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ORIGINAL ARTICLE

Discovering the 1858 Lava Flow Field at Somma-Vesuvius (Italy) Through geoitinerary, Virtual Tour and 3D Reconstruction of Volcanic Landforms

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Abstract

Geotourism in volcanic areas attracts millions of visitors each year travelling to see and explore volcanic areas. One of the world's most famous and visited volcanic areas is Somma-Vesuvius. Here, tourism is mainly concentrated around the central crater while the rest of the volcano, part of Vesuvius National Park, is largely unvisited. The volcano's worldwide fame is primarily linked to its explosive activity, most notably the famous eruption that destroyed Pompeii and Herculaneum in 79 CE. Yet Somma-Vesuvius underwent long periods of effusive activity, such as the 1631–1944 eruptive cycle. On the volcano, there are examples of archetypal lava flows, including the 1858 flow field in which lava tubes formed. We propose a geoitinerary through the 1858 lava flow field that includes five sites, three lava tubes, an ephemeral vent and a tumulus, that allows people to evidence effusive activity and discover volcanic features formed during such activity at Somma-Vesuvius. A website was developed to host a virtual tour, which includes 360° images and an explicative panel for each site. The largest lava tube was 3D scanned to reconstruct its geometry, and to conserve a virtual copy of this fragile structure. Both the website and 3D scan aim to sensibilize people either not used to hiking or with physical impediment about volcanic landforms and their scientific relevance. The pertinence of the geoitinerary has been assessed by a SWOT analysis. The geoitinerary may contribute to divert tourist traffic away from the volcanic cone, while raising awareness on volcanic processes.

Keywords Lava tube · 3D scan · Geotourism · Volcano tourism · Geomorphology · Geoconservation

Introduction

Geotourism in Volcanic Regions

Active volcanic regions are of high scientific interest due to their dynamic and geologically transformative nature. The eruption of molten lava, the seismic activity that often precedes and accompanies volcanic events, and the rapid formation of new landforms highlight the dynamic processes occurring within the Earth's lithosphere. These phenomena, including the creation of craters, lava flows, pyroclastic deposits, and the alteration of surrounding ecosystems, offer direct insight into the mechanisms of plate tectonics, magma movement, and landform evolution (Németh et al. 2017; Dóniz-Páez et al. 2020; Pérez-Umaña et al. 2020). Volcanic eruptions can reshape landscapes on a geologically short timescale, emphasizing the Earth's ever-changing nature. These phenomena attract people that may travel to appreciate volcanic activity, thus contributing to geotourism development. The concept of geotourism significantly increased its diffusion in scientific papers in the last decades (Hose 1995, 1996; Miccadei et al. 2011; Dowling and Newsome 2018; Migoń et al. 2018; Ólafsdóttir and Tverijonaite 2018; Sisto et al. 2020; Santangelo and Valente 2020; Valente et

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al. 2020). The definition of geotourism was first proposed by Hose (1995, 1996) as '*the provision of interpretive and service facilities to enable tourists to acquire knowledge and understanding of the geology and geomorphology of a site beyond the level of a mere aesthetic appreciation*'. This definition has been refined by Dowling and Newsome (2005) that introduced the concept of scale by including both small geological/palaeontological outcrops and large landforms as geotourism attraction. The latter include volcanic areas whose geotourism potential has been assessed in many areas of the world (Erfurt Cooper 2011, 2022; Erfurt Cooper et al. 2015; Alessio and De Lucia 2017; Megerle 2020). Volcanoes like Kilauea in Hawaii (US), Piton de la Fournaise on the island of La Reunion (France), Etna in Sicily or Stromboli in the Aeolian islands (Italy) and more recently the volcanoes of the Reykjanes peninsula (Iceland) are attracting many visitors each year due to their eruptive activities (Langridge and Michaud 2023). For example, the eight national parks of Hawaii attracted over 4.7 million visitors in 2020 (https://www.nps.gov/state/hi/index.htm).

Visiting dormant volcanoes, as currently is Vesuvius, or extinct volcanic regions provides a valuable opportunity to understand many of the processes shaping our planet in greater depth. These areas have preserved geological features that reflect the Earth's volcanic history, offering tangible means to study past eruptions, patterns of volcanic activity, and long-term impacts on both the environment and human populations (Németh and Moufti 2017; Zangmo et al. 2017; Planagumà and Martí 2018; Quesada-Román et al. 2020; Baadi et al. 2023). Dormant volcanoes, while not currently active, remain vital for studying eruption recurrence, the long-term stability of volcanic structures, and potential future hazards.

From a naturalistic perspective, many volcanic regions support diverse ecosystems that have adapted to the unique conditions created by past volcanic activity (Sklenář et al. 2010; Fazlutdinova et al. 2021; Berrios et al. 2022). Volcanic soils, rich in minerals, often foster lush vegetation, while animal populations may thrive in these nutrient-dense environments. In contrast, some volcanic landscapes appear barren, offering an opportunity to observe the gradual process of ecological succession as life returns to previously disturbed areas (Kienle et al. 2022). These regions can also hold significant cultural and historical value, as human civilizations have long interacted with volcanic landscapes, adapting to, or even leveraging volcanic activity for their livelihoods (Beltrán-Yanes et al. 2020; Zangmo Tefogoum et al. 2022). In addition, barren volcanic land can offer unique opportunities to test technologies and operational scenarios providing inputs for future lunar volcanic cave explorations during spatial missions (Sauro et al. 2024).

The value of visiting dormant or extinct volcanoes extends beyond the aesthetic and ecological appeal, and plays an important role in hazard perception and risk management (Petrosino et al. 2019). Exposure to volcanic landscapes enhances awareness of the potential risks posed by future eruptions or secondary hazards such as landslides or mudflows, even in currently dormant volcanoes. Studying the past behaviour of volcanoes, identifying precursor signals such as gas emissions or ground deformation, and understanding historical eruption patterns can inform early warning systems and emergency response strategies. This knowledge is critical for improving risk mitigation measures in areas vulnerable to volcanic hazards.

The interest in geotourism in volcanic areas is growing with many recent works in various volcanic centres around the world (Vereb et al. 2020; Ertekin et al. 2021; Sánchez-Cortez et al. 2023; Vegas et al. 2023; Yudiantoro et al. 2024; Mülayim et al. 2025). Multiple volcanic areas were listed in the UNESCO world heritage list like the Jeju Island in 2010 (Jeon et al. 2024), Mount Fuji in 2013 (Chakraborty and Jones 2018) or the Chaîne des Puys monogenetic volcanic field in 2018 (Merle et al. 2023). Several other volcanic areas are within geoparks included in the Global Geopark Network (GGN) like El Hierro island in Spain (Casillas Ruiz et al. 2023), the Colca y volcanes de Andagua in Peru (Gałaś et al. 2018), and the Tungurahua volcano in Ecuador (Soria et al. 2020) or will be considered for inclusion as Nevado del Ruiz in Colombia (Cifuentes-Correa et al. 2023). Geotourism in volcanic areas, particularly through guided geotours, offers an opportunity to deepen public understanding of the processes that shape the Earth. These tours can integrate educational content about volcano formation, and eruption mechanisms, while also offering insights into the long-term environmental and societal impacts of volcanic activity (Armiero et al. 2011; Alberico et al. 2023). Through scientific curiosity or educational outreach, these tours enrich the visitor's understanding of the interconnectedness between geological forces, natural landscapes, and human societies. In this context, geotours serve not only as a mean of exploring the awe-inspiring beauty of volcanic landscapes but also as a platform to raise awareness about the dynamic and potentially hazardous nature of Earth's volcanic activity.

On the volcanoes of southern Italy, geotourism dates back to the 18th century when the noble young men from other European countries came to witness volcanic eruptions or to discover volcanic rocks and deposits, as stops of a journey known as the "Grand Tour". While being well developed, recent works still aim at preserving and discovering Italian volcanoes (Pasquaré Mariotto et al. 2022; Platania et al. 2022; Alberico et al. 2023; Di Vito et al. 2023). In Sicily, guided excursions on Mount Etna are offered to visitors and the presence of expert guides is mandatory past a certain altitude fixed by local authorities. In the Aeolian Islands, guided excursions to observe the eruptions of Stromboli and free access to the crater of Vulcano to observe fumaroles are possible but limited by local authorities to certain elevations (below 400 m above sea level at Stromboli) and localities (Vulcano) (https://cme.ingv.it/statodi-attivita-dei-vulcani-eoliani/archivio-documenti-protezione-civile/ordinanze-sindacali-comune-di-lipari). In the Campanian region, a national park was created in 1997 to protect the nature of the Somma-Vesuvius stratovolcano. Here, the majority of tourists come to access the summit cone while the rest of the volcano is unvisited. With a maximum capacity of about one million visitors each year, Vesuvius is one of the most visited volcanoes in the world (Art. 2 of the Protocol for the tourist use of Path n. 5 of the Vesuvius National Park ("Crater of Vesuvius"; 620 000 visitors in 2024, https://www.parconazionaledelvesuvio.it/nel-2024-nuovo-record-di-visitatori-sul-gran-cono-del-vesuvio/).

As previously stated, many landforms develop during volcanic eruptions, explosive or effusive. Among these are lava tubes (less commonly named lava tunnel or pyroduct by specialists in scientific fields other than volcanology) which form during effusive events (Greeley 1971, 1987; Peterson et al. 1994; Kauahikaua et al. 1998; Calvari and Pinkerton 1998, 1999). Lava tubes are a peculiar, but very infrequent geological feature at Vesuvius. The recent discovery and analysis of lava tubes on Vesuvius (which were formed during the 1858 eruption; Lemaire et al. 2024) interrogates us on the opportunity to evaluate the geotourism potential of these landforms and to relocate tourist traffic in areas of the National Park different from the central crater. As the 1858 lava flow surface features are unknown landforms at Vesuvius, most visitors of the Vesuvius National Park are not aware of their presence and ignore how these kinds of volcanic landforms develop. In this paper, we propose a geoitinerary through the 1858 lava tube field at Somma-Vesuvius by integrating field work with a virtual tour and a 3D reconstruction of the largest lava tube geometry.

Lava Tubes as Part of Volcanic Geoheritage

Lava tubes are preferred pathways of molten lava under a static solid crust (Greeley 1987; Halliday 2004). The formation of a cooled roof over the flowing molten lava stops the convective cooling of the lava by the ambient air and allows it to remain hot for a longer time. Measured and theoretical cooling in lava tubes show a ≈ 1 °C/km cooling rate of the lava (Keszthelyi 1995; Sakimoto and Zuber 1998; Witter and Harris 2007) compared to the 5 to 7 °C/km cooling rate in open lava channels (Crisp et al. 1994; Cashman et al. 1999; Soule et al. 2004; Riker et al. 2009; Robert et al. 2014; Rhéty et al. 2017). The lava flowing inside lava tubes is then able to travel longer distances from the vents than the lava flowing on the ground or within open channels. Master lava tubes are hundreds of metres to tens of kilometres long. Among the longest lava tubes on Earth are the Kazumura lava tube located on the slopes of Kilauea volcano in Hawaii with a length of 65 km (Allred and Allred 1997), and the ≈ 100 km long Undara lava tube in Australia, even visible from satellites (Ollier and Brown 1965; Atkinson et al. 1975; Stephenson et al. 1998).

Three main lava tube formation mechanisms have been described in the literature. A lava tube can form by roofing over a lava channel in several ways depending on the rheology of the lava and on the effusion rate (Greeley 1987; Peterson et al. 1994). When the effusion rate is stable over time, a crust can extend from the channel levees on the lava surface, joining in the middle of the channel and thickening to form a solid roof. When the lava flow rate is fluctuating, the surface crustal slabs can break detaching from the levees or from the lava surface and float downflow. If they encounter a constriction or a turn, the crustal lava slabs can pile up, aggregate and merge to form a roof. When the effusion rate is varying, overflows of lava over the levees make them grow towards the middle of the channel until their merging. Another way a lava tube can form is by inflation of a pāhoehoe sheet flow (Hon et al. 1994) or of an ʻaʻā lava flow front (Calvari and Pinkerton 1998). And lastly, lava tubes can form by pāhoehoe lobe budding (Peterson et al. 1994; Kempe 2019). Pāhoehoe lava flows advance by the repeating process of lava lobe creation from the front or sides of previous lobes. In some cases, the lava lobes align in the flow direction allowing the formation of a primary lava pathway that can develop into a lava tube (Wentworth and Macdonald 1953).

Lava tubes are commonly found in basaltic volcanic areas all over the world, either on volcanic islands such as Hawaii, Iceland, Canary Islands, the Azores, Galapagos, Sicily, Reunion Island, Jeju island in South Korea, Comores or Mauritius (Hernandez et al. 1991; Hróarsson and Jónsson 1991; Nunes and Braga 1991; Calvari and Pinkerton 1999; Kempe 2016; Claudino-Sales 2019; Tomasi et al. 2022) or in intracontinental settings such as Australia, Saudi Arabia, Jordan or China (Atkinson et al. 1975; Moufti et al. 2013; Wang et al. 2014). Lava tubes in volcanic areas such as Somma-Vesuvius are less common and were unknown up to recently (Lemaire et al. 2024).

Geotourism focused on lava tubes is developed in the most famous volcanic places where lava tubes can be found (King 2010; Galindo et al. 2019; Dóniz-Páez and Pérez 2023). On Hawaii island, it is possible to visit and explore lava tubes either self-guided or trough guided tours provided by private companies or by the US National Park service (https://www.nps.gov/state/hi/index.htm). Since a few years, Iceland has become an attractive destination for volcano enthusiasts due to the recurrent eruptions (Parks et al. 2023). Private companies have developed here tourism in several lava tubes. The exploration of at least some portions of lava tubes is then possible for anyone, either self-guided in adapted parts of the lava tube or under the supervision of a guide to explore the entirety of the lava tube. In the Canary Islands, on the island of Lanzarote, a lava tube has been transformed by Cesar Manrique, a local artist, into an artistic, cultural and touristic centre (https://cactlanzarote.com/en/centre/jameos-del-agua-guide/). A restaurant, a natural pool, an artificial pool, and a natural auditorium can be found inside part of a large lava tube called La Corona at a skylight called 'Jameos del agua'. Other lava tubes are proposed to the visit in less renowned areas but located in natural parks that are UNESCO world heritage sites such as the Jeju volcanic island (South Korea), La Reunion island off the coast of Madagascar (France) or Mount Etna in Sicily (Italy) (https://whc.unesco.org/en/list/). However, on many of the less famous volcanic areas, the exploration of lava tubes is limited to experts or persons accompanied by local speleologists.

Geological Setting

Vesuvius is one of the volcanoes of southern Italy (Fig. 1a), situated in the Campanian region, 15 km to the east of Naples (Fig. 1b). Vesuvius is part of the Somma-Vesuvius complex which is a stratovolcano that went through multiple collapses and regrowth phases (Cioni et al. 1999). The first volcanic activity of the stratovolcano started after the Campania Ignimbrite eruption of the Phlegraean Fields (ca. 40 ka; Giaccio et al. 2017) by the emplacement of a repetitive series of thin lava flows from a central vent and from cinder cones mostly developed as parasitic and eccentric vents (McDonald et al. 2016). This mainly effusive activity changed to mainly explosive 22 ka.

The volcano produced four major Plinian eruptions: the Pomici di Base (22 ka), the Mercato pumice (ca. 9 ka), the Avellino pumice (ca. 3.9 ka) and the Pompeii pumice (79 CE) (Santacroce et al. 2008). Poorly known minor explosive events occurred in between these major eruptions. In particular, between the Avellino and Pompeii eruptions, at least six explosive events occurred (Rolandi et al. 1998), named AP1-AP6 eruptions (Andronico and Cioni 2002). Monte Somma

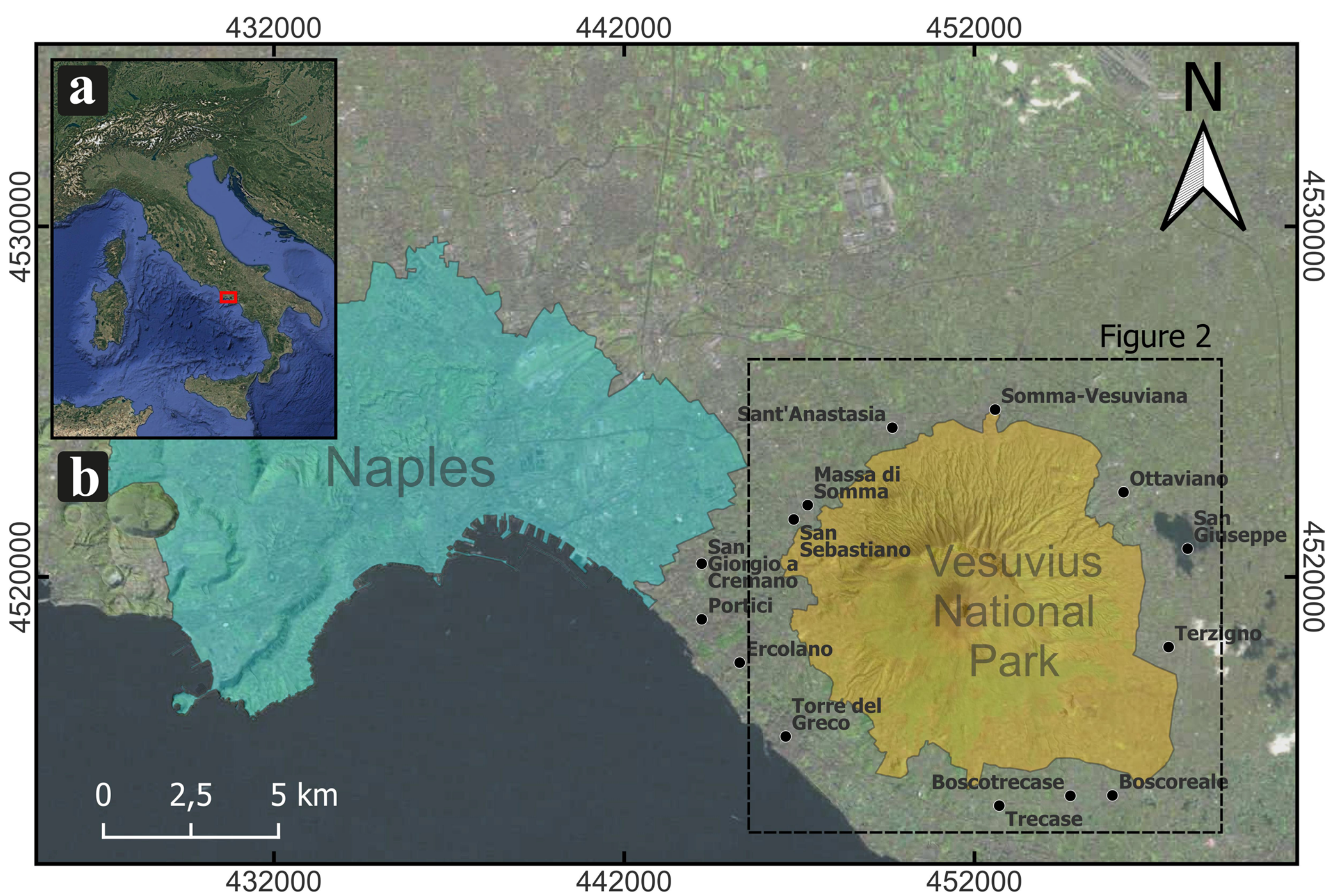

Fig. 1 Localization of the Vesuvius National Park 15 km east of the city of Naples in Southern Italy, and main towns located in the surrounding area (black dots)

is the older edifice that collapsed multiple times due to extensive drainage of the magma chamber, in concomitance with the explosive eruptions (Cioni et al. 1999). It resulted in the formation of a sub-circular caldera, and Vesuvius is the new cone that grew within the Monte Somma caldera after the 79 CE Pompeii eruption during periods of open-conduit activity (Arrighi et al. 2001; Cella et al. 2007; Cioni et al. 2008). The last open-conduit period initiated with a sub-Plinian eruption in 1631. During this phase, lateral and summit effusive and semi-persistent mild explosive eruptions took place (Carta et al. 1981; Arrighi et al. 2001). More than one hundred lava flows emplaced on the slopes of Vesuvius during this phase (Fig. 2), which ended with the 1944 eruption (Chester et al. 2007; Cubellis et al. 2016).

The surroundings of Somma-Vesuvius have been highly inhabited for a long time. The eruptions of the 1631–1944 period were observed and described in historical documentation. In a few historical documents, descriptions of lava tubes can be found. One lava tube is drawn in the book titled 'Vesuvius' by Phillips (1869). Palmieri describes the 1858 eruption in the Annals of the Vesuvius Observatory in 1859: "*Thus the curious phenomenon of flowing lavas was seen without being able to know the mouth from which they came. […] When the outer part of the lava has hardened and the inner part is still liquid, it often happens that it flows downwards as if through a tunnel of impetrated matter, as if it were a vaulted aqueduct worked by art. As the lava disappears, it no longer fills the entire capacity of that tunnel, and often through some fissure made in it one can see the fire flowing below*". Another description of lava tubes is found in the Annals of the Vesuvius Observatory of 1870, where Palmieri wrote about the 1867 eruption saying: "*This appearance arose from the fact that the lavas on the Vesuvian cone had formed a covered channel or tunnel of slag within which invisible slag descended from the summit to the base of the aforesaid cone, and when, because of the periodicity mentioned above, the tunnel could not accommodate a new flood, its walls broke in one or more places and streams of fire could be seen appearing on the cone*". Lava tubes were observed during eruptions but the only description of an inactive lava tube at Vesuvius was done by Malladra (1917), who described a lava tube preserved within the 1858 lava flow field. The 1858 eruption is well described. Nowadays, numerous surface features can be observed and are of interest to understand lava flow field emplacement (see Lemaire et al. 2024).

Methods

In this work, we used for the first time at Vesuvius a multidisciplinary approach combining fieldwork, 3D scanning, 360° photography, explicative panels, and SWOT analysis, aimed at creating and providing to visitors an easy and comprehensive itinerary for them to discover volcanic activity. As a result, we acquired data to create a virtual tour of the study area. Virtual tours allow people to visit and get knowledge of a site from their laptop or mobile devices anywhere in the world. The role of virtual tours in geotourism has been recently diffused in the scientific literature (Martinez Grana et al. 2013, 2023; Perotti et al. 2020; Filocamo et al. 2020; Fassoulas et al. 2022; Williams et al. 2025; Papadopoulou et al. 2025), even in the volcanic landscapes of Iceland (Pasquarè Mariotto et al. 2022). Each method used in this study is described here below.

Our study begun with field surveys that have been extensively carried out to identify surface features on the 1858 lava flow field of Vesuvius. As a result, we discovered and selected five landforms to be included in the geoitinerary, which are three lava tubes, a tumulus, and an ephemeral vent that formed during the 1858 eruption.

We developed panels that describe the formation and growth of the selected volcanic landforms to help visitors understand the mechanisms that drive the creation of such features during lava flow field emplacement. These panels should be placed next to the five selected sites as their use as a communication strategy is common in geotourism research (Melelli 2019).

For the accessibility of the selected features, we captured 360° photos using an Insta360×4 camera. The photos were edited and exported within the Insta360 Studio software. The 360° photos are hosted on Momento360 and implemented on a website alongside the explanatory panels, made on Google sites, where anyone can explore the virtual geoitinerary allowing an immersion into the sites (https://sites.google.com/view/vesuvius-1858lavaflow/).

Furthermore, a 3D reconstruction of the interior and surface of the largest lava tube found in the 1858 lava flow field using high-end technologies was carried out by Lemaire et al. (2024) and used in this work to preserve the morphology of the tube as a digital twin through time. The interior of the lava tube was scanned using a Riegl VZ-400 time-of-flight terrestrial laser scanner mounted on a tripod. Nineteen scans in different positions within the tube were acquired to avoid shadows due to the complex geometry of the inside. Twelve out of the nineteen scans were used to create a mesh in the RiSCAN Pro software. The overlying surface of the lava tube was scanned using a DJI Matrice 300 RTK UAV equipped with a stabilized Zenmuse P1 optical camera. Aerial images were transformed into a surface Digital Elevation Model (DEM) and a mesh in Agisoft Metashape. To correctly assemble both scans, we first positioned markers in different areas of the lava tube during the survey and then we carried out photogrammetry work using a Gopro 10 camera in two key areas to produce two

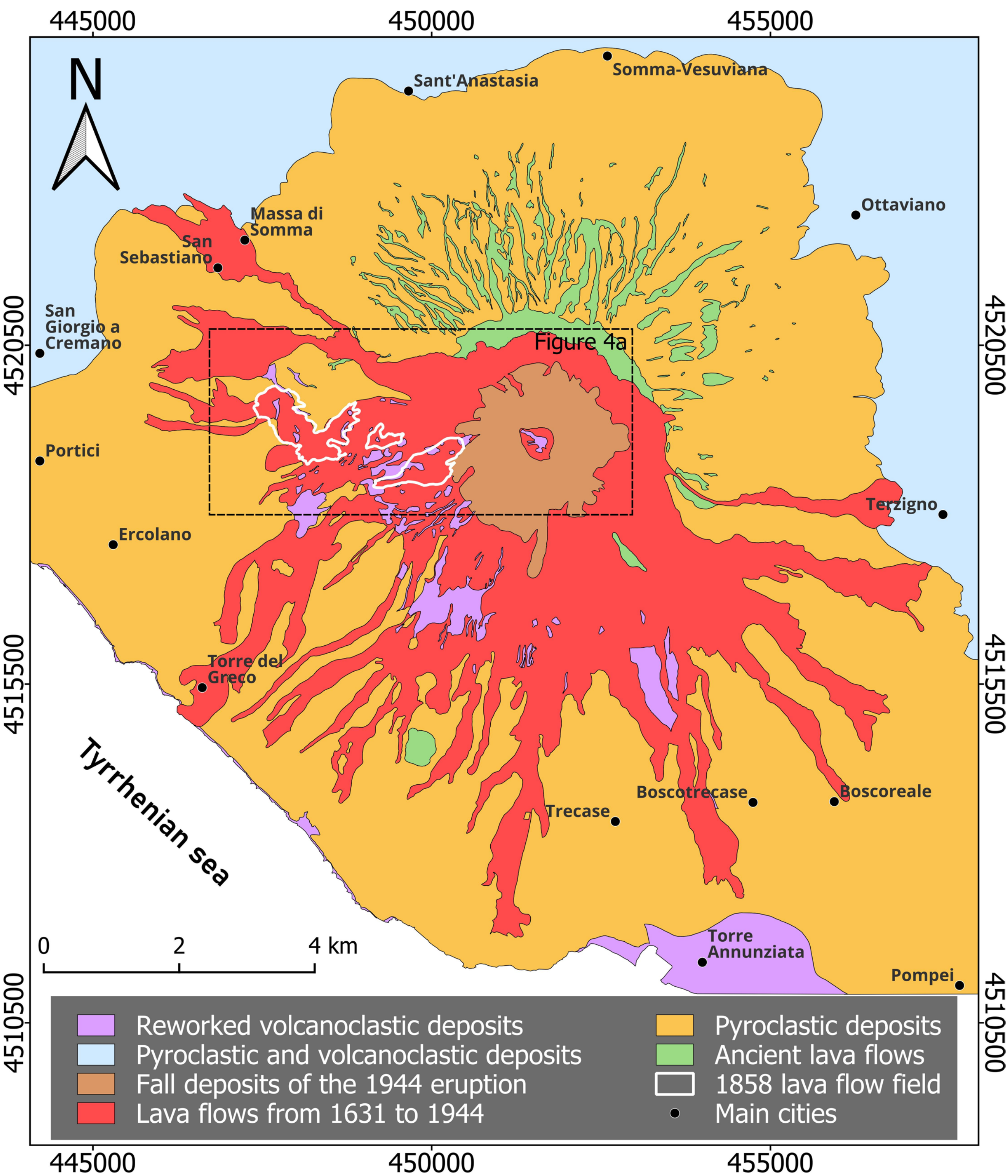

Fig. 2 Simplified geological map of Somma-Vesuvius modified from Santacroce and Sbrana (2003)

meshes that show both the interior and exterior of the lava tube. The interior and surface scans were assembled in the software CloudCompare.

Finally, we carried out the Strength, Weaknesses, Opportunity and Threats (SWOT) analysis to test the geotourism potential of the 1858 lava flow field and to propose initiatives for their efficient and effective use (Carrión-Mero et al. 2020; Kubalíková and Kirchner 2016; Valente et al. 2021).

Results

The Lava Flow Field Geoitinerary

The 1858 lava flow field is located on the western flank of Vesuvius at an elevation ranging from 200 to 800 m above sea level (Fig. 3). It was emplaced during the 1858–1861 eruption that begun on 27 May 1858 and ended on 12 April 1861, lasting almost three years. The maximum flow length is around 5.2 km, and the mean flow width is around 0.6 km. The emplaced lava flow field covered around 3.9 million square metres but the exposed area, uncovered by more recent lava flows, is just 1.3 million square metres, one third of the original area. The seven vents that opened during the eruption produced an estimated volume of 178 million cubic metres of lava (Lemaire et al. 2024), and are now recovered by more recent flows.

Within the 1858 lava flow field, five sites are described and proposed to the on-site visit along a geoitinerary (Fig. 4) and online through a virtual geoitinerary composed of 360° photos. For each site, a descriptive panel was designed to gives scientific information about the site and explain the mechanism behind its formation. The geoitinerary is 500 m long and is mainly addressed to people used to hiking, as walking on a lava flow field may be difficult. People not

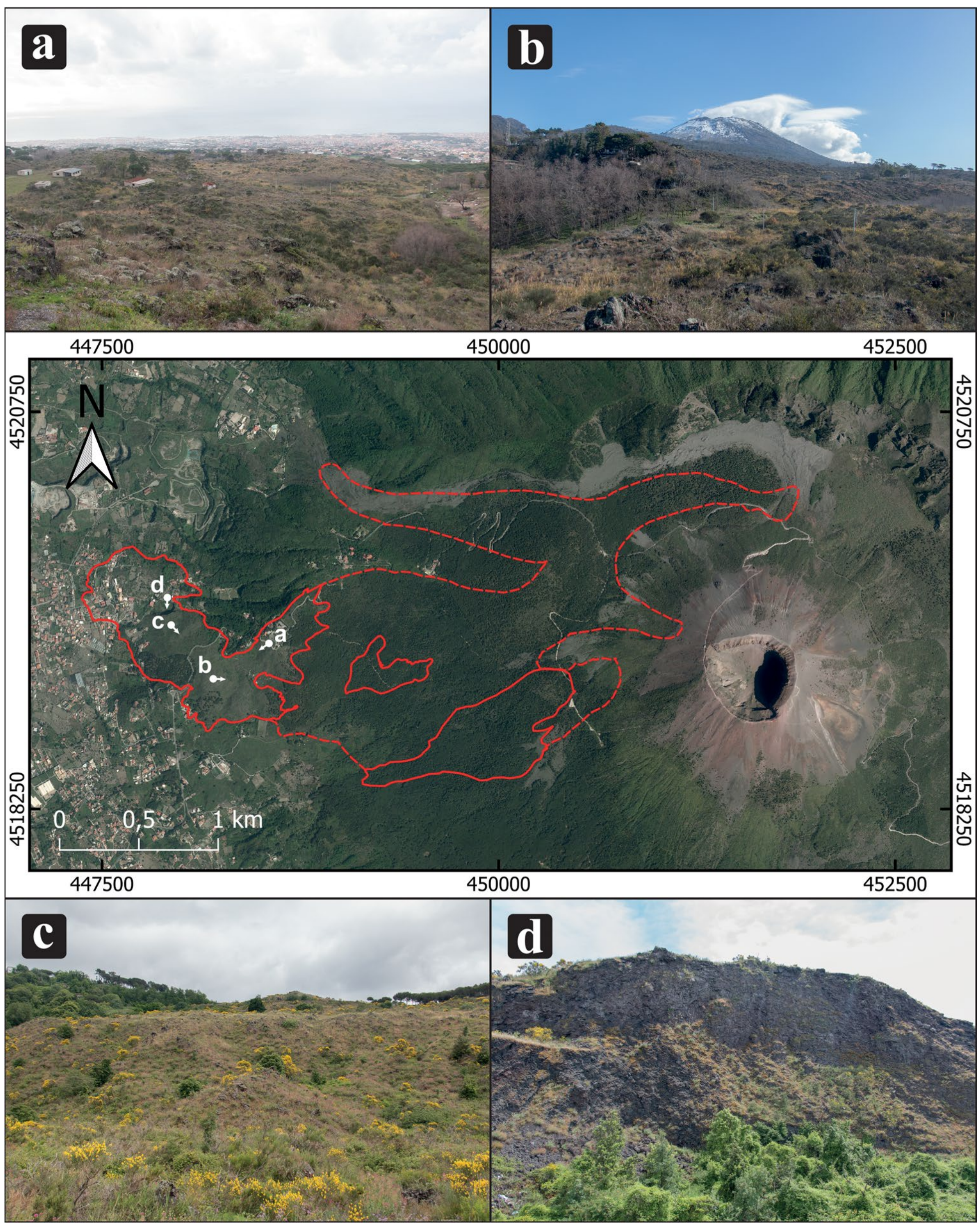

Fig. 3 Orthophoto of Vesuvius with the margins of the 1858 lava flow field highlighted in red (continuous line: exposed, dashed line: covered by more recent lava flows) and photos of the flow field. (**a**) Photo of the lava flow field looking toward the south west, the city of Torre del Greco is visible along the seaside. (**b**) Photo of the lava flow field looking toward the Vesuvius crater taken close to site 5. (**c**) Photo of the flow field taken close to the flow front. (**d**) Photo of a quarry wall located close to the flow front showing the piling up of small flows for a total thickness of about 100 m

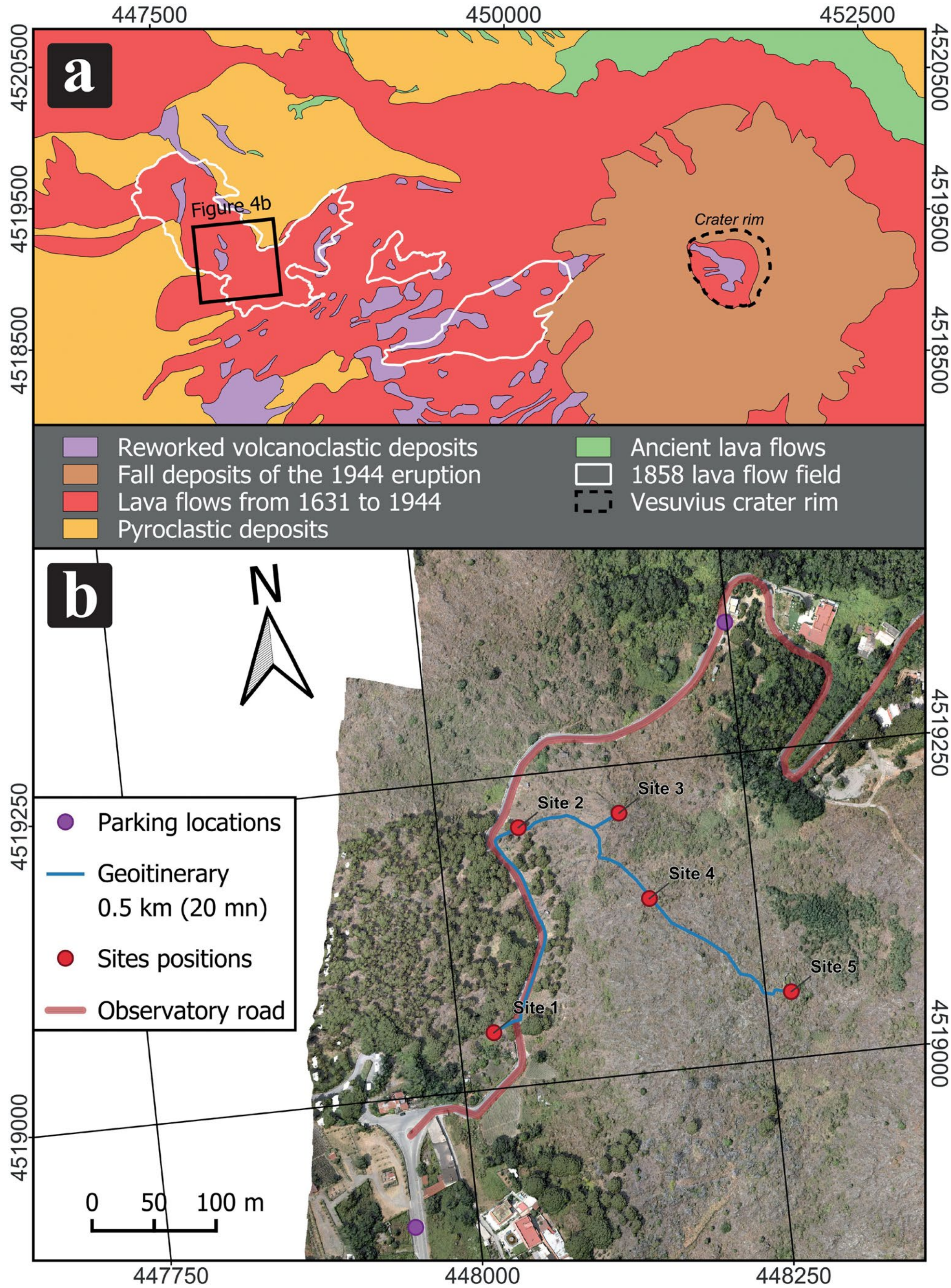

Fig. 4 (**a**) Detail of the geological map of Fig. 2 with location of the area (black box) where the geoitinerary is located; (**b**) Proposed geoitinerary (blue line) featuring five sites (red dots) along the 1858 lava flow field of Vesuvius

used to hike may appreciate the geoitinerary through the virtual tour (sub-Sect. 4.2). The best periods to enjoy the geoitinerary are autumn and winter, whereas vegetation blooming in spring and summer may reduce visibility. The description of each stop and the related explanatory panel are reported below. The presence of panels next to each site is essential to the comprehension and dissemination of the characteristics and scientific information we aim to disseminate, and it is our intention to collaborate with the local park authorities to realize them.

Site 1: Early-stage lava tube.

Site 1 corresponds to a lava tube (Fig. 5) located a few metres next to the Observatory Road. It is 5 m long, 1 m wide and about 2 m high. The outer rim (Fig. 5) is surrounded by overflows with pāhoehoe textures. Inside, in the deepest part of the tube, it is visible the ephemeral vent that originated the tube and probably formed at the margins of a former and larger lava flow located upslope. On the lateral walls there are several lava flows overlapped, showing that this tube was probably the vertical merging of the

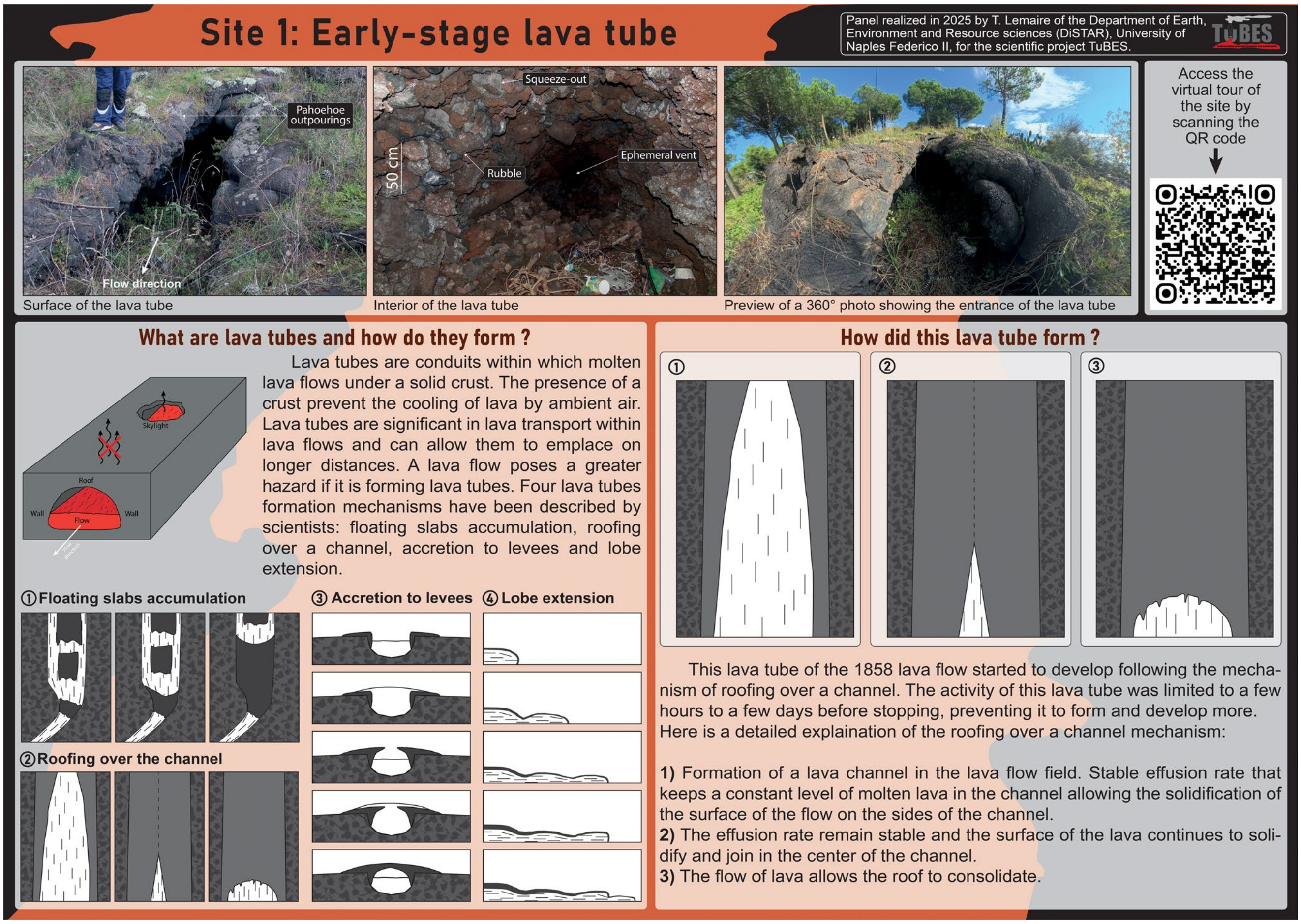

Fig. 5 Explicative panel presenting site 1, detailing the general processes of lava tube formation, and showing the model for the formation of the observed lava tube

voids formed within several lava flow units. In between the stacked flows there are pāhoehoe squeeze-outs fingering into the ʻaʻā rubbles (Fig. 5), suggesting that the tube was active for some time (probably days), allowing the pāhoehoe lobes to fill the voids left over in between the ʻaʻā rubbles comprising the outer crust of the lava flow that originated the tube. These lava fingers were probably attempts of the fluid lava inside the tube to open ephemeral vents at the sides of the tube when the pressure inside the tube was growing by accumulation of lava.

Site 2: Ephemeral vent.

This feature corresponds to the breakage of the crust at a lava flow front from which molten lava outpoured forming a new flow, usually short in duration and/or length. It is commonly associated with lava tubes, as it causes their drainage and thus the formation of a cavity into the drained flow upslope. Here, the lava outpoured from the former flow margins and formed a 2 m wide lava channel with pronounced lateral levees (Fig. 6). The lateral levees are 20 to 30 centimetres higher than the flow surface, suggesting a partial drainage after its initial emplacement. The location of this ephemeral vent suggests that the outpoured lava flow originated from Site 3 (Fig. 7).

Site 3: Tumulus.

Tumuli are positive topographic features that form by a mechanism of crustal uplift on lava flow fields (Duncan et al. 2004). A tumulus forms normally on a shallow sloping ground and at a break in slope, where the magmastatic pressure within the lava flow led to localized inflation processes that took place during lava flow emplacement (Duncan et al. 2004; Anderson et al. 2012). It is sign of lava accumulation below a stable crust and of flow inflation. The tumulus surface feature here described is 10 to 20 m high and has a 160 m diameter (Fig. 7). This tumulus shows numerous breakouts or ephemeral vents from its sides and top forming small channels and even small tubes on its flanks. A tumulus indicates that magmastatic pressure within the lava flow led to localized inflation processes that took place during lava flow emplacement (Duncan et al. 2004; Anderson et al. 2012), often located in places along the flow path where the ground slope suddenly decreases or increases. Tumuli are often indicative of the presence of lava tubes underneath

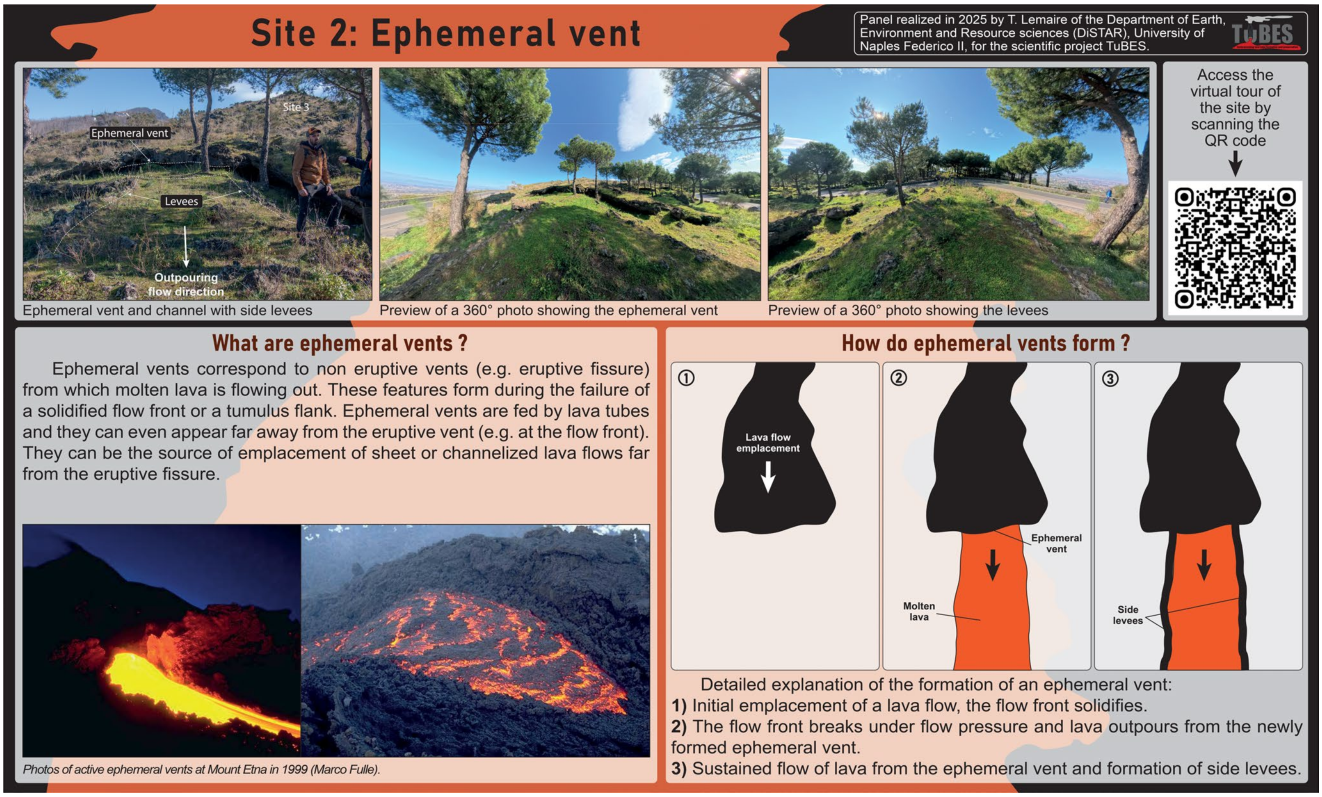

Fig. 6 Explicative panel presenting site 2, detailing the process of formation of ephemeral vents, such as the one observed here

because they emplace along the lava tube paths where the ground surface presents a break in slope allowing flow drainage and thus the formation of a cavity (Mattox et al. 1993; Calvari and Pinkerton 1999).

Site 4: Breakout with a small lava tube.

Site 4 is a small lava tube located next to the base of a small tumulus and originated from a side breakout. The tube is 20 centimetres wide conduit and with a thin broken crust about 1–2 centimetres thick allowing the view of the inside (Fig. 8). The roof is formed by two overlapped ropy pāhoehoe sheets of lava that broke in one place forming a triangular skylight (Fig. 8a). Inside it, we can observe smooth rounded and reddish parallel stalactites on the ceiling elongated along the flow direction, and a concave roof indicating flow inflation and later flow drainage. Some transversal fractures contain roots growing into the cavity (Fig. 8b), a common feature in cases of a thin tube crust increasing tube instability and erosion. The floor is mostly horizontal and with pāhoehoe textures.

Site 5: The largest lava tube.

Located in a very flat area, this lava tube is the largest one found in the 1858 lava flow field (Fig. 9). The outer surface is characterized by an inflated pāhoehoe flow showing longitudinal cracks and one skylight allowing access into the tube. The tube outer surface rises ≈ 1.5 m above ground, and is surrounded by vegetation, whose blooming in spring and summer may prevent the recognition of the site. The tube entrance is through the skylight that allows an easy access through several blocks collapsed from the ceiling. The roof is 1 to 3 m thick and the lava tube is about 30 m long, 1.5 to 17 m wide and the mean height inside is 1.4 m. Inside the tube there are lava stalactites, several inner linings, local collapses of the roof, and the floor is made of pāhoehoe surface texture. Flow direction in the lava tube was from north to south. The lava entered from a small twenty-five centimetres wide vent and exited the lava tube to the southwest by a small passage.

Virtual Tour

The 360° images collected on the field as well as the panels and explanations of each site are published on a dedicated website accessible online via the following link: https://sites.google.com/view/vesuvius-1858lavaflow/. The 'Geoitinerary' page introduces this study and the proposed geoitinerary through a descriptive text and an online interactive map (Fig. 10a). The 'Terminology' page defines the volcanological terms used in the descriptions of the sites (Fig. 10b). The 'Sites' page is redirecting to each of the five site's subpages that are reachable by clicking on the Explore button

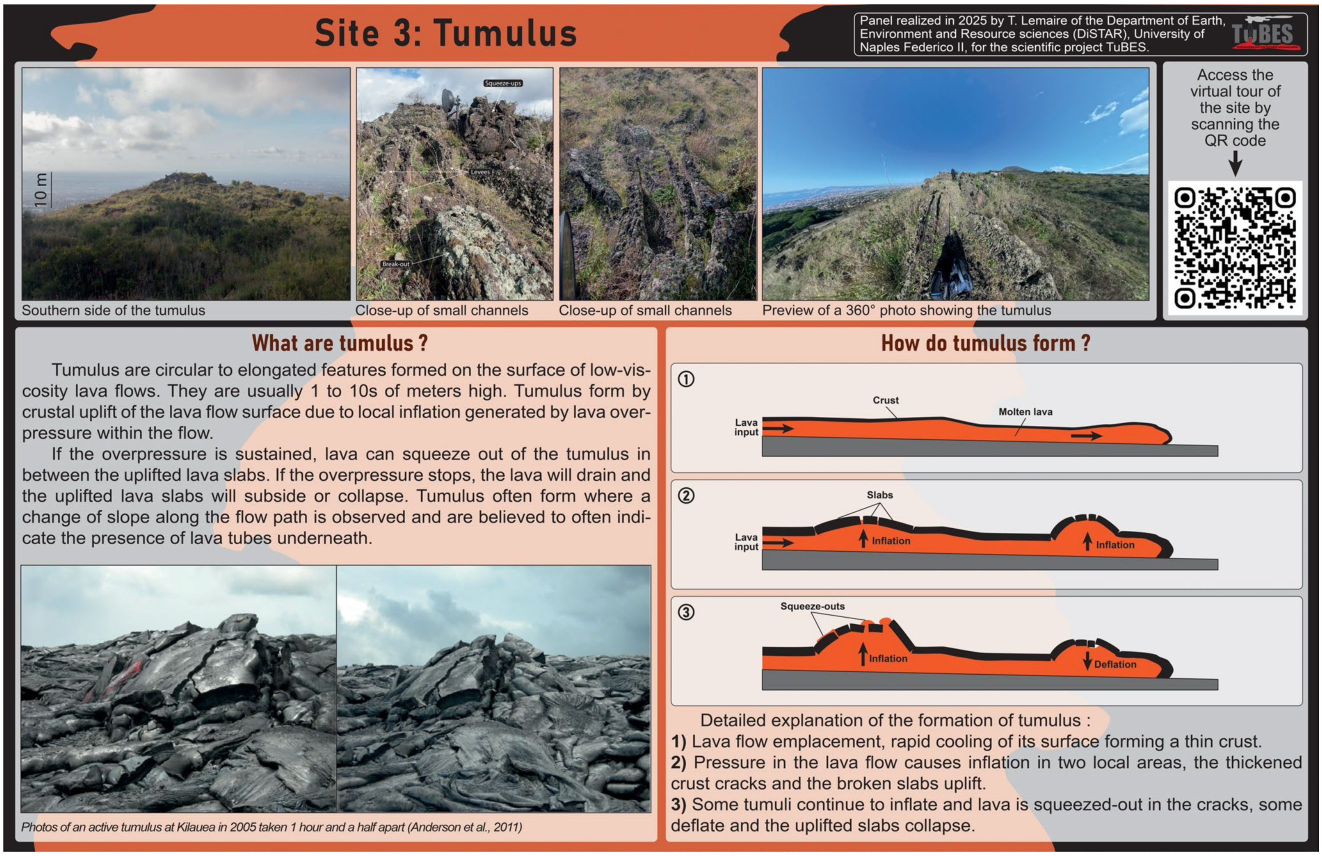

Fig. 7 Explicative panel presenting site 3, a tumulus, and detailing the mechanism of formation of such structure

of each site photograph (Fig. 10c). The five sub-pages show a description, the associated 360° photos and the explanatory panel of each site. These 360° photos are interactive and allow visitors to navigate and virtually explore each site (Fig. 10d).

3D Digitization of the Largest Lava Tube

Lemaire et al. (2024) have investigated the largest lava tube (Site 5) found in the 1858 lava flow field. The field surveys to 3D scan this lava tube allowed the construction of a complete 3D model in which the internal scan is aligned with the georeferenced overlying surface. Using the 3D model, Lemaire et al. (2024) described in detail the morphology of the lava tube (Fig. 11). The lava tube is 30.15 m long and 1.20 to 17.41 m wide. The mean height inside is 1.40 m while the maximum height is 2.47 m in the southern part of the lava tube. The 3D digital copy is incredibly helpful to characterise precisely its morphology but is also an excellent capture of its state at a moment in time, allowing to explore it even after possible collapses, as well as to preserve the record of this unique volcanic feature at Vesuvius.

Discussion

Mechanisms of Lava Tube Formation in the 1858 Lava Flow Field

Lava tubes are formed by three main mechanisms: roofing over a lava channel, pāhoehoe lobe extension or lava flow inflation (Greeley 1971, 1987; Peterson et al. 1994; Kauahikaua et al. 1998; Calvari and Pinkerton 1998, 1999). In the 1858 lava flow field, the lava tubes (sites 1, 4 and 5) have different sizes and morphologies indicating that they were subject to various mechanisms of formation. Site 1 formed by roofing over an ʻaʻā lava channel that produced several lateral pāhoehoe overflows increasing the thickness of the lateral levees. The ʻaʻā nature of the initial flow is testified by the stacked rubbles alternated to massive flows, each about 0.5 m thick, observed on the lateral inner walls of the tube (Fig. 5). This is an early-stage lava tube and given its small extent was probably active for a few hours to a few days, not being able to develop more due to its location at the margins of the lava flow field, thus receiving only a limited amount of lava supply for a short time. Site 4 formed

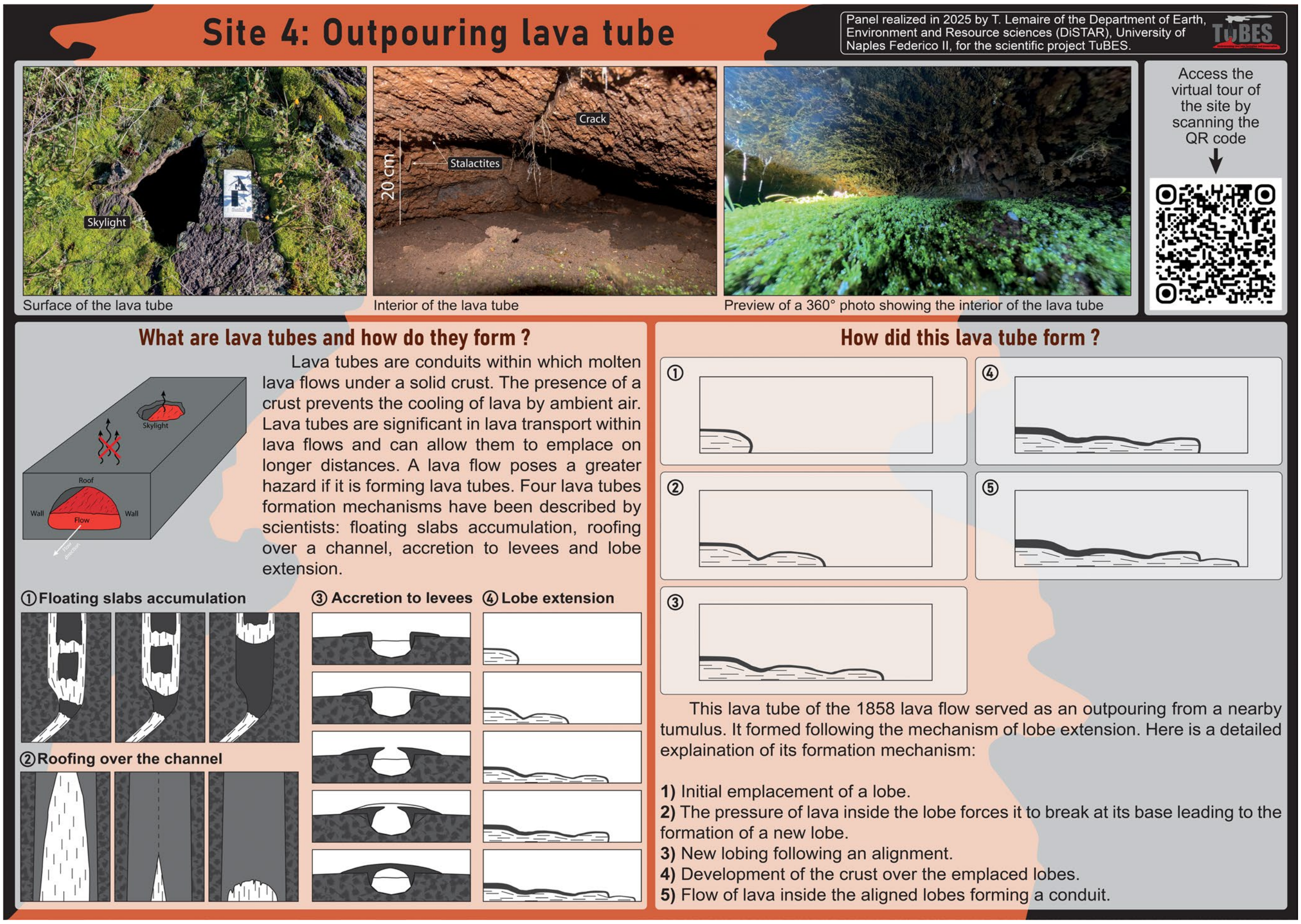

Fig. 8 Explicative panel presenting site 4, detailing the general processes of lava tube formation, and showing the model for the formation of the lava tube observed at Site 4

by inflation of a very small pāhoehoe lava flow and served as a draining path for the lava from a nearby tumulus (Site 3). Site 5 also formed by inflation of a pāhoehoe lava flow at a larger scale. This mechanism of formation was described as a new interpretative model by Lemaire et al. (2024) and detailed here in the related explanatory panel (Fig. 9). The process involves at first the emplacement of a small ropy pahoehoe lava flow. Its margins cooled down and solidified while the supply of lava continued to feed the flow leading to its inflation. Flow inflation in turn causes fracturing of the surface crust and the formation of large slabs of solidified crust. A sustained and steady flow of lava allowed the formation, growth and consolidation of the crust. The lava tube partially or completely drained due to the opening of ephemeral vents from its margins, then by a new supply of lava was partially or completely refilled. This change of lava level inside the tube happened at least twelve times throughout the activity of the tube, as suggested by the presence of twelve wall linings. Each lining in fact reveals that the tube was full of lava and drained to allow this thin film of lava to attach and coat the inner tube walls. When the lava supply stopped, the lava tube drained completely, leaving the empty cavity we observe nowadays.

It is worth noting that the young age of the lava tubes here described allows a vision not just of the flow surface and of the inner tube shape, but also of the inner features such as stalactites and inner coatings described above, normally not preserved within much older lava tubes such as those of Australia (Undara tube, Atkinson et al. 1975), Lanzarote (La Corona tube, Tomasi et al. 2022), or of the Kingdom of Saudi Arabia (Umm Jirsan, Németh and Moufti 2017) to give just a few examples.

The 1858 Lava Tubes as Possible Geotourism Attractions

The geoitinerary is a major opportunity for the scientific community to reach out to the public and disseminate scientific knowledge about volcanoes and their associated hazards, but also about lava flows and their surface features. Filling the gap in knowledge that the population can have about lava flow field occurrence is essential, especially for

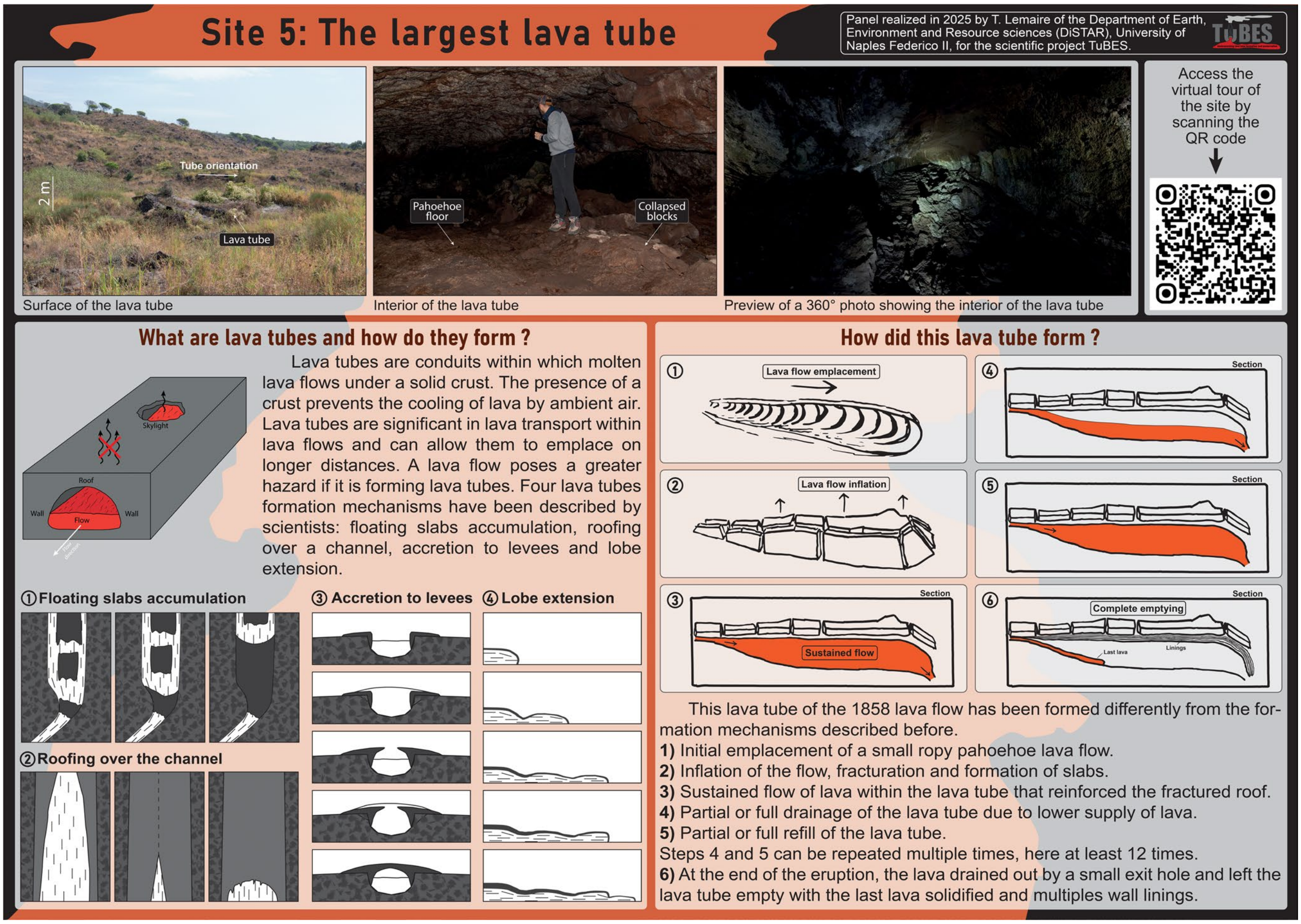

Fig. 9 Explicative panel presenting site 5, detailing the general processes of lava tube formation, and showing the model for the formation of the lava tube found at Site 5

the local inhabitants living next or even on the flanks of an active stratovolcano. Knowing how a volcano works will help people understand the hazards associated that they may face in the future. Although the last eruptive activity at Vesuvius was mostly effusive, the hazard due to effusive activity exists, but is, at the moment, largely unknown by local inhabitants. This is particularly important because the risk posed by lava flows at Somma-Vesuvius is increased by the proximity of inhabited areas to the eruptive centre, with the first buildings located just 3 km from the Vesuvius crater. This is a characteristic that Vesuvius shares with other volcanic areas (Chester et al. 2007), such as Hawaii, Iceland and Chile. Cities all around the coast of Hawaii Island are located a few kilometres from possible vents opening on the flanks of Mauna Loa, Kilauea, Mauna Kea, Hualalai and Kohala volcanoes, sometimes being less than a kilometre (Kauahikaua and Tilling 2014). The village of Vik in Iceland is exposed to volcanic risk due to the activity of the Katla volcano (Jóhannesdóttir and Gísladóttir 2010), and the 2021 Geldingardalir eruption directly impacted the Reykjanes Peninsula, the town of Grindavik and the South Coast Road (Sigtryggsdóttir et al. 2025). In the southern Andes of Chile, human reoccupation of rural settlements affected by volcanic events has been testified in the Carran-Los Venados and Puyehue-Cordón Caulle volcanic systems (Vergara-Pinto and Marín 2023). Noteworthy, the formation of lava tubes could increase the distance that lava flows can travel, further increasing the areas potentially at risk (Calvari and Pinkerton 1998; Kauahikaua et al. 1998). The use of questionnaires and interviews to citizens living near or within volcanic area is a common practice that help understand their risk perception related to volcanic events, and the local visitors of the geoitinerary could be profitably involved in such a programme. This method has been tested in Indonesia (Lavigne et al. 2008), Iceland (Jóhannesdóttir and Gísladóttir 2010) and Vesuvius (Avvisati et al. 2019).

The geoitinerary is visitable on-site by people used to hike because of an uneven path, but the presence of a wood path in the future would help expanding the possibility of visiting the sites. In addition, the proposed virtual tour allows everyone to access the geoitinerary. The free and easy access to an online virtual tour regrouping 360°

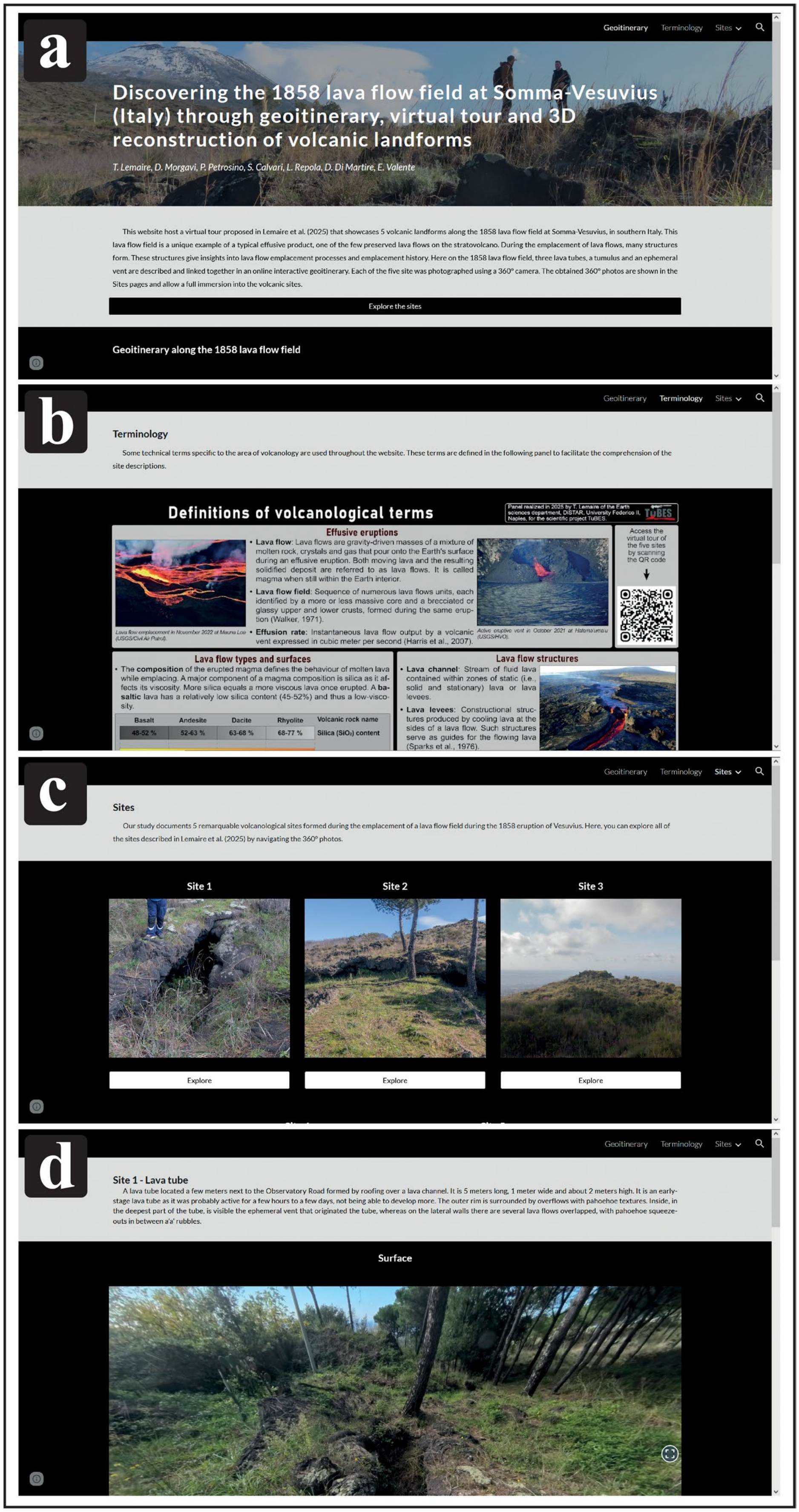

Fig. 10 Screenshots of the website. (**a**) Geoitinerary page with an introduction to the geoitinerary and an interactive map (**b**) Terminology page on which volcanological terms are defined (**c**) Sites page that redirect to the five subpages of the sites (**d**) Subpage of Site 1 with a description of the site, the interactive 360° photos and an explanatory panel

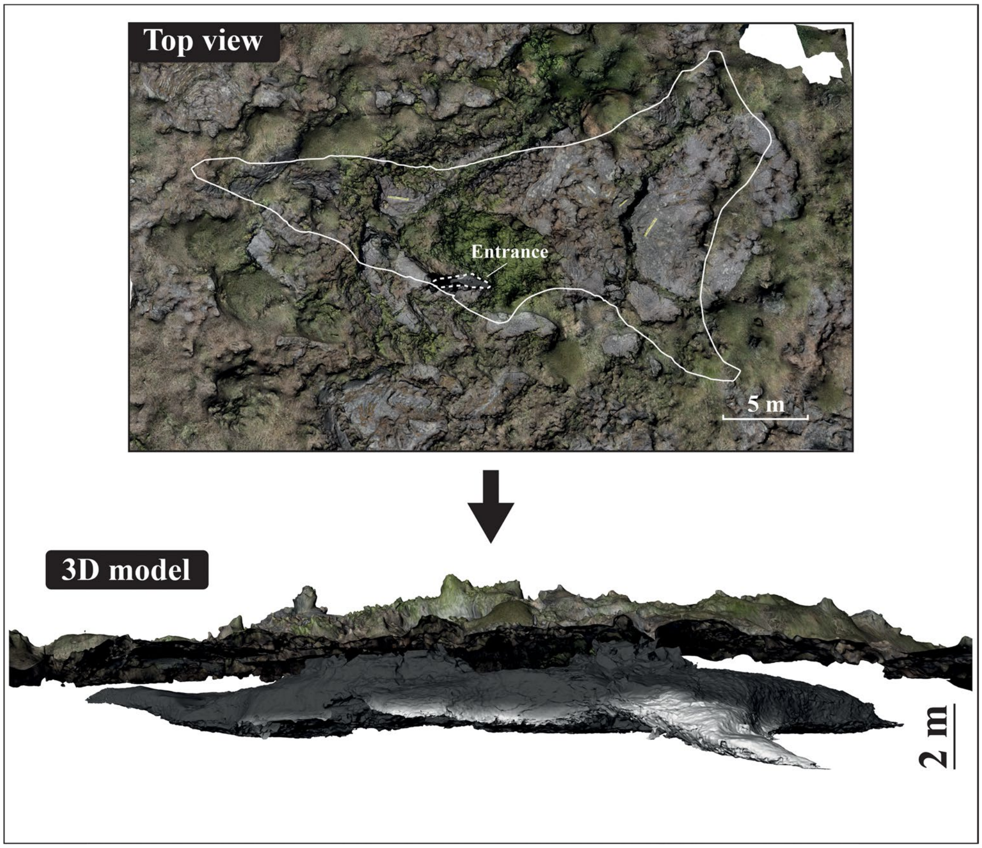

Fig. 11 3D model of the largest lava tube found in the 1858 lava flow field (Site 5) at Vesuvius. It is composed of the internal scan of the lava tube and the georeferenced scan of its overlying surface. At the top, a detailed view of the overlying lava tube surface with the contours of the skylight (dashed while line) and the underlying tube (white line)

photos of each site, allows the dissemination of knowledge, the observation and explanation of these volcanic features to a broader audience and to persons unable to reach the sites (e.g. persons with disabilities, elders). It also gives the possibility to see, explore and understand the sites without the possible risks of going to the field (e.g. collapses) or the difficulty of finding the sites due to vegetation overgrowth. The complete 3D digitization of Site 5, the largest lava tube found in the 1858 lava flow field, is crucial because it provides a record of this fragile structure heritage. This record stands as a numerical copy of the site that can be shown, explored, and studied in any place at any time. It is one of the very few 3D scans of lava tubes produced in the world (e.g. Tomasi et al. 2022).

In term of tourist management, the presence of the 1858 lava flow field and its associated features in a lower part of the stratovolcano could help redistribute the flow of tourists within the National Park which is presently focused on the summit crater. In this sense, it is close to the entrance of the "Lava River" path, which leads to the 1944 lava flow and close to the historical site of the Vesuvius Observatory. The three visits can easily be combined in a single itinerary to be fruited along the whole of a spring or summer day.

As introduced in the beginning of this study, in other volcanic areas local communities are taking advantage of lava tubes as touristic attractions. Even if the morphological scale is different between lava tubes at Vesuvius and Hawaii, still the comparison in terms of geotouristic attractions and management is interesting. In Hawaii, the National Parks services made itineraries to and within lava tubes. The Thurston lava tube present at Kilauea is adapted and lit up during the day for visitors to freely access and explore (https://www.nps.gov/places/nahuku.htm). Other lava tubes are only accessible by booking tours like the Kazumura cave (http://kazumuracave.com/#Tour_Information), the Pua Po'o lava tube (https://www.fhvnp.org/institute/wild-caves-exploration/) or the Kula Kai caverns (https://www.kulakaicaverns.com/). Even if Hawaii is internationally renowned for its volcanoes, lava tubes are important geotouristic sites for the natural parks of Hawaii. At Vesuvius, lava flows and lava structures could attract new visitors on the volcano but also to the city of Naples and its surroundings (e.g. Ercolano, Torre del Greco).

Quality of the Sites and Visitor Targets

A site that could be part of the geoheritage and worthy of promotion and development must have some characteristics that can be summarised as scientific, educational, additional and aesthetic features (Różycka and Migoń 2018). The scientific value of all the sites is unquestionable, due to the uniqueness of the Vesuvius lava tubes and the possibility of bringing together, on a reduced scale, all the structures that characterise this peculiar feature of lava fields. The sites are located in a lava flow field that can be easily observed, which is not a frequent characteristic of Vesuvius lava flow fields. The educational value derives directly from the scientific one, since the sites represent a sort of open-air classroom where the characteristics of low-viscosity lava flows can be demonstrated in a volcanic area where effusive products are, in general, poorly represented. The added value lies in the link between the lava tube and the history of observation and monitoring of this worldwide known volcano. The chronicles of the time (see Sect. 2) tell of the pioneering descriptions of the phenomenon, which had never been observed on the volcano (Palmieri 1859, 1870), and of the first speleological investigations by Malladra (1917), who described the largest lava tube found in the 1858 lava flow field for the first time. These chronicles remind the visitor of the progress made by scientific research in the last 150 years, but also of the importance of direct observation of volcanic phenomena, guaranteed here since the second half of the 19th century by the presence of the first volcanological observatory in the world. From a naturalistic point of view, the vital role of pioneer plant species such as the lichen (Stereocaulon Vesuvianum) in the creation of ecosystems can be demonstrated. This lichen is currently in the process of colonising barren lava flows, breaking down rocks and contributing to the formation of soil. The aesthetic value of the whole area is exceptionally high, as it offers a panoramic view of the Gulf of Naples, with the Sorrento peninsula and the island of Capri to the south, and Posillipo and the Camaldoli hills to the north-east (see the panoramic view from site 3 on the website: https://sites.google.com/view/vesuvius-1858lavaflow/sites/site-3-tumulus). This breathtaking landscape contains all the natural beauty that attracted the ancient Greek and Roman civilisations to settle in this active volcanic area. Unfortunately, the site's accessibility to the general public is limited by the steep ascent and very uneven paths. In addition, there are currently no dedicated car parks. Working with the local authorities would certainly address these problems, as there is a state-owned area just outside the entrance to the lava flow field, where there is also a small building used as a tool shed. This area could be used profitably for bus and car parking, and the building could be restored to provide a visitor point with equipment suitable for accessing the website and projecting videos of the sites.

The possible visitors who can profitably enjoy the sites can be divided into three main target groups. The first group could include people who are unfamiliar with the scientific context of volcanic areas, but who enjoy walking in the open air and beautiful panoramas, and who can increase their curiosity about geology thanks to a visit to unique sites such as the lava tubes. Meanwhile, this geo-tour can help make them aware of the hazards to which the Vesuvius area is exposed, which in the long term could increase the preparedness of the local population at risk. The second group of people for whom the visit could be fruitful are the students from nearby secondary schools, who can join the visit of the sites with the visit of the Vesuvian Observatory Museum, in the framework of school programmes dedicated to the diffusion of volcanological themes among young people. The final aim of these activities could be improving the level of resilience of the area, by increasing the correct knowledge of the volcano as a source of hazard, but also as a resource for the area. Finally, geo-experts would visit the sites to learn more about the various manifestations of effusive activity at Somma-Vesuvius and the characteristics of lava tubes formed in tephriphonolitic lava flows.

SWOT Analysis

The assessment of each site has highlighted the strengths and opportunities of this volcanic landforms geoitinerary along with the weaknesses and threats associated. These aspects are recapitulated using a SWOT analysis for the complete geoitinerary (Table 1).

Strengths and Weaknesses of the Applied Methods

Our employment of a multimethodological approach involving fieldwork, immersive photography and terrestrial laser scanning to document the distinctive Vesuvius lava tubes for the first time, ultimately prompts us to evaluate the strengths and limitations of the chosen methodology.

Fieldwork is necessary in order to locate interesting and important geological sites. It is also crucial to describe volcanological structures in detail, and to design and test a geotourism itinerary that links all the sites together. However, fieldwork can be challenging when the terrain is rough or heavily vegetated. In some cases, it can be dangerous, particularly in underground environments where there is a high risk of collapse. Capturing immersive photos of the sites using a 360° camera allows the visitor to navigate and observe the volcanological structure from anywhere. The instrumentation is small, cheap, mainstream and easily manipulated. Treatment of the data is simple in the constructor's software. The only limitation of this method resides in hosting and publishing the 360° images on compatible servers/platforms and online viewers to make them available to online visitors.

Digitizing the lava tube using a Terrestrial Laser Scanner provided a high-resolution 3D model that captures the morphometry and state of this site at a moment in time. 3D scanning allows the conservation of a digital twin of the site to

Table 1 Results of the SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis

Strengths	Weaknesses
1. Area internationally renowned 2. Discovery of a poorly known area of Vesuvius and its National Park 3. One area of the National Park already attracts many tourists (the summit cone, called Gran Cono) 4. High didactic value to explain the formation of volcanological landforms during lava flow emplacement 5. The site is easily accessible by car or public transport 6. Opportunity to observe the bay of Naples from a nice point of view	1. The geoitinerary is at an initial stage and deserves to be further developed 2. The geoitinerary is a personal initiative by the Authors and lacks, up to now, of an intense collaboration with local administration 3. The full development of the geoitinerary needs funding and a management policy 4. Local people and local administration have not yet fully understood the high touristic and didactic potential of the area 5. Within the National Park, the tourist traffic is limited to the summit cone 6. Lack of parking spaces near the geoitinerary 7. The geoitinerary can be very hard to follow during spring and summer due to the intense blooming of the vegetation, therefore maintenance is necessary
Opportunities	**Threats**
1. The geoitinerary could be integrated into a wider tour because of its closeness to the main touristic attraction of the National Park, the city of Naples and the archaeological sites of the Vesuvian area (i.e., Pompeii, Herculaneum, Oplontis) 2. Local accommodation facilities can easily host a large amount of tourists 3. The geoitinerary can be explored rapidly (less than 1 h) 4. The geoitinerary can be combined easily with other sites of utmost volcanic interest in the vicinity	1. Lack of financial resource to develop the geoitinerary 2. Low interest in local authorities for the development of geotourism

be re-examined or showed throughout time even if the original site erodes and/or collapses. However, this method is more complex to apply and requires large, expensive instrumentation operated by experts. The treatment of the data can be tedious, and the constructor's software is complex to use.

Conclusive Remarks

The Somma-Vesuvius volcanic complex boasts incredible geological features largely neglected by tourists. Although it is visited by large numbers of tourists, access to the Vesuvius National Park is limited to the top of the Vesuvius crater. To communicate and share knowledge about volcanoes, their products and their hazards, we believe that it is necessary to expand the visitor experience in the National Park to include peculiar geosites. In this study we focused our attention on the 1858 lava flow field due to the large variety of surface features that are beautiful volcanological examples of landforms formed during recent effusive eruptions and easily accessible by visitors. We proposed an on-site geoitinerary and an online virtual tour regrouping five interesting volcanological sites. We assessed and highlighted the geoheritage potential of the geoitinerary for local tourism, scientific dissemination, conservation and enhancement of volcanic risk perception.

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Declarations

Competing Interests 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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