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ORIGINAL ARTICLE

Cosmic Ray Muon Radiography: New Teaching and Educational Media for Geotourism and Museum—A Case Study from Italy

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Abstract
From 2019 to 2023, the MIMA-SITES research project tested the application of muon radiography (muography) at the Temperino mine in the Archaeological and Mining Park of San Silvestro, Italy. Through the collaboration of several partners, i.e., Regione Toscana, National Institute for Nuclear Physics INFN division of Florence, Institute of Geosciences and Earth Resources – CNR, Parchi della Val di Cornia SpA, and the Department of Earth Sciences of the University of Florence, the project has took advantage of the MIMA (Muon Imaging for Mining and Archaeology) muon tracker to test the reliability of muography for archaeological and mining purposes. Focusing on revealing density variations in the mine's overlying rock mass, this research project identified some unknown cavities and a Cu-Fe-enriched high-density ore shoots. Using the achieved results, multimedia contents were created by employing terrestrial, aerial, and mobile laser scanners (TLS, ALS, and MLS, respectively), unmanned aerial vehicle digital photogrammetry (UAV-DP), and muography data. The results of the muon radiography surveys have been integrated into a new exhibit within the museum pathway of the Temperino mine. This initiative stands as one of the early international examples of utilizing muography to enhance geological heritage within an archaeological and mining park. In addition to emphasizing its geological and archaeological importance, the exhibit sparks interest in local geotourism. This research confirms that incorporating innovative scientific content and multimedia elements can boosts the attractiveness of geological, archaeological, and mining parks, attracting new visitors. Muography can play a key role in cultivating knowledge and curiosity about the distinct geological and archaeological heritage of a site.

Keywords Muography · Archaeological mining park · Geotourism · Geomatics · Ore deposits · Science museum

Introduction

Geodiversity is the term usually given to the remarkable and complex variety of geological, geomorphological, soil, and hydrological features that characterize a territory (Gray 2008, 2019). It is employed as a conceptual synthesis analogous to the term biodiversity in the biological domain (Serrano and Ruiz-Flaño 2007; Carrión Mero et al. 2018). Several definitions of geodiversity have been discussed and are available in literature (Nieto 2001; Gray 2008; Carcavilla et al. 2008, 2009; Panizza and Piacente 2008). The geodiversity of Earth is the driving force that has propelled and continues to drive research and studies in various geological fields. The geodiversity of places has determined their social and economic development, or abandonment, throughout the history of human beings (Rodolico 1953),

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playing an active role in providing various ecosystem and abiotic systems (geology and topography) services, also known as geosystem services (Gray 2019; Fox et al. 2020). These services can fulfill human requirements by offering economically useful minerals, rare-earth elements, geothermal resources, culturally significant sites, and other natural resources (Gray 2019). Tuscany is a relevant example, on a global scale, of a place whose topographies, geological materials, and geomorphological features have facilitated the development and settlement of humans, who have modified its form and landscapes over centuries (Rodolico 1953; ISPRA 2005; Da Mommio et al. 2010; Alberico et al. 2023). Humans exploited its geological and mineralogical materials, especially minerals for the production of metals like iron (Fe), copper (Cu), lead (Pb), silver (Ag), tin (Sn), and zinc (Zn) (Dini 2022; Vezzoni et al. 2023).

Geotourism has evolved over time around the concept of geodiversity. Geotourism refers to all forms of travel and tourism, in which exploring and appreciating the geodiversity of a particular region is the principal objective (Newsome and Dowling 2018). To meet such interests, geoparks and national protected areas have been established worldwide (Dowling 2011), with crucial support from UNESCO, e.g., UNESCO Global Geoparks (Ferreira and Valdati 2023; UNESCO 2024). These kinds of parks serve a dual purpose: to enhance the appreciation of local geology and the activities that have developed around it, while also ensuring its long-term maintenance and protection. Geoparks stand out as captivating destinations for geotourists seeking a profound insight into Earth's history and geological processes. By actively interacting with the distinctive geological characteristics of a region, visitors can deepen their understanding of the planet's dynamic evolution (Dowling 2011; Newsome and Dowling 2018; Carrión Mero et al. 2018; Gray 2019; Martínez-Graña et al. 2023).

It is important to stress the fact that geotourism can yield either positive or negative impacts on geoheritage. Ideally, geotourism triggers an appreciation and connection with geological features through visitation, interpretation, and education. Nevertheless, inadequate planning and development in geotourism may lead to adverse impacts on geoheritage due to ineffective management of geological attractions and sites (Newsome and Dowling 2018). Many locations across the globe are acknowledged as geosites, geoparks, and mining parks which usually are geological sites with scientific, educational, and aesthetic value. The identification and conservation of these sites help in promoting geotourism by developing an appreciation for the Earth's geological heritage, while also making significant contributions to scientific understanding and educational activities (Ravanel et al. 2014; Marsico et al. 2016; Fernández-Lozano and Gutiérrez-Alonso 2017). Regarding the principles of geotourism and geodiversity, Italy hosts several parks of international scientific importance (ISPRA 2005). Geological formations, historical mining operations, and cultural landscapes are narrative structures of Italian archaeological and mining parks. On the basis of the national geodiversity index map proposed by Alberico et al. (2023), Tuscany results as one of the Italian region with relatively high geodiversity index value.

Geotourism should also coexist with mining activities. The contrast to the climate change will pass through the replacement of fossil energy sources by low CO_2 emission, renewable energy sources. The energy transition will require increased metal recycling and reuse, as well as an increase in primary production of metals. The European Union recently adopted the "Critical Raw Materials Act" to enhance metal recycling and to bring mining and refining activities back to Europe. This climatic, economic, and geopolitical challenge will have to combine the requests of the "Critical Raw Materials Act" with the conservation of biodiversity, with social acceptability, with the cultural and tourist valorization of the territory and also with the ethics of not relegate mining activities only to emerging or developing countries.

In this study, the digital representation of the results achieved during an innovative research project called MIMA-SITES, carried out at the Temperino mine (Baccani et al. 2019; Borselli et al. 2022; Beni et al. 2023a), is presented.

The Temperino mine area is part of the Archaeological and Mining Park of San Silvestro that is managed by the Parchi della Val di Cornia SpA. The MIMA-SITES project began in 2019 and was successfully completed in 2023. The research team was composed of physicists, geologists, and archaeologists belonging to different entities: the National Institute for Nuclear Physics (INFN) division of Florence, the Institute of Geosciences and Earth Resources—CNR, the Department of Earth Sciences of the University of Florence, the Parchi della Val di Cornia SpA, the Department of Physics and Astrophysics of the University of Florence, and the Institute of Geosciences and Georesources of the National Research Council of Italy of Pisa. The project aimed to investigate and test the muography technique survey for mining, archaeological, and engineering geological applications.

Muography, also known as muon radiography or muon imaging, is an innovative, non-invasive imaging technique that measures the naturally produced muon flux. This enables the internal imaging of a broad range of targets, that is, the studied objects (Procureur 2018; Bonechi et al. 2020b). Through an appropriate data analysis procedure, muography allows the estimation of the density distribution within the examined target for different lines of sight (LoS) of the detector. The resultant density maps facilitate the identification of contrasting density regions, which can be interpreted in various ways depending on the studied target and purposes of the planned muography campaign survey.

Over the past two decades, muography has undergone extensive testing across a wide range of research fields, including volcanology, mining, archaeology, planetary study, civil engineering, security, and nuclear waste monitoring. Several detailed review and papers are available on this topic (Bryman et al. 2014; Tanaka 2017; Morishima et al. 2017; D'Alessandro et al. 2019; Kaiser 2019; Saracino et al. 2019; Schouten 2019; Nishiyama et al. 2019; Bonechi et al. 2020b; Zhang et al. 2020; Holma et al. 2022; Oláh et al. 2023; Tanaka et al. 2023).

The MIMA-SITES project validated and confirmed the reliability of the transmission-based muography technique (TM) using the MIMA detector for both mining exploration purposes and preliminary cavities and ore shoot identification (Baccani et al. 2019, 2021; Bonechi et al. 2020a; Borselli et al. 2022; Beni et al. 2023a). Further, it confirms the potential of the muon imaging technique as a complementary tool to the other traditional geophysical methods, as discussed in Zhang et al. (2020) and Holma et al. (2022).

The entire process of the muography survey involves the use of three-dimensional environments, both for transmission simulations and results visualization, obtained through geomatic surveys. Several published muographic studies support the latter sentence (Morishima et al. 2017; Nishiyama et al. 2019; Lázaro Roche 2021; Procureur et al. 2023; Teixeira et al. 2023b; Beni et al. 2023b). During the MIMA-SITES project, numerous instruments and software were employed to obtain the most reliable three-dimensional reconstruction of the study site, that was the Temperino mine: terrestrial and mobile laser scanners (TLS and MLS), unmanned aerial vehicle digital photogrammetry (UAV-DP), and geological modeling software.

The results of the project, which were completely digital, allowed us to implement multimedia content and graphics to enrich the Temperino mine museum content. At the end of the MIMA-SITES project, the authors pooled their expertise to conceive, design, and subsequently implement an innovative museum pathway that is accessible to all, presented in both Italian and English language. This new museum journey reveals the scientific objectives achieved through the study of muons within the mine, enhancing the park as a scientific laboratory, in addition to being a site for geological and archaeological appreciation. Moreover, the scientific outreach related to muon imaging is emerging as a relatively new research area (Afonso et al. 2022; Teixeira et al. 2023b). Through research, collection, and documentation at the Temperino mine, the ultimate objective is to elevate, through science communication, the region's tourism sector in accordance with international and local standards for geotourism, which aims to promote respect, knowledge, and comprehension of the geological and archaeological heritage of the area.

Geomatics and Digital Technologies for Geoheritage Valorization

Over the past few years, the coupled use of geomatic instruments (TLS, MLS, UAV, GNSS) and digital technologies for research, restoration and documentation of cultural and geological heritage, and for instructional purposes in museums, science centers, and galleries has increased significantly (Hawkey 2004; Remondino 2011; Grussenmeyer et al. 2011; Remondino and Campana 2014; Ravanel et al. 2014; Themistocleous et al. 2016; Marsico et al. 2016; Rodríguez-Gonzálvez et al. 2017; Fernández-Lozano and Gutiérrez-Alonso 2017; Tucci et al. 2017; Martínez-Graña et al. 2018; Ulvi 2021; Capolupo 2021; Hincapie et al. 2023; Beni et al. 2023c). This expansion is seen in both physical and digital environments, as evidenced by the incorporation of digital interactivity and the creation of specialized websites for museums. The latter fulfills an essential function by promoting continuous education, which transcends technical and occupational domains to include intellectual, artistic, and cultural pursuits. The interdependence between scientific findings, digital technology, lifelong learning, and museums is clear, as they all prioritize active involvement in the discovery of knowledge and learning from products rather than only absorbing it. This viewpoint is supported by the Museums, Libraries, and Archives Council (MLA) and the Campaign for Learning in Museums and Galleries (CLMG), both of which honor the varied and significant results of informal learning (Hawkey 2004).

Digital technology facilitates an extensive range of collaborative initiatives among institutions, museums and learners. Currently, there is an endless selection of equipment and systems, including computers, portable devices, multitouch displays, and augmented and virtual reality (AR, VR) environments (Hijazi and Baharin 2022). Information and communication technology (ICT) is a common synonym of digital technologies. Certain applications, such as search engines and databases, improve accessibility and accelerate laborious and time-consuming processes. A multitude of these technologies have replaced preceding analog or alternative versions, including posters, music, film, graphics, photography, and televisions (Carrión Mero et al. 2018; Hincapie et al. 2023; Martínez-Graña et al. 2023). Furthermore, numerous applications and cheaper software solutions have unlocked possibilities that were once deemed unattainable, with a notable emphasis on platforms generating virtual realities (Hawkey 2004). This technological advancement facilitates a more impactful engagement of tourists, particularly resonating with a younger audience (Hijazi and Baharin 2022).

Digital technologies typically leverage and advance media content and research products using geomatic data across diverse research domains. These fields encompass architectural surveys, engineering, geological studies, and archaeological applications. Digital technologies tackle various challenges, including issues related to collection conservation, data management, and resolution of exhibition display problems, all aimed at enriching the human experience (Tong and Ma 2021).

Geomatics, as a term, denotes the scientific and technological domain that integrates various disciplines, including geography, surveying, remote sensing and geographic information systems (GIS). Its purpose is to acquire, analyze, interpret, manage, and visualize spatial and geographical information (Gomarasca 2009). So, geoheritage could be valorized and preserved merging scientific content through geomatic surveys and digital technologies in innovative physical and/or digital museum (Newsome and Dowling 2018; Afonso et al. 2022; Hincapie et al. 2023; Martínez-Graña et al. 2023). A digital museum is characterized as a museum employing information technology to digitally replicate the operations of a traditional physical museum and share cultural object resources online. Their principal significance lies in harnessing the capabilities of digital technology tools to address the limitations associated with traditional museums, particularly those centered around physical collections (Tong and Ma 2021).

In this framework, the presented paper supports the idea that scientific output, such those relative to the MIMA-SITES project, represent potential innovative content for natural parks and geotourism, given their three-dimensional digital nature of the output.

Case Study

The Archaeological and Mining Park of San Silvestro

The establishment of the San Silvestro open-air archaeological and mining park (Fig. 1a), situated across 450 ha in the hills of Campiglia Marittima, Tuscany (Italy), was driven by a specific research background. In 1984, the inaugural excavation season at the Rocca of San Silvestro castle was conducted by the Medieval Archaeology Department of the University of Siena, in collaboration with the Town Council of Campiglia Marittima and various departments from European universities. The Rocca of San Silvestro (Fig. 1b) is located in the area delimited by the Manienti, Lanzi, and Temperino valleys. These hills are crossed by two parallel seams of porphyritic rock running southeast to northwest. Along these seams, in contact with limestone, mineral

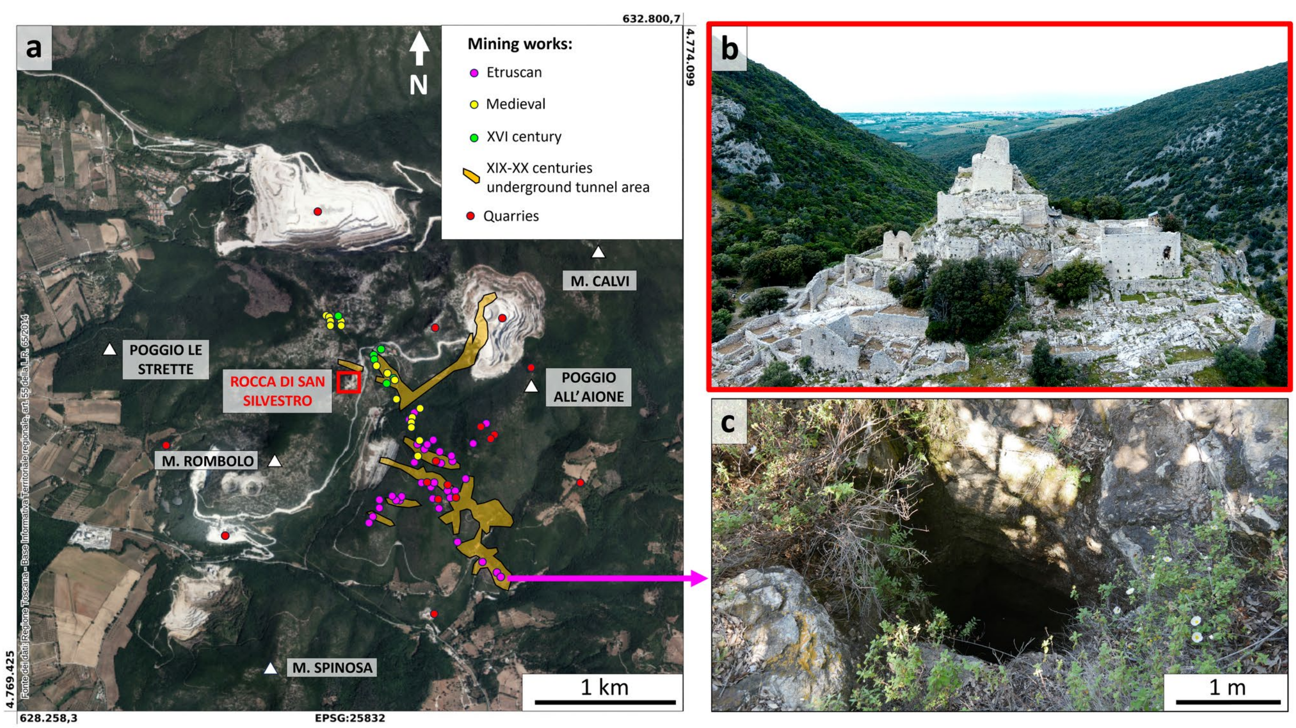

Fig. 1 The Archaeological and Mining Park of San Silvestro: **a** satellite view of the park (modified from Brocchini et al. 2017); **b** aerial photo of the medieval village of San Silvestro, highlighted with a red square in (**a**); **c** example of a well preserved Etruscan vertical shaft visible above the Temperino mine entrance

deposits formed. The latter primarily consists of mixed sulfides, including silver-bearing galena, copper pyrites, blende (zinc sulfide), and, in specific areas, cassiterite (tin dioxide). The surface layers of these mineral formations consist mainly of limonite (iron hydroxide), referred to as the "capping." The presence of abundant mineral resources undeniably shaped the location, distribution, and growth of settlements across various historical periods, beginning notably with the Etruscans. Manufacturing and economic activities associated with the exploitation of these metal-bearing seams persisted, albeit with fluctuations and intermittent breaks, extending into the recent past (Tanelli 1993; Tanelli et al. 1993; Guideri 2017). Nowadays, the park preserves abundant traces of historical mining activities, particularly focused on copper, lead, and silver extraction. The park testifies the intensive mining practices that once shaped this territory. The remains uncovered through decades of archaeological, geological, and speleological exploration offer insights into resource extraction techniques and the strategic positioning of mining operations (Francovich and Parenti 1987; Francovich 1994; Francovich and Wickham 1994; Guideri 2009, 2017). The Park is a valuable repository of historical and scientific importance (Acocella et al. 2000; Da Mommio et al. 2010; Dini et al. 2013; Vezzoni et al. 2016; Brocchini et al. 2017; Minutoli 2021) that provides a comprehensive understanding of the mining and metallurgical activities that characterize the Campiglia area from the pre-roman period to the modern mine-works. Its geological richness and focus on key minerals contribute to its status as a pivotal historical site in the development of scientific thinking on magmatic-hydrothermal ore deposits (Vezzoni et al. 2023).

The archaeological and mining park of San Silvestro is integrated into the broader Val di Cornia parks system (Parchi Val di Cornia 2024). This system, that consists in a network of parks and museums in the province of Livorno, was identified in the 1970 s with urban planning restrictions coordinated by municipalities of Piombino, San Vincenzo, Campiglia Marittima, Suvereto, and Sassetta. Currently, the Val di Cornia parks system stands as a key driver for the transformation of the local economy. This transformation is characterized by the emergence of major phenomena such as cultural resources, protected natural areas, landscapes, and tourism services. These elements have acquired strategic significance, playing a crucial role in shaping and advancing the economic landscape of the region.

The Val di Cornia region follows the Cornia river valley, a stretch of land descending from the Mt. Calvi massif to the cultivated plain (Fig. 1a), extending towards the Populonia promontory and the Tyrrhenian Sea. This geographical layout appears to trace the historical land connection with the island of Elba and the Tuscan archipelago.

In this administrative setting, scientific research played a crucial role. Here, it progressed closely and inseparably, initially contributing to territorial planning by guiding the identification of park perimeters, and subsequently facilitating interventions to make the enhanced features accessible to the public. In essence, this aimed to return the social value of scientific research to the communities. These represent sequential phases within a unified process that has been implemented on a broad scale in the Val di Cornia parks system (Guideri 2017).

In this network, the Archaeological and Mining Park of San Silvestro aims to highlight the historical landscape shaped by centuries of mining activities (Brocchini et al. 2017). To this goal, the park commits to several key initiatives for the promotion and documentation of mining remnants. Notably, challenges highlighted by Brocchini et al. (2017) include (i) the collection of high-quality images depicting significant mining remains and geological outcrops, (ii) the enrichment of their database with new three-dimensional models for research and educational applications, and (iii) the provision of equipment and security measures for underground spaces and ancient shafts to facilitate guided tours for small groups of tourists. Among the most distinctive attractions of the park, it is possible to visit the first level of the Temperino mine, allowing visitors to immerse themselves in the geological history of the area. In this context, the MIMA-SITES project was organized to address the key initiatives of the park. In fact, the project aimed to create new photographic and video materials and support the development of three-dimensional digital models of underground environments and the geology of the Temperino mine area using the cosmic ray muon radiography technique to facilitate the discovery of previously unknown cavities and dense ore shoots. These goals can help the planning of interventions of the park aimed at enhancing the safety of tourist sites and at educational and research purposes.

The Temperino Mine: Geological Setting and Museum

The Temperino mine, where the MIMA-SITES project was conducted, is situated within the Campiglia area in the Archaeological and Mining Park of San Silvestro (Fig. 2a, b). The latter is characterized by a N-S trending horst mainly composed of Mesozoic carbonate rocks, belonging to the Tuscan Nappe unit. The horst is bounded by high-angle normal and strike-slip faults, connecting the Tuscan Nappe formations with the overlying Jurassic-Eocene Ligurian unit successions. Campiglia Marittima was affected by multiple magmatic pulses, which were accompanied by metasomatic rocks (i.e., skarn bodies) and sulfide ores (Vezzoni et al. 2016).

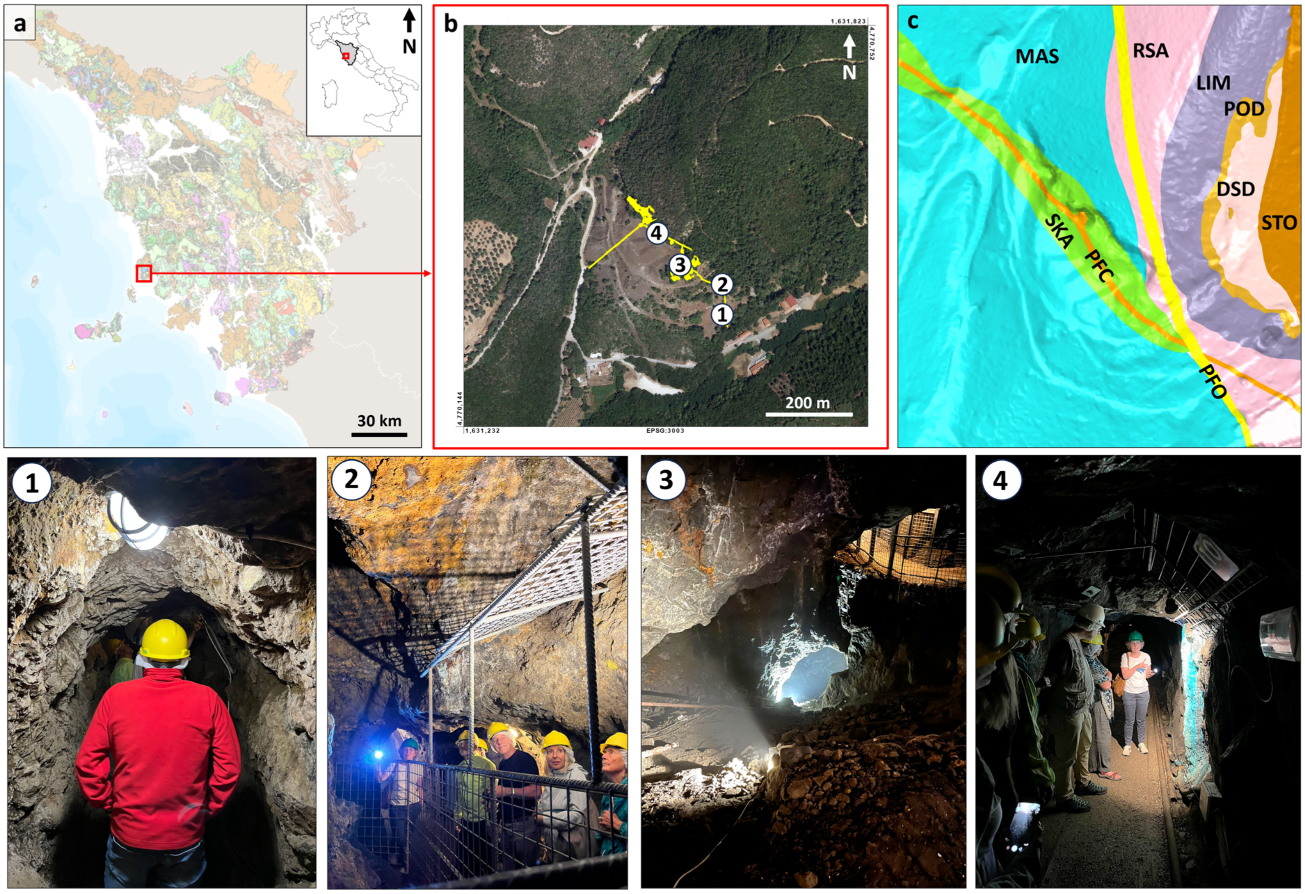

Fig. 2 Geographical location of the study site: **a** simplified geological map of the Tuscan region from the geological database of Tuscany Region (Regione Toscana 2024), with the study area of Campiglia highlighted by a red square; **b** satellite image of the Temperino hill, showcasing the tourist gallery inside the mine, highlighted in yellow. The numbered locations correspond to images reported at the bottom of the figure. From left to right: the entrance gallery of the Temperino mine, an example of a guide explaining the geology and history of the mine, one of the inclined shaft that connected the first level to the lower levels, and, in the last pictures, the chrysocolla outcrop. In (**c**), an orthogonal view of the created geological model is reported: MAS, metamorphosed Calcare Massiccio Fm; RSA, Rosso Ammonitico Fm; LIM, Calcare Selcifero Limano Fm; POD, Marne a *Posidonomya* Fm; DSD, Diaspri Fm; STO, Scaglia Toscana Fm; SKA, ilvaite-hedenbergite skarn; PFC, Coquand Felsic dike; PFO, Ortaccio Felsic dike

The magmatic-hydrothermal-tectonic setting and evolution of the area were totally revised during a long-term research project (started in 2008 and still ongoing) which involved the Institute of Geosciences and Earth Resources-CNR, the Department of Earth Sciences of the University of Pisa, and the Department of Earth Sciences of the University of Geneva (Switzerland). The new geological scenario, summarized below, differs greatly from that proposed by past authors (e.g., Corsini et al. 1980). The sequence of magmatic and hydrothermal events can be outlined in the following stages (Vezzoni et al. 2016, 2018; Di Vincenzo et al. 2022): (1) emplacement of the Botro ai Marmi monzogranite pluton (~5.4 Ma), creating an extensive thermal metamorphic aureole (marble; MAS); (2) metasomatic processes resulting in various ilvaite-hedenbergite skarn bodies and Pb–Zn(-Ag) ore deposition (SKA; between 5.38 and 5.13 Ma); (3) intrusion of mafic porphyry dikes and associated Fe-Cu ore (PM; ~5.1 Ma); and (4) intrusion of felsic porphyries (e.g., Coquand and Ortaccio felsic dikes; PFC and PFO; between 5.1 and 4.7 Ma), crossing all previous contacts and lithologies. Lastly, (5) two rhyolites lava flows and/or domes at around 5.00 and 4.44 Ma in the western area outside the carbonate horst closed the magmatic activities.

Skarn deposits, defined by their economically significant concentrations of metals, such as copper, lead, silver, zinc, and iron, are prevalent in the Temperino-Lanzi area. The skarn mineralogy in this region primarily includes hedenbergite and ilvaite along with johannsenite, and minor garnet associated to late quartz, calcite, and epidote. The most common ore minerals associated with skarn bodies are chalcopyrite, galena, sphalerite, pyrite, pyrrhotite, and tetrahedrite. Furthermore, Campiglia hills feature an abundance of karst cavities. These cavities, primarily vertical owing to tectonic influences, served as conduits for ancient miners during the Etruscan and Medieval periods (Cascone and Tinagli 2016; Brocchini et al. 2017). Several entrances to these ancient mines have been discovered in the Campiglia hills, with the most extensive mining complex at Poggio all'Aione, dating back to the first century BC.

The Temperino mine area testifies a prolonged history of mining activity (Tanelli et al. 1993) dating back to Etruscan–Roman times (seventh to first century BC) and extending until the late twentieth century (Brocchini et al. 2017). Distinct mining techniques were employed across three primary exploitation periods: narrow vertical shafts excavated from the surface (Fig. 1c), tracing ores underground (Etruscan and Middle Age period); opencast mines, often intersecting with previous mine works (sixteenth century period); and horizontal galleries carved into the Earle skarn body (modern period). In 1983, the last mining permit expired, leading to the inclusion of the entire mining area (Temperino–Lanzi–Ortaccio–Manienti) into the San Silvestro Archaeological and Mining Park (Da Mommio et al. 2010). The enduring significance of this mining area for over two millennia is attributed to the presence of skarn bodies associated to Fe-Cu–Zn-Pb(-Ag) sulfides. The Temperino mine tunnels and shafts were excavated within the ilvaite-hedenbergite skarn bodies, with a focus on identifying Fe-Cu–Zn-Pb(-Ag)-rich ore volumes. Predominantly, the primary ores are situated within the skarn body, whereas mineralization of the skarn–marble contact surfaces is infrequent. Specifically, the Earle body, one of the skarn bodies exploited by Temperino mine, mainly hosts Cu–Fe ore characterized by chalcopyrite–pyrrhotite–pyrite, with Cu concentrations reaching up to 10% by weight in small volumes, generally spatially associated with the mafic intrusions (Vezzoni et al. 2016). The mafic porphyry forms dikelets and infilling of primary skarn microporosity (pockets), which are concentrated in the internal portions of the skarn. The average Cu grade in the Cu–Fe ore type falls within the range of 1.9–2.7% by weight (e.g., Vezzoni et al. 2016, 2023).

Nowadays, certain structures that were initially dedicated to productive and administrative functions of the mining activities have been restored to accommodate the museum and provide services to visitors (Da Mommio et al. 2010; Brocchini et al. 2017). In Fig. 3, the entrance of the Temperino mine (Fig. 3a) and all the other services are shown (Fig. 3b). It represents one of the most captivating attractions as it gives tourists the opportunity to experience firsthand the sensations felt by miners descending into the mine, while also allowing them to directly engage with the geology and archaeology (Fig. 2) described in the previous sections.

Material and Methods

Geological and Mining Background

The research activity was based on the new interpretive geological model of the Temperino skarn deposit produced by the Institute of Geosciences and Earth Resources-CNR in collaboration with the Department of Earth Sciences of the University of Pisa (Vezzoni et al. 2016, 2018, 2023; Paoli et al. 2019). An extremely detailed geological survey was conducted (2007–2015) at surface and subsurface, mapping skarn-sulfide bodies, magmatic rocks, and host-rocks, as well as collecting structural data and samples

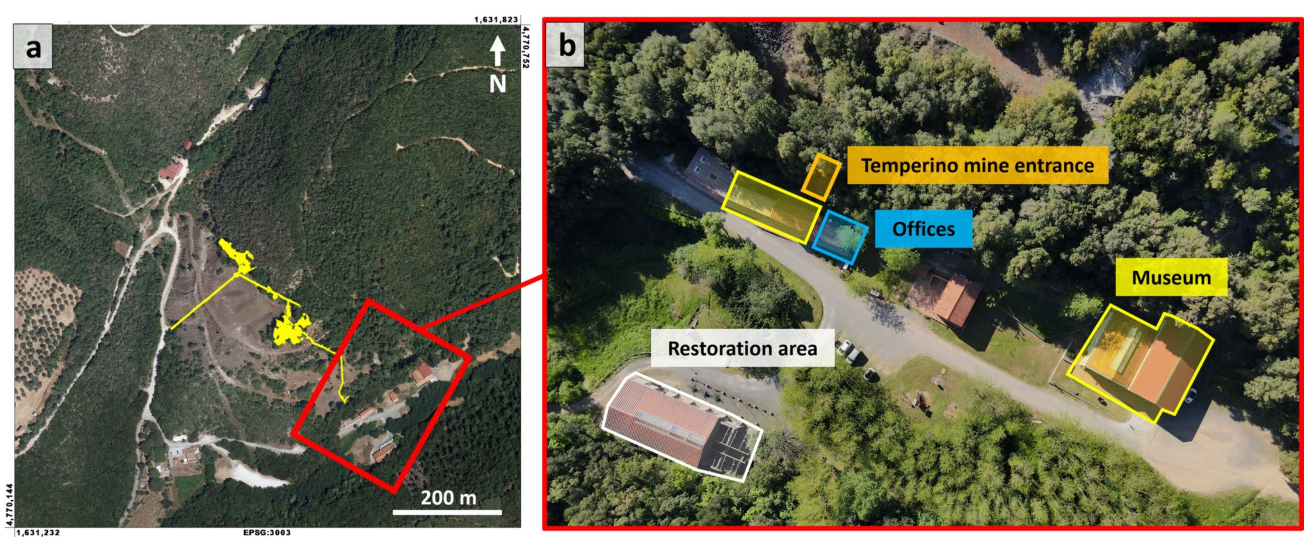

Fig. 3 Aerial view of the Temperino mine access area: **a** satellite image of Temperino hill, with the touristic first-level mine's point cloud highlighted in yellow (Temperino tunnel); **b** close-up on the mine entrance area, the spaces subdivision is shown

for geochemical-petrological-geochronological analyses. Underground geological mapping (1:500/1:1000 scale) was conducted, using speleological techniques, along almost 25 km of tunnels and shafts, from the uppermost surface occurrences (420 m a.s.l.), down to the deepest mining levels (46 m a.s.l.). The new survey was integrated with available drill log data (both external and internal drillings performed by mining companies in the past). Geological and structural data were included in horizontal and vertical cross sections that allowed to decipher the external geometry of the skarn-sulfide bodies, their internal mineralogical-textural features, and the crosscutting relationships with the magmatic dykes (Vezzoni et al. 2016). The exhaustive knowledge of geological and mining characters of the Temperino mine allowed the selection of the most favorable zone of the mine to develop the MIMA-SITES Project. The Temperino touristic tunnel was selected due to the easy accessibility, the presence of electric services, and the limited depth (< 100 m from surface), as well as for the existence, between the surface and the tunnel, of verifiable large exploitation cavities for test (Gran Cava), the existence of documented but not accessible exploitation cavities, and the presence of large portions of skarn still potentially containing high-density sulfide bodies.

Research Workflow: An Overview

Exploring the intricate intersection of archaeology, mining history, and technological innovation, this work aims to shed light on aspects of the park that are still unknown. Motivated by both the challenges of the park and the objective of testing the muon imaging method for mining and archaeological purposes, our research followed a rigorous workflow (Fig. 4).

Leveraging the success of the MIMA-SITES project, we delved into the creation of high-quality visual documentation, three-dimensional models and exploration of underground spaces. This comprehensive and multidisciplinary approach aims to contribute significantly to the understanding, preservation, and safety enhancement of the park. The workflow shown in Fig. 4 synthesizes the effort made by a large research team to carry out a 5-year study, during which numerous muographic surveys were conducted inside the Temperino mine concurrently with geomatic surveys.

Various tools and software were employed throughout this research project, including GIS applications such as QGIS (QGIS 2024) and ArcGIS Pro (ESRI 2024); three-dimensional data management and analysis software like RiSCAN PRO (RIEGL 2024), CloudCompare (CloudCompare 2024), Pix4D (Pix4D 2024), and Metashape (Agisoft 2024); muon imaging data analysis software including ROOT (ROOT 2024), GEANT4 (GEANT4 2024), and Python (Python 2024); and digital content management and creation editing tools such as Final Cut Pro X (Apple 2024), Photoshop (Adobe 2024), Sketchfab (Sketchfab 2024), and Unreal Engine (Unreal 2024). The obtained results were then materialized in the form of scientific, educational, and digital outputs (Fig. 4).

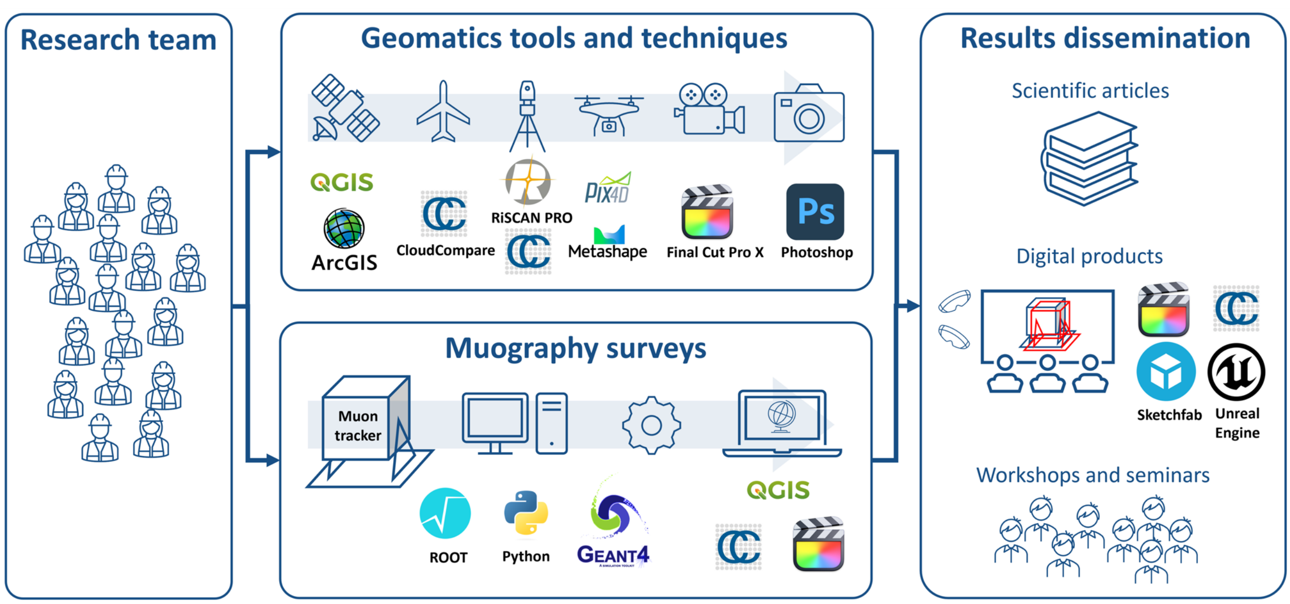

Fig. 4 Schematic workflow of the MIMA-SITES project. Each icon corresponds to the software used for that specific step in the workflow. The presented paper specifically focuses on the final phase, involving the dissemination of results through digital products

Close-Range Methods Surveys

Currently, in geological, muographic, and archaeological research, the integration of advanced close-range surveying methods has become indispensable for a comprehensive documentation and analysis of complex environments (Abellán et al. 2009; Lague et al. 2013; Procureur 2018; Frodella et al. 2021; Ulvi 2021; Lázaro Roche 2021; Beni et al. 2023b). Close-range methods surveys in a scientific context refer to surveying techniques and methodologies that are applied to capture detailed and high-resolution data of objects or areas in close proximity to the surveying instrument, at a distance less than 300 m (Sturzenegger and Stead 2009; Westoby et al. 2012). These methods are typically used for studying and documenting geological features, natural or man-made structures, or landscape, often requiring precise measurements and detailed representations. Close-range surveying can involve various technologies such as laser scanning, photogrammetry, or other imaging techniques, and it is commonly employed in fields like archaeology, geology, engineering, and cultural heritage preservation. The aim is to obtain accurate and comprehensive data for analysis, documentation, and visualization of the targeted subjects.

In this study, three close-range instruments (Fig. 5) and methods were utilized and integrated: a RIEGL VZ-1000 terrestrial laser scanner (TLS), DJI Mavic Air 2S unmanned aerial vehicle for digital photogrammetry (UAV-DP), and GeoSLAM ZEB-HORIZON handheld mobile laser scanning system (MLS). These state-of-the-art technologies offer distinct advantages in capturing high-resolution spatial data, enabling the detailed and accurate representation of both surface and subsurface environments. The RIEGL VZ-1000 (Fig. 5a) is a high-precision and accurate TLS that enables precise and reliable three-dimensional data acquisition. The ability to capture dense point clouds with high accuracy is fundamental for meticulously documenting archaeological sites, mining remnants, and geological outcrops. Complementing the TLS data, the DJI Mavic Air 2S UAV (Fig. 5c) introduces an aerial perspective. Equipped with an optical camera, this drone enables efficient and flexible data collection over an extended area. The high-resolution imagery acquired by the UAV enhances our ability to capture fine details, offer a holistic view of the study area from above, and create a three-dimensional model using structure from motion algorithms (SfM). Further, we completed our surveying toolkit with the GeoSLAM ZEB-HORIZON MLS (Fig. 5b), an instrument that offers a quick and straightforward method for acquiring 3D point cloud data. As the user moves through the area of interest, the device captures data, eliminating the necessity for time-consuming scanner setups and the data registration process typically required by traditional TLS methods. It consists of a system designed for rapid and versatile data acquisition in a wide range of challenging environments, such as building, underground tunnels, and tiny spaces. This relatively new technology empowers researchers to explore and document intricate spaces such as underground cavities and archaeological structures with unprecedented speed and efficiency (Brocchini et al. 2017; Teixeira et al. 2023a).

The synergy between these technologies facilitates a holistic understanding of the targeted landscapes, i.e., the first level of the Temperino mine and hill surface, fostering reference geometrical information useful for the cosmic ray muon radiography application. Moreover, all the acquired data represent an updated database for the preservation, interpretation, and safeguarding of cultural and geological heritage of the site (Baccani et al. 2019; Beni et al. 2023c).

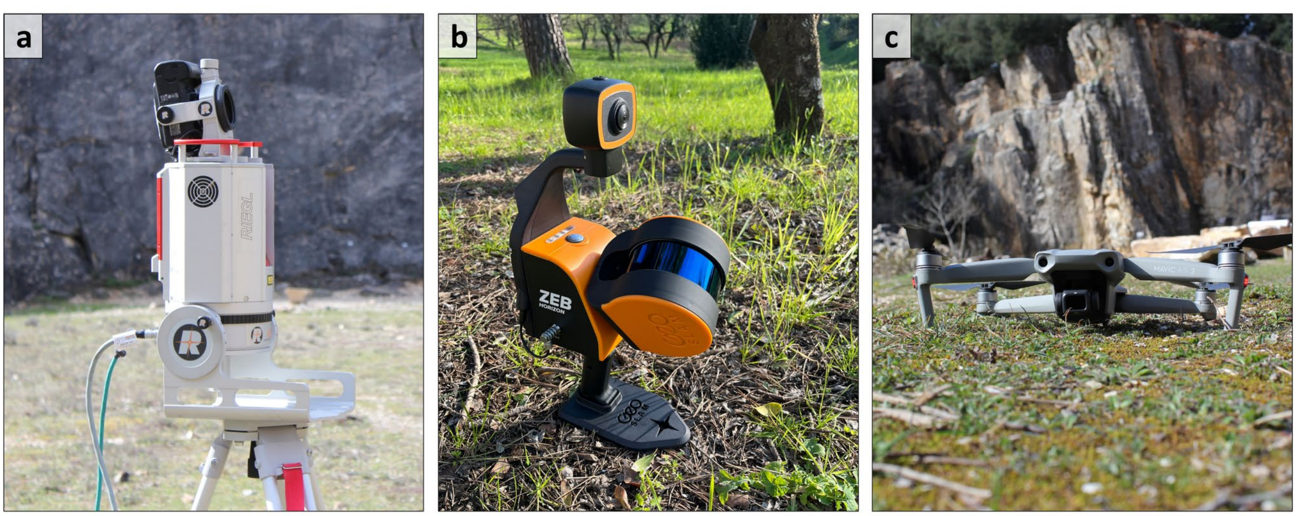

Fig. 5 The instruments employed during the muon imaging campaign to carry out the geomatic survey included the following: **a** RIEGL VZ-1000 terrestrial laser scanner (TLS); **b** GEOSLAM ZEB Horizon mobile laser scanner (MLS); and **c** DJI Mavic AIR 2S unmanned aerial vehicle (UAV)

The final output of each technique consists in a point cloud, that is a group of points identified by three coordinates (x, y, z) in a chosen reference system and characterized by different volume densities and scalar fields. Every dataset has been processed using both licensed and open-source software. The TLS data were processed using both the commercial software RISCAN PRO and the open-source software CloudCompare (CC) (CloudCompare 2024). RISCAN PRO was employed during the first phases of the processing, to merge scan positions and georeference the final TLS point cloud. Cylindrical reflectors served as markers, and their positions were precisely measured with centimetric accuracy using a Global Positioning System (GPS). Additionally, the RIEGL VZ1000's multi-echo features were utilized to remove part of the vegetation from the scene. Then, CC was used for all subsequent operations, including data management, further manual and semi-automatic cleaning, merging, subsampling, and point cloud format conversion.

A comparable workflow was implemented for both the ZEB-HORIZON MLS and the UAV-DP data analysis, utilizing licensed software, that are the GeoSLAM Connect Viewer (GeoSLAM 2024) and the Pix4D Pro Mapper software, respectively. The fundamental divergence between laser scanning and digital photogrammetry lies in the accuracy, time of acquisition, point cloud generation processes, and in the scalar fields attributed to individual points within the dataset. The point cloud derived from UAV-DP is generally less accurate and devoid of reflectivity values (or signal intensity). In contrast, it exhibits more detailed RGB values associated to the points, an outcome of the utilization of the structure-from-motion algorithm during cloud generation (tie points are chosen using image colors). Both TLS and MLS instruments leverage the time-of-flight (TOF) process to ascertain precise point positions. Following this determination, RGB values are appended to each point later, by means of a calibrated camera connected to the laser scanner (see Fig. 5a, b). The laser scanner output could present several shadow zones with respect to the aerial UAV-DP obtained cloud; for this reason, the best cloud is given by the merging of the dataset (Son et al. 2020; Capolupo 2021; Mao et al. 2021; Beni et al. 2023c). Clearly, each of the three techniques has its own advantages and disadvantages due to its technical characteristics and specific range of application.

The ZEB-HORIZON uses a near-infrared laser wavelength and has a maximum range of 100 m, a scan rate of 300,000 points per second, a weight of approximately 4 kg, and 3 h battery life. Comprising a two-dimensional TOF laser range scanner firmly coupled to an inertial measurement unit (IMU) mounted on a motor drive, this system's scanning head motion on the motor drive provides the crucial third dimension for generating three-dimensional information. An advanced three-dimensional simultaneous localization and mapping (SLAM) algorithm is employed to seamlessly integrate the two-dimensional laser scan data with the IMU data, resulting in the creation of precise three-dimensional point clouds. The ZEB-HORIZON captures raw laser range measurements and inertial data, which require processing through GeoSLAM's algorithm to transform the raw data into a comprehensive three-dimensional point cloud.

The RIEGL VZ-1000, about 10 kg weight, utilizes a near-infrared laser wavelength and achieves an acquisition speed of up to 122,000 points per second. At a distance of 100 m, the instrument exhibits an accuracy with a standard deviation of 8 mm and precision with a standard deviation of 5 mm (RIEGL 2023). The coordinates of each point (x, y, z) are determined based on its distance and relative direction from the TLS. The scanner-object distance is calculated by measuring the round-trip time of a laser pulse to reach the object surface from the emission point and return (TOF process). The resolution is influenced by the object distance and the chosen angular spacing between two points. The manufacturer specifies a scanning range from 2.5 to 1400 m for a target with 90% reflectivity and 700 m for a target with 20% reflectivity.

The DJI Mavic Air 2, about 0.6 kg weight, is a commercial quadcopter equipped with a three-axis gimbal-stabilized digital camera. The latter has a 1/2 inch sensor with 24-mm focal lens equivalent and an aperture of f/2.8 and acquires 12–48 MP photos from at least 1 m (DJI 2024).

Three-Dimensional Geological Modeling

In the domain of geological investigation and resource assessment, the adoption of cutting-edge technologies is a key point for advancing our comprehension of subsurface geological complexities. Among these technological advancements, a new geological modeling software such as Leapfrog Geo (Seequent 2024), used for this study, emerges as a sophisticated software platform allowing accurate and fast modeling of the geological environment (Cowan et al. 2002, 2003; Basson et al. 2016; Creus et al. 2019). This kind of tools empower geoscientists and professionals by facilitating the visualization and interpretation of intricate geological data. The construction of 3D models typically involves manual processes, such as connecting digitized 2D sections. However, in recent years, there has been a shift towards implicit modeling approaches, where the geological characteristics of a rock mass are represented through a three-dimensional mathematical function (Braga et al. 2019). This approach, unlike the traditional method, minimizes user-based modeling bias by automatically generating surfaces based on lithological and structural data, eliminating the need for manual digitization and linking of sections or level plans (Cowan et al. 2002, 2003; Vollgger et al. 2015). An implicit representation of a solid is expressed through a function that is defined across space. This volumetric function is created by spatially interpolating sampled drillhole data, and the solid's surface is derived as triangulations from this function. Unlike the explicit method where surfaces are directly constructed, the surfaces in this implicit model are finite approximations that embody surfaces with infinite detail. These surfaces are considered to exist within a continuous volume function; hence, they are termed implicit surfaces (Cowan et al. 2003). The reliability of this geological modeling approach has been validated through various applications in the mining industry. It has proven effective in addressing safety concerns, identifying ore shoots, and calculating volumes. Additionally, its applicability extends to the realms of geophysics, volcanology research, and groundwater modeling (Cowan et al. 2002, 2003; Basson et al. 2016; Minimo and Lagmay 2016; Stoch et al. 2018; Creus et al. 2019; Åberg et al. 2021).

The three-dimensional geological model created for the Temperino mine (Fig. 6) was generated using Leapfrog Geo Seequent software employing implicit 3D geological modeling (Copyright Seequent Systems, Incorporated). The latter is a robust geological modeling software designed to streamline and optimize the process of constructing three-dimensional geological models. The software employs a voxel modeling approach, where the subsurface is discretized into a grid of volumetric elements or voxels. This voxel-based methodology allows Leapfrog Geo to handle complex geological structures and heterogeneities with a high degree of flexibility and precision.

The geological model is constructed based on the new geological interpretive model described in the "Geological and mining background" section as well as on existing underground geological survey and drill log data produced

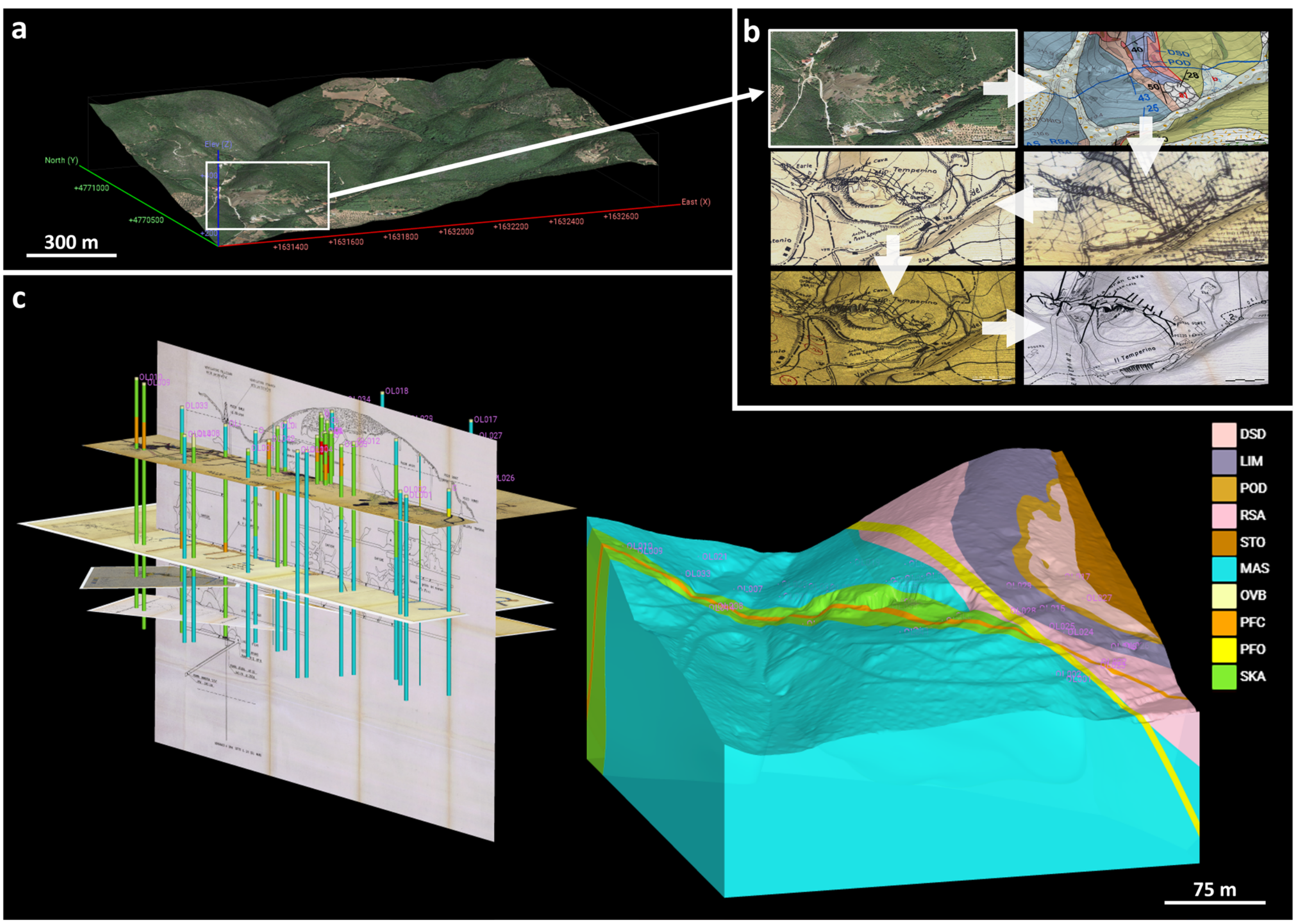

Fig. 6 The key steps involved in creating the geological model of the Temperino area using Leapfrog Geo licensed software are illustrated: **a** establishing a three-dimensional topographical reference; **b** overlaying the most recent geological chart and historical data to accurately define lithological contact orientations, accesses, and shafts; **c** on the left, incorporating modeling references and log data derived from underground geological survey, and on the right, presenting the final three-dimensional geological model (refer to the caption of Fig. 2 for lithology acronyms)

by mining companies in the latter half of the twentieth century (Fig. 6a–c). Quantifying potential systemic failures impacting the geological model's accuracy is challenging. Nevertheless, in this instance, part of the rock mass within the MIMA detector acceptance, where the studied target was situated, was accessible through a known big cavity (Gran Cava). This accessibility allowed us a direct confirmation of the outcropping lithologies and contacts to fix the geological model.

The workflow typically involves importing geological data (Fig. 6), such as drillhole information, geological interpretations, and structural data, into the software (Fig. 6b, c). Leapfrog Geo then utilizes these data inputs to generate a three-dimensional representation of the geological contacts. The software employs advanced interpolation algorithms to model geological features between data points, enabling users to visualize, analyze, and manage the geological setting in a comprehensive manner. One of the key strengths of Leapfrog Geo lies in its intuitive and interactive modeling environment. Geoscientists can dynamically adjust and modify interpretations in real time, immediately observing the impact on the three-dimensional model. This iterative and interactive approach enhances the efficiency of geological modeling, allowing for quick validation and refinement of interpretations also for the interpretation phase of the muon imaging data. Furthermore, the software incorporates powerful visualization tools that enable users to analyze and communicate geological information effectively. These include cross-sections, geological maps, and isosurfaces, providing a holistic view of the subsurface geology and the imported datasets, e.g., geophysical, geotechnical, or geochemical datasets.

Overall, this study generated a variety of output files useful for the MIMA-SITES project aim, primarily comprising cross sections and meshes. These files were exported in.xyz,.obj, and.png formats, providing three-dimensional representations of all lithologies outcropping in the study area.

Transmission-Based Muography

Muography technique is based on the measurement and analysis of the muon flux. Muons are charged particles, which possess high energy values (energies ranging from GeV to TeV), a mass 200 times that of the electron, and an average lifetime of 2.2 µs (Tanabashi et al. 2018; Zyla et al. 2020); these features enable them to traverse hundreds of meters of rock before stopping their run. Muons are continuously generated in Earth's upper atmospheric layers. Their production primarily results from the decay of pions and kaons, particles generated by the collision between primary cosmic rays and atmospheric nuclei, such as oxygen and nitrogen (Fig. 7a,b). The muon flux varies with latitude, altitude, and altazimuth detector pointing angles, i.e., zenith (θ) and azimuth (φ). The natural muon flux is measured along user-defined directions (θ, φ) and then compared to the simulated flux obtained using the same detector setting and a reconstructed three-dimensional environment. Atmospheric muons constitute the predominant component of cosmic radiation observed at the sea level. Their distinct features, including natural abundance, energy-based penetrative capabilities, and harmlessness, make them useful for non-destructive imaging of internal structures (Kaiser 2019; Saracino et al. 2019; Bonechi et al. 2020b; Tanaka et al. 2023). The goal is to obtain muon transmission maps, hence the name transmission-based muography technique (TM), which differs from the scattering-based approach (SM) utilized for smaller targets that relies on muon scattering instead of absorption. Specifically optimized TM technique allows for examining extensive objects like mountains (Fig. 7). For TM measurements, because of the natural downward trajectory of muons (from the upper atmosphere to the Earth's surface), the muon detector must be positioned beneath or near the studied object. The target is the volume of rock located between the detector and the surface of the hill (Fig. 7c, d).

The TM technique employed during the MIMA-SITES project (Fig. 7c) relies on precise track reconstruction of muon events originating from various lines of sight (LoS) within the muon detector's acceptance range (approximately ± 60°; Fig. 7d). This method primarily utilizes two measurements configuration: target and free-sky. The former involves measuring muon flux inside the mine, where the rock strata between the detector and the surface act as the target; the latter, entails measuring muon flux outside the mine, without any target obstructing the path between the detector and the sky (free-sky), while maintaining the same orientation as the target measurement. In addition to these field measurements, simulations of underground muon flux were conducted using the detector center and the digital terrain model (DTM) of the area to assess expected transmission values for various rock density values (Bonechi et al. 2005; Zyla et al. 2020; Bonomi et al. 2022; Gonzi et al. 2023). Multiple simulations considering the rock between the point-like detector and the surface as a homogeneous material, accounting only for energy loss in material with an assigned density has been carried out. The measured muon transmission (T_M) is contingent on the observation direction, identified by the zenith angle (θ), representing the angle between the vertical direction and the LoS, and the azimuth angle (φ), indicating the clockwise angle from the North direction. The T_M is defined as:

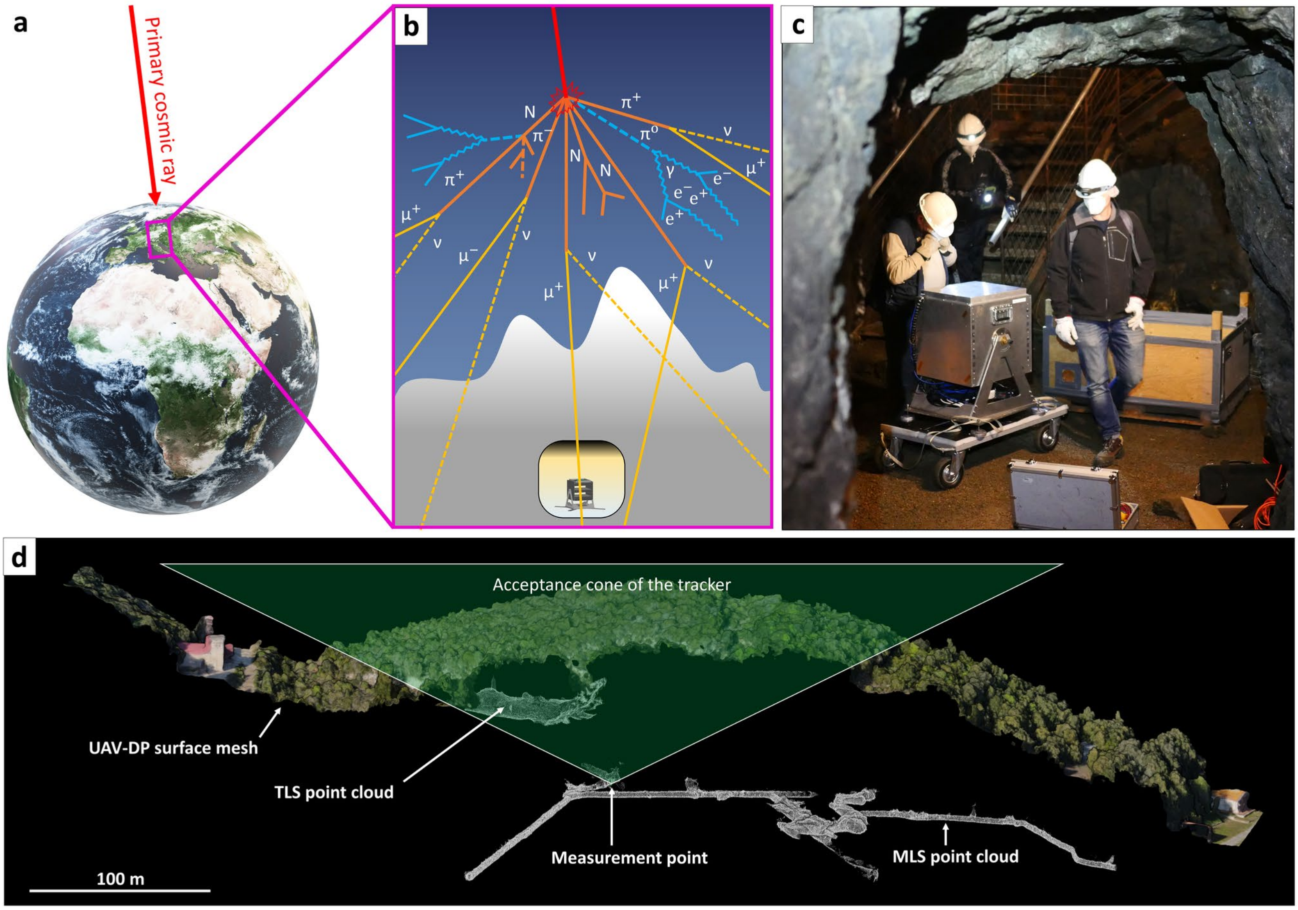

Fig. 7 **a**, **b** The synthesis of the process for generating secondary cosmic rays. This involves the impact of primary cosmic rays from outer space colliding with particles in the Earth's upper atmosphere, ultimately producing muons as the primary end products. In (**c**), the MIMA tracker measures the muon flux inside the Temperino mine, and in (**d**), a section of the hill displays the detector's measuring position and the investigated area, falling within the green cone (acceptance cone of the tracker)

$$T_M = \frac{\phi_{M,target}(\theta,\varphi)}{\phi_{M,free-sky}(\theta,\varphi)}$$

where $\phi_{M,target}(\theta,\varphi)$ and $\phi_{M,free-sky}(\theta,\varphi)$ are the muon flux measured in the target configuration inside the mine (Fig. 7c) and in the free-sky configuration, relatively. The calculated T_M can be compared to an expected value. At this step, using the reconstructed DTM obtained merging different geomatic survey techniques, we can generate a representation of rock depth along each LoS of the MIMA tracker $L(\theta,\varphi)$, under the assumption of no cavity presence. This passage allowed, using a single muographic measurement, to infer insight regarding the amount of crossed matter by muons, along certain direction. Follow the definition of the opacity X as:

$$X(\theta,\varphi,\overline{\rho}) = \int_{LoS} \rho dL = \overline{\rho}(\theta,\varphi) \bullet L(\theta,\varphi)$$

where ρ is the density of the crossed rock and $\overline{\rho}$ is mean density along a given direction (θ, φ). The opacity is important to define the simulated transmission (T_S):

$$T_S = \frac{\phi_{S,target}(\theta,\varphi)}{\phi_{S,free-sky}(\theta,\varphi)}$$

where $\phi_{S,target}(\theta,\varphi)$ and $\phi_{S,free-sky}(\theta,\varphi)$ are the muon flux measured in the target configuration inside the mine and in the free-sky configuration, relatively. And these fluxes can be computed as

$$\phi_{S,target}(\theta,\varphi,\overline{\rho}) = \int_{E_{\min}(X)}^{\infty} j(\theta,\varphi,E)\,dE$$

$$\phi_{S,free-sky}(\theta,\varphi) = \int_{E_0}^{\infty} j(\theta,\varphi,E)\,dE$$

where *j(θ, φ, E)* represents the differential muon flux concerning muon trajectories (θ, φ) and muon energy (E). The lower integral limit, $E_{min}(X)$, derived from opacity (X) using tabulated values from literature (Groom et al. 2001), signifies the minimum energy a muon must possess to be detected by MIMA in the target configuration, that is approximately 23 GeV, considering a standard rock with a density of 2.7 g/cm^3 (Borselli 2018). In the free-sky configuration, the lower integral limit, E_0, is identical to $E_{min}(X)$ but for the free-sky configuration, accounting for the opacity of the detector itself (around 130 MeV is the energy required by a muon to traverse the detector). For the differential muon flux, values measured by the ADAMO experiment were utilized (Bonechi et al. 2005; Borselli 2018, p. 20; Baccani et al. 2019; Borselli et al. 2022; Beni et al. 2023a; Gonzi et al. 2023). By comparing T_M with T_S, one can ascertain the correctness of the average density used in the simulation. Different results may indicate the presence of voids or dense bodies along that LoS.

Given the focus of this work, on utilizing research findings from cosmic ray muon radiography to enhance and modernize the park's museum, the reader interested in exploring further the muon imaging process is encouraged to explore more comprehensive insights in the reports by Baccani et al. (2019), Borselli et al. (2022), Beni et al. (2023a), and Gonzi et al. (2023). These published articles provide in-depth details about the measurement campaign, data analysis process and outcomes achieved during the muon imaging survey at carried out at the Temperino mine. In summary, TM muography was employed to image the internal section of the Cu–Fe–Zn–Pb(–Ag) enriched skarn body at the Temperino mine, located in Campiglia Marittima, Italy, within the San Silvestro Archaeological and Mining Park. This study marks one of the initial applications of muon radiography for prospecting skarn ore bodies in the realm of mining exploration and cavities identification.

Results

Three-Dimensional Data Outputs

At the end of the MIMA-SITES project, a large amount of data was collected, managed, and analyzed, leading to a substantial number of results. Unknown cavities and high-density bodies were discovered and reconstructed in two- and three-dimensions (Baccani et al. 2019; Borselli et al. 2022; Beni et al. 2023a). These results have been interpreted from two different perspectives: archaeological knowledge and geological understanding. The presence of unknown voids within the rock mass, in which the Temperino mine has developed, may lead to archaeological discoveries regarding extraction techniques and underground mining progression. Simultaneously, it holds the potential for geological discoveries, such as geodes and new ore associations, and for geotechnical considerations about rock mass stability. The capacity to identify potential high-density bodies using cosmic ray muon radiography could suggest the volume and extension of potential sulfide-enriched zones.

All these discoveries were documented in a unified three-dimensional space (Fig. 8), enabling the development of innovative animated content through proficient utilization of software and geomatic output expertise. To achieve this, we have managed and organized all the georeferenced data coming from the different close-range survey methods, the geological modeling, and the muon radiography survey in one single digital project. The primary outcomes include the development of the following entities: (1) a three-dimensional surface and subsurface model achieved by integrating TLS, MLS, and UAV-DP data (Fig. 8a); (2) a three-dimensional geological model incorporating voids and high-density bodies identified by the muon imaging campaign (Fig. 8a); and (3) a three-dimensional representation of muographic transmission and density data (Fig. 8b–d).

In Fig. 8, all the created entities are depicted along with their respective formats. The meshes were saved as.obj files, and the point cloud data was stored as.xyz files. The selection of these formats was based on their compatibility with various analysis and visualization software (Fig. 4), including CC, Unreal Engine, GEANT4, Final Cut Pro X (FCPX), and Sketchfab. The didactic potential of all these digital contents is evident and comprehensible, as stressed by the authors. Using this material, a detailed explanation of the geological evolution of the study area was provided, depicting how humanity exploited mineral resources throughout different epochs. Furthermore, the continuous evolution of this park, utilized as a laboratory, with the constant addition of new elements, was highlighted.

Multimedia Products: Video, Animations, and VR

Recent advances in scientific research, particularly in the field of muography applied to geological issues, have opened new avenues for enriching archaeological, mining, and geological parks and enhancing geotourism experiences (Afonso et al. 2022; Teixeira et al. 2023b; LouMu 2024). Through the integration of new technologies, such as three-dimensional modeling, video animations, interactive panels, AR, and VR, geological findings are brought to life, offering visitors an immersive and educational journey (Hawkey 2004; Gray 2008). Moreover, the application of innovative techniques like muography at the Temperino mine has provided unprecedented insights into subsurface structures and density variations, contributing valuable data for the creation of immersive digital content. These muographic

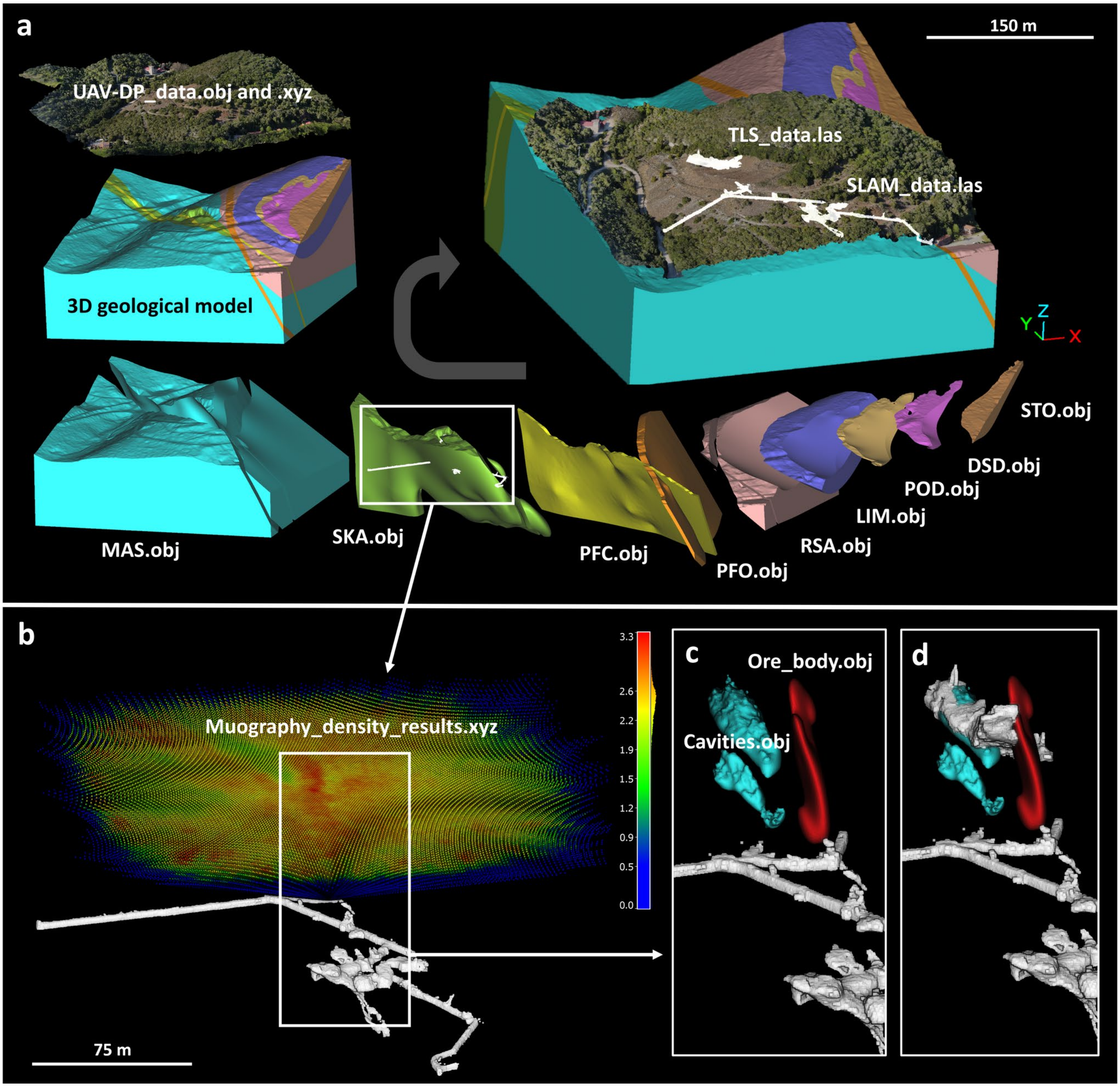

Fig. 8 Comprehensive representation of MIMA-SITES three-dimensional output products: **a** an exploded view of objects derived from geological modeling and close-range surveys are shown, primarily presented as meshes in.obj format and point clouds in.las and.xyz; **b** a three-dimensional cloud displaying directional density values obtained from the muographic survey; **c** reconstructed cavities and a high-density body; **d** the same content as (**c**) showcasing reconstructed cavities and the high-density body using the muon imaging technique, supplemented by the TLS survey of the accessible Gran Cava cavity. This TLS survey was crucial in evaluating the reliability of the muon imaging technique for the cavity reconstruction

results, when incorporated into museum exhibits, add an extra layer of authenticity and scientific rigor to the overall visitor experience. By combining muography with multimedia technologies, geoscientific data becomes not only accessible but also captivating, further enhancing the appeal of the park for a diverse audience. In accordance with the directives of the scientific director and the local coordinator of the Archaeological and Mining Park of San Silvestro and the Parchi della Val di Cornia SpA, our research team has dedicated its efforts to plan, produce, film, and edit a professionally crafted video documentary, composed by numerous interviews to the authors of the research and three-dimensional animations. Infused with the scientific rigor of physicists and geologists, this documentary delves into the history of the MIMA-SITES project, the muon imaging process, and the significant achievements obtained (Fig. 9a–f).

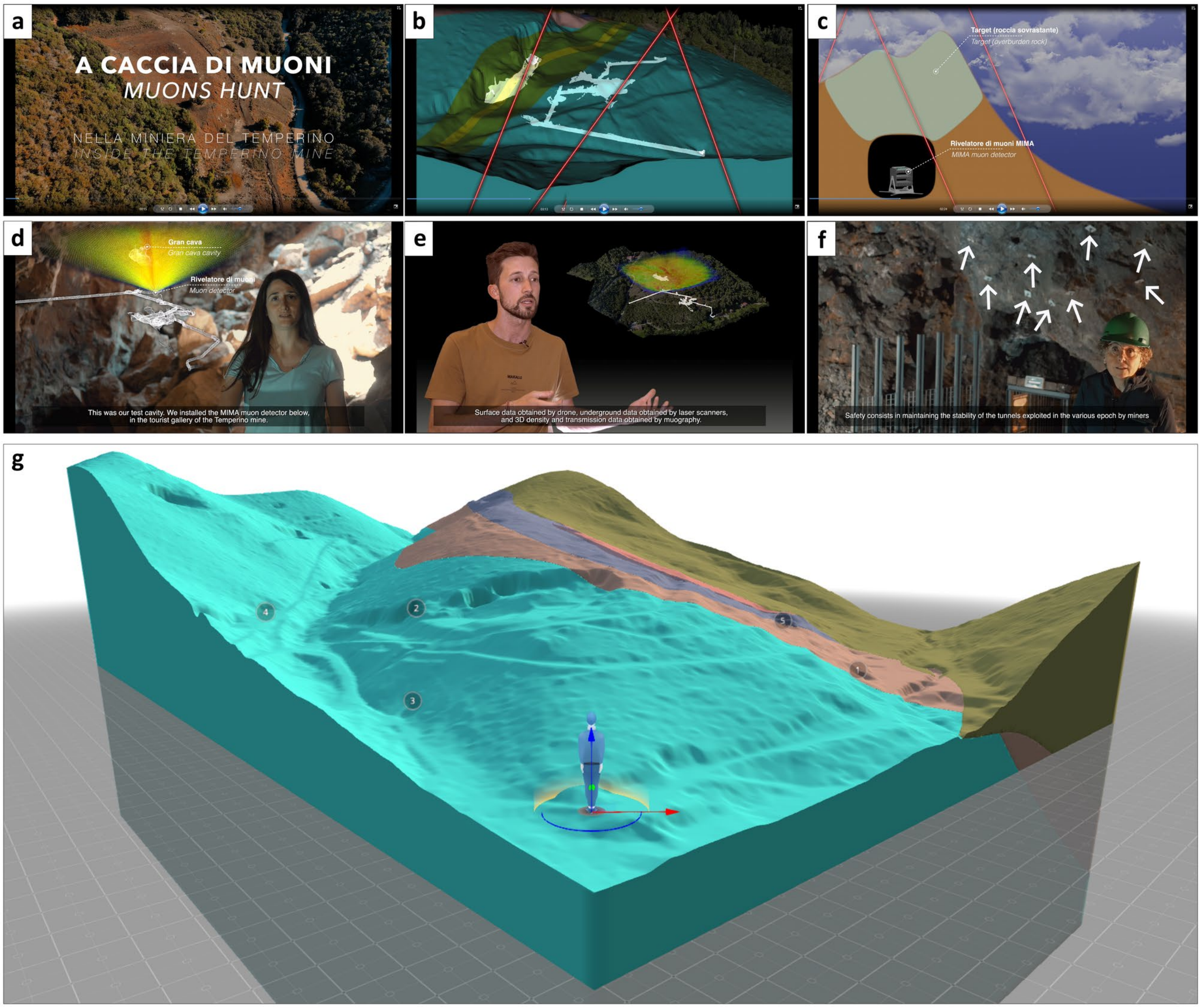

Fig. 9 Digital content generated upon completion of the MIMA-SITES project as new content for the park: **a**–**c** screenshots from the project documentary, displaying the initial video frame, a digital animation illustrating the interaction between muons and the study site's matter, and a basic sketch outlining the fundamental steps of the muon imaging technique. In panels **d** and **e**, some authors present and discuss the obtained results using a three-dimensional view of the data. In panel **g**, a virtual reality (VR) environment created on Sketchfab showcases geological data from the Temperino mine, accompanied by annotated notes (circled numbers)

To the aim of an innovative outcome, numerous UAV images and videos were captured (Fig. 9a), facilitating the creation of animated environments in both two- and three-dimensional view (Fig. 9b, c). To edit and post-process the acquired images and videos, Photoshop and the Final Cut Pro X software (FCPX) were used coupled with CC software. Additionally, using Unreal Engine software and the Sketchfab shearing platform, a virtual reality (VR) project was initiated (Fig. 9), incorporating layers detailing the geology of the Temperino mine area, muon imaging results, and close-range survey created environment (Figs. 8 and 9). While this VR project is not yet available for mine's museum tourists, it will enable immersive exploration and interrogation of the Temperino mine site, accessible through VR headsets like the visors and hololens or, more simply, via smartphones. This project gave also the starting point for the development and implementation of hololens use for AR or mixed reality environment. The digital and physical created content of the Temperino mine's museum are available both in Italian and English language subtitles as shown in the screenshots of Fig. 9. All the shooted video, images, and created animation have become part of a database of approximately 1 Tb that can be updated, modified, and enriched in the future.

The New Muographic Room Within the Temperino Mine Museum

To fulfill the predetermined scientific communication plan and effectively disseminate the digital content created concerning the outcomes of the MIMA-SITES project, a new museum room has been conceptualized, developed, and inaugurated at the Temperino mine museum in 2023. The collaborative creative process spanned 2 months and involved all the authors. In Fig. 10, the definitive project of the new museum room is reported. The installation encapsulates the efforts made, starting with the concept of utilizing the natural park as a laboratory and finishing clockwise with the most recent scientific research about muography (digital contents). This fact is particularly relevant for the Temperino Mine, which has served as a geological laboratory since the Etruscan period. Currently, the wealth of knowledge regarding the skarn body, which is enriched with economically valuable Cu-Fe-bearing ores cultivated at the Earle body, Temperino Mine, along with archaeological studies and recent muon imaging reconstructions of cavities and dense bodies, collectively contributes to a deeper comprehension of the geological evolution of the area. This underscores the paramount importance of the Archaeological and Mining Park of San Silvestro both for citizen education and for scientific research.

At the center of one of the two longest installation walls, a 65-inch display equipped with a soundbar continuously showcases the MIMA-SITES documentary and three-dimensional animations (Fig. 11). This room must always be ready as it serves as a mandatory passage to enter the gallery inside the Temperino Mine (indicated by the yellow square on the left in Fig. 3b).

Discussion

The main goals achieved by the cosmic ray muon radiography measurement campaign carried out at the Temperino mine during the MIMA-SITES project were the following: (1) confirming the reliability of TM for visualizing internal structures within the skarn body located above the muon detector; (2) validating muography as a complementary tool for other mining and archaeological exploration methods, providing insights into variations in underground rock density distributions, detecting potential ore bodies or cavities, and offering guidance for the directions of future excavations or drilling; and (4) showcasing the utility of 3D management of

Fig. 10 Graphic design project for the dedicated museum space showcasing the MIMA-SITES project at the Temperino mine

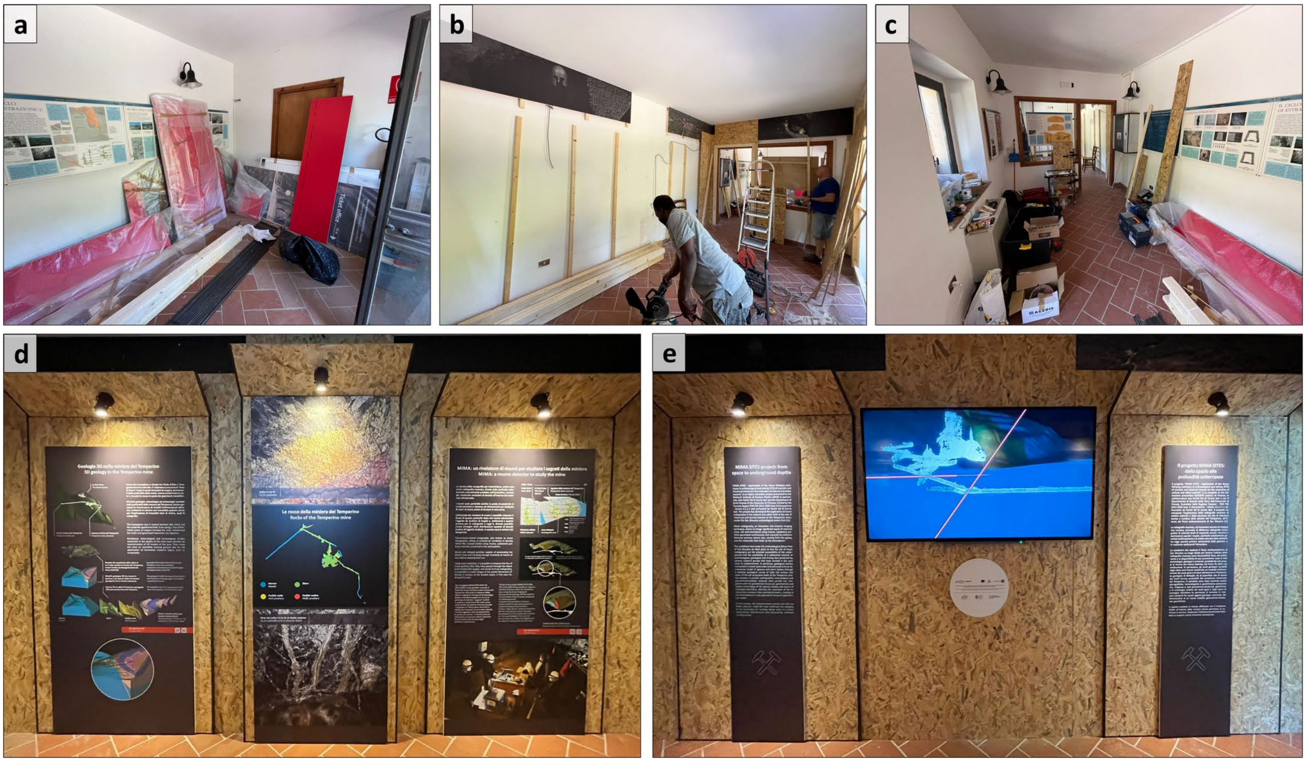

Fig. 11 Photographic documentation of the evolution of the MIMA-SITES project room at the Temperino mine museum: **a**–**c** construction and installation phases; **d**, **e** final appearance of the two longest wall installations. Additional elements include: **d** graphical explanation of the geology and the muon imaging process; **e** two totem displays explaining the MIMA-SITES project, alongside a central 65-inch display looping the documentary in both Italian and English

muographic data in conjunction with 3D geological modeling for interpreting results effectively and clearly communicate the results. The latter is one of the main challenges in the cosmic ray muon radiography research field: the clear and non-ambiguous communication and spreading of the achieved results to the scientific community and to the citizen.

The muon imaging research field is increasingly intertwined with the commercial sector and the sale of the related services; this fact, over time, may limit locally the widespread dissemination of concepts and results. Few citizens and private companies are aware of muography technique potentialities; it is only discussed on significant occasions, such as for the ScanPyramids project findings (Scanpyramids 2016, 2024; Procureur et al. 2023). Locally, even fewer people are aware of it, and this situation depends on the choices made by those groups working with muography. Nonetheless, some European research teams have embarked on initiatives for local dissemination and promotion of the muography technique and its real-case study results. These initiatives can have a dual purpose: to enhance the visibility of scientific research in the field of muography applications and to enrich the offering of content for geotourism in natural parks and museum in general.

An illustrative example is the LouMu project, where scientific muography outcomes and techniques, applied in an underground mine, are the key element for the scientific outreach goals of the project (LouMu 2024). Similarly to the findings presented in this work for the MIMA-SITES project, LouMu team is actively advancing in this topic, utilizing the Lousal mine as a scientific and didactic muography case study (Afonso et al. 2022; Teixeira et al. 2023b; LouMu 2024). That is, to enhance the geological heritage through muography. In this direction, the research group of the INFN of Florence has taken a significant step forward. Thanks to the collaboration and willingness of the Archaeological and Mining Park of San Silvestro and to the Parchi della Val di Cornia SpA, they have materialized something that, to the best of the authors knowledge, has not been achieved until now—a permanent museum room entirely dedicated to muographic radiography techniques, and the obtained results during the MIMA-SITES project, within one of the most important visitable mine in Tuscany (Italy): the Temperino mine. The new museum room, through which all guided tours pass before entering the mine, enriches the educational journey for tourists and adds value to the archaeological and mining history of the park. In the months since its opening, numerous local and national television programs have talked about this activity, and many regional and national scientific communication pages have discussed it (Fig. 12; see the RAI

Fig. 12 Media echo of the MIMA-SITES project activities. Screenshots from six Italian online communication platforms illustrating the media coverage of the MIMA-SITES project: the official websites of the National Institute for Nuclear Physics and the National Research Council, the ANSA Science portal, the University of Florence's official online magazine, and two local online journals

program "Newton – La Scienza in Miniera"; https://www.raiplay.it/video/2023/12/Newton-La-scienza-in-miniera-85aae97c-1162-45a6-9f99-89299e893c56.html). Every week, hundreds of geotourists, of all ages, visit the Archaeological and Mining Park of San Silvestro, and an increasing number of people are becoming familiar with muography thanks to this scientific dissemination facilitated by the use of digital content deriving from the conducted scientific research.

Conclusion

The implementation of muon imaging technology during the MIMA-SITES project has proven to be a groundbreaking endeavor with multifaceted implications for the understanding and promotion of geoheritage, geotourism, and park management. The application of muon radiography technique has provided unprecedented insights into the internal structures of the Temperino Mine, contributing significantly to the geological and archaeological knowledge of the area. The creation of a new museum room, as outlined in this study, exemplifies a successful synergy between scientific research and public engagement. The permanent installation, open for visitation starting from June 2023, serves as an innovative platform for disseminating knowledge, offering a dynamic visual representation of the skarn bodies, ore deposits, historical mining activities, and muography measurements. The integration of digital content, including the MIMA-SITES documentary and three-dimensional animations, not only enhances the educational experience for visitors but also highlights the park's role as a living laboratory. Furthermore, the project's impact extends beyond the realm of scientific inquiry, fostering a deeper connection between the local community and its geological heritage. The archaeological significance of the Temperino mine, coupled with the recent advancements in muon imaging technology achieved by the INFN of Florence, underscores the relevance of the Archaeological and Mining Park of San Silvestro in preserving and promoting the region's rich geological and cultural legacy.

The success of the MIMA-SITES project, testified also by a non-negligible mediatic echo (Fig. 12), emphasizes the potential of innovative scientific survey techniques, such as cosmic ray muon radiography, in enhancing the appeal and educational value of a park museum. These activities open avenues for future research and collaborative efforts among different professionals, aimed at further leveraging technology to unravel the complexities of geological formations, support sustainable park management, and engage a diverse audience through immersive educational experiences.

The presented study underscores the promising model that emerges from the fusion of science, technology, and heritage preservation. This combination represents a significant advancement, bringing together scientific muographic exploration and public outreach in the realm of geoheritage and geotourism.

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Data Availability Correspondence and requests for materials should be addressed to T.B.

Declarations

Competing interests The authors declare no competing interests.

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