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Multi-scale non-invasive techniques for assessing instability conditions: examples from the Val di Cornia parks system (Tuscany, Italy)

Tommaso Beni[1], Silvia Guideri[2], Debora Brocchini[2], Marta Coccoluto[2], Diletta Borselli[3,4], Lorenzo Bonechi[4], Sandro Gonzi[3,4], Irene Centauro[1], Anna Palamidessi[1], Vitaliano Ciulli[3,4], Raffaello D'Alessandro[3,4], Giovanni Gigli[1], Deodato Tapete[5], Veronica Tofani[1], Silvia Bianchini[1]

[1] *Department of Earth Sciences, University of Florence, Via Giorgio La Pira 4, 50121 Florence, Italy,* tommaso.beni@unifi.it, irene.centauro@unifi.it, anna.palamidessi@unifi.it, giovanni.gigli@unifi.it, veronica.tofani@unifi.it, silvia.bianchini@unifi.it
[2] *Parchi Val di Cornia S.p.A, Via Leonardo da Vinci 13, 57025 Piombino, Italy.* guideris@parchivaldicornia.it, brocchini@parchivaldicornia.it, coccoluto@parchivaldicornia.it,
[3] *Department of Physics and Astronomy, University of Florence, Via Giovanni Sansone 1, 50019 Sesto Fiorentino, Italy,* diletta.borselli@unifi.it, sandro.gonzi@unifi.it, vitaliano.ciulli@unifi.it, raffaello.dalessandro@unifi.it
[4] *National Institute for Nuclear Physics INFN, Division of Florence, Via Bruno Rossi 1, 50019 Sesto Fiorentino, Italy,* lorenzo.bonechi@fi.infn.it
[5] *Italian Space Agency ASI, Via del Politecnico snc, 00133 Rome, Italy,* deodato.tapete@asi.it

Abstract **– This work aims to demonstrate how integrating multi-scale, non-invasive techniques can support early detection and risk mitigation in complex heritage landscapes, such as the Val di Cornia parks system in southern Tuscany (Italy). Here, multi-temporal satellite InSAR data were used to measure surface deformations with millimetric accuracy over a wide area in a recent time span. At local/hypogean scale, muon imaging (muography) was applied inside the Temperino mine gallery, in the Archaeological and Mining Park of San Silvestro, alongside close-range geomatic and geological surveys to detect subsurface density anomalies for preliminary assessment of potential rock mass instability phenomena. InSAR data on the Acropolis and Necropolis areas of the Baratti and Populonia Archaeological Park show mostly linear and stable trends. Site-specific muography measurement campaign combined with digital photogrammetry and LiDAR systems at the Temperino mine revealed no significant stability issues in the analysed gallery sections.**

I. INTRODUCTION

The use of non-invasive and non-destructive surveying techniques is increasingly important for conserving and monitoring cultural heritage. These methods, which avoid physical contact with structures or ground, enable detection and documentation of instability without compromising site integrity. At the regional scale, satellite-based Interferometric Synthetic Aperture Radar (InSAR) is a key tool for mapping ground deformations with millimetric accuracy, detecting slow landslides and subsidence that may affect heritage sites. Its temporal and spatial continuity over wide, often inaccessible areas makes it an ideal complement to ground-based surveys [1,2]. At the local scale, mobile/terrestrial LiDAR and UAV-based Digital Photogrammetry (UAV-DP) generate high-resolution 3D models for identifying structural discontinuities, surface instabilities and anthropogenic features in complex archaeological and geomorphological contexts [3].

This study focuses on the Val di Cornia parks system [4–6], in southern Tuscany (Italy), which includes major archaeological and mining landscapes. The Archaeological Park of Baratti and Populonia [7] preserves extensive Etruscan and Roman remains facing the Gulf of Baratti, while the Archaeological and Mining Park of San Silvestro [8] documents over two millennia of mining history, with the Temperino mine (an underground network of ancient extraction tunnels) standing out for its scientific and cultural value.

To investigate potential instability, a multi-scale and interdisciplinary approach was adopted (Table 1). At territorial scale, satellite multi-temporal InSAR data (MT-InSAR) were used to monitor shallow ground deformation of terrain and structures. LiDAR and UAV-DP surveys, coupled with muon imaging, provided detailed models for localizing potential unstable areas in archaeological and mining contexts. In the Temperino mine, transmission-based muography imaged part of the rock mass, revealing low-density zones (unknown cavities) that may threaten tunnel stability. Integrating these techniques links detailed site investigations with broader territorial analyses, supporting preventive conservation, risk mitigation and informed management in archaeologically and geologically sensitive areas.

Table 1. Survey scales and corresponding techniques

Survey scale	Techniques
Territorial (macro)	Satellite InSAR
Local (meso)	LiDAR, UAV-DP
Ipogean (meso-micro)	Muography

II. STUDY AREA

The study examines two parks within the Val di Cornia system (Fig. 1) in southern Tuscany (Italy), which spans five municipalities and includes several archaeological and mining sites [5,8].

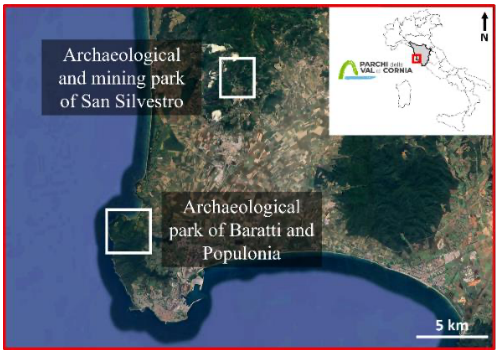

Fig. 1. Satellite view of the Val di Cornia parks system area. The two white squares highlight the case study areas presented in this work.

The Archaeological Park of Baratti and Populonia preserves necropolises, industrial areas and monumental ruins of the ancient city, integrated within a geomorphologically sensitive coastal landscape. Further inland, the Archaeological and Mining Park of San Silvestro conserves mining tunnels, processing areas and historic settlements, with the Temperino Mine as a reference feature. The cultural value, accessibility and geological vulnerability of these sites make them ideal for applying non-invasive monitoring and conservation techniques.

III. TECHNIQUES AND DATA

A. Multi-temporal satellite InSAR technique

Multi-temporal satellite InSAR data, processed with the Persistent Scatterers Interferometry (PSI) technique, were analyzed to detect deformation and possible instabilities across the Baratti and Populonia Archaeological Park, focusing on built heritage. InSAR measures displacement from phase shifts in repeated radar acquisitions along the same orbit (Fig. 2) [9]. PSI refines this by analyzing long time series of SAR images to derive annual velocities and deformation trends on Persistent Scatterers (PS), that are stable radar targets such as buildings or natural features with strong, coherent backscatter [10] (Fig. 2). PSI deformation data used in this work come from high resolution COSMO-SkyMed (CSK) X-band SAR imagery processed with the SqueeSAR technique [11]. The COSMO-SkyMed system includes the initial CSK constellation of four satellites with a nominal revisit time of 16 days and additional satellites from Second-Generation COSMO-SkyMed mission (CSG), operative since 2021 [12].

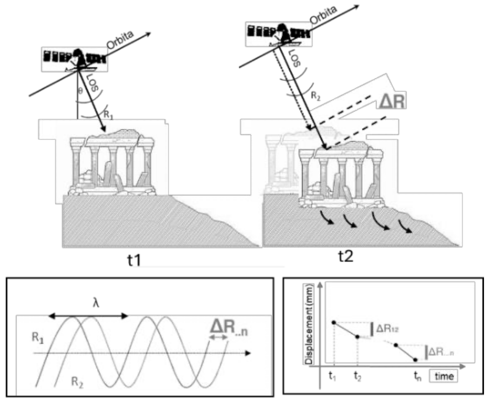

Fig. 2. Principles of satellite InSAR technique.

PSI data derived from 131 ascending and 115 descending SAR CSK and CSG images (Table 2), acquired in the temporal period 2015-2023 with look angles of ~33° and ground spatial resolution of 3x3 m^2 were used. Each PSI measurement is provided with geographic coordinates, a velocity value (expressed in mm/year) estimated along the satellite acquisition LOS (Line Of Sight) and a time series of displacements, i.e. a plot that shows the displacement (in mm) of the radar target at the satellite acquisition date [13]. On-site surveys performed in 2024 permitted to validate and confirm the remotely-sensed data to retrieve a feasible and updated screening of the present deformational scenario.

Table 2. InSAR PSI data

Acquisition orbit	Time span	Number of SAR images
Ascending	02/01/2015 - 15/06/2023	131
Descending	08/01/2015 - 25/06/2023	115

Fig. 3 presents the spatial distribution of PSI CSK data in ascending geometry over the Archaeological Park of Baratti and Populonia. Very similar spatial display is also retrieved by PSI in the descending orbit. The stability range of LOS ascending and descending velocity was set as ± 1.00 mm/year according to the standard deviation value (0.5) of the PSI population. Two main sub-areas were investigated, i.e. the Acropolis and the Necropolis. On the study area some landslide bodies are mapped within the IFFI (italian landslide inventory), mainly as translational/rotational slide types, especially along the coastline (Fig.3). Density of PSI radar benchmarks is quite low and irregular on the territory since the study area is rural and targets are located over manufacts, while vegetated areas show no PSI measurements.

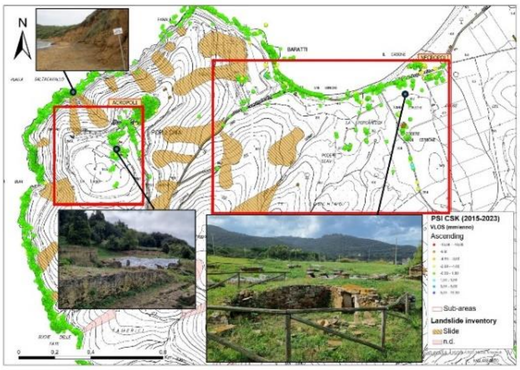

Fig. 3. Distribution of PSI CSK data (colored dots) in ascending orbit over Baratti and Populonia area and some photos taken on-site.

B. Close-range techniques: LiDAR and UAV-DP

Close-range survey methods such as LiDAR (mobile/terrestrial) and UAV-DP are now key tools for documenting, analyzing and preserving complex terrains and built environments, especially in cultural heritage and archaeology [14–16]. Terrestrial LiDAR rapidly produces dense 3D point clouds with centimetric accuracy, supporting morphometric analysis, structural mapping, and monitoring of deformations or cracks that may threaten sites [17,18]. Its ability to capture topography even under vegetation enables the detection of buried or obscured features without disturbing them, preserving site integrity. UAV-DP, through structure-from-motion processing of aerial images, offers flexible and cost-effective generation of high-resolution orthophotos and 3D models. It is particularly suited for rapid site-scale documentation, accessing hazardous areas, and integrating with LiDAR data for more complete reconstructions. Together, LiDAR and UAV-DP allow multi-temporal analyses to track structural changes and degradation. Combined with other non-invasive techniques such as muography, GPR, ERT and gravimetry, they provide effective, non-destructive documentation and monitoring that safeguard archaeological heritage while advancing research and public engagement.

For this study, the GeoSLAM ZEB HORIZON mobile laser scanner was employed in conjunction with the RIEGL VZ-2000i terrestrial laser scanner, the DJI Mavic Air 2 UAV, and the Emlid Reach RS2 GNSS receiver. Figure 4 presents selected images from the field surveys, along with a section of the point cloud generated for the Temperino mine.

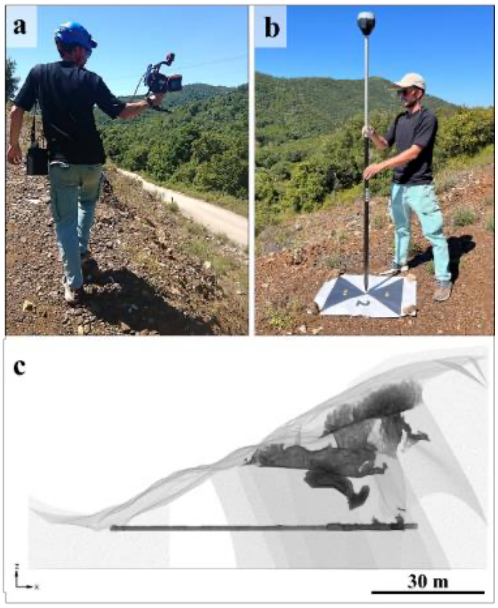

Fig. 4. In-situ LiDAR and UAV-DP survey phases: a) mobile laser scanner acquisition; b) GNSS ground control point measurement; c) point cloud cross-section of the Temperino mine hill.

C. Muon imaging technique

Muon imaging, or muography, is an emerging non-invasive imaging technique increasingly applied in archaeological and geological contexts for detailed internal imaging of structures and rock masses [19,20]. This method exploits the penetration power of the naturally produced muons (secondary cosmic rays), which can penetrate large volumes of rock and matter (depending on several variables and boundary conditions), enabling the reconstruction of transmission and density variations within the studied target (Fig. 5); underground spaces or archaeological manufacts. By detecting the attenuation of muon flux through materials, muography produces images that can suggest the presence of unknown cavities [21], fractures, or zones of weakness without physical intrusion or damage.

In heritage and mining applications, muography offers unique advantages for investigating subsurface features that are inaccessible or when direct exploration is not possible or allowed. The technique's non-contact nature preserves the integrity of sensitive sites, while its high spatial resolution supports detailed structural analyses. For instance, at the Temperino mine, during the MIMA-SITES research project (2019-2023) muography has been successfully employed to image the internal rock mass structure and locate instability zones [22], complementing surface-based surveys and enriching multi-scale assessments of geological and archaeological knowledge.

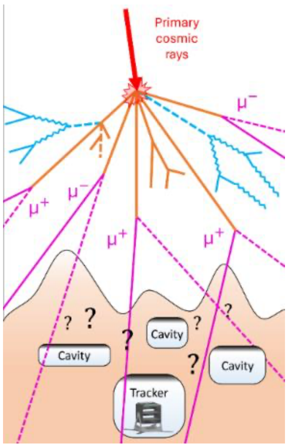

Fig. 5. Simplified sketch of the muon imaging technique used at the Temperino mine to detect unknown cavities within the rock mass.

IV. RESULTS AND DISCUSSION

This section presents the results obtained with multi-scale non-invasive approaches. MT-InSAR analyses, based on ascending and descending CSK PSI data, generally indicate stability across the two sub-areas. The Necropolis, located beneath metallurgical slag deposits and consisting mainly of mound tombs, aedicule tombs and building remains, shows overall stability. The main movements (2015–2023) occur in the “Casone” area near the Gulf of Baratti (Fig. 6), where average velocities above the stability threshold and linear cumulative displacements were recorded; on-site surveys in 2024 confirmed the presence of abandoned buildings near, but outside, the archaeological park.

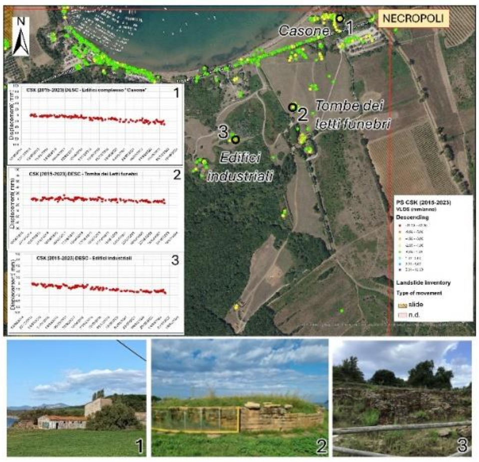

Fig. 6. Necropolis sub-area: PSI descending velocity data, related Time series of displacement and photos of some investigated sites.

Within the Necropolis, PSI targets on the “Tomba dei Letti funebri” show slightly negative mean velocities (~-2 mm/yr) with total displacements of -23 mm over eight years. On the “Edifici industriali” structures, descending PSI benchmarks reveal higher values (~ -4 mm/yr; up to -32 mm), though field surveys found only low-elevation ruins without evidence of structural instability or sliding. The structures in the Acropolis area are remnants of temples and dwellings characterized by limited above-ground elevation, with the exception of the Logge (Loggias) building. This sub-area is characterized by substantial stability (Fig. 7) with the exception of a few points observed at Temples B and Temple C, Domus, and Visitor Center.

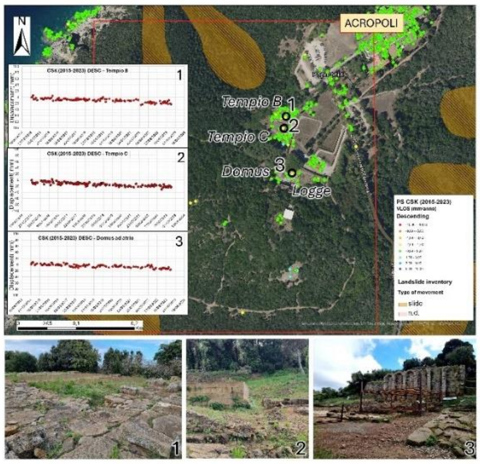

Fig. 7. Acropolis sub-area: PSI descending velocity data, related Time series of displacement and photos of some investigated sites.

The Temple B, which is nevertheless stable, is located a few tens of meters above a mapped landslide body and some evidence can be seen in the steep slope of the surrounding terrain. Near Temple C, some slightly moving targets were detected from the sensor in descending geometry. On-site campaign revealed that the podium of this manufact was reconstructed in artificial stone in recent times. Just in the northern corner of the podium, some disconnections of the masonry blocks are evident. Moreover, westwards of Temple C excavation campaigns are ongoing. Over the Domus area, where ascending and descending CSK datasets recorded upwards and downwards movements and displacement rates with linear trend and minor seasonal variations, evidences of ground movements were highlighted on the basalt road leading right to the Domus area during on-site survey, and on the mosaic floor of the Domus showing a central depression, as potential indicator of ground settlement; the presence of a metal pergola covering the excavation area could interfere with the measurements and seasonal oscillations. It is worth noting that PSI data are relative values and displacements are underestimated since they are measured only along the satellite LOS. Moreover, the technique efficiency is limited by the presence of vegetation that reduces the radar benchmarks density.

For what concern the Archaeological and Mining Park of San Silvestro, non-invasive techniques (LiDAR, UAV-DP and muography) have been employed to assess potential instabilities within the accessible and visitable galleries of the Temperino mine. The main results (Fig. 8) include the development of a comprehensive digital model of both the underground structures and the overlying hill, a three-dimensional geological reconstruction, transmission and density maps of the rock mass obtained through muography [22,23].

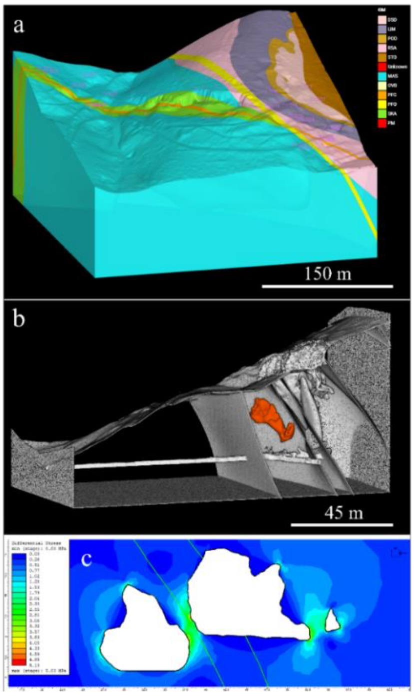

Fig. 8. Results from local-scale surveys at the Temperino mine: a) geological model; b) integrated three-dimensional model of the underground and surface environments derived from LiDAR, UAV-DP, and muography techniques; c) differential stress map used for preliminary stability assessment.

These local-scale surveys significantly enhance the information that could be provided by satellite-based analyses, which in this study were applied only to the Baratti and Populonia area but not to the San Silvestro site, that is a future case study. They offer insights about subsurface features and potential instability zones, not detectable by using other geophysical methods, going beyond the surface anomalies typically captured by satellite remote sensing data.

Muography inherently presents limitations in spatial resolution and acquisition time, which can vary from case to case, with measurements requiring from hours to years. These variations result from multiple factors, including the target dimensions, the measurement depth, the distance of the potential anomaly (e.g., cavity or dense body) from the detector, the detector's geometry and active area, the properties and thickness of the crossed material and the complexity of the surrounding environment. As a result, the instrument's intrinsic angular resolution can translate into different effective resolutions in the resulting images.

V. CONCLUSIONS

This study illustrates how a multi-scale, non-invasive and integrated approach improves the understanding of instability phenomena in areas of high cultural and historical value.

Focusing on the Val di Cornia parks system, the results confirm that combining techniques such as MT-InSAR, LiDAR, UAV-DP and muography through interdisciplinary collaboration provides an effective methodology for assessing extended and complex heritage contexts. This holistic strategy enhances monitoring, research and site management, supporting conservation planning, visitor safety and informed decision-making by local heritage managers.

VI. AKNOWLEDGEMENT

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