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Underground landscapes: volcanism, lava tubes, and man

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ABSTRACT

Lava tubes, or pyroducts, have played a significant role in human history, serving as shelters, storage spaces, and dwellings across diverse cultures, times, and geographies. However, knowledge about their uses remains fragmented across various disciplines and sources. This research consolidates an extensive review of human interactions with lava tubes through bibliographical studies and on-site expeditions, culminating in the creation of the Atlas of Lava Tube Uses. Integrating geological and anthropological insights, this atlas provides a comprehensive resource that bridges the gap between terrestrial history and extraterrestrial exploration. In fact, since the 1960s, researchers have hypothesized the existence of similar underground volcanic caves on the Moon and Mars. To date, 271 and 1062 potential cave entrances have been identified on the lunar and Martian surfaces, respectively. These extraterrestrial structures are increasingly viewed as promising candidates for future space habitats, offering protection from extreme environmental conditions. By connecting Earth's historical use of pyroducts with modern exploration efforts, this study lays the groundwork for designing liveable and sustainable underground habitats beyond our planet while highlighting the significance of these underground landscapes in Earth's heritage.

1. Introduction

When considering Earth, Mars, and the Moon, it is common to see them as three distinct planetary bodies. On Earth, a thick atmosphere and abundant water have played a crucial role in shaping its ever-changing landscapes over time through constant weathering and erosion. Life forms, including plants and animals, have spread across its surface, and, in particular, humans—since their appearance—have significantly contributed to the transformation of landscapes through agriculture, industrial activities, and urbanization, with an ever-increasing impact on terrestrial ecosystems. On the other hand, the other rocky bodies in the Solar System either lack these agents altogether—such as the Moon—or lost them long ago, as in the case of Mars, which has been debated to have had liquid water running on its surface until around 3,7 to 3,0 billion years (Di Achille and Hynek, 2010; Carr and Head, 2015; Nazari-Sharabian et al., 2020; Wright et al., 2024). However, despite these significant differences, these planets have striking similarities. One of the most notable is the presence of volcanic activity. Volcanism is an intrinsic characteristic of rocky planetary bodies in the solar system, and these planets must dissipate the internal heat accumulated during their formation due to the decay of radioactive materials. More specifically, one particular type of volcanism, known as basaltic volcanism, is critical process that closely links these three planets: basalts have erupted on Earth throughout all its known geological history, the dark areas of the moon's surface, named "mària" by the early observer Giovanni Riccioli in 1651, are basaltic lava flows accounting for around the 17 % of its surface and more than the 50 % of the Martian surface is covered by basaltic material (Greeley, 1994). In this research, we show how volcanism on Earth, Mars, and the Moon led to the formation of a specific kind of volcanic cave that is well-known on our planet and called with the historical name of "pyroducts" (Coan, 1844) or "lava tubes". Starting from 1985, scientists from all over the world have proposed these structures as the best possible location for long-term human bases on both planetary bodies, as they would offer a stable and protected environment from all the hazards that characterize both the lunar and the Martian surfaces, namely radiation, extreme temperature fluctuations, possible impact of micrometeorites and dust (Horz, 1985; Coombs and Hawke, 1992; Martin and Benaroya, 2023). At present, different habitation proposals, which leverage the presence of these structures, have already been published (Grandl, 2017; Romio, 2022; Mizuguchi and Ikeda, 2023; Bier et al., 2024; Zhang et al., 2024). In the latest years, thanks to breakthroughs in their detection, a renewed

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interest in these underground structures and their potential for future human exploration fostered reviews on the current state of the knowledge on lava tubes (Sauro et al., 2020) and on the state of the art for lava tube habitation proposals, evidencing the opportunities and the challenges of such solution and environments (Feng et al., 2024). Therefore, this research paper aims to contribute to this discussion, covering a topic that has been overlooked: the historical human habitation and use of lava tubes on Earth, to extract shared insights and commonalities that might be useful to inform liveable and sustainable planning and use of underground bases in Martian and lunar lava tubes. The case histories

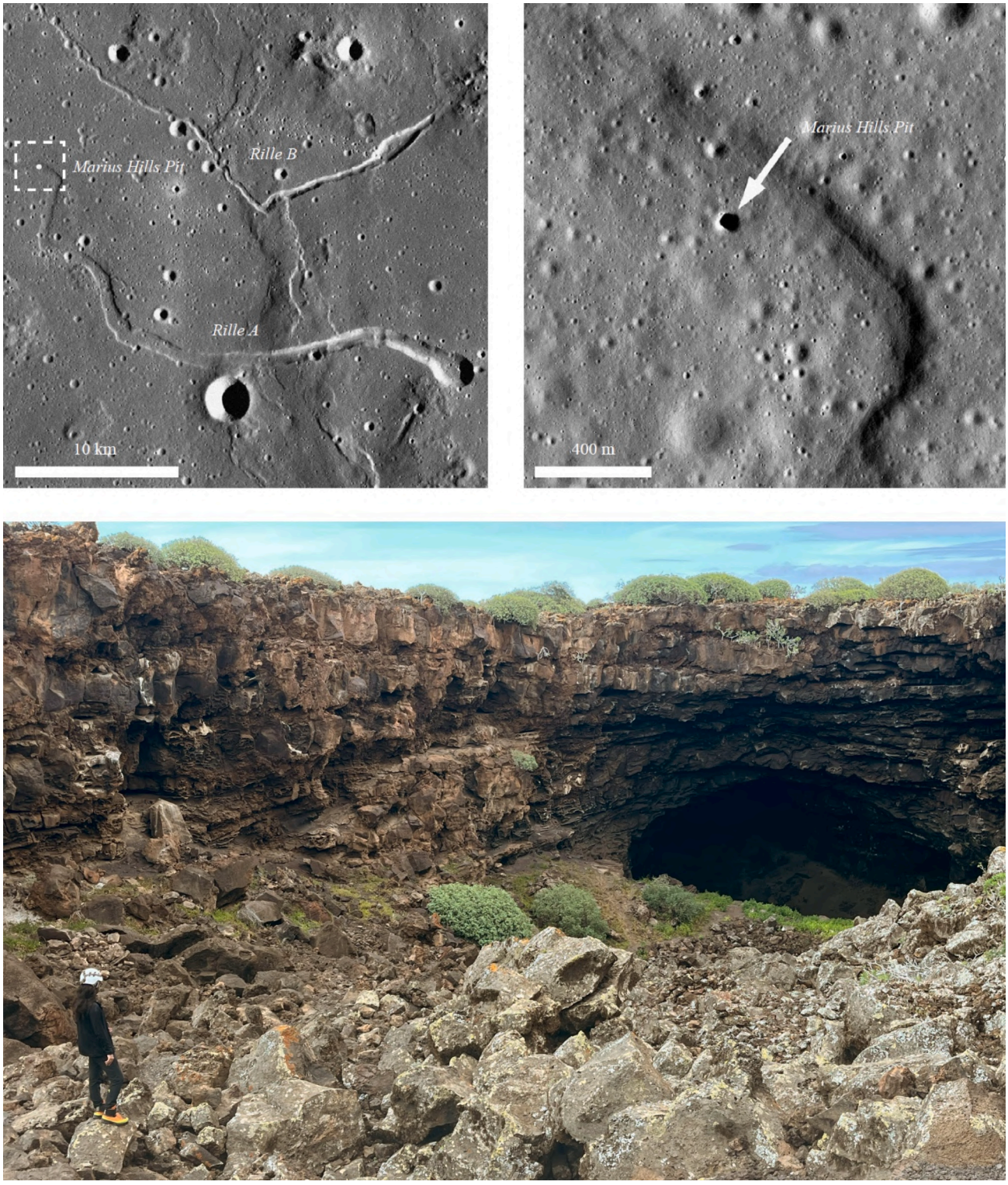

Fig. 1. From left to right: the lunar sinuous rilles observed by Oberbeck et al. (1969) and Greeley (1971b) and the Marius Hills Pit, the first lunar pit ever observed, by Haruyama et al. (2009). Below: Jameo de la Puerta Falsa, Lanzarote, one of the skylights of the lava tube La Corona, in Lanzarote (see Section 3.3.1). With dimensions of around 100 m × 30 m, it works as a reference for lunar and Martian lava tube skylight dimensions. The darker area in the back corresponds to the pyroduct entrance from the collapse.

presented here are derived from ongoing research on the internal shapes of Terrestrial lava tubes, in the effort to create a software capable of parametrically generating realistic lava tubes 3D models to inform future exploration and planning endeavors, until the first robotic mission will eventually unveil the internal asset of lunar and Martian lava tubes. This research led to the creation of the Pyroduct Digital Catalog v1, the first catalog of Terrestrial lava tubes cross-sections, containing more than 1200 entries from more than 92 lava tubes across the world (Romio et al., 2024a), and to Pyroduct, the first realistic and parametric software for the creation of lava tubes 3D models for Earth, Moon, and Mars (Romio et al., 2024b, Romio et al., 2025). In these regards, we aimed to expand this research, providing accounts of the human uses of the lava tubes available in the catalog, aiming to release a v2 with the inclusion of this information in the attached data sheet of the Catalog Index. We acknowledge that the database does not cover all the possible worldwide lava tube entries and countries of provenience. If the readers have information regarding lava tube surveys and human uses that could be added to the database, we are happy to include them for a new release update. The results of this process are presented here for the first time.

1.1. Planetary landscapes and caves

On Earth, lava tubes, or pyroducts, are well-known geological structures defined by Halliday as a "roofed conduit of flowing lava, either active, drained or plugged" (Halliday, 2004a, p. 1624). Pyroducts are known to develop during volcanic eruptions, especially within fluid basaltic pahoehoe and viscous A'A lava flows, even if lava tubes account for different types of lava flows, such as andesite and rhyolite, have been reported (Halliday, 2004; Calvari and Pinkerton, 1998; Calvari and Pinkerton, 1999). In particular, the traditional hypothesis that lava tubes form due to the crusting over of a lava flow in a channel – became very popular and adopted by many scientists (Jaggar, 1921; Wentworth and MacDonald, 1953; Greeley 1971c; Bunnell, 2008) who documented the formation of active lava tubes and expanded on the different ways the roof could be formed. Successively, other scholars noticed that these theories couldn't account for all the observed pyroducts, shapes, and structural features ; Calvari and Pinkerton, 1998, 1999; Hon et al., 1994; Ollier and Brown, 1965; Sauro, 2020; Kempe et al., 2010), so, over the years, other lava tube genetic mechanisms have been described. Starting from the 1960s, with the advent of space exploration, satellites, probes, and manned missions have provided scientists with a great amount of data, which has been used to interpret and understand the geology of the observed planets and the processes that shaped their landforms. In the late 1960s and 1970s, Oberbeck et al. (1969) and Greeley (1971b) were the first to notice that some river channel-like lunar volcanic features, known as "sinuous rilles", had striking similarities with terrestrial lava channels and partly collapsed underground conduits known as "lava tubes", making the hypothesis that similar structures existed on the moon (see Fig. 1). A decade after these first speculations, Horz (1985) evidenced the possible implications that such structures could have on future human exploration and habitation on the Moon. In particular, given the extreme lunar environment, lava tubes could act as a haven from the hazards that characterize the surface, protecting the astronauts and the structures of a lunar base from radiation, micrometeorite impacts, and extreme thermal fluctuations, while also requiring less construction efforts compared to a surface lunar base. Successively, Coombs & Hawke (1992) followed by identifying 20 additional sinuous rilles and mostly proposing 67 of what they interpreted as possible intact lava tube segments, creating the first list of candidate lava tube sites at the time, which were also ranked in regards to the potential presence of useful lunar resources close by, readability to host a lunar base and other factors. Recently, their research on sinuous rilles has been updated, with the identification of 195 features globally distributed on the lunar surface, with most of them formed during the same period of emplacement of the abovementioned mària basalts, between 3,0 and 3,8 Ga ago (Hurwitz et al., 2013). Significant breakthroughs happened between 2007 and 2009 when different groups of scientists provided the first direct evidence of potential cave accesses on the Moon and Mars. In particular, Haruyama et al. (2009)were the first to observe the Marius Hills Pit, located inside one of the sinuous rilles observed by Greeley (Greeley, 1971b), which then became famous as the first "lunar pit", which stands for a superficial collapse potentially leading to an underground cave (see Fig. 1). Specifically for lava tubes, these features are more commonly referred as "skylights" (Sauro et al., 2020). Similarly for Mars, Cushing et al. (2007) provided the first insights about numerous potential cave accesses. In 2024, more than 278 and 1062 cave accesses have been identified respectively for the Moon and Mars, many of them potentially leading to lava tubes (Cushing et al., 2007; Cushing, 2012; Wagner and Robinson, 2014; Cushing and Okubo, 2017; Wagner and Robinson, 2021). From these experiences, the significance of remote imagery analyses for identifying possible surface expressions and candidate lava tube sites is clear. However, satellite imagery alone cannot provide additional evidence, especially for possible lava tubes that lack skylights or other surface features (Chappaz et al., 2017). In an effort of trying to reveal additional information on the available candidate site areas previously discussed, different researchers have tried to apply further remote sensing techniques, trying to look beneath the surface: Chappaz et al. (2017) and Zhu et al. (2024) utilized gravimeters and acquired significant information regarding the possible presence of much larger underground voids than previously accounted in different candidate areas, while Kaku et al. (2017) utilized ground penetrating radar data, integrating their observations with the ones performed by Chappaz et al., showing some common features. However, some authors discussed these results as inconclusive (Kobayashi et al., 2020; Carrer et al., 2024). In 2024, another significant breakthrough was achieved by Carrer et al. (2024), who provided the first radar evidence of the existence of a cave conduit under the Mare Tranquillitatis Pit. By utilizing synthetic aperture radar (SAR) imaging systems from the Mini RF instrument aboard the Lunar Reconnaissance Orbiter (LRO), the researchers were able to see inside the pit and confirm that a conduit exists indeed, with a width possibly exceeding 200 m in diameter. While impossible on Earth, different authors have demonstrated the possibility of the existence of stable lava tubes in the order of 40 to 400 m for Mars and well beyond 200 m and to 5 km for the Moon (Bunnell, 1991; Greeley, 1991; Blair et al., 2017; Sauro et al., 2020). If confirmed by future robotic exploration missions, these dimensions would be more than enough to develop safe and sustainable long-term research bases and settlements. For this reason, research on how to enhance the livability of such spaces is more than necessary at this moment in time. Terrestrial examples of how lava tubes have been used and inhabited in different cultures across the globe may offer a fresh view and useful insights for the future lunar and Martian lava tube sustainable use and planning.

1.2. Terrestrial lava tubes and Atlas of Lava Tube Uses

On Earth, lava tubes began to be described and studied in the late 18th and 19th centuries, mostly thanks to travelers and naturalists, who often pictured how the caves were used by the local cultures. It is during this timeframe that early accounts of pyroducts in Sicily, Iceland, Canary Islands, Azores, Mauritius, Reunion, Hawaii, and others appeared in the literature (Hartung, 1857; Jaggar, 1921; Mills and Wood, 1972; Puglisi and Santi, 1999; Halliday, 2004b). However, is only during the 20th century, with the development of vulcanospeleology, a subdivision of speleology – the multidisciplinary subject that focuses on the study of caves – that a systematic exploration and mapping of lava tubes started to take place worldwide, and the discoveries of potential lunar caves mentioned in the previous paragraph have also favored a broader interest, inside the scientific community, for the study and the comprehension of these forgotten underground landscapes and the variety of processes that lead to their formation (Halliday, 2004a; Sauro et al.,

2020). Because of the isolated nature of lava tubes, and caves in general, from the climate and the action of agents, these explorations often led also to various significant anthropological and archeological discoveries of intact artifacts, human and animal remains, which put light on the use of ancient cultures of lava tubes worldwide (see Section 3.). As stated in the previous paragraphs, if it is true that with regards to the geological aspects there have been significant advancements and efforts concerning the comprehension of lava tubes and the production of reviews what is known so far (Sauro et al., 2020), it is not possible to state the same for the forms and the historical uses of these underground landscapes. In fact, at present, the great amount of knowledge regarding the surveying and the documentation of the anthropological use of lava tubes worldwide is scattered between numerous publications and congress proceedings, not always available in a digital format.

To address these issues, in this article, we present a first and non-exhaustive and diachronic collection of the usages of lava tubes in various cultures and locations across the globe, which we hereby call the "Atlas of Lava Tube Uses". With this research, we hope to create a milestone that sheds light on a forgotten and often overlooked chapter of the history and heritage of underground use by mankind, as well as its possible return into caves in future space exploration. As mentioned before, this work leverages the research done by the authors for the development of the Pyroduct Digital Catalog to implement research on the human utilization of the lava tubes available in the Catalog. For this reason, the list of the lava tubes and relative countries in which they are located, discussed in Section 3 of the present article, is not arbitrary and follows this rationale. Update works on the catalog are ongoing, and more countries and lava tubes will be added in the future, as well as the documentation regarding the human uses that we will find. Prof. Giovanni Badino, an astrophysicist and one of the most esteemed speleologists in the world, used to say that speleological research should not limit itself to the search of geographically deep caves but should also investigate their cultural depth. Caves own the dimension of time; they are archives of time. For this reason, Badino insisted that scientists must communicate their discoveries to the communities they belong to and the general public to give cultural depth to caves (Badino, 2021). We completely agree with him, and with this work, we hope to create a seminal reference that fulfills this goal for terrestrial and extra-terrestrial lava tube research.

2. Materials and Methods

For the realization of the present research, our main methodology regarded deep bibliographical research on all the accounts we could find and the visit to some of these locations.

2.1. Bibliographical research

In August 1972, the American National Speleological Society (NSS) held the first International Symposium on Vulcanospeleology and its Extraterrestrial Applications as a special session during its 29th Annual Convention. Since then, many congresses have followed, with the 21st edition taking place in 2024 in Puerto Ayora, Galapagos. These symposia have become the primary venue for sharing the latest advancements in the field and for lava tube research. To access these and other materials, we conducted our bibliographical research at the Speleoteca Franco Anelli in the BiGeA Department of the University of Bologna. This institution, managed by the Italian Speleological Society (SSI), is one of the most well-stocked in the world, with more than 30.000 volumes, journals, and documents related to caves.

Thanks to the invaluable support of the librarian Dr. Luca Pisani of the Italian Speleological Society, we were able to access all the proceedings mentioned above, along with other documents, books from which we collected surveys for the development of the Pyrodcut Digital Catalog and documents regarding the anthropic use of pyroducts in various countries and regions of origin, which are here discussed for the first time and will be implemented in the next update of the Catalog, linking geological and morphological data with cultural, architectonical and planning insights.

2.2. On-site expeditions

We embarked on several on-site expeditions to acquire additional data and experience these landscapes: i) Lanzarote, Canary Islands, Spain, and ii) Mt. Etna, Sicily, Italy. There, we experienced and could evaluate the characteristics of these sites, such as habitability parameters and actual interior assets in terms of shapes, accessibility, and development. Moreover, these missions allowed us to visit and provide new documentation on how some lava tubes were used in the past and, in some cases, are still in use today (see Sections 3.3.1 and 3.4.1).

In the case of Mt. Etna, we were there during the summer and fall of 2024 as part of two separate survey expeditions. The first was in collaboration with the Department of Geosciences of the University of Padova and with the local support of the Italian National Institute of Geophysics and Volcanology of Catania, while the second was with the Delft University of Technology of the Netherlands.

Regarding Lanzarote, we were there in 2023 to attend the 4th International Planetary Caves Conference. During these visits, we could visit the lava tubes discussed further in the paper (see Section 3.3.1) and access areas currently used for scientific work, which aren't accessible to the public.

3. Results

In this section, we provide an overview of all the human usage of lava tubes we encountered in our research, divided by country and region. The scope of this work is to provide the first compact collection of the cultural heritage of these geological structures. Below is a synthetic summary/ index of the Atlas (see Table 1).

3.1. Iceland

Lava tubes in Iceland have been known for a very long time. Early descriptions of these structures can be found in ancient stories, such as the scaldic poem Hallmundarkviða, in Bergbúaþáttur, one of the shortest chronicles of the Icelandic Sagas in which the famous lava tube Surtrshellir is first mentioned (Snæfellsás, 1991). This pyroduct, along with 20 others that are known at present, such as the Víðgelmir and the Hallmundarhellir, formed within the western Iceland Hallmundarhraun lava field which was generated by the homonymous eruption, which is dated around the 880 – 910 CE, shortly after proposed dates in literature for Iceland's settlement (Smith et al., 2021).

The first documentation of these caves, in particular the Surtshellir, begins in 1753 when the naturalist team Eggert Ólafsson and Bjarni Pálsson explored and surveyed the pyroduct (Ólafsson et al., 1978). Successively, many other naturalists and travelers visited the caves during the 19th and 20th centuries (see Fig. 2), also causing degradation of the environment by taking samples of whatever formation as a souvenir, even animal bones, a habit which unfortunately continues at present (Stefánsson and Stefánsdóttr, 2016).

Since the first explorations, some man-made structures and animal bones were found inside the lava tube: a stone wall of around 4,5m of eight was erected at a depth of around 250 m from the main entrance, while other structures such as a boat-shaped stone enclosure were found in secondary galleries of the lava tube, along with piles of animal bones (Ólafsson and Pálsson, 1772). For a long time, many authors accounted these findings to the use of the cave by outlaws (Ólafsson and Pálsson, 1772; Arngrímsson, 1979), but recent research has demonstrated strong evidence that these traces might account for the use of the cave for ritualistic and sacrificial purposes, from around 920–930 CE and continued for 80–120 years, until pre-Christian practices were banned in Iceland (Smith et al., 2021). The Surtshellir lava tube was named so after

Table 1
Synthetic summary of the Atlas of Lava Tube Uses.

Country	State/ Region	Diachronic Typologies of Utilization	Years of Utilization
Iceland	Western Iceland	Ritualistic, fortified shelter for temporary habitation.	From around 920 – 930 CE until 1040 CE and from 1180 to 1250 CE
United States	Oregon	Shelter, ice mining, and storage of Bison products in ice caves.	From before 2050 BCE
United States	Hawaii	Catchment of potable water, permanent and prolonged habitation, underground fortification, religious, burial, and hidden routes for soldiers and people.	From 1220 to 1261 to 1893 CE
United States	New Mexico	Ice mining and melting for domestic, ceremonial, and medicinal use, bison trap, storage of Bison products in ice caves, and shelter from the invaders.	From 50 BC to 1900 CE
Spain	Canary Islands	Temporary and prolonged dwelling, seasonal and shepherd's shelters, a refuge from invaders and pirates, the catchment of potable water, places of worship, burial, modern recreational spaces (bar, restaurant, auditorium), astronaut training	From 100 CE to the present
Italy	Sicily	Habitation, temporary and seasonal shelter, shelter for travelers, storage, warehouse, burial, funerary ceremonies, religious and initiatory rituals, ice storage and commerce, and catchment of potable water.	From 3050 BCE to the present
Italy	Sicily (Pantelleria)	Temporary shelter	1861 CE
Jordan	Mafraq Governatorate (East Jordan)	Shelter (?), water storage, drip water catchment, and sealing of the cave entrance to keep hyenas away from the caves.	Unknown
Saudi Arabia	Makkah Province (West Saudi)	Temporary shelter, pastoralists stopping off shelter	From 4850 BCE to 1050 BCE
Kenya	Chyulu Hills (Makueni County)	Tourism, bat guano mining, and poaching activities	From after 1965
Kenya	Mount Suswa (Great Rift Valley, Narok/ Kajiado County)	Shelter (?), refuge, movie set	Unknown – 1952 to 1960, 1984
China	Heilongjiang province	Mining of water ice (?), military encampments, tourism	Unknown – 1937 to 1945 CE-Present
China	Guangdong and Hainan provinces	No data, tourism	No data; at present
China	Yunnan province	Shelters for civilians	1939 to 1945 CE
Vietnam	Đắk Nông province	Permanent habitation, tool-making workshop, burial	From 5050 BCE to 2050 BCE
South Korea	Jeju Island (Jeju Province)	Touristic	From 1962 CE
Australia	Queensland	Shelter (?), ritual, and habitation purposes (?).	Used at least in the last 700 – 1.000 years
Portugal	Azores	No data, tourism	No data; at present
Japan	Yamanashi and Shizuoka Prefectures	No data, tourism	No data; at present

*For the exact use-period of use relationship, see the subsections of the results section. The data in the table refers to the lava tubes reported in this study. Lava tube uses are here listed in a diachronic order. More utilization types might have happened at the same time or in the same cave.

Surtr, an elemental being present at the world's creation, who would kill the last of the gods in the battle of Ragnarök and then engulf the world in flame and which in the ancient medieval poem Hallmundarkviða is said to direct fire giants into caves to cause volcanoes to erupt (Hollander, 1962; Hjartarson, 2014). After the Hallmundarhraun eruption, pieces of evidence support the hypothesis that islanders went to practice sacrifices in the cave to appease the anger of the Giant (Smith et al., 2021).

Apart from the Surtshellir, archeological remains have also been found in other cases, such as the Hallmundarhellir. There, just after the cave entrance, is located a defense wall of 4,5m in height, with a small one-person doorway. Behind it, the cave was modified and adapted for habitation: the floor was regularized by removing slabs that were used to divide the internal space with dry stone walls around a central isle that partitions the internal space of the cave into three areas of almost equal dimension. Due to the significant effort to realize the retreat, and the careful division of spaces for cooking, storage, and sleeping, researchers interpreted this site as a fortified shelter built in 1180 ± 10 AD circa and used throughout a violent period of the Icelandic's history known as the "Age of the Sturlungs", which lasted until middle 13th century. Researchers argue that it was built for periodic use by a small but structured group of 2–6 individuals with a somewhat hierarchical organization (Smith et al., 2017).

3.2. United States

Lava tubes have been used by humans with similar uses through time, across many states of the US: many native American cultures had deep relationships with the surrounding landscapes, upon which they relied for their survival. For this reason, caves were interpreted as places to shelter and acquire resources. Even after the arrival of the Europeans, lava tubes kept being utilized, while at other times they were forgotten, as not considered interesting or useful. However, as anticipated in the introduction, numerous scientists during the end of the 1960 s and beginning of the 1970 s pointed out the striking similarities between lunar sinuous rilles and terrestrial pyroducts (Oberbeck et al., 1969; Greeley, 1971b; Cruikshank and Wood, 1972) In particular, during the 1970s, Hatheway and Herring were asked by the NASA astronomer Gerard Kuiper to investigate the pyroducts of the Zuni-Bandera Volcanic Field, mapping and characterizing many of the major lava tubes of the area (Hatheway and Herring, 1970), while, also for NASA, Ronald Greeley pursued important researches in the lava tubes of Oregon and Hawaii, trying to understand and validate, with empirical and on-site observations, the theories which were proposed at the time for lava tube formation by scientists such as Jaggar, Baldwin, Ollier and Brown, MacDonald (Greeley, 1971c, 1971a). He aimed to understand terrestrial lava tubes to explain the possible existence of similar structures on the moon and hypothesize their possible internal morphologies (Greeley, 1971b, 1971a). Nowadays, many of the lava tubes present in this Atlas are located inside protected areas, such as the Hawai'i Volcanoes National Park, El Malpais National Monument, and Newberry National Volcanic Monument. Unfortunately, some of them, due to inappropriate

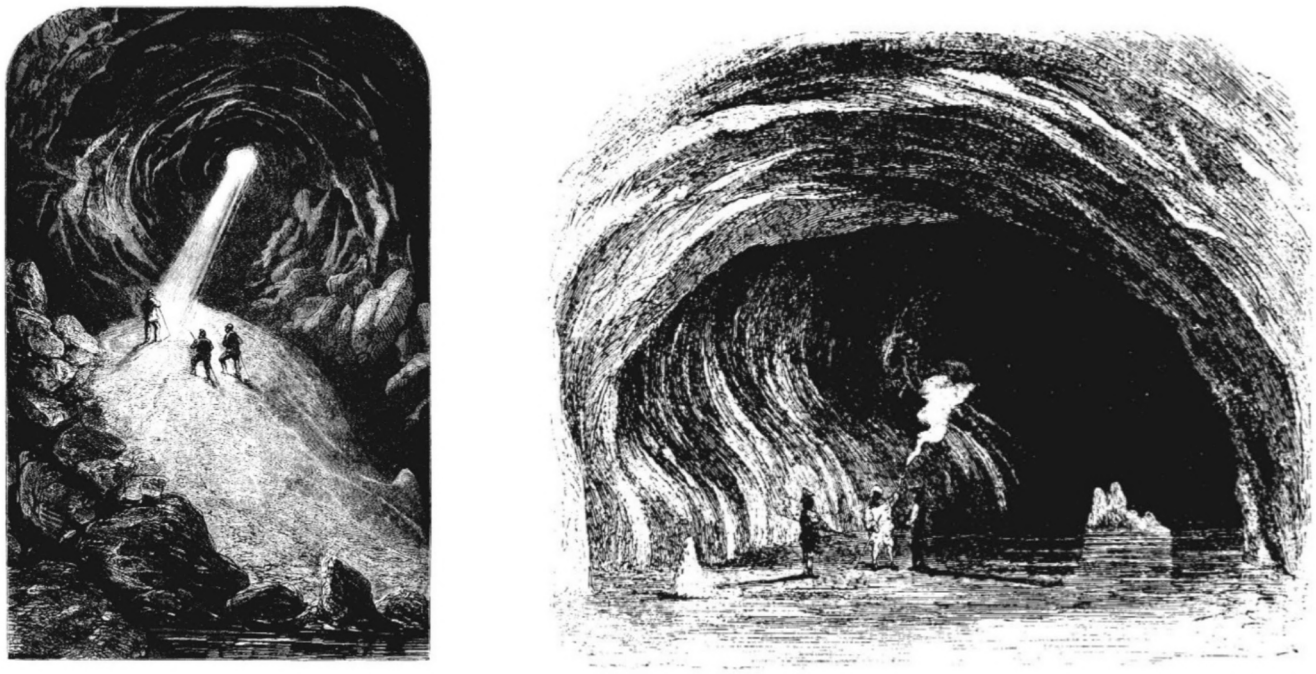

Fig. 2. Early representations of the Shurtshellir in 1860, from Forbes (Forbes, 2013).

practices and visitors' behaviors, experienced degradation, trash dumping, and damage to their unique historical heritage and delicate ecosystems, such as in the case of various caves of the Arnold Lava Tube System in Oregon (Petrie, 1997).

3.2.1. Oregon

Among the states of the US, Oregon is one of those with the greatest diversity of volcanic rocks and landforms. Specifically, the area around the city of Bend hosts numerous lava tubes, many part of greater systems such as the Arnold Lava Tube System and the Horse Lava Tube System. Numerous of these caves, such as the Arnold Ice Cave, Pictograph Cave, and Charcoal Cave, were used at different times by different indigenous populations. Researchers date their use by Native Americans back to at least 4000 years BP (Greeley, 1971a; Petrie, 1997). These people used lava tubes as shelters and for gathering ice from caves where permanent ice was available due to the peculiar insulation properties of basalt. In fact, due to its high porosity and low thermal conductivity, it serves as an excellent natural insulating material. Combined with the roof thickness and the orientation of the tube entrance relative to the sun, this results in the preservation of ice throughout the year. Evidence of this usage is evident in Pictograph Cave, where Native American pictographs are painted on the cave entrance's north wall, and in Charcoal Cave, where charred wood and stone axes were found (Halliday, 1952; Greeley, 1971a). Recent research for cave usage in the Snake River Plain area, in the state of Idaho, has provided proof that Natives started utilizing ice lava tubes episodically to keep bison products insulated and frozen, to cope with climatic variability and resource availability as early as 9460 years BP (Byers, Henrikson and Breslawski, 2016). It is possible that also in this area, there could have been similar uses. Other caves in the area, such as the Arnold Ice Cave, kept being utilized by the early settlers in the Bend area for mining ice, which at one point was also commercially exploited (Greeley, 1971a).

3.2.2. Hawaii

Discovered by Captain Cook in 1778 and first named "Sandwich islands", and inhabited at least from 1220 to 1261 CE by the first Polynesian colonizers (Rieth et al., 2011), Hawaii is one of the most important volcanic landscapes of Earth, having the largest terrestrial shield volcano, the Mauna Loa. It is on top of this volcano that Titus Coan, in 1844, first observed and described an active lava tunnel during its making and coined the historical term "pyroduct" to describe this phenomenon (Coan, 1844). There exist some of the most impressive terrestrial features of this kind, such as the Kazumura and Kaumana caves, respectively 11.713 m and 2544 m, and listed within the longest lava tunnels on Earth (Crawford, 1982). Various research has demonstrated how lava tubes had a very important role in ancient Hawaiian populations. In some cases, their exploitation lasted until recent times, as for the case of the catchment of potable water in caves, which started in very ancient times and has been documented to have continued even through the 1900s. The location of these caves, specifically in the arid lands of the island, was not offered as a piece of general knowledge but only available to selected individuals. In particular, Native Hawaiians had a peculiar administration of their land: each island, within the major geopolitical divisions, was subdivided into numerous "ahupua'a" which were established to provide an equal distribution of the resources of the territory, from the mountain to the sea (Sinoto, 1991). In this regard, some scholars have noted that the ahupua'a, which hosted caves that provided water resources, probably had a greater political strength (Handy and Pukui, 1976). This is also evidenced by the fact that lava tubes such as the Ainahou Cave System, where water resources are abundant, were fortified, presenting artificial stone walls erected at the entrances of the caves, often at roof collapses called known as skylights or in Hawaiian "pukas", which only allowed one person at a time to enter (Martin, 1991). The fortification and modification of pyroducts for different purposes were very common within Native Hawaiian cultures, which, apart from water collection, used lava tubes for permanent or temporary habitation sites, but also for religious functions, and for burying their dead (Sinoto, 1991). Lava tubes used for permanent or temporary dwellings have been investigated widely during the last century, providing important information about the cultural sequences of the ancient Hawaiian populations (Emory and Sinoto, 1969; Sinoto, 1991). In particular, lava tubes used for dwelling were often the shortest ones and present living spaces characterized by the presence of huts foundations, low rock alignments, platforms, and terraced platforms – for sleeping and fireplaces – and storage areas, such in the case of the Hilina Pali Site (Martin, 1991; Sinoto, 1991). In many other caves,

especially for long lava tubes, real underground fortresses exist, which can be counted as refuge tube shelters (Sinoto, 1991) (Fig. 3). In these cases, the pukas were modified, stairs were added to connect the surface and the lava tube level, and thick defense walls were erected, allowing just one person at a time to pass through the very narrow entrance in the middle, who had to crawl for several meters to pass through them. Behind the defense walls were often located numerous sleeping platforms for the defenders and fireplaces. As an example, the Lua Nunu Mauka Cave presents a 2 m high and 1 m thick defense wall, 25 m in length, which separates the entrance from the Pork Pen Puka and the rest of the lava tube. Behind the wall, 102 sleeping platforms were counted, extending way into the areas of complete darkness of the tunnel. In most cases, charcoal from torches, seafood shells, fish bones, and human artifacts were found, testifying to the different periods in which the caves were used (Bonk, 1967; Emory and Sinoto, 1969; Kempe et al., 2006a; Sinoto, 1991; . Other examples of this kind are the Lua Nunu Makai Cave, the Cave of Refuge, and the Ainhaou Ranch Cave, while for some other long lava tubes such as Kaumana and Kazamura, it has been also speculated, due to the findings of torch charcoal throughout all their length, that they might serve as hidden routeway through which warriors could move unnoticed by the enemies (Jennings, 1979). Apart from habitation and sheltering, pyroducts also had important religious and burial functions in Ancient Hawaiian societies. It has been known for a long time that caves were sacred burial places (Withney, 1893; Sinoto, 1991). Often far from habitation sites and hidden, camouflaged with the uttermost care, adopting similar techniques as the one adopted for the defensive walls of the lava tube shelters, natives guarded and still have great reverence for the burying caves of their ancestors, where their bodies were often laid in their depths inside wide chambers, far from the entrances (Withney, 1893; La Plante, 1991; Sinoto, 1991). Until now, we described precise uses of caves, but some scholars have evidenced that in some cases, lava tubes were used together for resource gathering, shelter, dwelling, and burial or at the same time or at different times throughout their history (La Plante, 1991; Martin, 1991, 1996). Nonetheless, Native Hawaiians had settlements and infrastructures on the surface, It is clear from all the examples described the complex relationship that runs within their societies and lava tubes, being probably one of the greatest terrestrial examples of the use and adaptation of these structures for human use and settlement. In many of the above-mentioned caves, many beautiful pictographs are present. Having found no details in the literature we consulted regarding the cessation of the use of lava tubes by Native Hawaiians, we take here the fall of the Hawaiian Kingdom, 1839 CE ((Whitfield Potter et al., 2003)), as the possible period of the end of the utilization of such structures.

3.2.3. New Mexico

Inside the area of the El Malpais National Monument (ELMA), in the western part of the state of New Mexico, more than 453 lava tubes have been documented, of which 94 have seasonal and/or perennial ice or once had it (Onac et al., 2020). Instituted in 1987, El Malpais National Monument includes a significant part of the Zuni-Bandera Volcanic Field (ZBVF) and additional surrounding lands. In the course of the last 10.000 years, this area has witnessed the presence of various populations, which have created peculiar relationships with its landscape, in particular with its pyroducts, which were used for different purposes. The Anasazi civilization, which lasted from AD 1 to 1130, was probably the first to regularly visit and use the ice caves of the ZBVF. The Anasazi civilization was a great society that, at the moment of its peak expansion, had a network of roads and hundreds of small farming communities, many of which surrounded the ZBVF (Magnum, 1990; Fagan, 1991). Over the years, more than 60 Anasazi campsites have been found in the area (Carlton, 1988), most of which are located near ice caves. Here, it is suggested by the presence of large charcoal, ash deposits, and pottery shards that this ancient population utilized ice caves for melting perennial ice to obtain water for drinking and domestic purposes and probably also for ceremonial and medicinal use (Marinakis, 2012; Onac et al., 2020). Later populations, such as the Acoma, Zuni, and Laguna peoples, who succeeded the Anasazi after their fall in CE 1130, kept locating campsites near the lava tubes and kept utilizing the ice caves to replenish their water, for domestic and religious purposes, but also utilized the caves as sheep traps for hunting Bighorn sheep (Powers and Orcutt, 2005; Marinakis, 2012). Starting from CE 1540, with the arrival of Spanish conquistadores and Europeans, Native Americans were slaughtered and displaced. In this period, they would often use their knowledge of the many lava tubes of the ZBVF to take refuge from the conflicts and stock provisions (Powers and Orcutt, 2005).

Years later, during the 1880s, after the territory of Nuevo Mexico was

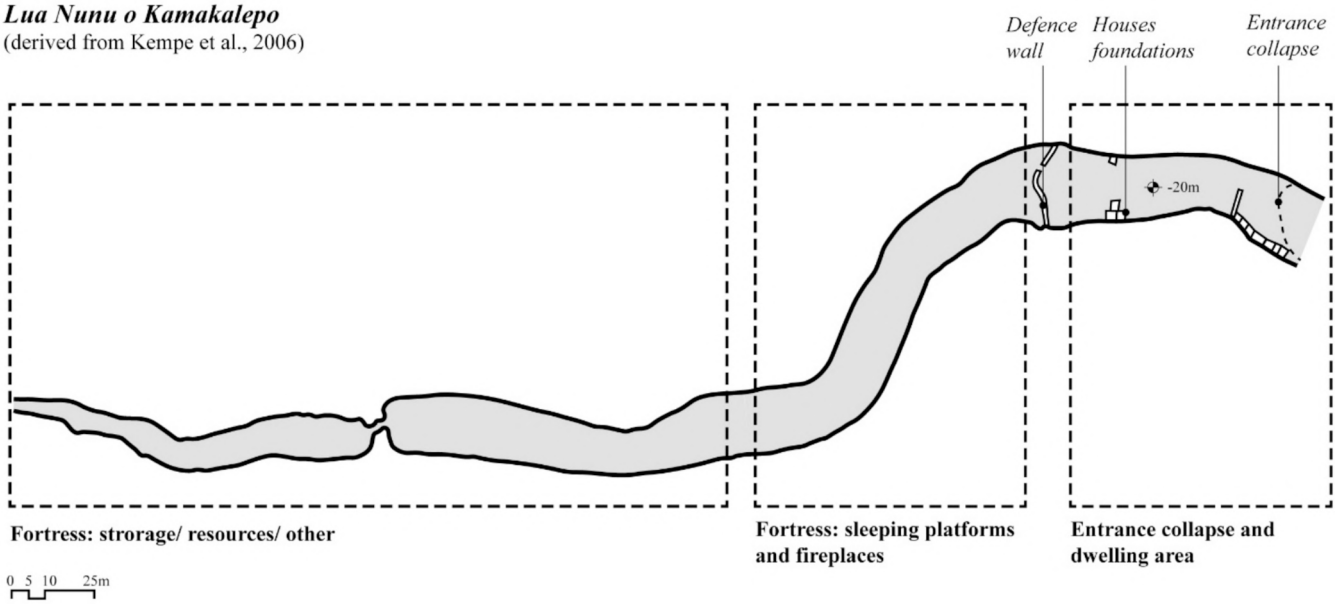

Fig. 3. Lua Nunu o Kamakalepo lava tube functional distribution. Some huts' foundations were located at and just after the entrance collapse and before the entrance of the underground fortress, behind which many sleeping platforms and fireplaces are present to a depth of around 100 m. After that, the lava tube was used for other purposes. Plan redrawing derived from (Kempe et al., 2006a) .

conceded to the USA, many settlers arrived at the city of Grant to work for the construction of a railway line that crossed the ZBVF on the northern edge. There, workers quarried ice from a large ice cave, which came to be known as the Grants Perpetual Ice Cave (Magnum, 1990) and continued until the 1940s (Marinakis, 2012). During the past century, the lava tubes of this area were explored and surveyed by different scientists due to their similarities with lunar rilles (Hatheway and Herring, 1970). Today, as part of the El Malpais National Monument, the caves of the area are all protected, with only a few being visitable to the public, such as the Giant Ice Cave, Junction Cave, and Xenolith Cave, after the obtainment of a free permit.

3.3. Spain, Canary Islands

The Canary Islands are an archipelago of volcanic origin that is constituted by seven main islands and is around 100 km from the northwest African coast in the Atlantic Ocean. From East to West, the islands are Lanzarote, Fuerteventura, Gran Canaria, Tenerife, El Hierro, La Gomera, and La Palma. Their geological history dates back to the Oligocene, 39 million years BP, with several constructive and destructive events and geological processes, which have taken place up to nowadays, with great impacts on the island's landscapes, lives, and cultural heritage of their inhabitants (Sánchez et al., 2019).

Known also as the 'Lucky Islands', or the 'Eternal Islands' in Arabic literature, the Canary Islands were first documented by Greek and Roman sources, which attributed their discovery to the Phoenicians around 2470 years ago and later to King Juba II of Numidia and Mauretania around 2050 years ago. Arabic sources recount further exploration during the 10th century, describing islands inhabited by an organized society, but systematic exploration resumed only in the 14th century with Portuguese expeditions, followed by the Spanish conquest in 1496 CE after nearly a century of conflict with the natives (Mutti, 2023).

The local pre-Hispanic populations, collectively known as the "Guanches", had distinct names on each island, such as the Majos in Lanzarote and the Benahoaritas in La Palma. These groups, likely of Berber origin, are thought to have settled in the Canary Islands between 100 and 400 CE (Santana et al., 2024). However, following the Spanish conquest, much of their culture was lost as they were assimilated by the new rulers.

Due to their origin and basaltic volcanism, lava tubes are very common features in the Canary Islands, which host some of the most impressive volcanic cavities in the world, such as the La Corona Lava Tube System in Lanzarote (Sauro et al., 2019; Tomasi et al., 2022).

Starting from the 18th century travelers, geologists, and naturalists started with the first pioneering speleological works in the Archipelago (Hartung, 1857), which, over the years, resulted also in archaeological shreds of evidence showing that the native populations, despite lacking inter-island contact, shared a deep connection with these volcanic formations: as reported already by the European reporters of the 16th century (Espinosa, 1980; Macías Hernández, 2024; Torriani, 1978) the native populations of the Canary Islands utilized natural caves and inhabited artificially created ones. In particular, they often used the lava tubes as dwellings, storage sites for agricultural goods—especially cereals and legumes—seasonal shelters, refuges from invaders —and later pirates—acquisition of water resources, places of worship, and burial sites for their mummified dead, often establishing true necropolises within them and examples of these kinds have been documented in Fuerteventura, Lanzarote, La Palma, Tenerife (Macías Hernández, 2024; Mutti, 2023; León Hernánz, 2019; Pais Pais, 1994; ; Mutti, 2023; .

At present, the lava tubes of the Canaries not only present extremely valuable resources to study the remains of populations long forgotten, which have left very few traces and none written (Pais Pais, 1994; Mutti, 2023), but they also show some of the most interesting examples of caves of this kind being used for touristic, societal and scientific purposes (Peñate, 2019; Sauro et al., 2019).

3.3.1. Lanzarote

On the island of Lanzarote, whose Native name is "*Tytheroygaka*" (Mutti, 2023, p. 126), is located one of the most remarkable lava tubes in the world, La Corona Lava Tube System, also known as La Cueva de Los Verdes, which represents just one of its parts. Originating around 21.000 years ago, from the volcanic activity of the La Corona volcano (Tomasi et al., 2022), it was first depicted in 1857 (Hartung, 1857) and, over the years, has been the subject of numerous surveys (Montoriol-Pous and De Mier, 1969; Santagata et al., 2018). Various sources in literature account for the use of this pyroduct by the islanders since ancient times as a refuge from the incursions of invaders and pirates after the European conquest (Chil, 1876; Peñate, 2019). Other authors have reported its use for the search of water resources and burial due to the finding of human remains (Chil, 1876). On this last point, some researchers do not consider the case reported by Chil as evidence that the Natives of Lanzarote, the "*Majos*", mummified and buried their bodies in underground necropoleis, as in the case of other Islands such as Tenerife or Gran Canaria (Atoche et al., 2008; Soler Segura, 2016). However, the Cueva de la Chifletera, a lava tube of 500 m of development in the area of the Malpaís de El Mojón, inside the Parque Natural de Los Volcanes, not only shows signs of past use due to the presence of ceramics, sea shells, and lithics but also hosts the archeological remains of a Majos sepulture, which were found by a group of local speleologists and were dated to the 3rd century CE, being amongst the oldest archeological findings of the whole archipelago (de León Hernández, 2024). Other caves in the area, such as the Cueva de las Plumas near the Cueva de la Chifletera and others in the area of El Mojón, were utilized for habitation purposes and show clear signs of past utilization by the Majos and in post-colonization times. These caves were also used by hunters and shepherds and their flocks as overnight shelters and often had an entrance wall made of stacked rocks at the mouth of the cave (de León Hernández, 2024); Macías Hernández, 2024). Recently, scientists have reported the presence of significant quantities of animal bones and pottery in some sections of the La Corona lava tunnel, which haven't been dated and so may be either from pre- or post-colonization times (Sauro and Barbieri, 2025). Given the setting, it is essential to remark that from 1730 to 1736 and again in 1824, recent volcanic eruptions dramatically changed the landscapes of the Island, covering one-quarter of its surface with lava and ashes, which nowadays constitute the National Park of Timanfaya, the Parque Natural de Los Volcanes and areas such as La Geria. Before the eruptions, this area was renewed to host several fertile lands of the island and had a significant cultural heritage which was all destroyed: 14 villages and 8 small towns completely disappeared, while more than 30 volcanic cones appeared, many new lava tubes of originated, such as the famous Cueva de Los Naturalistas, and probably many were lost. In particular, this area was occupied significantly by the Majos, and many archeological remains were present. Perhaps it is possible that much knowledge about some of their practices was lost forever (de León Hernández, 2019). However, in a recent study, Macías Hernández (2024) stated that, despite popular opinion, Majos didn't live exclusively in natural caves or artificial caves but also, and possibly mostly, in villages (Macías Hernández, 2024).

During the 1960s, a portion of La Cueva de Los Verdes was adapted by the artists César Manrique and Jesús Soto to make it accessible for tourism and to promote Lanzarote's unique landscapes. The project included the design of specific lights, which illuminate this tourist section of the cave, and the installation of speakers that play soundtracks from the movie *2001: A Space Odyssey*. The result is a tourist pathway that guides visitors through the volcanic underground landscapes of Lanzarote, enhancing and showcasing their unique features (Peñate, 2019; Scarpa, 2019). In 1966, another section of the Lava Tube, La Corona started to be adopted by Manrique: Los Jameos del Agua. This time the project, which lasted till the 80 s, not only adapted a significant portion of a lava tube for being visited by tourists, but he transformed it into a communal underground space for the island, featuring a bar, a restaurant, and an auditorium—all located within the lava tube, making

it a unique case worldwide (Peñate, 2019; Scarpa, 2019) (see Fig. 4).

Since 2016, because of the striking analogies between this cave and candidate lava tube collapses detected on Mars and the Moon, the European Space Agency has used the Corona cave system for the geologic training for astronauts and for testing new exploration and scientific technologies within the CAVES and PANGEA programs (de León Hernández, 2019; Massironi et al., 2023).

During our visit in May 2023, we visited the Cueva de Los Verdes and Los Jameos del Agua in the context of the 4th International Planetary Caves Conference. There, we had the possibility of first-hand experiencing and visiting both touristic and non-touristic areas of the pyroduct, making part of the modern users of this stunning underground landscape.

3.3.2. La Palma

On the island of La Palma, whose original name is "*Benahoare*", the local native population, the "*Benahoritas*", made good use of caves and lava tubes, as pre-Hispanic remains have been found in most of the ones that are known at present such as La Cueva de Las Tijaraferas, Riscos de La Caldereta, Cuevas de Herrera (Pais Pais, 1994). Due to the great availability of these geological resources on the island, the Natives used pyroducts intensively as a shelter for shepherds, as seasonal or permanent habitations, or as tombs.

Some authors report that Benahoritas had specific habitability parameters for deciding which lava tube would be best for a certain function. As an example, in the case of habitation, some of these parameters were: i) the ease of access, ii) the depth, iii) the amount of natural light, iv) humidity, and v) proximity to water resources. On the other hand, the pyroducts that had unnoticed entrances or were difficult to access due to very narrow crawls and rooms were preferred for burials as they would discourage natural predators, such as dogs or people, from disturbing their ancestor's sleep. It is important to notice that not all caves were used for one purpose at a time throughout their history. There are examples such as the Lava Tube El Rincon and the Lava Tube de Tiglate, which had a habitation zone near and behind the entrance area and burials in their deeper and darker areas (Pais Pais, 1994).

Habitation caves were usually inhabited without excessive modifications of their original asset and were organized having the living spaces near the mouth of the cave, to have most of the natural light available and the least humidity. The entrance, however, was often closed with dry stone walls to protect the inside and the spaces in its proximity from the atmospheric agents. The internal floor was often regularized to have a flat plane, and the internal space was partitioned with walls made of leather or woven vegetal structures for dividing the various zones of the cave house, such as the living and the sleeping areas. On the walls, shelves or ledges were often created shelves or ledges where to store tools and utensils, while tables and seatings were made out of locally sourced rock. Despite what was stated in the paragraph above, sometimes, deeper and darker sections of the caves were also used for habitation, but probably for seasonal use only (Pais Pais, 1994).

3.3.3. Tenerife

Regarding Tenerife, whose original Indigenous name is "*Achinach*", resources in the literature refer to lava tubes and caves used for religious purposes, for burials of mummified corpses, and others for habitation (Chil, 1876; Atoche et al., 2008; Mutti, 2023).

3.4. Italy

In Italy, the occurrence of human habitation and use of lava tubes seems to be mostly limited to one specific area: the flanks of Mt. Etna, in Sicily. Etna is a complex stratovolcano with a height of 3357 a.s.l. Here, complex and long relationships entwine the local populations with its numerous caves, from prehistorical times until present times (Privitera, 1999; Puglisi and Santi, 1999).

3.4.1. Mt. Etna

Pyroducts on Mount Etna have existed since ancient times. Due to its ongoing activity during the last 500.000 years, many lava tubes were created, and many others were destroyed years after their creation. Its volcanic landscape is in constant change, and caves are just one of its landforms. However, volcanic caves have had a strong relationship with the numerous populations and cultures who have lived on its flanks. Numerous myths depicted Mt.Etna and its caves as the places where ancient gods and mythological beings lived: the Roman poet Claudiano, in his *De raptu Proserpinae*, tells that the Persephone was abducted by Hades on the flanks of the volcano and Catanese writers from the XVII century imagined that he exited hell from a cave known as Santa Sofia Cave (Santi, 1999).

Historically, the first pieces of evidence of human occupation and use of Etna's pyroducts are dated to the Late Copper Age and the Ancient



Fig. 4. From left to right: Touristic section of La Cueva de Los Verdes, the research module in the non-touristic portion, and the central section of Los Jameos del Agua, with a small skylight on the ceiling above. This could well represent situations like the one in Fig. 1, where the underlying lava tube is much bigger than the observable pit/skylight.

Bronze Age, from around 5000 years to 3400 years BP, with an abrupt decline of their use from the Middle Bronze Age, 3400 – 3270 years BP, to modern times. The reasons for this abandonment are still uncertain (Privitera, 1999). Within this timeframe, caves were used for habitation, burial, and religious/initiatory ritual functions by prehistoric cultures. Some of these caves, such as Grotta Petralia, present proof of prolonged use in time for different purposes. Concerning habitation, caves have been used in support of surface dwellings, as seasonal shelters, storage, and warehouses, as evidenced by the numerous findings of hearths, animal bones, and remains of processing materials. Other caves, such as Grotta del Santo di Adrano and Grotta di Nuovalucello, were used instead as collective burial grounds, where dead individuals were buried or their bones were brought after decomposition. These same caves were often used for religious/ initiatory practices, related to ancestor worship and funeral ceremonies, and specific challenges to overcome, to access a particular societal group (Privitera, 1999).

Long after the prehistoric times, during the XVIII and XIX centuries, Etna's lava tubes started to be described by numerous travelers and artists and surveyed by naturalists who were visiting Sicily for the experience of the heroic ascension to the top of Mt. Etna. It is in this period, especially thanks to scientists such as Déodat de Dolomieu and Wolfgang Sartorius von Waltershausen, that Sicilian lava tubes started to be scientifically described, as in the case of Grotta delle Palombe, explored by the first for its entrance part and surveyed by the latter, representing the first survey of a volcanic cave in Italy. Sartorius's pioneering work laid the foundation for vulcanospeleology in the area. Its development resulted in the exploration of more than 261 caves and the survey of many of them (Centro Speleologico Etneo, 1999), allowing much of the knowledge of today regarding their geological genesis and human use through history. From the reports of the above-mentioned travelers and naturalists, it is possible to learn about some of the uses of lava tubes at that time. In particular, we learn that during the ascension to Mt.Etna, local guides would lead their followers to some specific caves on the path to the top, where to shelter, eat, and rest before the last part of their trip, which would begin at midnight, to reach the summit craters with the first lights of the day. One of these caves, which no longer exists, was known as Grotta delle Capre (Puglisi and Santi, 1999). Another extremely interesting description of the use of lava tubes that was done at that time is offered by the artist Jean-Pierre Houël, who depicted and described the utilization of the Grotta dei Ladri for the accumulation and storage of snow. The cave was artificially modified with the creation of a stair that connects the surface and the underground through a partial collapse of the lava tube and three artificial holes in its roof, from where, during winter, the snow collected on the surface was shoveled from the surface down into the cave for storage. In summer, the snow was pressed, enveloped in leaves, and put into sacks of straw to be transported. In fact, since the XVI century, the commerce of ice in Sicily was a very important economic activity for the people of Etna, who provided ice to Sicily, Naples, but also Malta, which, as for the case of the Grotta dei Ladri, had several of these caves rented and modified at their expenses (Puglisi and Santi, 1999; Battiato, 2024; Priolo, 2024).

Another historical typology of the use of Etna's pyroducts, which still live to the present time, is the religious one. An example is the Grotta del Santo di Adrano, which has been mentioned before for its burial site and religious/initiatory uses during prehistoric times. The cave takes its name from the Christian saint Nicolò Politi of Adrano, who lived as a hermit in the entrance area of the cave for three years when he was 17. Because of this, the lava tube became a sanctuary for his fellows in the town of Adrano, who every year hold a procession to pay a visit to the cave and the saint (Privitera, 1999; Santi, 1999), creating a sort of continuity in use from prehistoric to today times. Similarly, the Grotta dell'Intraleo, in its northeast-facing branch, presents a small sanctuary with an altar and Virgin Mary (see Fig. 5). We tried gathering data regarding its date and use, also asking our local colleagues of the Istituto Nazionale Geofisica e Vulcanologia of Catania, but we didn't obtain any. In describing the cave, Sartorius (Von Waltershausen, 1880) mentions that this section was used by shepherds as a shelter for themselves and their flocks since ancient times (Von Waltershausen, 1880). This might also explain the little sanctuary and why somebody took care of partially closing the entrance to this section of the cave with an artificial wall, leaving a door in the middle. However, this is another clear evidence how the still ongoing use of caves by the locals (see Fig. 5). In the depth of the southern branches of this cave, we also found several fragments of ceramics, which testify to the practice of collecting potable water observed by Sartorius (Von Waltershausen, 1880).

3.4.2. Pantelleria island

Pantelleria is an island located in the Mediterranean Sea, near Sicily, and represents the tip of an underwater volcano complex, which lies more than 70 % below sea level. Nonetheless active volcanism in the area over the last 320.000 years; the last eruption activity occurred in



Fig. 5. North-east facing branch of Grotta di Monte Intraleo. It is possible to observe the man-made wall at the mouth of the cave and the recent hearth. Facing the entrance lies a small sanctuary, which seems to be still visited. In the back, the cave continues through narrow passages where a great quantity of animal bones is present, to then stop abruptly.

the year 1891 CE (Bucolo et al., 2021). Here, despite the potential of future discoveries, at present, only a few lava tubes and volcanic caves are known, with an almost complete lack of speleological bibliography. One recent work has surveyed some of the lava tubes and volcanic caves in old lavas datable 35.000 to 29.000 years old. Only one lava tube, the Grotta dei Briganti, is associated with a temporary occupation by a group of young people who, during the Unification of Italy, which happened eventually in 1861, refused to carry out military service and fled to hide in the cave. Unfortunately, they were found and executed in public. The other cave that was found is not a lava tube, but a fracture cave called Grotta della Cisterna, which possibly contained artifacts from the Punic period and more recent human remains, probably dating back to the Middle Ages, since the "*IHS*" Christian graffiti was found nearby (Bucolo et al., 2021).

3.4.3. Mt. Vesuvius

Despite a fascinating report in 1918 described in detail a lava tube formed during the 1858–1861 eruption (Malladra, 1917) and recent studies, which have studied again the same pyroduct with modern technologies (Lemaire et al., 2024), no documents or shreds of evidence of human use of lava tubes on Mt. Vesuvius were found in the literature by the authors.

3.5. Jordan

Similarly, for Saudi Arabia, vulcanospeleology research in Jordan is quite young. Much of the work has been done starting from 2003, and in 2012, more than 23 lava caves were surveyed, 9 of which are pyroducts (Kempe, Al-Malabeh, and Horst-Volker Henschel, 2012). Mostly located in the center of Jordan, towards the Syrian border, these lava tubes are contained in the Harrat Al-Shaam, a basaltic lava plateau with an extension of 700 km, which crosses south Syria, central Jordan, and north Saudi Arabia. Compared to other lava tubes seen in this article, the ones located within the Harrat Al-Shaam are very old, as the youngest flow of this plateau, located in the Al-Fahda area in Jordan, is more than 400.000 years old (Tarawneh, 2000; Kempe, Al-Malabeh and Horst-Volker Henschel, 2012).

At present, despite some findings of human remains and a Byzantine oil lamp inside the Al-Fahda Cave (Al-Malabeh et al., 2008), we haven't been able to find in literature specific sources regarding the exact human uses of lava tubes as shelters or for habitation. However, some sources refer to some uses by the Bedouins. The first is to close the entrances of lava tubes and caves to keep hyenas away from the area, as many of them in the country are intensively used by these predators (Kempe et al., 2006b). The second is instead related to the creation of water reservoirs. In fact, despite the arid climate, a wet roof and dripping water have been reported for caves such as Al-Fahda, even at the end of September, demonstrating their characteristics of insulation (Kempe et al., 2006b). It is reported in the literature that Bedouins had the custom of building artificial channels that could bring winter rainwater inside the caves to be stored for the more arid months (Al-Malabeh et al., 2008; Helms, 1981; Kempe et al., 2006b). Ruins of these kinds of channels were found in the proximity of Al-Fahda Cave, actually leading to its discovery in 2006 (Kempe et al., 2012).

3.6. Saudi Arabia

Even though Saudi Arabia is a country that has over 80.000 square km of lava fields. Before the year 2001, only a few reports regarding lava tubes were made, and no surveys were known to be conducted. Starting from 2001, thanks to the work of scientists such as Dr. J. Robool and J. Pint, the first exploration and survey endeavors were undertaken and published (Roobol et al., 2002; Pint, 2006). These first experiences inside the lava tubes located within the Harrat Kishb lava field, in the vicinities of the Jebel Hil Volcano around 300 km northeast of the city of Jeddah, found remains of ancient human occupation of the Mut'eb, Ghostly, and Dahl Faisal Caves. At first, they found the remains of what seemed to be an ancient man-made wall across the front of the cave open towards the collapse entrance, indicating its possible use as a shelter in undefined past times. Similarly, in the second cave, the remains of a stone wall were found at its entrance, and two curved throwing sticks, resembling instruments depicted in Neolithic rock art found in Saudi Arabia, were found in the deeper and darker areas of the cave. The same applies to Dahl Faisal, which also showed traces of past human occupation. Although the discovery of these human artifacts indicated possible past occupation of lava tubes in Saudi Arabia, significant archaeological efforts were not undertaken until recent times. In particular, a study focusing on the Umm Jirsan Lava Tube, located in the Harrath Khaybar, in the northwest area of the country, revealed repeated phases of human occupation of the site ranging from at least the Neolithic through to the Chalcolithic/Bronze Age – 6800 to 3000 years ago. In particular, the pieces of evidence collected by the archaeologists comprehend several lithics acquired both inside the cave and in great numbers at its entrances, where particular circular stone structures were found, accounting for the possible utilization of the caves as temporary shelters. Linking the occupation stages with nearby archeological findings of megalithic structures and engravings and the geographical location of the cave within two important oases of the region, it has been proposed that Umm Jirsan was used at various stages in time by pastoralists as a stopping-off point providing protecting for the sun and wind, but also possibly providing water resources (Stewart et al., 2024).

3.7. Kenya

Cave exploration and habitation in Kenya date back at least 5000 years (Clarke, 1996), and caves in general were used among various Kenyan communities as refuges, burial centers, mineral mining, and for religious purposes (Mwaniki, 1973). Of course, this also applies to lava tubes. Kenya hosts numerous volcanoes, and different lava tubes have been discovered within their lava fields, thanks to the effort of international speleologists, scientists, and mostly by the huge effort of the local caving team Cave Exploration Group of East Africa (CEGEA) over the last century.

Examples of past human uses of lava tubes are found in the area of Mount Suswa, a volcano located in the Rift Valley, 90 km N/W from Nairobi, where the first lava tube explorations started to take place around 1962. There, Glover (1965) reports pieces of evidence of visit and use by primitive man, in the form of obsidian artifacts and stone tools, and the use by the Wandorobo hunter-gatherers. Also, the caves of the area were used as refuges by the Mau Mau freedom fighters during the Kenya Emergency, known as the Mau Mau Rebellion, between 1952 and 1960 (Glover, 1965). Exploration and visits with negative impacts on the cave environment have also been reported before 1964, which led to increased efforts on cave conservation and the encouragement of respectful scientific activities (Kennedy, 1998). Also, a lava tube named Cave 18 was used as the location for the film Sheena – Queen of the Jungle before its release in 1984 (Kennedy, 1998; Middleton, 1998).

Other caves mapped by the CEGEA, which show traces of human use, are located in the lava flows of the Chyulu Hills, which cover an area of around 2000 km^2 south of Nairobi and near Mt. Kilimanjaro, with the most recent lava flows dated at 535 – 255 years ago. One of these, the Mathaioni Lava Cave, in 1972 became the country's first touristic cave, which also hosts mysterious man-made rock cairns, deep in the tube (Simons, 1972; Middleton, 1998; Kennedy, 1998). Similarly, Shaitani Lava Cave, a small lava tube of 200 m, has also been opened to the public. Another cave in the area, named Kimakia Cave, was first explored in 1965 and was used for mining Bat Guano to be used as fertilizer in agriculture, and internal routers were marked by the miners (Middleton, 1998; Kennedy, 1998). Unfortunately, in recent times, between 1992 and 1993, caves in the Chyulu Hills area were used as shelters by poachers (Kennedy, 1998).

3.8. China

Many active volcanic centers in China occur in contrasting geotectonic zones, and some of these are known to possess basaltic lava flows. In particular, the volcanic fields of Wudalianchi and Jingpo Hu in Heilongjiang province, the Tianchi Volcano in the Jilin province, northeast China, the Leiqiong volcanic field in Guangdong and Hainan provinces, South-East China and, lastly, the Tengchong volcanic field in the Yunnan province, South-West China, are all known to host several lava tubes (Wood and Zhang, 2010; Chen et al., 2015; Chen et al., 2016). Unfortunately, a systematic mapping hasn't yet been performed, and only a few surveys and limited information are available, especially in the English language (Wood and Zhang, 2010).

The Wudalianchi volcanic field is believed to have developed through seven different phases between 2.1 million years ago and 1720–1776, when the last eruptions occurred. There, different volcanic caves are known in the recent lavas close to the Laoheishan crater (1720–1721), such as the Fairy Palace Cave and Waterfall Palace Cave, and the much older lava erupted from the East Jiaodebushan volcano (0,70–0,88 Ma), where the Ice Cave and Underground Ice River Cave are located. While the authors haven't been able to find direct information in the literature regarding the current or past human utilization of these lava tubes, on the web it is possible to assess how some of these ice caves have been adapted to touristic purposes, with the creation of walkable paths and showcasing beautiful ice sculptures (Flossie, 2018). In addition, as seen in other parts of the world (see Sections 3.2.1, 3.2.2, 3.2.3, 3.4.1), those ice caves could likely have been used by the local populations to acquire water ice or as cold storage.

In the Heilongjiang province is located the Jingpo Hu volcanic field, which has been dated to Pleistocene-Holocene. Here, several caves are known, and many have been adapted to receive tourists. One particular example regarding past human uses is the Kanlianmiying Cave, also known as "Anti-J Allied Army Secret Camp", that, during the anti-Japanese period was used by anti-J soldiers, which were encamped there from around 1937 to 1945 remains of their encampments are still present, therefore giving great historical significance to the cave (Wood and Zhang, 2010). In this area, one recent survey endeavor has been undertaken by Yang et al. (2024), who surveyed the Shenyang Cave lava Cave with the application of several innovative approaches and technologies.

Eventually, little information is available on the lava tubes of the Leiqiong volcanic area, a 7300 km^2 basalt-basanite plateau that extends across the Leizhou Peninsula, the Guangzhou Province, and the northern part of Hainan Island, in Southeast China. Volcanic activity in this area dates back mainly to the Pleistocene and Holocene. However, the latest eruptions, which took place in the northern Hainan area, took place in 1883 and 1933 (Wood and Zhang, 2010). Little information is available regarding the lava tubes of this area, some of which have been opened to tourists (Wood and Zhang, 2010). Recently, Feng et al. (2024) surveyed one lava tube in the area, known as "Seventy-Two Caves", which, contrarily to other pyroducts in the area, has not been converted into a tourist site.

In addition to these three main locations, lava tubes have been described also on the flanks of the Tianchi, a hazardous volcano located on the border between China and North Korea, with an eruptive history spanning from 5 to 0,75 Ma to 1 Ma (Fan, 2008; Fan et al., 2006; Liu et al., 1998; Wei, 2004; Wei et al., 2013,). In particular, Chen et al. (2015) produced a survey of a lava tube named Silidong, reporting interesting geological findings but nothing regarding possible human uses in the past. For sure not at present, as they reported a thriving fauna nesting in the cave (Chen et al., 2015).

Lastly, Chen et al. (2016) surveyed and described a lava tube, named Jingfudong, within the flow of the Laoguipo volcano, in the Tengchong volcanic area, in the Yunnan Province, South-West China. Here, the authors state that many other lava tubes exist within the flows of another volcano in the area, the Heikongshan, that were used as refuges by Chinese citizens during World War II (Chen et al., 2016).

3.9. Vietnam

Nonetheless, prehistoric archaeology in Vietnam has more than 100 years of history; the first traces of human uses of volcanic caves and lava tubes are very recent. These were found inside caves located in the most active volcanic region in Vietnam, the Central Highlands Province, specifically in the rural Krông Nô District, part of the Đắk Nông province (Sử et al., 2022). Formed from the volcanic eruptions of Pleistocene, between 2,58 Ma BP to 11.700 years BP, since 2007 more than 45 of these lava tubes have been discovered, 10 of which contain traces of prehistoric humans, such as some tools, pottery, coal ash, stoves, graves, jewelry, and human remains (Phúc et al., 2018; Cường, 2022; Sử et al., 2022). Despite the presence of many prehistoric archaeological sites, organic remains are extremely rare in Vietnam. As many of these sites are open-air, so remains were often destroyed over time. For this reason, these findings have a great cultural and heritage value for the country, with a great potential for sustainable tourism development (Sử et al., 2022).

Archaeological shreds of evidence show that these caves were continuously inhabited by hunter-gatherers for nearly 3000 years, from 7000 to 4500 years BP, with the total abandonment of the settlement around 4.000 years BP. This period has been divided into two: during the first, going from 7000 to 5500 years BP, humans resided mostly in caves. During the second, which goes from 5500 years to 4000 years BP, some people left the caves to live outdoors while others kept permanently inhabiting the lava tubes. The analyzed pyroducts showed that humans inhabited the mouth of the cave, near the collapsed entrance. Here, finds show a mixed usage of the cave as a workshop for the production of lithics, stoves, pottery, and animals remain, showing the domestic use of the cave, and graves, which were curiously located near the hearth, showing that burial happened at the same time the cave was used as habitation. In particular, some jewelry made of shells of sea snails was buried with the dead, which were laid in a flexed position with their legs bent and heads facing northwest. Moreover, the study of these communities evidenced how, nonetheless, they were hunter-gatherers, they only killed a few individuals of each animal species, somehow with attention to the ecological balance of the area, so that they could permanently settle, without the risk of having to change location due to the depletion of resources (Sử et al., 2022).

3.10. Republic of Korea

Located in South Korea, Jeju Island hosts one of the most significant examples of terrestrial lava tubes, the Manjang Lava Tube, which has been ranked the 15th longest lava tube in the world, with a development of 7416 m. Its age of formation dates back to 300.000 – 200.000 years ago, and it still presents very intact internal morphology and features. The first mapping of this cave is dated to 1946, while starting from the 1970s the cave was again investigated, along with other lava tubes in the area. Surprisingly, almost at the same time and similarly as for La Cueva de Los Verdes in Lanzarote (see section 3.3.1), since 1967, a part of the lava tube of around 1000 m has been opened to the public, while all the rest of the cave is protected. Other lava tubes in the area have been used in the past. Examples are the Soecheon Cave, where ancient pottery can be found, and the Gimnyeonggul Lava Tube, which possibly was connected to the Manjanggul in the past, as they lie at a distance of 90 m, separated by a collapse. The cave, also known with the name of "Sagul" (Snake Cave), was opened to the public in 1962, earlier than the Manjanggul, but was closed due to safety reasons in 1991 and was opened again during the last decade. A cultural account is entwined with the lava tube, which, in a popular legend, was said to have hosted a snake in the past, which caused natural disasters unless a 15-year-old girl was offered in sacrifice. The legend also reports that in 1515, a judge, Mr. Line Seo, killed the snake and freed the village from the creature. This is

the reason why, by the entrance of the cave, a monument was established to honor him (13th International Symposium on Vulcanospeleology, 2008).

3.11. Australia

Until not so long ago, it was believed that Australian Aborigines did not use lava tubes in prehistoric times, neither during the pre-European/post-European conquest of the continent. Moreover, it was reported that they avoided them (Atkinson, 1991).

The Undara Lava Tube System, located in the state of Queensland and part of the Undara Volcanic National Park, originated around 190.000 years ago (Griffin and McDougall, 1975), by the eruption of the volcano Undara, which produced a lava flow with a length of 160 km and covering an area of 1550 km^2 with basaltic lavas. As a result of this activity, a lava tube system extending 110 km was created, of which more than 60 lava tubes have been discovered (Atkinson, 1991).

Aboriginal people first occupied the Australian continent between 65.000 to 40.000 years BP, living in many different environments. The Undara Lava Tubes are located in the cultural estate of the *Ewamian First Nation people*, inside a dry and tropical environment with vast savannahs and various landscapes. Here, as in other locations of the world, some lava tubes are known to contain permanent or semi-permanent water resources, in addition to a stable and cooler environment. Nonetheless, despite the finding of some artifacts at one cave entrance (Atkinson, 1991), it was thought for several years that the Natives did not use lava tubes, and also the Ewamian community did not possess any knowledge about it, as large-scale Indigenous community-led archaeological projects in Australia are exceedingly rare (Buhrich et al., 2023). Recent research in 2022, conducted with the participation of Aboriginal people, has brought evidence that indeed the Ewamians did use lava tubes, even if it is still not clear for what kind of purposes. In particular, the Darcy Cave, along with 14 other lava tubes, was surveyed and investigated. In 12 lava tubes out of 15, stone artifacts, animal bones, and charcoal were found, especially in the area near the entrance. Material recovered from Darcy Cave and dated proof of the use of the lava tubes in the last 700–1000 years. Inside this cave were also found 6 stone arrangements, inside of which the floor was cleared, indicating some kind of platform for resting or with another kind of unknown function. However, the Aboriginals participating in the expedition accounted for the utilization of the caves for ritual and habitation purposes (Buhrich et al., 2023).

3.12. Others

3.12.1. Portugal, Azores Islands

For the Azores, we weren't able to gather specific references regarding their use in the past by Natives or islanders. However, at present, 272 lava caves are known to exist in the Islands, many of which are lava tubes, and this is due to the active work of the local associations. Since 1963, with the foundation of the speleological society *Sociedade de Exploração Espeleológica Os Montanheiros* vulcanospeleology started in the islands, and the results of this research gathered important national and international attention. The first cave to be surveyed and scientifically described was the Furna de Henrique Maciel on Pico Island. In 1993, the first list of the Azorean caves was published, including 112 caves and several surveys (Borges, Silva, and Pereira, 1991), which have been updated recently (Pereira et al., 2015). Nowadays, caves open to tourism include Algar do Carvão, Gruta do Natal, Gruta das Torres, Furna do Enxofre, and Gruta do Carvão (Pereira et al., 2015).

3.12.2. Japan

Of all Earth's volcanoes, 67 are in Japan. On Mt. Fuji alone, which last erupted in 1707 CE, there are over 92 known lava caves, including the Mitsuike Ana, which spans an impressive 2139,75 m (Ogawa, 1982). However, despite the abundance and interest of these caves, we found no references in the literature regarding their human occupation or use.

4. Discussion

As shown throughout section 3, lava tubes are prominent features on Earth that have held lasting significance for various human cultures (Fig. 6). In some locations, such as Mt. Etna in Italy (see Section 3.4.1), Lanzarote in the Canary Islands (see Section 3.3.1), and the Heilongjiang province in China (see Section 3.8), these cultural connections endure to this day. Despite the geographical distances among the countries and regions studied, it is evident that many local cultures have used lava tubes in similar ways, particularly for purposes like dwelling, shelter, storage, water collection, burial, and ritual or religious practices. To better quantify these shared uses of the subterranean landscape, we conducted a statistical analysis examining the occurrence of these functions across the cases analyzed in the Atlas (see Fig. 7). Notably, a significant number of lava tubes have been used in similar ways, with unique exceptions in Iceland and Hawaii for fortified shelters, and in Los Jameos del Agua in Lanzarote, which stands as the only known example of a landscape design project of a lava tube, repurposed with modern functions such as bars, restaurants, and auditoriums. In 2016 alone, Los Jameos del Agua attracted 750.552 visitors (Peñate, 2019).

It is also essential to highlight that, in many cases, the information available in the literature is limited. This is partly due to the restricted availability of archaeological data — as observed in regions like Jordan, Saudi Arabia, and Australia — or the difficulty of finding available data in the literature, as in the cases of the Azores and Japan. Therefore, rather than a definitive "*yes or no*" classification for the practices in question, we adopted a "*yes or no data*" approach. This approach allows for the possibility that future archaeological discoveries could reveal additional uses previously undocumented in specific countries, regions, or populations.

In the following subsections, we will highlight notable characteristics in the utilization of lava tubes, which we find particularly fascinating, as they provide us with centuries of tested knowledge that might be relevant for future uses of these landscapes (see Fig. 10).

4.1. Habitations, shelters, and refuges

The first interesting aspect we noticed regards the choice of lava tubes suitable for habitation or shelter is that some cultures, such as the Benahoritas (see Section 3.3.2) and the Hawaiians (see Section 3.2.2), probably also due to the great availability of caves on their islands, had some parameters that guided their site selection, with of course some exceptions.

Hawaiians generally preferred short lava tubes for habitation, while they selected long lava tubes for the creation of refuges and fortified shelters (Sinoto, 1991).

Benahoritas instead had a true set of parameters for the choice of lava tubes suited for dwelling, either prolonged or temporary, which included both habitability factors, but also logistical ones, which were (Pais Pais, 1994):

- Lava tube dimensions;
- Internal asset – they preferred lava tubes that were almost ready to be inhabited, without the need to do much internal reshaping/adaptation work;
- Luminosity;
- Grade of protection from the atmospheric agents;
- Low humidity;
- Proximity to water and other resources;
- Proximity to pastoral paths.

A second aspect we noticed is that when lava tubes were used either for temporary shelter or proper dwelling, settlers tended to locate themselves at the entrance of the lava tube, where they had the most of the light coming in but were also more exposed to atmospheric agents such as rain and wind.

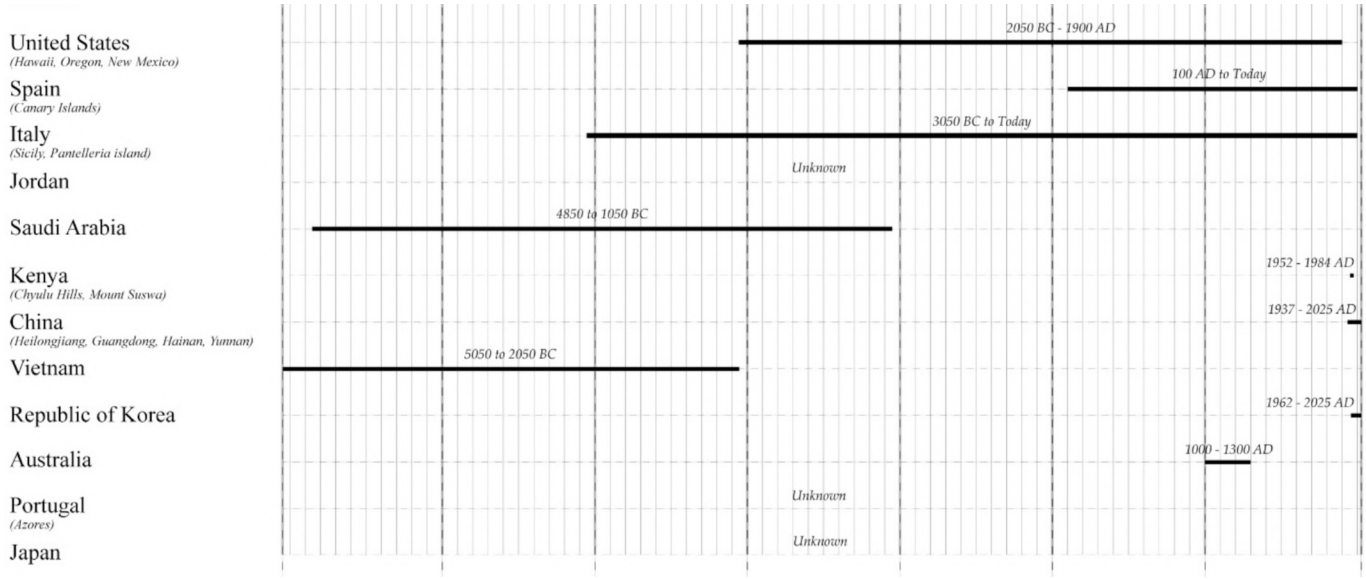

Fig. 6. Timeline of the uses of lava tubes for each analyzed country and region. The information in the figure is relative to the data we were able to find in the literature. Here, we exclude the contemporary tourist uses only, except for the Canaries and China, due to the modern uses of la Cueva de Los Verdes, Los Jameos del Agua in Lanzarote, and the ice lava tubes of the Heilongjiang province in China. For the United States, as we didn't find a specific date for which lava tubes stopped being used by Natives, we consider here 1900 CE, as it is after both the Massacre of Wounded Knee (1890), one of the last events of the Indian Wars and the End of the Kingdom of Hawaii (1893).

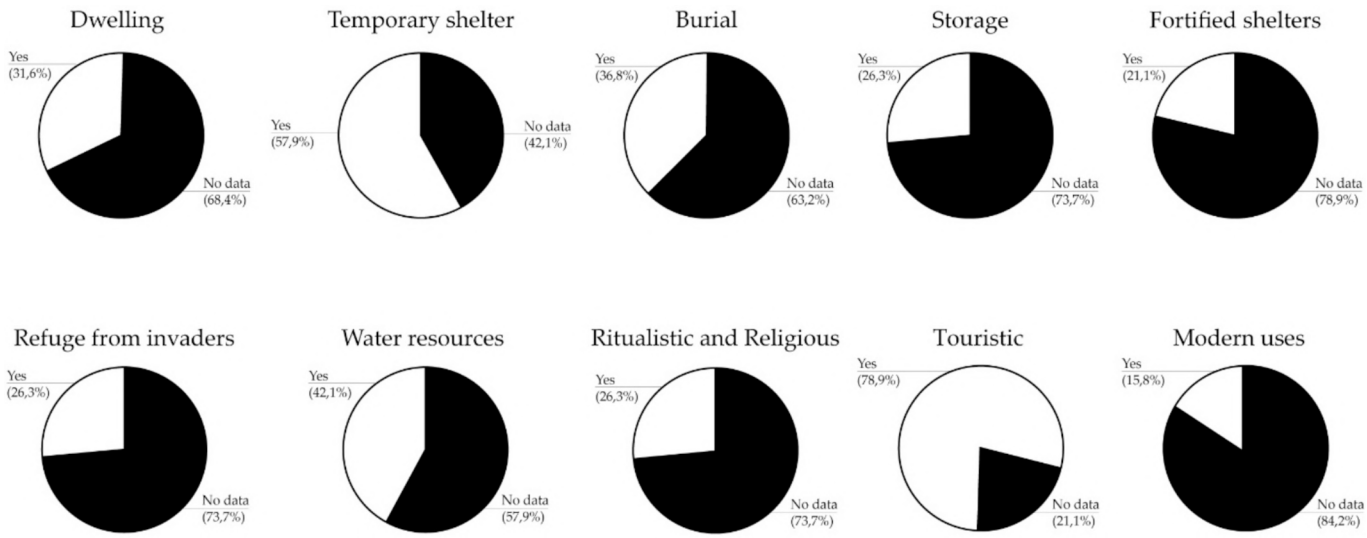

Fig. 7. The Atlas of Lava Tube Uses analyzes statistics about the uses of lava tubes in countries and regions. Regarding new modern uses, it refers only to the Canaries and China. In particular, Lanzarote hosts the only examples known to the authors of large-scale adaptation and implementation of a lava tube with modern functions, Los Jameos Del Agua (see Section 3.3.1).

This sometimes resulted in the creation of artificial walls to partially enclose the mouth of the cave to provide protection, as in the case of the pyroducts of La Palma (Pais Pais, 1994) or not, as in Vietnam's lava tubes (Sử et al., 2022). Behind the entrance, populations like Benahoritas would inhabit the cave until it received enough natural light, which would be around 20–30 m in depth, level the pyroduct floor and partitioning the living zone in different areas and functions, with material acquired in-situ (Pais Pais, 1994) (see Fig. 8), as we have also seen in the case of the fortified shelter of Hallmundarhellir, in Iceland (Smith et al., 2017). Similarly, Native Hawaiians used to clear the cave floor to create platforms that had several uses, such as sleeping areas, spaces for the hearth, and eating, as in the case of the Hilina Pali Site or the Lua Nunu Makai Cave (Sinoto, 1991).

4.2. Burial, storage, and other functions

A third fascinating aspect is that pyroducts that were not chosen for habitation or shelter purposes were utilized for other functions, which also had their parameters.

For example, in choosing caves suited for burial, Hawaiians preferred caves that had difficult accesses (Withney, 1893; La Plante, 1991; Sinoto, 1991), and the same applied to the Benahoritas, who, differently than the Hawaiians, sometimes buried their dead in the same caves they lived in, but very deep, in the areas too dark and too humid to be inhabited (Pais Pais, 1994). This is also true for the prehistoric populations inhabiting the caves on Mt. Etna, who also buried their ancestors deep into the caves and tortuous sections (Privitera, 1999) (see Fig. 9).

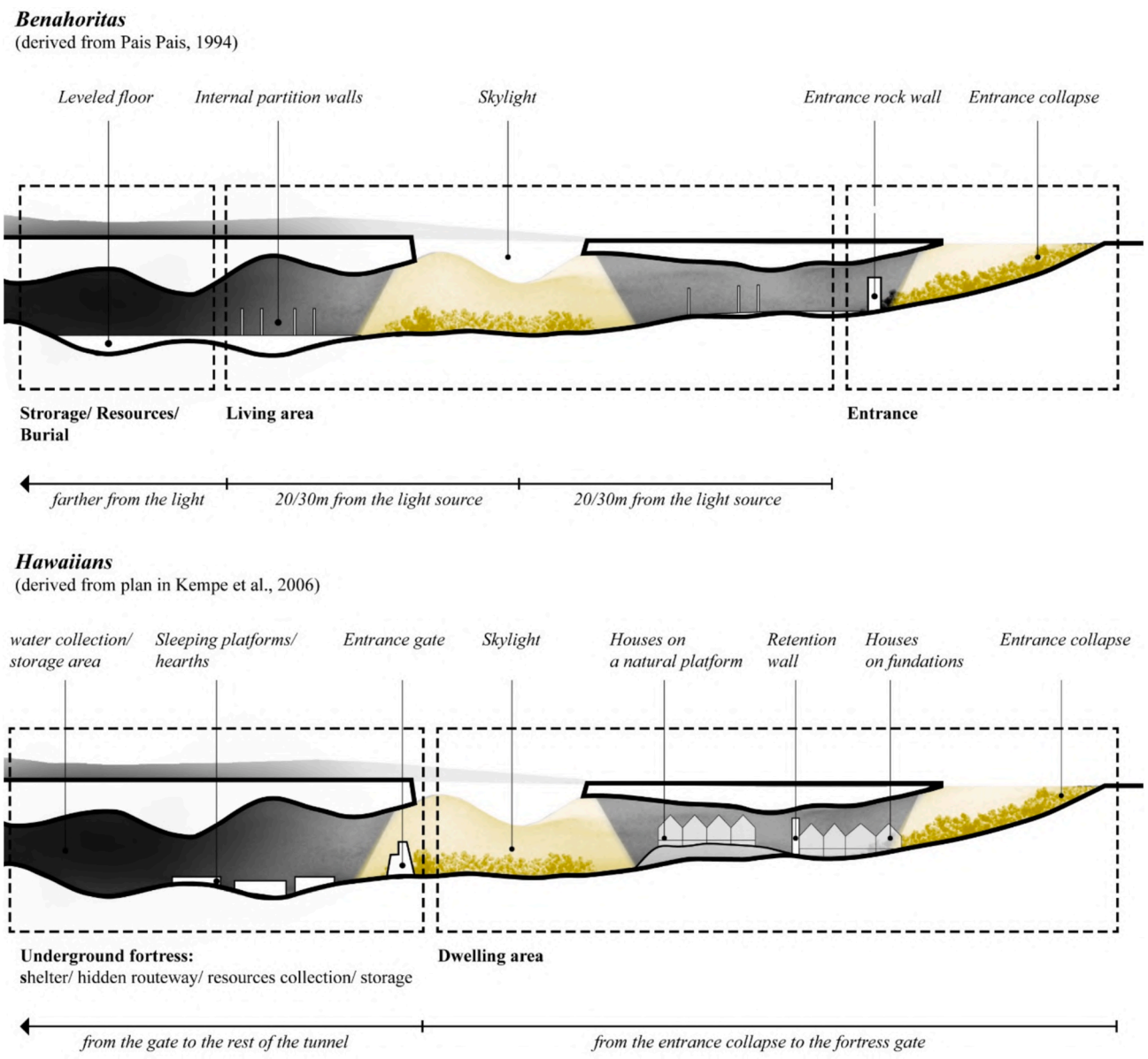

Fig. 8. Above: notional internal lava tube assets inhabited from the Benahoritas (see Section 3.4.1): they would construct a stone wall at the mouth of the cave, to protect the inside from the elements, level the floor with in-situ material, and then proceed to partition the interior space with walls made of leather or woven vegetal structures, for dividing the various zones of the cave house, such as the living and the sleeping area. On the walls, shelves or ledges were often created shelves or ledges where to store tools and utensils, while tables and seatings were made out of locally sourced rock. Below: Notional Native Hawaiians internal arrangement of a lava tube, based on the Lua Nunu O Kamakalepo and Luanunu Makai Cave surveys in (Kempe et al., 2006a).

Eventually, one last common valuable point, present in many of the different cultures studied, is the exploitation of lava tubes for the acquisition of valuable resources, like drip water or permanent ice, or for the prolonged storage of water and provisions, taking advantage of their great insulation properties, even in dry and hot environments (Al-Malabeh et al., 2008; Martin, 1991; Von Waltershausen, 1880; Helms, 1981; Atkinson, 1991; Greeley, 1971a; Onac et al., 2020).

4.3. Takeouts and future directions

Eventually, what are the lessons that it is possible to derive from the Atlas of Lava Tube Uses that can both inform future Space and Terrestrial planning and the valorization of these hidden underground anthropological and geo heritage? We think there are many (see Fig. 10):

Future applications of past knowledge: even though the principal aims of NASA Artemis endeavors are to return to the moon's surface and not underground (Artemis - NASA., 2024), lava tubes offer a terrific environment for future lunar and Martian exploration. Just like on Earth, they would provide a safe and protected environment from all the hazards present on the surface (Haviland, 2021). Moreover, in the lunar environment, due to the lack of atmospheric agents and water, which on Earth brings sediment inside the caves, pyroducts might be free from lunar dust (Martin and Benaroya, 2023), which is known to be a great risk for the health of future astronauts and researchers, especially in the long-term (Pohlen et al., 2022). In this sense, the past experiences of human habitation and the use of pyroducts are an invaluable source of knowledge for engineers, planners, and designers from which to learn possible utilizations, adaptation, and planning strategies. In particular:

Set of parameters for the selection of a site concerning its use. Hawaiians and Benahoritas had specific sets of parameters to select which lava tube was more suitable for which function. Future lunar and



Fig. 9. Narrow and tortuous passages deep in one of the branches of the Grotta del Santo di Adrano, a true lava tube maze. In these dark and narrow passages, more than a hundred meters from the entrance, ceramics and human bones can be found (see Section 3.4.1).

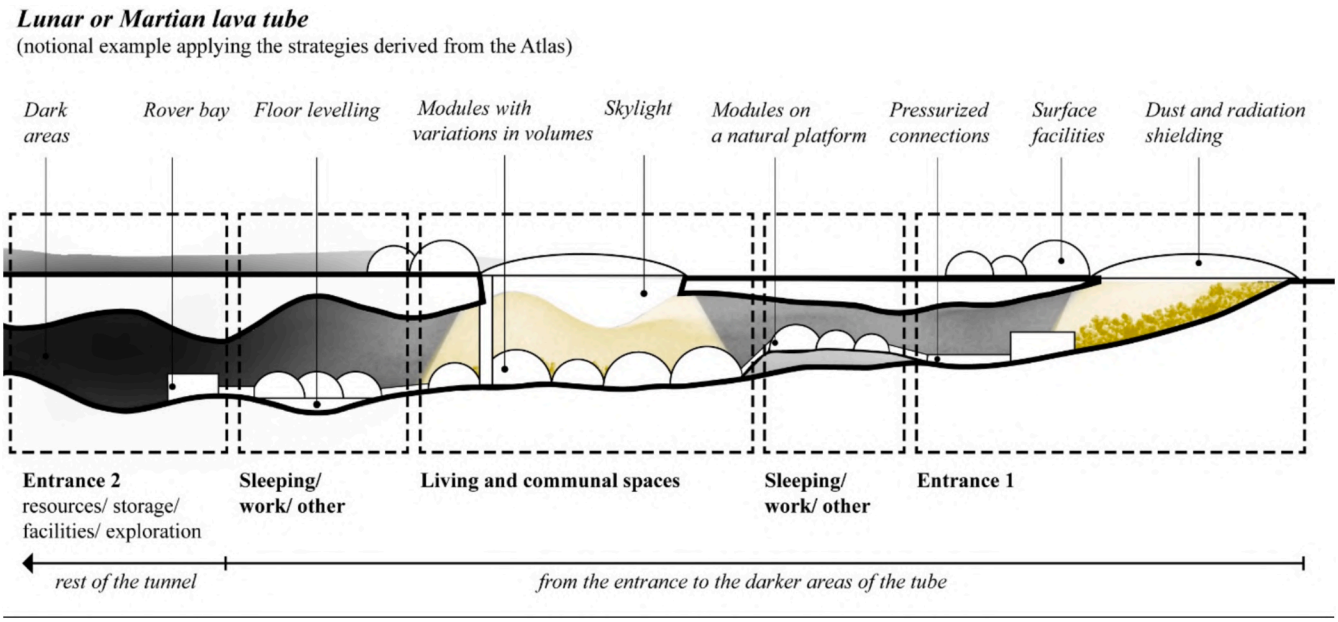

Fig. 10. Example of potential lava tube planning for future off-Earth applying the insights derived and used from the case studies here analyzed.

Martian lava tube exploration might benefit from this approach, which would provide future planners and decision-makers with a standard and consistent toolset for cave evaluation and appropriate use. Also, lava tubes that require less adaptation and modification work should be preferred.

Living spaces near the accesses and sunlight. It is clear from the experiences we analyzed how important the location of the habitation section at the cave entrances, the most lit areas of the tube, and the closest to surface resources. Regarding habitability, linking intuitive vernacular dwelling examples and best practices derived from world-wide underground urban developments (see Table 2), recent research on Terrestrial Urban Underground Space (UUS) has demonstrated how factors such as spaciousness, natural light, and Nature are key elements in tackling negative associations and emotions linked with the use of the underground space and how the points of contact between the surface and the underground are occasions for both physical and visual connectivity with the outside, both for logistical benefits, the establishment of a network of surface–subsurface relations and psychological well-being of the users (Debrock et al., 2023). However, it is also possible to learn that the entrances or local collapses of the pyroduct roof are also the most exposed areas to the atmospheric agents on Earth and mainly radiation on the Moon and Mars. Just like Benahoritas used to erect artificial walls to protect the living area of the lava tube, similar strategies would need to be adopted for future lunar and Martian lava tube habitats;

Darker, less comfortable areas: Internal and dark areas deeper in the cave and far from the entrance present a lower illumination quality but are less exposed to the atmospheric agents or radiation. These characteristics might be utilized for functions that require less natural light, as evidenced in the cases of the burial sites of Hawaiians, Benahoritas, and Ancient Peoples on Mt. Etna or the sleeping platforms of the Hawaiian underground fortress Lua Nunu Kamakalepo Cave;

Table 2
State-of-the-art livability requirements for the development of a sustainable Underground Urban Space from Debrock et al. (2023). It is interesting to confront some of the vernacular examples of lava tube habitations from the Atlas, in this case the Benahoritas and the Hawaiians, and note that some of the parameters they adopted to identify which lava tubes were more suitable for habitation purposes, or which parts of them were more suitable for dwelling or other functions, actually agree with modern UUS livability recommendations. When deciding where to locate the living areas, both the Benahoritas and the Hawaiians (who preferred short lava tubes for dwelling and long ones for refuge shelters, see Section 4.1) seemed to prefer places with the availability of natural light, close to the entrance or skylight.

Underground Urban Space (UUS)		
Main stressors Darkness, Humidity, Fear of entrapment, Feelings of crowding and stress, Lack of natural light, Dim lighting, Disorientation, Limited access to nature, Lack of windows, Poor ventilation.		
Design recommendations	**Mitigated stressor**	**Action needed**
Spaciousness	Fear of entrapment, feelings of crowding and stress, poor ventilation	Desing of sizeable spaces that provide a sense of openness, changes in volumes, noticeable entrances.
Atmosphere	Disorientation	Variation in design, in elements that provide environmental stimuli, creation of different perceived atmospheres.
Natural light	Lack of windows, limited access to nature, dim lighting, fear of entrapment, darkness	Use of skylights, light shafts.
Nature	Limited access to nature	Incorporate greenery, water fountains,

Vernacular Lava Tube Habitations about modern UUS requirements

Case study	**Habitability parameters**	**Mitigated stressors**	**UUS reference recommendations**
Benahoritas	Lava tube dimensions, readily inhabitable lava tubes, luminosity (to decide where to locate which functions), protection from the atmospheric agents, low humidity, proximity to water and other resources, proximity to pastoral paths.	Darkness, Humidity, Fear of entrapment, Feelings of crowding and stress, Lack of natural light, Dim lighting, Disorientation.	Spaciousness, Atmosphere, Natural light.
Hawaiians	Lava tube length (to decide if the lava tube would be used as a refuge shelter or as a dwelling), luminosity and habitation functions, protection from the atmospheric agents.	Darkness, Humidity, Fear of entrapment, Feelings of crowding and stress, Lack of natural light, Dim lighting, Disorientation.	Spaciousness, Atmosphere, Natural light.

Resource gathering and storage: Due to their particular insulation properties, just like on Earth, as seen in the case of lava tubes in Oregon, Saud Arabia, Jordan, and Sicily, to cite a few, caves might contain significant resources like water and ice, which might be locally acquired. Indeed, water ice has been hypothesized to be possibly present and trapped in Martian and lunar lava tubes (Williams et al., 2010; Cushing, 2012; Blamont, 2014). Also, like in the case of the Guanches of the Canaries, the Bedouins of Jordan, and the Native Americans of Oregon, Idaho, and New Mexico, lunar and Martian lava tubes might be great places to store provisions, assets;

Valorization and conservation of theEarth's underground landscapes: as we have seen throughout the cases proposed in the results section, caves are time machines. Due to their insulation properties, lava tubes can preserve manufactures, artifacts, and remains for a very long time, potentially leading to important archeological discoveries, and contributing to a better understanding of specific periods and habits of specific cultures. Moreover, when thinking about landscapes and man on Earth, it is often a relationship that is limited to the surface, while many equally important untold stories are happening in its underground lands. Therefore, we think there is an important need to valorize, protect, while at the same time communicating the existence and importance of these landscapes and the history of mankind that they witnessed.

5. Conclusions

In this paper, we have presented for the first time in literature a comprehensive Atlas of the various uses that many different cultures have done of volcanic underground landscapes worldwide. To do so, we analyzed documents related to pyroducts in Iceland, the United States, the Azores, Italy, the Canary Islands, Jordan, Saudi Arabia, Vietnam, Australia, and Japan. In the paper, we have also evidenced how, since the 1960s and the 1970s, different scientists noticed how some lunar features, such as the lunar rilles, presented striking similarities with their terrestrial counterparts and started to be interpreted as possible lava tubes. These observations boosted the discipline of volcanospeleology, which immediately became relevant also for space agencies such as NASA, which had already started during the 18th and 19th centuries, thanks to naturalists and geologists such as Georg Hartung, Déodat de Dolomieu, Wolfgang Sartorius von Waltershausen, and many other pioneers. We showed how the development of this branch of speleology and the discovery of lava tubes worldwide resulted in a great increase in archaeological findings in these structures, which resulted in the reconstruction of ancient relationships between ancient human

populations, the underground, and the uses they made of pyroducts. Further, we have analyzed the similarities between the uses of pyroducts by different cultures and recreated a timeline of their use across different cultures worldwide. Eventually, we have derived a list of past and centuries-tested lessons that might be useful for future lunar and Martian exploration, especially for what regards lava tube exploration and planning for the establishment of long-term habitats, which benefit from the protection and insulation from hazards such as radiation, micrometeorites impacts and lunar dust, which these geological structures offer. Throughout our research, we learned much about the importance of Terrestrial underground cultural heritage, which often is too relegated to specialized fields, such as speleology, archeology, and vulcanospeleology, and not communicated to the general public. Embracing the encouragement of Prof. Giovanni Badino, we hope with the present publication to provide tools for the specialists, but also interesting stories to the wider public of the Journal, expanding the knowledge about lava tubes worldwide. We are aware of the limitations of the present work, which needs to be implemented in several additional countries, regions, populations, and lava tube uses and forms, but we hope that the Atlas of Lava Tube Uses, here presented can serve as a foundational work to give cultural depth to lava tubes, from Earth to Space, from the past to the future.

CRediT authorship contribution statement

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

Declaration of competing interest

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

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Data availability

The datasets generated during the presented research have been made open-access and are available at https://zenodo.org/records/14535886.

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