog and the LROC Pit Atlas (Cushing, 2015; Wagner and Robinson, 2014). These findings have been supported by growing evidence that many of these collapses might potentially lead to lava tubes (Cushing, 2012; Wagner and Robinson, 2014, 2021; Sauro et al., 2020; Carrer et al., 2024) (Fig. 2).

For this reason, nowadays, as in the '70s, scientists and space agencies are studying, surveying, and training astronauts in terrestrial lava tubes to prepare them for possible future space exploration (Massironi et al., 2023; Santagata et al., 2023). lunar and Martian lava tubes would be able to shield future astronauts and settlers from the extreme environmental conditions and hazards which characterize these planetary bodies, in particular radiation, meteorite impacts, dust, while also providing an environment with stable temperatures compared to the extreme fluctuations which characterize the surfaces of both planets (Cushing, 2012; Sauro et al., 2020; Haviland, 2021; Pohlen et al., 2022; Martin and Benaroya, 2023).

However, until a mission reaches and successfully explores these underground geological structures, their internal asset remains speculative, and comparisons to terrestrial lava tube analogues still represent the highest degree of confidence possible (Sauro et al., 2020). As a consequence, scientists, engineers, and architects lack, at present, an instrument that allows them to think parametrically and elaborate on different possible scenarios and assets of lunar and Martian lava tubes. In these regards, despite their usefulness in helping scientists understand possible internal morphologies and lava tube types, traditional 2D surveys and LiDAR scans do not provide scientists with an effective scenario planning tool, as each lava tube scan represents only one specific state/case and to be acquired requires a specific survey mission and time. Moreover, compared to 2D surveys, only a few LiDAR lava tube scans are currently available in the literature, and they are not always open-access (see Table 1). For this reason, we present an innovative software named "Pyroduct": the first fully parametric lava tube generator, which aims to support scientists by leveraging the vast documentation of terrestrial lava tubes and using this data to generate realistic 3D models of lava tunnels for future exploration and settlement planning (Romio et al., 2025a).

2. Materials and methods

To develop Pyroduct, several steps had to be undertaken. The first

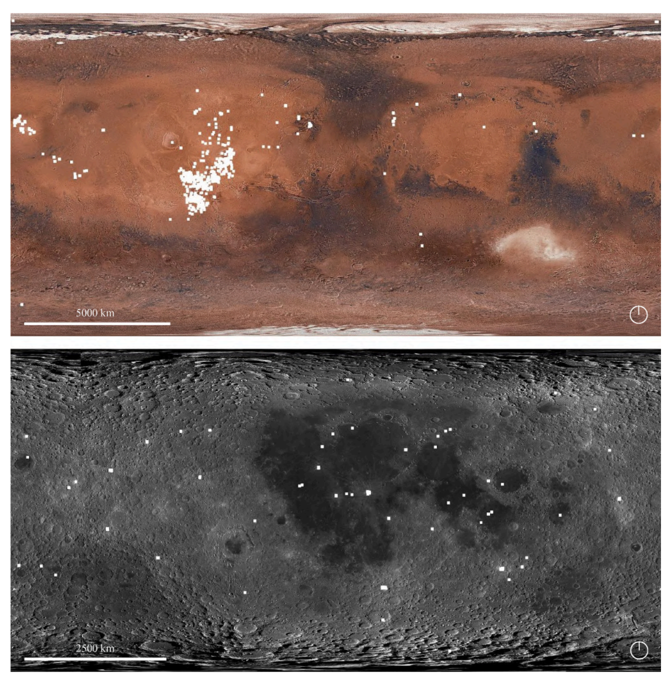


Fig. 2. Above: Martian cave accesses from Mars Global Cave Candidate Catalog (MGC3) (Cushing, 2015; Cushing and Okubo, 2017). Below: lunar cave access locations (Wagner and Robinson, 2021). At present, more than 1062 potential cave accesses have been mapped for Mars and 278 for the Moon.

Table 1
Results of research on Google Scholar and online repositories of existing lava tube LiDAR surveys, which are either freely available or available upon request to the authors. Papers that mentioned LiDAR surveys but made no reference to the data availability were not considered.

Reference	Lava tube(s)	Country	State/ Area	Survey instruments*	LiDAR data availability
Tomasi et al., 2022	Corona Lava Tube	ES	Lanzarote Island	Leica P40 Leica Pegasus	Data will be made available on request
Bell et al., 2022	Skull Cave, Ship Cave, Incline Cave (Modoc Crater lava tube complex)	US	Lava Beds National Monument (California)	Riegl VZ-400	https://doi.org/10.13016/ovqx-j09w
Grechi et al., 2024	Tabernacle Hill Lava Tube	US	Tabernacle Hill Lavafield (Utah)	Apple Iphone 13 LiDAR	Data will be made available on request.
Lemaire et al., 2024	Grotta lavica negli efflussi vesuviani del 1858	IT	Somma-Vesuvius (Campania)	Riegl VZ-400	Data will be made available on request.
Hidding et al., 2025	Grotta di Monte Intraleo	IT	Mt. Etna (Sicily)	Unitree L1	10.4121/778253cc-3193-4f66-bc13-03b80380424e
Romio et al., 2025b	Grotta di Monte Intraleo	IT	Mt. Etna (Sicily)	Unitree L1	10.4121/0cc49d43-8a5c-453e-9370-8e9088b00b48
Yang et al., 2024	Shenyang Cave	CN	Jingpo Lake Geopark (Heilongjiang Province)	/	Data will be made available on request.
Montañez Muñoz et al., 2024	Ape Cave	WA	Mount St. Helens volcano (Washington State, USA)	Geoslam Zeb Horizon	https://doi.org/10.5281/zenodo.14189358

one was to understand the possible parameters that could act as the basis for a realistic lava tube generator and which software could be optimal for creating such a tool, allowing the user to have total control over the resulting 3D models. The second aspect was to gather enough terrestrial data to input into the developed algorithm.

2.1. Developing Pyroduct

The guiding principles behind the programming of Pyroduct were to enable scientists to explore multiple possible lava tube scenarios and assist them in preparing for a wide range of potential environments. For example, by allowing the users to convert their own Remote Sensing observations into realistic, parametric 3D models of potential lunar and Martian lava tubes. Generally, lunar and Martian lava tube representations that can be found in literature, ranging from engineering analyses to architectural design proposals of future off-Earth settlements, are often notional if compared to their terrestrial counterparts. These studies either adopt idealised elliptical or circular, perfectly symmetrical cross-sections or random internal shapes, which, even if generated through rigorous procedures, are still far from being realistic (Blair et al., 2017; Theinat et al., 2020; Chwała et al., 2024a, 2024b; Fox and Benaroya, 2026). On Earth, lava tubes have a wide array of internal shapes, and their internal shapes vary along their path (Chwała et al., 2024b). In particular, their cross-sections are important elements for morphological analyses, as they are strictly related to their genetic mechanisms and tell about the processes that led to their formation and often complex development (Calvari and Pinkerton, 1998, 1999; Sauro et al., 2020; Tomasi et al., 2022; Marraffa, 2023).

A survey campaign on two of the largest Etna lava tubes was carried out in June 2024, in collaboration with the University of Padua and the Italian INGV. There, we utilized a Dexter 360 Laser Level, which allowed us to visualize, in real-time, the cross-section and shape changes inside various lava tunnels, such as the Grotta dei Tre Livelli and Grotta del Monte Intraleo (Fig. 3), which resulted in the identification of real underground landscapes characterized by unique shapes and forms, which sometimes shared similarities. Similar approaches have also been implemented by other researchers, leading to interesting results on the reconstruction of a lava tube 3D mesh from cross-sections extracted from the related point cloud survey (Yang et al., 2024). However, despite terrestrial lava tube cross-sections being potential analogues of lunar and Martian possible scenarios, it is important to take into account the significant differences in terms of scale. Previous researchers have inferred that factors such as lesser gravity, rheology of the lava, and higher effusion rates would allow the presence of much bigger conduits than on Earth,with diameters that might reach 40 to 400 m for Mars and up to 900-1000 m for the Moon, and still be theoretically stable, which is also consistent with recent observations (Keszthelyi, 1995; Blair et al., 2017; Sauro et al., 2020; Carrer et al., 2024). On the other hand, recent studies have challenged this hypothesis, showing that gravity alone is not a major factor in controlling lava tube scale and that terrestrial-sized lava tubes are indeed possible on the Moon, also suggesting that lunar lava tubes are unlikely to exceed 20 m in height (Wilson et al., 2025). In fact, on Earth, it is fairly common to find lava tunnels that present a greater main channel and smaller side tubes, especially in the case of complex lava tube systems (Bell et al., 2022) and within multiple-branch - also referred to as “braided” (Sauro et al., 2020) - lava tubes. Examples of this kind are the Grotta della Catanese I and Grotta del Santo on Mt. Etna, the Cueva de Los Naturalistas and Cueva de Maguez in Lanzarote, and Junction Cave in New Mexico. For all these reasons, we came to consider three the main parameters for our parametric lava tube 3D model generator: i) the cross-sections, which act as building blocks; ii) a path, which is the central axis along which the cross-sections develop (Fig. 3); iii) the scale, which needed to be adjustable to terrestrial, lunar and Martian conditions.

To develop a fully parametric lava tube generator around the three main parameters mentioned above, we chose the Visual Programming Language “*Grasshopper*”, native to the 3D modelling program “*Rhinoceros*” developed by Robert McNeel & Associates. Grasshopper provides the users with an intuitive way to handle the complexity of parametric design, both with the use of native and custom components programmable by the user and shareable as easily installable plug-ins or libraries on platforms such as “*Food4Rhino*”, GitHub, and fully integrates with the 2D and 3D environment of Rhinoceros, allowing geometries to be imported or exported from the latter into its VPL environments and vice versa. After creating the rationale and selecting the right software for its development, the last aspect we were missing was the data to feed the program, enabling the creation of realistic lava tube reproductions.

2.2. Bibliographical research and Pyroduct Digital Catalog

To acquire data on terrestrial lava tubes, the authors conducted extensive bibliographical research at one of the world’s best-supplied

Fig. 3. Above: the Grotta dei Tre Livelli-KTM, upper branch, around 10 m from the entrance pit. Below: sections of the north-east upper branch of Grotta del Monte Intraleo, from the entrance through the dark areas of the caves. In both cases, it is possible to observe how the utilisation of a 360-laser level, in this case a Dexter 360 laser level, allows the creation of “real-time cross-sections” that describe very well the actual internal forms and shape transitions.

speleological libraries: the Speleoteca Franco Anelli of the Italian Speleological Society. There, we had access to a vast collection of articles and surveys – many of which are not available online - that provided a significant amount of material, which we digitised and organised into a digital database named the “*Pyroduct Digital Catalog*” (PDC) (Romio et al., 2024). Together with the 2D data provided by the speleological reports, the authors have recently updated the Catalog by adding cross-sections extracted from available and accessible LiDAR datasets found in open-access repositories, in particular those of Intraleo Cave (Romio et al., 2025a, 2025b) and Ship and Skull Caves (Bell et al., 2022) (see Table 1). The PDC consists of both a .dxf file and an explanatory .csv file. Using Rhinoceros, we manually retraced approximately 1.200 cross-sections from more than 90 surveys of lava tubes (2D drawings of plan views, profiles, and selected cross-sections) distributed worldwide, categorising and organising them into tables within a .dxf file divided by countries and regions. Within each table, the curve located in the upper-left cell corresponds to the first cross-section of the survey, while the one in the lower-right cell represents the last (Fig. 4). Each cell measures 35 m × 35 m.

Moreover, each table is labelled with the name of the lava tube and an identification code, which helps the user identify the cave in the .csv file of the database. Each unique code follows this format:

Initials of the country. Initials of the region. progressive number.

Example: *IT*.SIC.*04* (Italy.Sicily.lava tube n.04).

The explanatory .csv file is organised as follows: each row represents a lava tube, and the nine columns contain all the information we were

Grotta del Burrò
IT.SIC.04

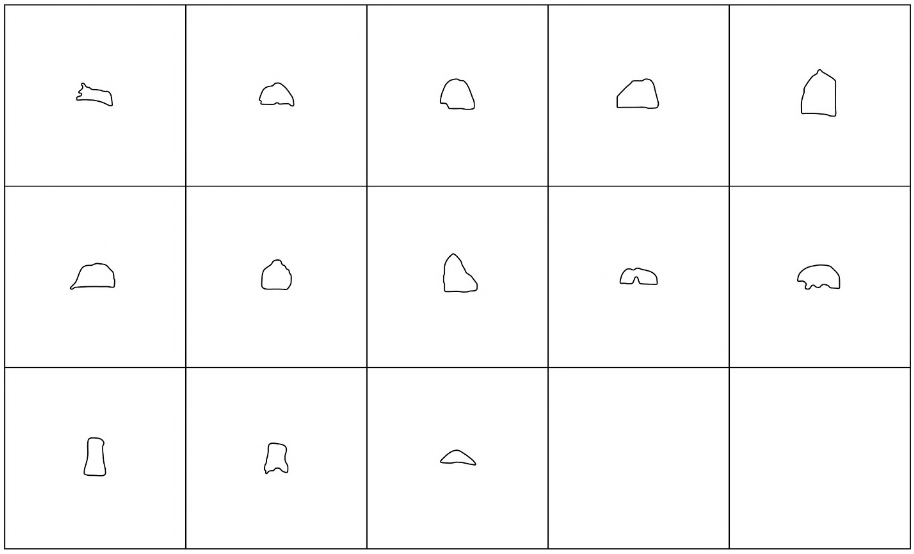


Fig. 4. Example of lava tube cross-sections in the Pyroduct Digital Catalog, Grotta del Burrò survey (Giudice and Santi, 1999). Each cell is 35x35m.

Table 2
Example of the organisation of the explanatory .csv file of the Pyroduct Digital Catalog.

Db code	Name	Country	State	Reference	Authors of the survey	Authors of the survey drawings	Survey instruments*	Date
IT.SIC.01	Si CT 1037 Grotta Corsaro	IT	Sicily	Marino and Santi (1999). La Grotta Corsaro. In: DENTRO IL VULCANO: IL LIBRO Le Grotte dell'Etna Catania: Centro Speleologico Etneo - Parco dell'Etna, 215–216.	Bonaccorso, R., Marino, A., Santonocito, F.	Centro Speleologico Etneo (CSE); Bonaccorso, R. (survey drawing).	Traditional: compass, clinometer, tape meter, metrical rod.	1997

* Note that not all this information is available for each lava tube, especially for the survey instruments and the date. When the instruments are not specified, it is assumed that traditional cave surveying methods (Wookey, 2004) are used. If the survey was done after 2007–2008, it is assumed that a laser distance meter DistoX was used in place of a tape meter, thanks to the widespread adoption of this tool by caving communities around the world.

able to gather (see Table 2).

As pointed out in the paragraph above, the Catalog is constantly evolving with the addition of new entries, aiming to become a global reference for what regards lava tube morphologies (see Section 4.3).

Recently, in addition to the .dxf file, we uploaded the dataset in .txt format. The Catalog was divided into individual folders, each representing a specific lava tube and containing the .txt files corresponding to its cross-sections

2.3. Testing Pyroduct

To assess the accuracy of the lava tube models generated with Pyroduct, we compared them with high-resolution LiDAR surveys from Grotta di Monte Intraleo and Skull Cave (see Table 1). We first extracted cross-sections from the LiDAR point clouds by computing an interpolated central axis based on the K-Means centroids of the point distribution. The K-Means algorithm groups nearby points into clusters by minimizing their distance to a cluster center. This central axis was then used in Pyroduct as the path along which the synthetic lava tube geometries for both caves were generated. After producing the 3D models, we converted them into meshes within the Grasshopper environment and sampled their vertices to obtain artificial dense point clouds. These synthetic point clouds were then imported into the open-source software CloudCompare to compute Cloud-to-Cloud (C2C) distances against the original LiDAR datasets. The C2C tool calculates absolute distances between the two point clouds by selecting one as the reference and the

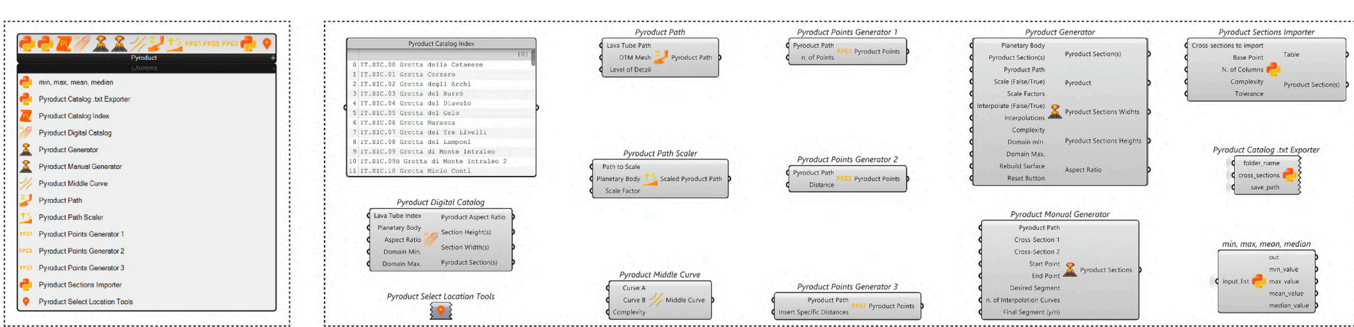


Fig. 5. Starting from the left, the Pyroduct plug-in window in the Grasshopper toolbar and all its components.

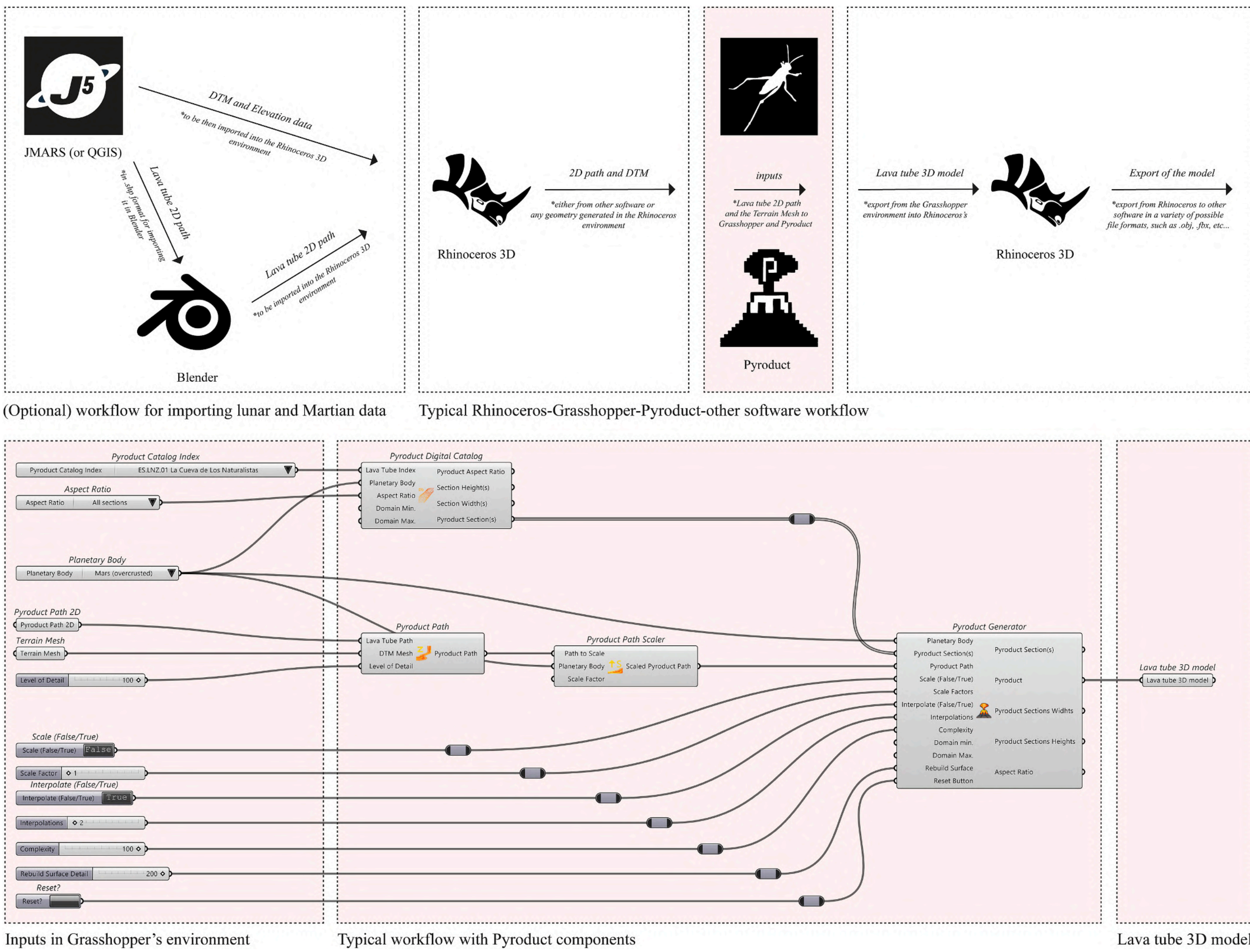


Fig. 6. Above: the complete workflow for turning RS observation into realistic 3D models, through the optional use of GIS software - such as JMARS (Christensen et al., 2009) or QGIS -and Blender to convert .shp format to .dxf, to import it into Rhinoceros, Grasshopper, and Pyroduct, for the generation of the lava tube 3D models. Otherwise, lava tubes can also be generated through lava tube paths directly drawn in Rhinoceros as curves. Below: a typical workflow in Grasshopper with the use of the Pyroduct plug-in. Left: the geometries imported from Rhinoceros and directly defined in the Grasshopper environment are the inputs for Pyroduct, which then can perform its operations and produce as output a lava tube 3D model.

other as the comparison dataset, producing both a color-coded distance map and a distribution of point-to-point deviations. The results of this analysis are discussed later in the paper (see Section 3.2).

3. Results

As a result of the described process, we have developed Pyroduct as a plug-in for Grasshopper. The software is freely available for download on Zenodo (Romio et al., 2025a, 2025b) and comprises 11 custom components, each of which performs specific operations (Fig. 5). Every component acts as a node that requires some inputs to be connected to it and provides outputs that can then be connected as inputs to other components. By performing these connections, these components allow the user to have total parametric control over the generation of realistic lava tube 3D models (Fig. 6).

3.1. *Pyroduct: plug-in components and specific functions*

Each of the Pyroduct plug-in components was programmed inside Grasshopper as VPL scripts with the exclusive use of native components, which were grouped into Grasshopper "cluster" objects, to be easily shared and installed by other users by just copying and pasting the plug-in files in the directory:

Grasshopper > File > Special Folders > User Object Folder directory.

As mentioned in the previous paragraph, each component receives inputs, performs operations, and provides outputs. Inputs in Grasshopper can be geometries such as curves, surfaces, meshes, and points, which can either be defined directly within Grasshopper or imported from Rhinoceros into its VPL environment. To manage these inputs, some components act as "containers" for imported geometries or data types, such as integers, decimal numbers, and text. In Grasshopper, numbers and text are typically handled using specific components called number sliders and panels, respectively. Other components, called "value lists," provide dropdown menus where numbers are associated with text labels, making it easier to select items within a list (Fig. 6).

Below, the description of each component and its function.

Main components:

- Pyroduct Digital Catalog: this component is the database of the whole plug-in. It contains all the data of the homonymous .dxf file readily available, allowing the user to choose the specific lava tube from which to select the cross-sections (Fig. 7a). Eventually, the user can choose to filter the selection by aspect ratio and scale the curves to terrestrial, lunar, or Martian size. The process works as follows: a

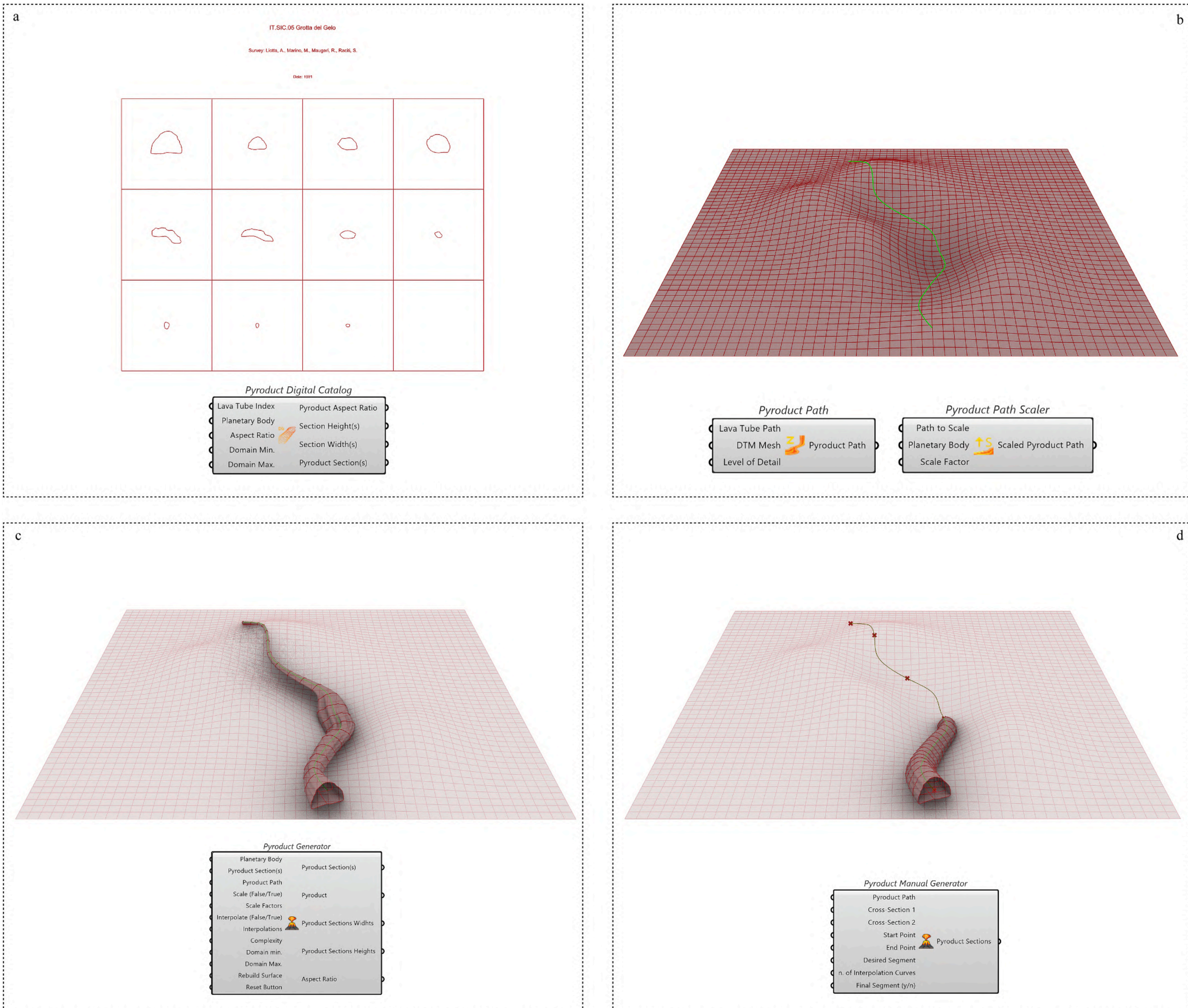


Fig. 7. The Pyroduct main components and their functions. Above: the Pyroduct Digital Catalog, the Pyroduct Path and the Pyroduct Path Scaler (Fig. 7a and b). Below: the Pyroduct Generator and the Pyroduct Manual Generator (Fig. 7c and d).

2D bounding box is defined for each cross-section, and its aspect ratio is defined. To achieve the large dimensions expected for lunar and Martian lava tubes, the bounding box is scaled proportionally according to several predefined domain options, each associated with a specific planetary body and lava tube type, following reference values reported in previous studies (Sauro et al., 2020). For Mars, two configurations are available: "Mars (overcrusted)", designed for modelling overcrusted lava tubes, with a domain range between 30 and 70 m; and "Mars (inflated)", intended for tubes formed through inflation or deep inflation processes, with a domain between 100 and 400 m. For the Moon, a domain range between 500 and 900 m was defined. To ensure full flexibility, a "Custom" option is also provided, allowing users to specify the minimum and maximum domain values manually. This is particularly useful for modelling special cases or for generating terrestrial-scale lava tubes in lunar or Martian scenarios.

- Pyroduct Path: it allows the users to project a 2D path on a Mesh, to derive a 3D curve (Fig. 7b). To do so, the algorithm divides the input curve, either drawn directly in the Rhinoceros environment or imported, into n points defined by the user (level of detail input), which are then projected on the Mesh and interpolated again into a new three-dimensional curve defined by the x,y,z values of the projected points. Moreover, the user can also control the definition of the projected curve by increasing the n points that are projected on the Mesh. This component was specifically developed to enable scientists to turn 2D lava tube paths observed with Remote Sensing (RS) data and traced in other software, such as QGIS or JMARS (Christensen et al., 2009), into 3D by projecting them on the DTM mesh of the region under analysis. At present, doing so requires additional steps, which are needed to import the shapefiles of the paths in Rhinoceros and Grasshopper, which can be done by utilising other Grasshopper plug-ins such as Heron, or exporting the .shp files in the .dxf format by utilising Blender. A future release of the Pyroduct plug-in will include its component for allowing a smoother import process.
- Pyroduct Generator: This component allows the user to a quick and automatic lava tube 3D model generation (Fig. 7c). Here, the output sections of the Pyroduct Digital Catalog component - or two or more curves directly drawn by the user - can be inserted as inputs, together with the path along which the user desires to develop the lava tube 3D model. The path can be provided both through the Pyroduct Path component or any other curve drawn by the user in the Rhinoceros

environment and imported into Grasshopper. The component proceeds to interpolate the abovementioned cross-sections to create n additional synthetic curves within each provided pair, simulating the transitions between the two. The closer the sections are to the original survey from which they originate, the more accurate the reconstruction obtained. Successively, the component automatically proceeds in positioning the obtained geometries on a variable number of planes, which coincide with n of the obtained curves, perpendicular and with their normal vectors aligned to the provided lava tube path. Eventually, the component proceeds in operating a loft operation of all the cross-sections, real and synthetic, providing as output a Non-Uniform Rational B-Splines (NURBS) surface, which are mathematical representations of 3D geometry that can accurately describe any shapes (Tedeschi, 2020), which can then be modified and refined or turned into a mesh with Grasshopper native components or plug-ins, such as Kangaroo, before being exported into the Rhinoceros environment and/or to other software.

- Pyroduct Manual Generator: this component works similarly to the precedent. Still, it grants more control to the user and a more accurate construction of the 3D model, at the price of a more laborious manual process (Fig. 7d). The component works by allowing the construction of the lava tube segment by segment, by inputting a specific pair of cross-sections for each (see the “Pyroduct Point Generators” components) and generating a variable n of synthetic interpolations, which in this case need to be set by the user. This manual generator was designed for users with experience with lava tubes who would want to design their lava tube simulations more accurately, possibly focusing on segments more than on the whole lava tube. Moreover, this tool was also designed to accurately reconstruct 3D models from existing 2D surveys.

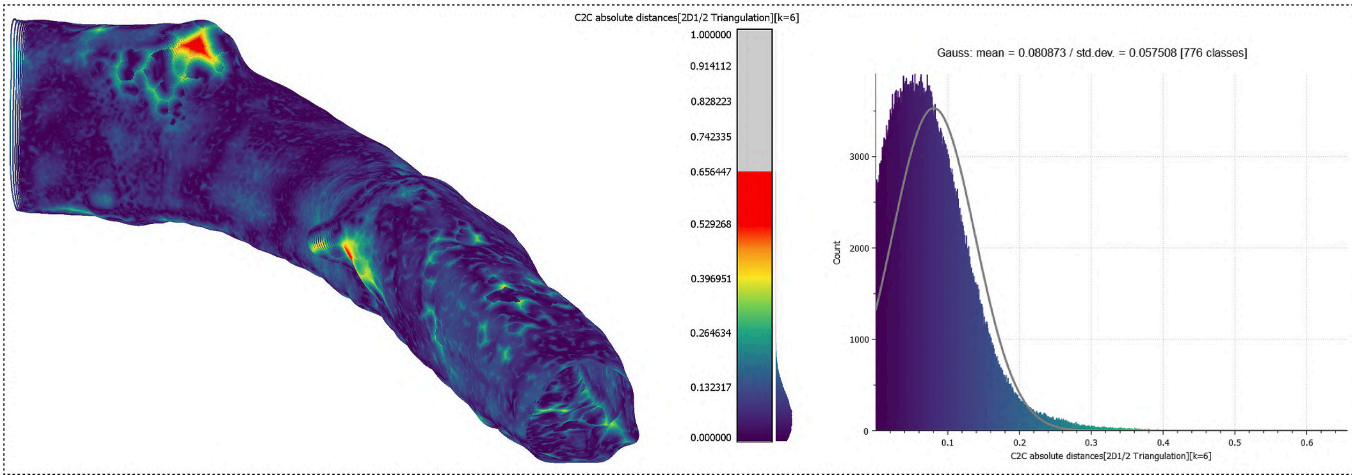
Secondary components:

- Pyroduct Digital Catalog Index: it contains all the information regarding the lava tubes available for selection inside the Pyroduct Digital Catalog component. It serves to guide and help the user identify and choose which lava tube to recall.
- Pyroduct Path Scaler: this scaler can be used to adapt a terrestrial lava tube path to lunar or Martian dimensions. It works by enlarging the input curve by factors of 10^1 and 10^2, respectively, corresponding to one or two orders of magnitude above typical Earth-based scales. In the Pyroduct Digital Catalog, selecting the Planetary Body option “Custom” allows users to specify their own scaling factor, enabling further customization of the generated lava tube path.
- Pyroduct Select Location Tools: a folder containing item selectors already set for being used as inputs of the Pyroduct Digital Catalog, for the selection process.
- Pyroduct Point Generators (PPG): these components are to be used together with the Pyroduct Manual Generator, as they allow the user to split the lava tube path curve into segments by different means: the PPG1 divides the path into n segments of equal length defined by the user; The PPG2 component does the same but dividing the path into segments with a specified length. The terminal section may have a different length, as it corresponds to the remaining portion of the path; eventually, the PPG3 allows the user to input several specific distances at which to split the lava tube path. The PPG3 is particularly useful for the reconstruction of 3D pyroduct models from existing surveys, as survey measurements are not always taken at equal distances.
- Pyroduct Middle Curve: this tool is particularly useful for obtaining the middle axis or lava tube path from existing surveys. In particular, by providing as input two curves of an existing plan or section, the component proceeds in dividing each curve into points and making an average of the points’ location, creating a new list of points. Successively, each of the points is set as the centre of a circle tangent to both the input curves, and circles created by the algorithm, which fail to be tangent to both curves are filtered out. Eventually, the resulting points, which represent points that belong to the central axis in between the two input curves, are interpolated into a new curve, which control numbers (complexity input) can be set by the user.
- Pyroduct Sections Importer: this tool allows users to import their own lava tube cross-sections into Grasshopper and use them to generate a 3D model of the desired lava tube. It works both with curves already positioned on the XY plane and with curves extracted from LiDAR or photogrammetric point clouds that lie on different planes in space. The component creates a 35×35 m grid along the length defined by the number of input cross-sections and generates n XY target planes on which the imported sections are placed. Users can also choose to simplify the input curves through the complexity parameter, which samples each curve into n points that are then interpolated to produce new, simplified curves.
- Pyroduct Catalog .txt Exporter: this simple script takes as input a folder name, a file path, and the cross-sections that the user wishes to export from the Pyroduct Digital Catalog component in .txt format.
- Pyroduct min, max, mean, median: this Python component outputs the minimum, maximum, mean, and median values of an input list of integers or float numbers. It is a useful tool for quickly visualising statistical information related to the heights, widths, or aspect ratios of lava tube data obtained from the outputs of the Pyroduct Digital Catalog or the Pyroduct Generators.

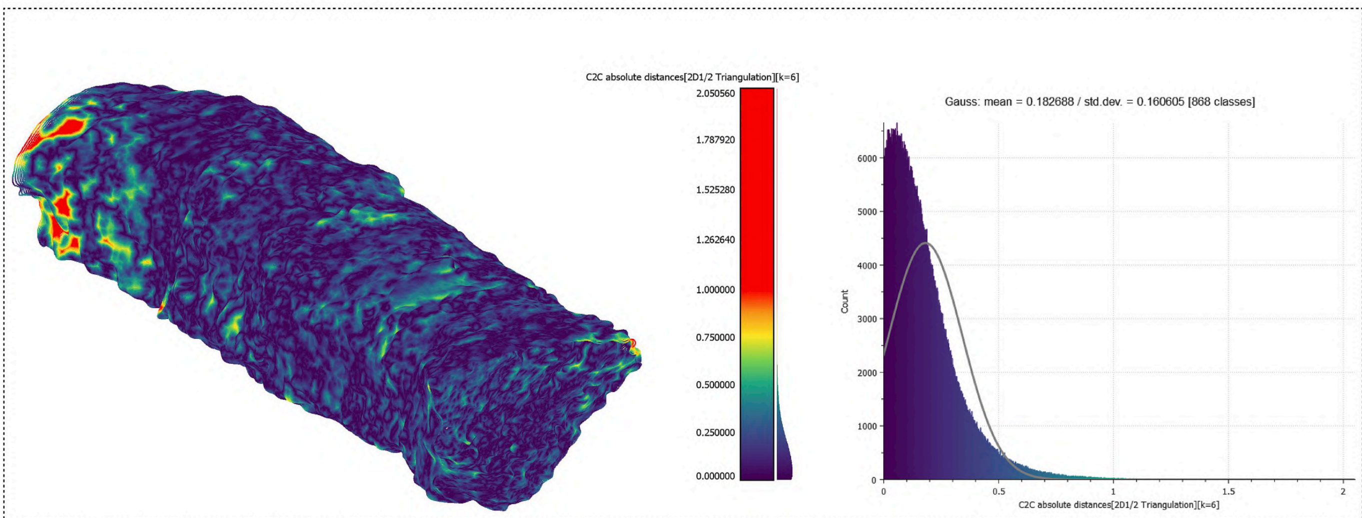
3.2. Comparison of LiDAR and Pyroduct models

As anticipated in Section 2.3, to validate the results produced by Pyroduct, we used the software to reconstruct synthetic 3D models of Grotta di Monte Intraleo and Skull Cave, two lava tubes for which high-resolution LiDAR surveys are available (see Table 1). After reconstructing synthetic lava tube models by utilising as input the cross-sections extracted from the original LiDAR survey, we proceeded to extract synthetic point clouds from the reconstructed models and compared them with the corresponding LiDAR datasets in CloudCompare. Subsequently, we computed the Gaussian mean and standard deviation from the Cloud-to-Cloud (C2C) distance analysis using the software’s dedicated statistical tools. The results are as follows:

- Intraleo Cave: the LiDAR point cloud of Intraleo Cave contains 78.410 points, subsampled to 5 cm from the original survey. From this dataset, we extracted 99 real cross-sections spaced 0,30 m apart. For the reconstruction, we used only 50 of these and generated two synthetic cross-sections between each consecutive pair, resulting in a total of 147 cross-sections, including both real and synthetic ones. The synthetic point cloud generated with Pyroduct includes 601.601 points, with an inter-point spacing of 0,03 m. The resulting Cloud-to-Cloud distances range from 0,0 m to 0,66 m, with a Gaussian mean of 0,081 m and a standard deviation of 0,058 m (Fig. 8). For context, the mean width of the cross-sections in the reconstructed portion of the lava tube is 4,6 m, which helps to contextualize the magnitude of the achieved error.
- Skull Cave: the LiDAR point cloud, subsampled to 1 cm from the original surveyed dataset, includes 661.990 points. From this dataset, we extracted 79 cross-sections at 1 m intervals along the lava tube. For the reconstruction, we used 44 of these cross-sections and generated two synthetic interpolations between each of them, resulting in a total of 132 cross-sections, both real and synthetic (see Pyroduct Generator in Section 3.1). The synthetic point cloud produced with Pyroduct contains 751.851 points, with an inter-point spacing of 0,10 m. The computed Cloud-to-Cloud distances between the LiDAR and the synthetic datasets range from 0,00 m to 2,05 m, with a Gaussian mean of 0,18 m and a standard deviation of 0,16 m (Fig. 8). For reference, the analysed portion of the lava tube features a mean cross-sectional width of 21,00 m.



Results of the Cloud-to-Cloud analysis of Grotta di Monte Intraleo



Results of the Cloud-to-Cloud analysis of Skull Cave

Fig. 8. Results of the Cloud-to-Cloud analysis performed between the synthetic point clouds derived from the Pyroduct-generated lava tube models and the real LiDAR data of Grotta di Monte Intraleo and Skull Cave. On the left, the synthetic lava tube point clouds are colourized according to the computed distance error with respect to the corresponding real datasets. On the right, the statistical results of the analysis are shown, as described in the paragraph above.

From these results, it is evident that Pyroduct is capable of realistically reconstructing existing lava tubes from LiDAR data, producing 3D models that accurately represent their internal morphology. While this validation is possible for terrestrial lava tubes, the same cannot yet be demonstrated for Martian and lunar tubes, as comparable high-resolution survey data are not currently available. Nevertheless, because the tool incorporates a wide range of terrestrial morphologies in its dataset, it can be used in combination with dimensional estimates derived from gravimetric measurements (Chappaz et al., 2017; Zhu et al., 2024) or ground-penetrating radar data (Kaku et al., 2017) to generate plausible scenarios of subsurface caves that may be explored and surveyed in the coming decades. Additionally, Pyroduct can be employed to reconstruct lava tube models from 2D survey data, an application discussed further in Section 4.3.

4. Discussion

As described in the previous section, through the Pyroduct plug-in, diverse and realistic lava tubes are achievable, which can help users and stakeholders produce credible simulations of how observed Martian and lunar lava tubes might be, based on the available data and the observations performed. Also, because the process is completely parametric, it allows complete control over the geometry, so that multiple variants of the same lava tunnel can be produced and evaluated, with interesting implications from the scenario planning point of view.

4.1. Pyroduct as a scenario evaluation and planning tool

Since its introduction, the Scenario Planning model, elaborated by Pierre Wack for Royal Dutch/ Shell before and during the oil crisis in 1973, has become an instrument adopted by many disciplines to support strategic thinking and resiliency to face uncertain times and circumstances, including urban and territorial planning (Di Giulio et al., 2018). Despite recent discoveries - which confirmed the presence of underground caves on the moon, strongly indicating that lava tubes may exist under the lunar surface and may have dimensions greater than 200 m (Carrer et al., 2024), as previously hypothesized by different authors (Keszthelyi, 1995; Blair et al., 2017; Sauro et al., 2020) – and several interesting mission concepts by NASA and ESA for the exploration of lunar lava tubes (Nesnas et al., 2019; Pozzobon et al., 2023), no manned or unmanned missions have ever explored extraterrestrial lava tubes and their interior settings remain elusive. In this sense, Pyroduct can serve as an effective scenario-thinking and evaluation tool for future exploration and exploitation planning: by providing the user with a vast array of possible terrestrial lava tube internal settings, the software allows scientists, roboticists, engineers and architects to prepare for different and

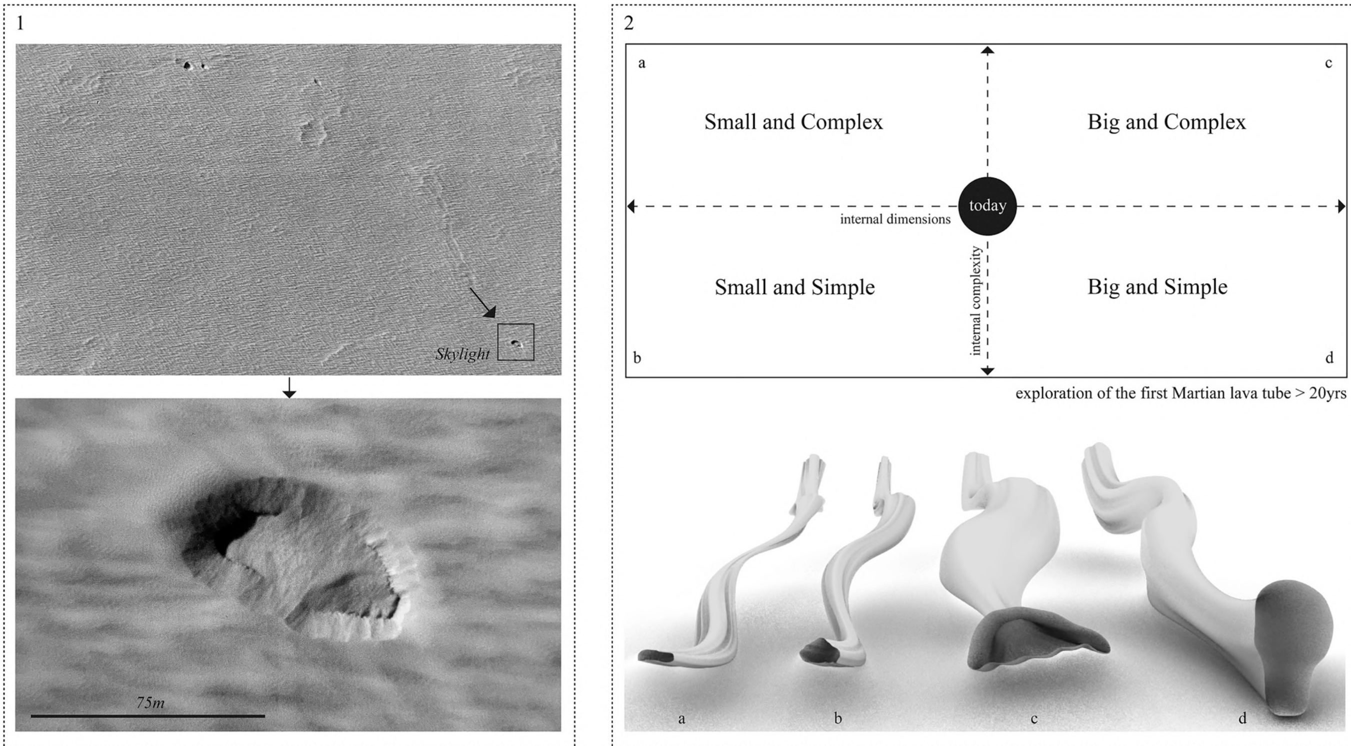


Fig. 9. Left: image of a Martian lava tube candidate, with several cave accesses (skylights) and a close-up of one of them (NASA/JPL-Caltech/UArizona, n.d.). Right: four different possible scenarios of the underlying Martian lava tube produced with the Pyroduct plug-in.

plausible scenarios, from the worst to the best possible, and evaluate and test possible strategies, which this way can be empowered by an increased resiliency and adaptation readiness (Fig. 9) (see Video 1 in the Supplementary Materials). This approach could be particularly useful for the assessment of the stability of lunar and Martian lava tubes, a research direction currently under development, which has recently shifted attention from stability analyses performed on ideal cross-sections (Blair et al., 2017; Theniat et al., 2020; Fox and Benaroya, 2026) to irregularly shaped cross-sections that are synthetically generated rather than derived from real surveys. In this regard, despite the few studies currently available (Chwała et al., 2024a, 2024b), more recent developments have carried out finite element limit analysis (FELA) on real terrestrial lava tube cross-sectional data, specifically from Skull and Valentine Caves (Chwała et al., 2025). Studies of this kind, performed on Pyroduct-generated 3D models or on cross-sections extracted from the Pyroduct Digital Catalog, could significantly advance current knowledge of both terrestrial and planetary lava tube stability, leveraging a fully user-oriented parametric approach capable of enabling myriad different analyses and conditions, and strongly anchored to known terrestrial data.

4.2. *Give a context to the lunar and Martian underground architecture*

On Earth, many underground parts of cities are striking examples of the human use of underground space for many different purposes. Both ancient populations such as those of the vast underground city of Derinkuyu in Cappadocia and Chinese farmers of the Loess Plateau in Northwest China – living in underground dwellings known as yáodòng - and modern such as the people of Montreal and Coober Pedy have used the underground to shelter themselves from the extreme environmental conditions of the surface while using this hidden landscape for many aspects of their lives, such as dwelling, commerce, transportation and leisure time (Broere, 2016; Johnston et al., 2020; Ovenden, 2020). Other examples, such as the cities of Stockholm and Helsinki, have found in the underground a landscape with an intrinsic value: a proper environment with which to create visual and volumetric dialogues and bonds within what is anthropic and what is natural, nonetheless excavated by man (Johnston et al., 2020; Ovenden, 2020). As anticipated in the introduction, terrestrial lava tubes themselves have been widely used by different populations worldwide, providing interesting insights into human habitation and the use of the underground space (Romio and Lobosco, 2025). In this regard, in Section 1.1, we have previously anticipated that lava tubes are particularly interesting locations for the settlement of future lunar and Martian research stations. In fact, due to their underground setting, lava tunnels provide an invaluable, stable, and protected environment, capable of protecting future inhabitants from the dangers and hazards that characterize both the planetary bodies, such as extreme temperatures, toxic dust, and radiation (Horz, 1985; Coombs and Hawke, 1992; Martin and Benaroya, 2023). In this sense, the future human uses of off-Earth lava tubes are not so different from how humans across different countries and cultures used these geological structures on Earth in ancient, past, and present history and, more generally, the underground space.

Despite the value of existing studies as a resource for understanding adaptation strategies for underground human settlement, highlighting, for instance, the importance of natural light and vegetation in confined environments (Johnston et al., 2020; Debrock et al., 2023), as well as approaches to subdividing internal space based on environmental factors and the morphologies and dimensions of available lava tube sections (Romio and Lobosco, 2025), the field of Architecture for Outer Space still lacks proper and credible environmental models in which to develop realistic lunar and Martian settlement proposals (Romio, 2022; Mizuguchi and Ikeda, 2023; Port San Antonio, 2023; ZA Architects, n.d.). In this sense, through its extensive database and possibilities of lava tube landscape generation, Pyroduct provides the means for the development of credible architectural and engineering proposals of lava tube adaptation for future human use, aiding students, architects, engineers, and planners in developing projects and visions of the future human use of the lunar and Martian underground. In these regards, the authors of this paper have collaborated on the development of an international

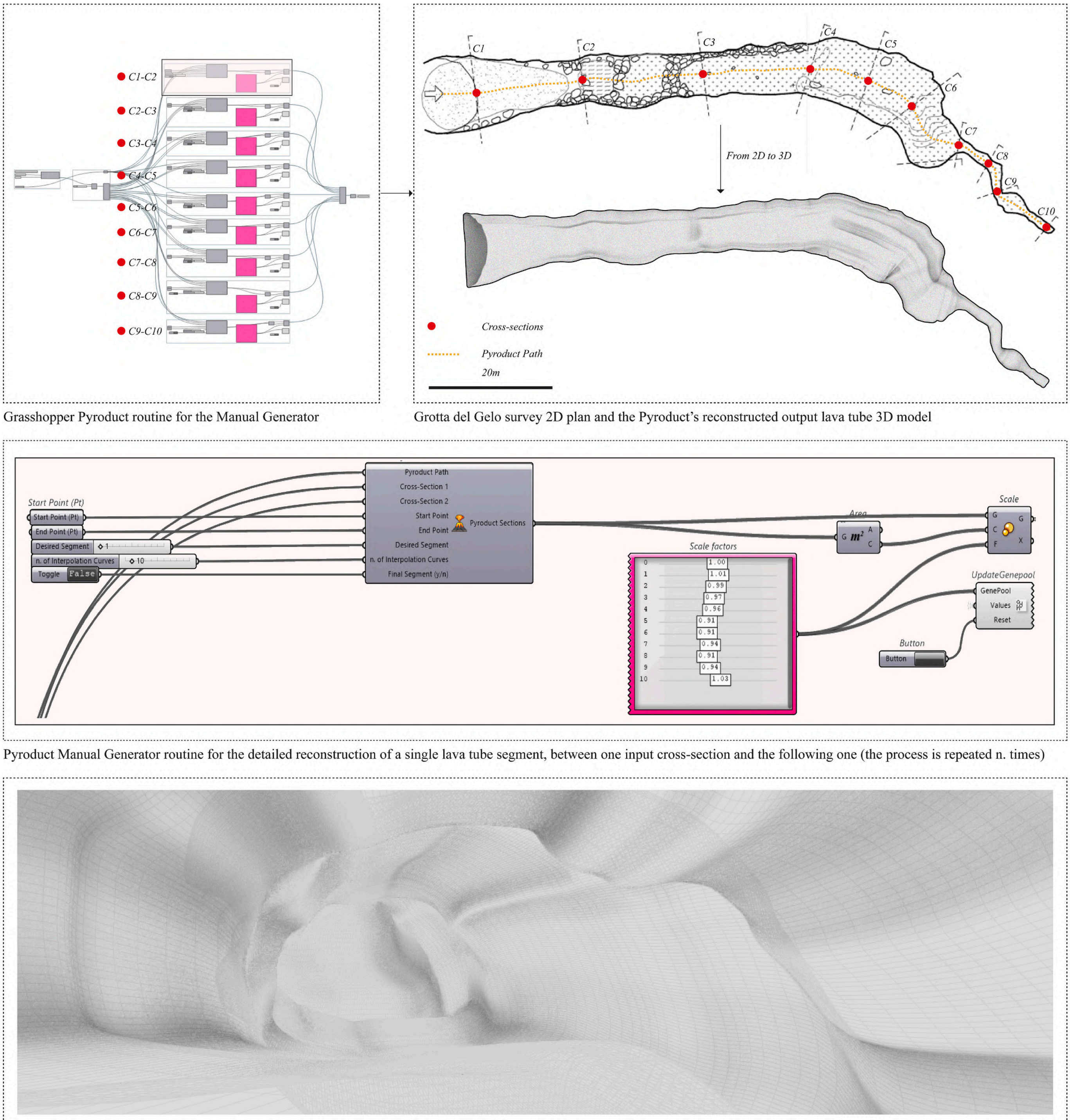


Fig. 10. Top left: routine to manually reconstruct the 3D model of a lava tube from 2D survey data, by utilising the Pyroduct Manual Generator. Below: detail of the routine to reconstruct a single segment of the lava tube. Each segment is defined by a starting cross-section and a following one (e.g., C1 and C2), which are taken from the Grotta del Gelo survey data and are available in the "Pyroduct Digital Catalog" component of the Pyroduct plug-in. The curves are then displaced and interpolated along the defined pyroduct path and scaled to match the lava tube survey data (see image above right). Top right: all the resulting scaled curves defining each reconstructed lava tube segment are merged into a single list and lofted to create the final lava tube 3D model, here shown in comparison with the original reference survey plan of Grotta del Gelo. Bottom: visualisation of the interior of the reconstructed lava tube 3D model.

architectural competition launched by the organizer Young Architects Competitions (YAC) – a private company which develops international architectural competitions with a strong scientific background and the support of institutional and/or private companies - with the support of the ESA's Topical Team on Planetary Caves in which an early prototype of Pyroduct was first used to model the hypothetical lava tube possibly accessible from the lunar "Lacus Mortis Pit". The competition had more than 100 design proposals from around the world, which provided interesting and, in some cases, disruptive proposals for adaptation and settlement (YAC, 2023).

4.3. Terrestrial applications

During the research process for the creation of the Pyroduct Digital Catalog, discussed earlier in Section 2.2, we discovered a very large number of existing lava tube 2D surveys from different volcanic areas around the world. It is interesting to notice that the first survey of the Surtshellir lava tube, by Eggert Ólafsson and Bjarni Pálsson, was done in 1772, just a century after the practice of cave surveying began to spread. Until the 20th century, the tools and methodologies used by the surveyors didn't change much (Wookey, 2004). Generally, the equipment used included a notebook, a compass, a clinometer, or sometimes a theodolite, and a tape meter, which, starting in 1990, started to be replaced by laser distance meters (Judson, 1974; Wookey, 2004). For these reasons, until the first uses of LiDAR technologies in caves in the late 90s and especially the 2000s, most of this wealth is composed of 2D plans and sections, and, as shown in the Introduction, only a few LiDAR lava tube surveys exist and are available (see Table 1). Since access to this data is limited, this poses a significant limitation for researchers who are not equipped with the expertise or the equipment to perform LiDAR surveys of lava tubes to pursue analyses and research. In such cases, Pyroduct can be used as an alternative way to obtain lava tube 3D models: if 2D surveys of such lava tubes are available, either in literature or inside the Pyroduct Digital Catalog (PDC), researchers can easily reconstruct a 3D model of the cave of interest by utilising the software, giving them the possibility to perform different kinds of analyses and simulations, which would not be possible to perform on 2D data alone (Fig. 10). An example of this application could concern the reconstruction of 3D models of lava tubes for the calculation of their internal volume, which provides scientists with valuable information about physical properties such as thermal conductivity and heat capacity (Yang et al., 2024). Furthermore, if integrated with additional data, such as the rheological properties of the lava, the internal geometry of lava tubes can also offer insights into the effusion rate of the eruption that formed them (Keszthelyi, 1995; Sauro, 2024), providing important insights into the lava discharge capacity of tubes in specific regions for volcanic hazard assessments. In addition to these uses, Pyroduct can also aid scientists in the modelling of inferred lava tube segments that are not possible to explore and survey due to their dangerousness. An example is the study of newly formed lava tunnels in places such as Iceland (Fagradalsfjall eruptions). While some sections of such caves might be possible to explore and survey, others might be too hot and dangerous. However, with the use of Pyroduct, scientists could reconstruct the segments they are missing in the overall survey, hypothesising the possible shapes of that inaccessible area and performing analyses (Sauro, 2024; Sauro et al., 2024). Similarly, national parks and public institutions could benefit from using Pyroduct to create digital environments of existing lava tubes without the need for costly LiDAR surveys. When 2D survey data is available or can be acquired, Pyroduct enables the reconstruction of 3D cave models that can serve as effective tools for making these underground landscapes more accessible to the public through VR or AR experiences. This is especially valuable in cases where caves are either too fragile or too hazardous to be physically explored. A compelling case study is the Museo Casa de los Volcanes in Lanzarote, Canary Islands, where visitors can engage with immersive and interactive experiences of digital lava tube environments. These installations allow access even for those who may be unable or unwilling to explore touristic sites such as La Cueva de Los Verdes (CACT Lanzarote, 2025). Furthermore, researchers have demonstrated the value of digital forest environments in supporting forest managers with decision-making and stakeholder communication (Holm and Schweier, 2024). Similarly, when coupled with real-time visualisation platforms such as Epic Games' Twinmotion, Pyroduct could support the creation of digital environments that not only enhance public accessibility but also serve as powerful tools for conservation, planning, and education (Fig. 11). In

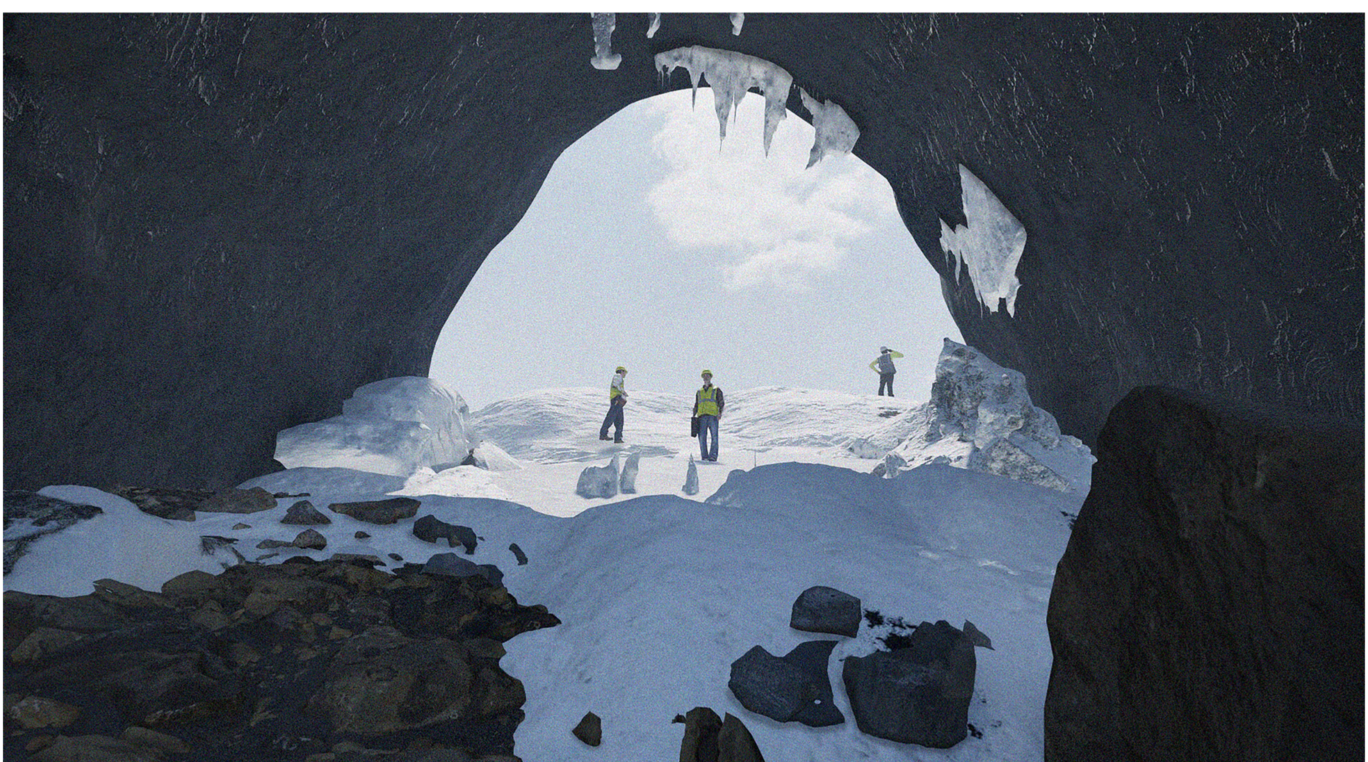


Fig. 11. Rendered view of the 3D model of the lava tube Grotta del Gelo. The visualisation was set with Epic Games' free real-time visualisation tool "Twinmotion 2025 1.1". By utilising the software, it is possible to turn the Pyroduct's output 3D models into Virtual Reality environments, to provide immersive experiences. This approach can help institutions, such as national parks, in the effort of making such landscapes available to the public, while achieving their protection, especially for the ones that are particularly delicate or dangerous.

this sense, a widespread adoption of the Pyroduct Generator and the Pyroduct Digital Catalog among researchers, conservators and educators would offer the opportunity to foster a collaborative, open-access reference platform that could eventually become the most complete and up-to-date global repository of lava tube morphologies, while acknowledging the pioneering efforts of previous initiatives, such as Dr. Ronald Greeley's "Lava Tube Database", hosted at the Ronald Greeley Center for Planetary Studies at Arizona State University. Building upon this vision, we are currently developing a platform that will allow interested parties worldwide to request the upload of new entries by following a required format, namely, providing the essential information for each reference (see Table 2) and submitting the corresponding speleological or LiDAR survey for digitisation or inclusion in future updates of the Pyroduct Digital Catalog. Furthermore, we recognise the need for a shared, open repository for uploading and distributing lava tube LiDAR and speleological surveys globally, to which we aim to contribute through the present work, as this knowledge is currently scattered across repositories and libraries shelves or remains unpublished on proprietary hard drives.

5. Conclusions

In this paper, we have presented Pyroduct, an innovative and first-of-its-kind parametric generator for realistic 3D models of lava tubes. The software is released on Zenodo as an easily installable plug-in for Grasshopper, the visual programming language within the well-known 3D modelling software Rhinoceros 3D. It includes what is likely the largest existing digital database of lava tube cross-sections: the Pyroduct Digital Catalog (PDC). With future lunar and Martian exploration and settlement missions in mind, where lava tubes remain unexplored by humans or robots, we have demonstrated the potential of Pyroduct to support scientists, engineers, architects, and planners in scenario development and strategic planning, enhancing robustness and resilience in design processes. The article has also highlighted how current representations of extraterrestrial lava tubes are often highly schematic and disconnected from terrestrial analogues, revealing a lack of tools capable of generating credible and geologically grounded digital environments. Moreover, we have shown how Pyroduct can be applied on Earth, aiding in the 3D reconstruction of lava tubes from 2D survey data, especially in cases where access to certain cave segments is limited or unsafe. The 3D models produced can be integrated with real-time rendering software to enable immersive experiences for tourism and education, and can also support conservation efforts and planning processes. In this context, Pyroduct offers a valuable platform for stakeholders, decision-makers, and park authorities to communicate strategies more effectively. Ultimately, this work aims to contribute to the advancement of the understanding, study, and design of underground landscapes on Earth, the Moon, and Mars by introducing a fundamental tool for the international scientific and design community. While this is only the second version of Pyroduct, we foresee many future developments, including expanded functionality and a growing dataset within the PDC.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.icarus.2025.116904.

Disclosure of use of AI

During the preparation of this work, the authors used ChatGPT in order to enhance the language and refine the sentence structure. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Image credits

Fig. 1: *Grotta dei Ladri*, Jean Houel, 1782, Hermitage, St. Petersbourg.

Fig. 2: the authors, utilising cave access data from Wagner & Robinson *LROC Pit Atlas* (Wagner and Robinson, 2021) and the *Mars Global Cave Candidate Catalog* (Cushing, 2015).

Fig. 3: the authors.

Fig. 4: the authors.

Fig. 5: the authors.

Fig. 6: the authors.

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Fig. 8: the authors.

Fig. 9: the authors.

Fig. 10: the authors.

Fig. 11: the authors

Video 1: Francesco Axel Pio Romio (music and video).

CRediT authorship contribution statement

Francesco Axel Pio Romio: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gianni Lobosco:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Formal analysis, Conceptualization. **Francesco Sauro:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Riccardo Pozzobon:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Alessandro Marraffa:** Validation, Investigation, Data curation.

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Dedication

The authors wish to dedicate this work to the memory of their friend and colleague, Dr. Riccardo Pozzobon, who passed away on September 2nd, 2025, during a field expedition on a glacier, before the publication of this paper. We honour Dr. Pozzobon as one of the world's leading scientists in lava tube research, both on Earth and on other planetary bodies, and his contributions over the past decade to the understanding of these unique volcanic caves have been invaluable. He conducted extensive fieldwork to investigate the formation mechanisms of lava tubes on terrestrial shield volcanoes, from Italy to the Canary archipelago and up to the Icelandic highlands, and his pioneering development of remote sensing techniques to characterize lava tube collapses across different planetary bodies provided the first estimates of the dimensions of these subsurface conduits throughout the Solar System. Since 2021, Dr. Pozzobon has been one of the most active members of the Planetary Caves Topical Team of the European Space Agency and served as an organizer of the 4th International Planetary Caves Conference held in Lanzarote in May 2023. Since 2016, he had also been an instructor for the ESA training programme PANGAEA, guiding more than 15 astronauts from various agencies through field geology training, including multiple successful expeditions to the Corona lava tube system in Lanzarote. His legacy in advancing the study of subsurface environments on Earth and other planets will endure, as will his kindness and generosity toward colleagues and students. A tribute published by ESA, featuring contributions from academic colleagues and astronauts, can be found at https://blogs.esa.int/caves/2025/09/11/a-tribute-to-dr-riccardo-pozzobon/

Dr. Riccardo Pozzobon mapping with a laser scanner the interior of a lava tube in Iceland.
Marco Vattano with permission.

Declaration of competing interest

The authors declare that they have no known competing financial or personal interests that could have influenced the work reported in this paper.

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Data availability

Both the Pyroduct Digital Catalog (PDC) dataset and the Pyroduct Generator software are freely available on Zenodo: https://doi.org/10.5281/zenodo.14604786, https://doi.org/10.5281/zenodo.14535885.

References

Bell, E., Schmerr, N., Young, K., Esmaeili, S., Garry, W.B., Jazayeri, S., Kruse, S., Richardson, J., Whelley, P., 2022. Field mapping and modeling of terrestrial lava tube magnetic anomalies as an analog for lunar lava tube exploration and prospecting. J. Geophys. Res. 127 (6), e2021JE007140. https://doi.org/10.1029/2021JE007140.

Blair, D.M., Chappaz, L., Sood, R., Milbury, C., Bobet, A., Melosh, H.J., Howell, K.C., Freed, A.M., 2017. The structural stability of lunar lava tubes. Icarus 282, 47–55. https://doi.org/10.1016/j.icarus.2016.10.008.

Broere, W., 2016. Urban underground space: solving the problems of today's cities. Tunn. Undergr. Space Technol. 55, 245–248.

CACT Lanzarote, 2025. Museo Casa de los Volcanes. https://cactlanzarote.com/museo-casa-de-los-volcanes/ (accessed 10 June 2025).

Calvari, S., Pinkerton, H., 1998. Formation of lava tubes and extensive flow field during the 1991–1993 eruption of Mount Etna. J. Geophys. Res. Solid Earth 103, 27291–27301.

Calvari, S., Pinkerton, H., 1999. Lava tube morphology on Etna and evidence for lava flow emplacement mechanisms. J. Volcanol. Geotherm. Res. 90, 263–280.

Carrer, L., Pozzobon, R., Sauro, F., Castelletti, D., Patterson, G.W., Bruzzone, L., 2024. Radar evidence of an accessible cave conduit on the Moon below the Mare Tranquillitatis pit. Nat. Astron. 8, 1119–1126. https://doi.org/10.1038/s41550-024-02302-y.

Chappaz, L., Sood, R., Melosh, H.J., Howell, K.C., Blair, D.M., Milbury, C., Zuber, M.T., 2017. Evidence of large empty lava tubes on the Moon using GRAIL gravity. Geophys. Res. Lett. 44 (1), 105–112. https://doi.org/10.1002/2016GL071588.

Christensen, P., Engle, E., Anwar, S., Dickenshied, S., Noss, D., Gorelick, N., Weiss-Malik, M., 2009. JMARS - A Planetary GIS. AGU Fall Meeting Abstracts IN22A-06.

Chwała, M., Komatsu, G., Haruyama, J., 2024a. Effects of layered roof for stability and exploration of lunar lava tubes. Earth Planet. Sci. Lett. 643, 118918. https://doi.org/10.1016/j.epsl.2024.118918.

Chwała, M., Komatsu, G., Haruyama, J., 2024b. Structural stability of lunar lava tubes with consideration of variable cross-section geometry. Icarus 411, 115928. https://doi.org/10.1016/j.icarus.2023.115928.

Chwała, M., Bodlak, M., Whelley, P., 2025. Stability and collapse analysis of terrestrial lava tubes under irregular shapes: case study of skull and valentine caves. J. Geophys. Res. 130 (8), e2025JE009109. https://doi.org/10.1029/2025JE009109.

Coan, T., 1844. Letter of March 15, 1843, Describing the Mauna Loa.

Coombs, C., Hawke, R., 1992. A search for intact lava tubes on the Moon: possible lunar base habitats. In: Mendell, W.R. (Ed.), The Second Conference on Lunar Bases and Space Activities of the 21st Century, 1. NASA Conference Publication, pp. 219–229, 3166.

Cushing, G.E., 2012. Candidate cave entrances on Mars. J. Cave Karst Stud. 74, 33–47. https://doi.org/10.4311/2010EX0167R.

Cushing, G.E., 2015. Mars Global Cave Candidate Catalog (MGC3) PDS4 Archive Bundle. PDS Cartography and Imaging Sciences Node (IMG). https://doi.org/10.17189/1519222.

Cushing, G.E., Okubo, C.H., 2017. Description of the Mars Global Cave Candidate Catalog (MGC3). PDS Archive.

Cushing, G.E., Titus, T.N., Wynne, J.J., Christensen, P.R., 2007. THEMIS observes possible cave skylights on Mars. Geophys. Res. Lett. 34.

Debrock, S., van Acker, M., Admiraal, H., 2023. Design recommendations for sustainable urban underground spaces. Tunn. Undergr. Space Technol. 140, 105332. https://doi.org/10.1016/J.TUST.2023.105332.

Di Giulio, R., Emanueli, L., Lobosco, G., 2018. Scenario's evaluation by design. A" scenarios approach" to resilience. TECHNE 15, 92–100.

Fox, J.M., Benaroya, H., 2026. Investigation of meteoroid impacts on lunar lava tubes. Acta Astronaut. 239, 747–765. https://doi.org/10.1016/J.ACTAASTRO.2025.11.042.

Giudice, G., Santi, G., 1999. La Grotta del Burrò, in: Dentro Il Vulcano: Il Libro Le Grotte Dell'Etna. Centro Speleologico Etneo, pp. 246–247.

Grechi, G., Moore, J.R., Jensen, E.K., McCreary, M.E., Czech, T.L., Festin, M.M., 2024. Modal analysis of a lava tube roof complex: Tabernacle Hill, Utah, USA. Rock Mech. Rock. Eng. 57 (9), 1–10. https://doi.org/10.1007/S00603-024-03868-9.

Greeley, R., 1971a. Observations of Actively Forming Lava Tubes and Associated Structures, Hawaii.

Greeley, R., 1971b. Lava tubes and channels in the lunar Marius Hills. The Moon 3, 289–314.

Greeley, R., 1971c. Geology of Selected Lava Tubes in the Bend Area, Oregon. State of Oregon Dept. of Geol. and Mineral Ind.

Greeley, R., 1994. Planetary Landscapes. Springer Science & Business Media, Berlin/ Heidelberg, Germany.

Greeley, R., Hyde, J.H., 1972. Lava tubes of the cave basalt, Mount St. Helens, Washington. Geol. Soc. Am. Bull. 83, 2397–2418.

Halliday, W.R., 2004a. Volcanic caves. In: Encyclopedia of Caves and Karst Science. John Gunn, pp. 1624–1633.

Halliday, W.R., 2004b. Vulcanospeleology: history. In: Encyclopedia of Caves and Karst Science. John Gunn, pp. 1633–1637.

Haruyama, J., Hioki, K., Shirao, M., Morota, T., Hiesinger, H., van der Bogert, C.H., Miyamoto, H., Iwasaki, A., Yokota, Y., Ohtake, M., 2009. Possible lunar lava tube skylight observed by SELENE cameras. Geophys. Res. Lett. 36.

Hatheway, A.W., Herring, A.K., 1970. Bandera lava tubes of New Mexico, and lunar implications. Commun. Lunar Planet. Lab. 8, 299–327.

Haviland, H.F., 2021. The changing lunar surface environment: hazards and resources. In: Rappaport, M.B., Szocik, K. (Eds.), The Human Factor in the Settlement of the Moon: An Interdisciplinary Approach. Springer International Publishing, Cham, pp. 43–53. https://doi.org/10.1007/978-3-030-81388-8_3.

Hidding, A., Bier, H., Peternel, L., Becoy, A.J., Romio, F.A.P., Calabrese, G., 2025. Robotic Lava Tube Mapping and Multimodal Data Collection Using Quadruped and Lidar. https://doi.org/10.2139/SSRN.5238812.

Holm, S., Schweier, J., 2024. Virtual forests for decision support and stakeholder communication. Environ. Model. Software 180, 106159. https://doi.org/10.1016/J.ENVSOFT.2024.106159.

Hon, K.E.N., Kauahikaua, J.I.M., Denlinger, R., Mackay, K., 1994. Emplacement and inflation of pahoehoe sheet flows: observations and measurements of active lava flows on Kilauea Volcano, Hawaii. Geol. Soc. Am. Bull. 106, 351–370.

Horz, F., 1985. Lava tubes: potential shelters for habitats. In: Houston, U.S. (Ed.), Lunar Bases and Space Activities of the 21st Century. Lunar and Planetary Institute, pp. 405–412, 1985.

Houel, J.-P.-L., 1782. La Grotta della Neve.

Jaggar, A., 1921. Volcanic conditions in February, activity of Halemaumau. Month. Bull. Hawaiian Volcano Observ. 9, 21–37.

Johnston, P., Endicott, J., Lin, N.F., 2020. Underground Cities: New Frontiers in Urban Living.

Judson, D., 1974. Cave surveying for expeditions. Geogr. J. 140, 292–300. https://doi.org/10.2307/1797087.

Kaku, T., Haruyama, J., Miyake, W., Kumamoto, A., Ishiyama, K., Nishibori, T., Yamamoto, K., Crites, S.T., Michikami, T., Yokota, Y., Sood, R., Melosh, H.J., Chappaz, L., Howell, K.C., 2017. Detection of intact lava tubes at Marius Hills on the Moon by SELENE (Kaguya) lunar radar sounder. Geophys. Res. Lett. 44 (20), 10,155–10,161. https://doi.org/10.1002/2017GL074998.

Kempe, S., 2009. Principles of pyroduct (lava tunnel) formation. In: 2009 ICS Proceedings. Presented at the 15th International Congress of Speleology, July 19–26, 2009, Kerrville, Texas, USA, pp. 668–674.

Keszthelyi, L., 1995. A preliminary thermal budget for lava tubes on the Earth and planets. J. Geophys. Res. Solid Earth 100, 20411–20420. https://doi.org/10.1029/95JB01965.

Kuiper, G.P., Strom, R.G., Le Poole, R.S., VIII, A.R., 1966. III. Interpretation of the Ranger Records. Technical Report-Jet Propulsion Laboratory, California Institute of Technology, pp. 32–35.

Lemaire, T., Morgavi, D., Petrosino, P., Calvari, S., Repola, L., Esposito, L., di Martire, D., Morra, V., Frondini, F., 2024. Lava flow field development and lava tube formation during the 1858–1861 eruption of Vesuvius (Italy), unravelled by historical documentation, lidar data and 3D mapping. J. Volcanol. Geotherm. Res. 455, 108197. https://doi.org/10.1016/J.JVOLGEORES.2024.108197.

Marino, A., Santi, G., 1999. La Grotta Corsaro. In: Dentro il Vulcano: il libro. Le Grotte dell'Etna. Centro Speleologico Etneo – Parco dell'Etna, Catania, pp. 215–216.

Marraffa, A., 2023. Morphometric Analysis of Lava Tubes. University of Padua.

Martin, R.P., Benaroya, H., 2023. Pressurized lunar lava tubes for habitation. Acta Astronaut. 204, 157–174. https://doi.org/10.1016/j.actaastro.2022.12.013.

Massironi, M., Sauro, F., Payler, S.J., Pozzobon, R., Hiesinger, H., Mangold, N., Cockell, C.S., Frias, J.M., Kullerud, K., Turchi, L., 2023. The ESA PANGAEA programme: training astronauts in field science. In: Materials Research Proceedings (Aeronautics and Astronautics - AIDAA XXVII International Congress), 37, pp. 721–724. https://doi.org/10.21741/9781644902813-154.

Mills, M.T., Wood, C., 1972. Original contributions to vulcano-speleology from Iceland. In: Proceedings of the International Symposium on Vulcanospeleology and Its Extraterrestrial Applications. Presented at the International Symposium on Vulcanospeleology and its Extraterrestrial Applications, August, 16, 1972, Washington, USA, pp. 43–51.

Mizuguchi, T., Ikeda, Y., 2023. Swarm habitat: lava tube base design with non-orthogonal modular coordination of the truncated octahedral modules. In: Proceedings of the 53th International Conference on Environmental Systems. Presented at the 52th International Conference on Environmental Systems, July, 16–20, 2023, p. 15.

Montañez Muñoz, S., Williams-Jones, G., Sepúlveda, S.A., Connelly, J.P., 2024. Morphometric Analysis of Ape Cave (WA, USA): Comprehensive Supplementary Material (Version 1.0). Zenodo. https://doi.org/10.5281/zenodo.14189358.

NASA/JPL-Caltech/UArizona, n.d. HiRISE | Possible Skylight on a Lava Tube Northeast of Arsia Mons (ESP_016767_1785) https://www.uahirise.org/ESP_016767_1785 (accessed 12.16.24).

Nesnas, I.A., Kerber, L., Parness, A., Kornfeld, R., Sellar, G., McGarey, P., Brown, T., Paton, M., Smith, M., Johnson, A., Heverly, M., Sawoniewicz, J., Yahnker, C., Pailevanian, T., Sunada, E., Gaume, B., Curtis, A., Elder, C., Uckert, K., Vaquero, M., Cheng, Y., Denevi, B., Jozwiak, L., Stickle, A., Whitten, J.L., Keszthelyi, L., Haruyama, J., Wagner, R., Hayne, P., Horvath, T., Head, J.W., Hopkins, J.B., Ricks, J., Boster, E., 2019. Moon diver: a discovery mission concept for understanding the history of secondary crusts through the exploration of a lunar mare pit. In: Proceedings of the 2019 IEEE Aerospace Conference. Presented at the 2019 IEEE Aerospace Conference, March, 2-9, 2019, pp. 1–23. https://doi.org/10.1109/AERO.2019.8741788.

Oberbeck, V.R., Greeley, R., Quaide, W.L., 1969. On the origin of lunar sinuous rilles. Mod. Geol. 1.

Ólafsson, E., Pálsson, B., 1772. Reise Igiennem Island, Foranstaltet A f Videnskabernes Sælskab I Kjøbenhavn. Jonas Lindgrens, Sorøe.

Ollier, C.D., Brown, M.C., 1965. Lava caves of Victoria. Bull. Volcanol. 28, 215–229.

Ovenden, M., 2020. Underground Cities: Mapping the Tunnels, Transits and Networks underneath our Feet. Frances Lincoln.

Pohlen, M., Carroll, D., Prisk, G.K., Sawyer, A.J., 2022. Overview of lunar dust toxicity risk. npj Microgravity 8, 55. https://doi.org/10.1038/s41526-022-00244-1.

Port San Antonio, 2023. San Antonio Innovators Advance Exploration Of The Moon Ahead Of Human Settlement With Lunar Cave Research. https://www.portsanantonio.us/Leto-Mission (accessed 12.9.24).

Pozzobon, R., Sauro, F., Rossi, A.P., Pajola, M., Massironi, M., 2023. Landing site characterization of Marius Hills Pit (Moon): a feasibility evaluation for the ESA lunar caves CDF study. LPI Contrib. 2697, 1009.

Puglisi, G., Santi, G., 1999. Le Grotte dell'Etna ed i Viaggiatori del Passato: Testimonianze di Viaggio. In: Dentro i Vulcani: Atti del IX Simposio Internazionale de Vulcanospeleologia. Presented at the IX International Symposium on Vulcanospeleology, September, 11–19, 1999, Nicola Barone, Renato Bonaccorso, and Giuseppe Licitra, Catania, IT, pp. 86–104.

Romio, F.A.P., 2022. Mars underground: a landscape strategy for long term human colonies on the red planet. In: 73rd International Astronautical Congress. Presented at the 73rd International Astronautical Congress. International Astronautical Federation. https://doi.org/10.5281/zenodo.7979256.

Romio, F.A.P., Lobosco, G., 2025. Underground landscapes: volcanism, lava tubes, and man. Tunnell. Undergr. Space Technol. 162, 106618. https://doi.org/10.1016/J.TUST.2025.106618.

Romio, F.A.P., Lobosco, G., Marraffa, A., Pisani, L., Tomasi, I., 2024. Pyroduct Digital Catalog (1.0.0) [Dataset]. Zenodo. https://doi.org/10.5281/zenodo.14535886.

Romio, F.A.P., Lobosco, G., Sauro, F., Pozzobon, R., Marraffa, A., 2025a. Pyroduct: The First Realistic and Parametric Lava Tube Generator for Earth, Moon, and Mars. [Software]. Zenodo. https://doi.org/10.5281/zenodo.14860753.

Romio, F., Hidding, A., Becoy, A.J., Bier, H., Calabrese, G., 2025b. LiDAR and Photogrammetry Data Evaluation from a Lava Tube Mission in Sicily (Version 1) [Dataset]. 4TU.ResearchData. https://doi.org/10.4121/0CC49D43-8A5C-453E-9370-8E9088B00B48.V1.

Santagata, T.S., Sauro, F.S., Pozzobon, R.P., Massironi, M.M., 2023. 3D scanning of lava tubes on earth as a tool to predict lava tube morphology and morphometry on other planets. LPI Contrib. 2697, 1059.

Sartorius Von Waltershausen, W., 1880. Der Aetna. Verlag von WilhelmEngelmann, Leipzig.

Sauro, F., 2024. Conversation with Francesco Axel Pio Romio.

Sauro, F., Pozzobon, R., Massironi, M., De Berardinis, P., Santagata, T., De Waele, J., 2020. Lava tubes on Earth, Moon and Mars: a review on their size and morphology revealed by comparative planetology. Earth Sci. Rev. 209, 103288. https://doi.org/10.1016/j.earscirev.2020.103288.

Sauro, F., Pozzobon, R., Cappelletti, M., Onac, B., Miller, A., Birkefeldt Moller Pedersen, G., Santagata, T., 2024. Hraunrásir: Exploring and studying the steaming lava tubes of Fagradalsfjall Volcano (Iceland). In: Banciu, H.L., Meleg, I.N., Onac, B. P. (Eds.), Frontiers Unbound: Exploring Extreme Environments. EGR. https://doi.org/10.5038/FUE3-2024-10.

Stefánsson, Á.B., Stefánsdóttr, G., 2016. Surtshellir in Hallmundarhraun: historical overview, exploration, memories, damage, an attempt to reconstruct its glorious past. In: Proceedings of the 17th International Symposium on Vulcanospeleology. Presented at the 17th International Symposium on Vulcanospeleology, Ocean View, Hawaii, pp. 1–11.

Tedeschi, A., 2020. AAD_Algorithms-Aided Design: Parametric Strategies Using Grasshopper. Le Penseur Publisher, Brienza, Italy.

Theinat, A.K., Modiriasari, A., Bobet, A., Melosh, H.J., Dyke, S.J., Ramirez, J., Maghareh, A., Gomez, D., 2020. Lunar lava tubes: morphology to structural stability. Icarus 338, 113442. https://doi.org/10.1016/J.ICARUS.2019.113442.

Tomasi, I., Massironi, M., Meyzen, C.M., Pozzobon, R., Sauro, F., Penasa, L., Santagata, T., Tonello, M., Santana Gomez, G.D., Martinez-Frìas, J., 2022. Inception and evolution of La Corona Lava Tube System (Lanzarote, Canary Islands, Spain). J. Geophys. Res. 127, e2022JB024056. https://doi.org/10.1029/2022JB024056.

von Troil, U., 1779. Briefe welche eine von Herrn Dr. Uno von Troil im Jahr 1772 nach Island angestellte Reise betreffen. In: Aus dem Schwedischen übersetzt und mit Anmerkungen herausgegeben. Mit vielen Kupfern. bey Magnus Swederus, Upsala und Leipzig.

Wagner, R.V., Robinson, M.S., 2014. Distribution, formation mechanisms, and significance of lunar pits. Icarus 237, 52–60. https://doi.org/10.1016/j.icarus.2014.04.002.

Wagner, R.V., Robinson, M.S., 2021. Occurrence and Origin of Lunar Pits: Observations from a New Catalog. Presented at the 52nd Lunar and Planetary Science Conference, Online. https://www.hou.usra.edu/meetings/lpsc2021/pdf/2530.pdf.

Wentworth, C.K., Macdonald, G.A., 1953. Structures and Forms of Basaltic Rocks in Hawaii (Report No. 994), Bulletin. https://doi.org/10.3133/b994.

Wilson, L., Head, J.W., Wilson, L., Head, J.W., 2025. Lunar Lava Tubes: An Assessment of Geometry and Scale on the Basis of Geological Observations and Physical Volcanology. LPICo, p. 1263, 3090. https://ui.adsabs.harvard.edu/abs/2025LPICo3090.1263W/abstract.

Wookey, 2004. Surveying caves. In: Encyclopedia of Caves and Karst Science. John Gunn, pp. 1530–1536.

YAC, 2023. Moon Station | YAC [WWW Document]. https://www.youngarchitectscompetitions.com/open-competitions/moon-station (accessed 12.9.24).

Yang, Q., Kang, Z., Hu, T., Cao, Z., Ye, C., Liu, D., Hu, H., Shao, S., 2024. Cross-section extraction and model reconstruction of lava tube based on L1-medial skeleton. Int. J. Appl. Earth Obs. Geoinf. 132, 104062. https://doi.org/10.1016/J.JAG.2024.104062.

ZA Architects, n.d. Mars Underground [WWW Document]. Roca Gallery. https://www.rocagallery.com/articles/mars-underground (accessed 12.9.24).

Zhu, K., Yang, M., Yan, X.Y., Li, W.K., Feng, W., Zhong, M., 2024. GRAIL gravity gradients evidence for a potential lava tube at Marius Hills on the moon. Icarus 408, 115814. https://doi.org/10.1016/J.ICARUS.2023.115814.