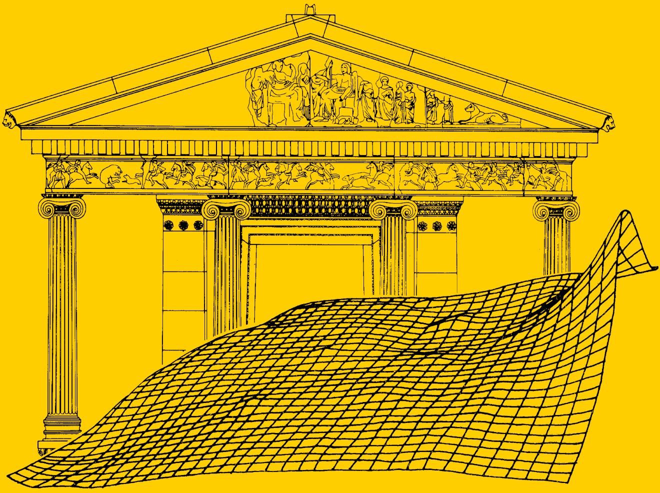

NEXT-GEN ARCHAEOLOGY

INNOVAZIONI E TRADIZIONI TECNOLOGICHE PER LO STUDIO DEL PASSATO

Atti delle Giornate di Studio
“Archeologia e Nuove Tecnologie:
dalla teoria ai protocolli esecutivi”
(Siena, 25-27 ottobre 2023)

a cura di
Stefano Bertoldi e Luca Luppino

ARCHEOLOGIA E CALCOLATORI
Supplemento 13, 2025

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ENHANCING ARCHAEOLOGICAL PROSPECTION THROUGH INTEGRATED GPR-MULTISPECTRAL ANALYSIS. THE FIRST RESULTS FROM THE ALPINE HILLTOP SETTLEMENT OF TEGLIO (VALTELLINA, SO)

1. Introduction: The Castle of Teglio and its archaeological context

The municipality of Teglio (SO) held significant prominence during the early and high medieval periods in the Valtellina region. Situated at an altitude of approximately 500 meters above sea level, the hamlet commands a strategic position overlooking the Adda River, the Aprica pass linking Valtellina and Valle Camonica, and Tirano, the gateway to Val Poschiavo (CH) leading to the Bernina pass and St. Moritz (CH).

The 'Dos del Castel' is a hillock positioned on the southern periphery of the plain housing the ancient and modern settlement of Teglio. Its summit features a plateau oriented east-west, rising approximately 40 meters above the village (Fig. 1). The southern slope of the hill descends steeply towards the bottom of the Adda valley. Unlike the village, which has undergone extensive archaeological excavations, demonstrating a continuity of settlement from protohistory to the present day, the castle hill had not been subject to specific archaeological investigations until the research discussed in this paper (De Vanna 2015; Zoni, Bona 2024). Two medieval castle structures still stand: the small church of S. Stefano and the tower known as 'Torre de li beli miri,' locally named for its panoramic vista of the Adda Valley, the Belviso Valley, and the Aprica pass (1176 meters above sea level).

Initial activities in this area commenced in 2021 under a concession from the Ministry of Culture for non-invasive surveys of the castle hill. These surveys included topographical and architectural assessments of the summit structures, along with a stratigraphic analysis of their elevation. The surveys employed aero-photogrammetric techniques, laser scanning, and terrestrial photogrammetry, anchored to a topographical network established with DGPS in the WGS84-UTM32N reference system and refined using a total electronic station. Additionally, geophysical surveys were conducted using Ground-Penetrating Radar (GPR) to detect buried structures and guide subsequent stratigraphic excavation efforts. Furthermore, multispectral images complemented the aero-photogrammetric survey, enabling analysis of vegetation indices in the castle's grassy cover to identify potential archaeological features. The findings of these analyses will be presented in this paper.

F.Z.

Fig. 1 – The 'Dos del Castel' of Teglio (SO). Aerial view from south-west.

2. Multispectral UAV analysis in archaeology

The analysis of vegetation indices obtained through multispectral sensing represents a relatively recent development in archaeological research. Large-scale applications of this technology began in the early 2000s, initially exploring the capabilities of multispectral sensors aboard major commercial satellites such as Quickbird and Copernicus Sentinel-2. The primary objective of these early experiments was to assess the potential of multispectral techniques for archaeological prospection (Donoghue 2001; Lasaponara, Masini 2006). These initial studies focused on detecting specific crop marks in ground cover vegetation (Lasaponara, Masini 2007) or identifying areas with high archaeological potential (Alexakis *et al.* 2009; Estanqueiro *et al.* 2023).

A significant breakthrough in this field occurred with the commercialization of cameras integrating multispectral sensors that can be mounted on standard commercial drones (Ciccone 2022). Notable examples include products such as SAL - Maya, Parrot Sequoia, and DJI P4 Multispectral (utilized in this case study). While avoiding specific endorsements of individual models, this technology enables simultaneous recording of RGB and multispectral camera data, typically including Blue, Green, Red-Edge, and Near-Infrared Bands. Following initial experiments in archaeological mapping (Koucká *et al.* 2018; Brooke, Clutterbuck 2019), subsequent research has demonstrated the effectiveness of this methodology in detecting indicators of ground vegetation stress, which can be interpreted as anomalies indicative of buried archaeological structures (Fuldain González, Varón Hernández 2019; James *et al.* 2020; Abate *et al.* 2021). In recent years, scientific literature has featured several studies evaluating the potential of this non-invasive survey method in comparison to other technologies for archaeological prospection, including multispectral sensors and thermal cameras (Salgado Carmona *et al.* 2020), or the integration of vegetation index representations with data derived from GPR prospecting (Ronchi *et al.* 2023).

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3. Integrating GPR and multispectral surveys in archaeology

At the Teglio medieval archaeological site, a series of non-invasive surveys were conducted, employing both multispectral drone imaging and geophysical methods. The Ground Penetrating Radar (GPR) system is widely used in archaeological diagnostics and is distinguished by its versatility in both intensive and extensive territorial exploration. If the application of multispectral surveys in archaeology is relatively recent (see the previous paragraph), the use of GPR, introduced in the mid-1970s, is now well-established and thoroughly documented in the literature, to which readers are referred for further details (Lekebusch 2003; Goodman, Piro 2013; Conyers 2016; Cozzolino *et al.* 2018).

3.1 *GPR methodology*

Geophysical surveys utilized an IDS RIS MF Hi-Mod GPR system, equipped with a multifrequency antenna operating at 600-200 MHz (see Tab. 1). For this investigation, data from 600 MHz frequency were specifically analyzed to achieve high-resolution imaging with a maximum soil penetration depth of approximately 2.5 meters. To ensure optimal area coverage and improve data quality, seven grids were created, each covered by one-way parallel and orthogonal profiles spaced at regular intervals of 0.50 meters. The GPR profiles were processed using GPR-Slice software[1], with a suite of filters applied to enhance the visualization of subsurface archaeological features. The processing procedure included trace editing and normalization of the horizontal scale, essential operations to obtain an accurate depth estimate for the vertical profiles, expressed in meters. Subsequently, various procedures and filters were applied to enhance the visual quality of the data, including Gain, Slice and Resample, Background Removal, and Bandpass. Through

[1] https://gpr-survey.com/archaeology.html (March 2024).

GPR SETTINGS		200 MHz antenna	
600 MHz antenna			
Time Scale Range	60 ns	Time Scale Range	128 ns
Dynamic range	16 bits	Dynamic range	16 bits
Samples per Scan	512	Samples per Scan	348
Maximum Depth Reached	2.50	Maximum Depth Reached	3.00

Tab. 1 – GPR settings.

the Gridding process, 20 two-dimensional horizontal representations (time-slices – see Goodman, Piro 2013; De Angeli *et al.* 2022) of the subsurface at specific depths were created by interpolating vertical profiles.

3.2 *Multispectral drone survey*

The Phantom 4 Multispectral drone, selected for multispectral surveys, is a high-end model featuring with six 1/2.9" CMOS sensors. Each sensor has a resolution of 2.08 megapixels and includes a color-composite Red, Green, and Blue (RGB), along with five sensors covering the visible spectral image bands, Red, Green, Blue, Red-Edge and Near Infra-Red (NIR) sensors (see Tab. 2). Healthy vegetation rich in chlorophyll absorbs light primarily in the Blue and Red wavelengths, while reflecting Green light, which gives vegetation its green appearance to the human eye (De Guio 2015, 116). In the Near-Infrared (NIR), vegetation exhibits high reflectance due to the internal leaf structure, which varies among plant species (De Guio 2015, 117, fig. 4). This variation enables the differentiation of plant types through multispectral remote sensing, which is a valuable tool for detecting specific species or identifying plants under stress or disease, as these conditions alter their spectral signatures.

In contrast, bare soil generally shows increasing reflectance, with higher values in the Near-Infrared. Soil reflectance can be influenced by several factors, including moisture content, texture, proportions of sand, silt, and clay, surface roughness, the presence of iron oxide, and organic matter content. This capability is particularly valuable in archaeology, where plant growth and health may be influenced by underlying buried structures, such as foundations, roads, or ancient pits. For instance, a plant growing over a buried wall may exhibit limited root development, appearing less healthy compared to plants in adjacent, undisturbed soil (for further information on this topic see Cowley *et al.* 2017; James *et al.* 2020; Abate *et al.* 2021; Ciccone 2024).

3.3 *Vegetation Indices (VIs) and analysis*

The most commonly used index in vegetation analysis is the Normalized Difference Vegetation Index (NDVI) (Rondeaux *et al.* 1996; Agapiou *et al.*

Phantom 4 Multispectral sensors					
Band	Central Wavelength (nm)	Tolerance	Band	Central Wavelength (nm)	Tolerance
Red	650	± 16	Red-Edge	730	± 16
Green	560	± 16	NIR	840	± 26
Blue	450	± 16	Visible	-	-

Tab. 2 – Phantom 4 Bands.

2011; Pan *et al.* 2017; Kalayci *et al.* 2019), which provides insights into vegetation health and density in a specific area. NDVI is calculated using the spectral reflectance values of the Red and NIR bands, according to the formula:

$$NDVI = (NIR - RED)/(NIR + RED)$$

NDVI values range from -1 and +1. Negative values typically indicate non-vegetated areas or artificial surfaces, such as asphalt or water. Values close to zero suggest minimal vegetation presence, while positive values, usually between 0.2 to 0.8, denote healthy vegetation, with higher values reflecting greater vegetation density and health. In addition to NDVI, DJI software computes other indices, including the Optimized Soil-Adjusted Vegetation Index (OSAVI) and Green Normalized Difference Vegetation Index (GNDVI). OSAVI is an optimized version of NDVI designed to evaluate vegetation health and cover while accounting for variations in soil reflectance. This makes OSAVI particularly useful in images where prominent soil exposure might otherwise affect NDVI accuracy. GNDVI is an index used to measure vegetation health and density, offering reduced sensitivity to soil reflectance compared to the traditional NDVI. It is frequently applied in areas with dense vegetation or high-reflectance soils.

In the specific context of Teglio, where vegetation was sparse and in its early growth stages, the vegetation indices did not reveal significant differences. This outcome is expected, as sparse or early-stage vegetation often lacks the density and spectral variation required for spectral indices to detect meaningful changes effectively. Consequently, interpreting subtle archaeological features becomes challenging in such conditions, highlighting the need for complementary methods, such as geophysical surveys, or alternative indices suited to low-vegetation environments. To enhance the readability of certain VIs, new ones were created using the QGIS raster calculator, including the Soil-Adjusted Vegetation Index (SAVI) and updated OSAVI parameters, tailored to the study's context (Brivio *et al.* 2006, 450-453; De Guio 2011, 114-126).

SAVI is a spectral index commonly used in multispectral image analysis, similar to the NDVI but with an added correction for soil conditions. The SAVI formula is:

$$SAVI = ((NIR - Red)/(NIR + Red + L)) * (1 + L)$$

The constant L in the formula allows adjustment based on specific soil conditions and is set to 0.5 in this case. Thus, the SAVI index provides a soil-adjusted measure of vegetation health and cover, making it especially useful when soil has a significant influence in multispectral imaging. However, it is important to note that there were no substantial differences from previous results in this context.

OSAVI is a spectral index used to evaluate vegetation health and coverage. It is an optimized version of the SAVI, specifically designed to account for variations in soil reflectance. OSAVI is particularly useful in situations where distinct soil visibility in an image might affect NDVI calculations. The formula for OSAVI is:

$$OSAVI = (1 + L) \cdot NIR + Red + LNIR - Red$$

Where the correction factor L is set to 0.16.

Although manually adjusting the correction factors significantly enhanced the visibility of certain indices, the effectiveness of these indices was still limited by the sparse and early-stage vegetation, hindering the detection of meaningful archaeological features. To further enhance image analysis beyond VIs, the Intensity-Hue-Saturation (HIS) transformation, available in QGIS's Whitebox Tool plugin[2], provides notable enhancements in image processing. IHS transformation, commonly used in photogrammetry and multispectral image processing, improves visualization and interpretation by adjusting Intensity[3], Hue[4], and Saturation[5] (Brivio *et al.* 2006, 260-261). This transformation selectively emphasizes image intensity, enhancing detail and contrast, which aids in identifying subtle features in archaeological contexts.

4. Methodology and interpretation

During the data collection phase, the soil was wet due to snowfall in the previous weeks. This raised concerns about the success of the surveys, given the high soil moisture content. The surrounding vegetation consisted mainly of a meadow in the early stages of growth, which greatly facilitated the GPR survey operations. However, there were concerns about the negative impact that low vegetation could have on multispectral surveys. Despite this, both methodologies produced significant results and contributed substantially to our understanding of the archaeological deposit in the study area.

[2] https://www.whiteboxgeo.com/.

[3] This range represents the brightness of the image. A value of 0 means completely dark, while a value of 1 means completely bright. Intermediate values represent varying levels of brightness.

[4] The range of the Hue is usually measured in radians.

[5] The saturated color ranging from 0 (gray) to 1 (fully saturated color).

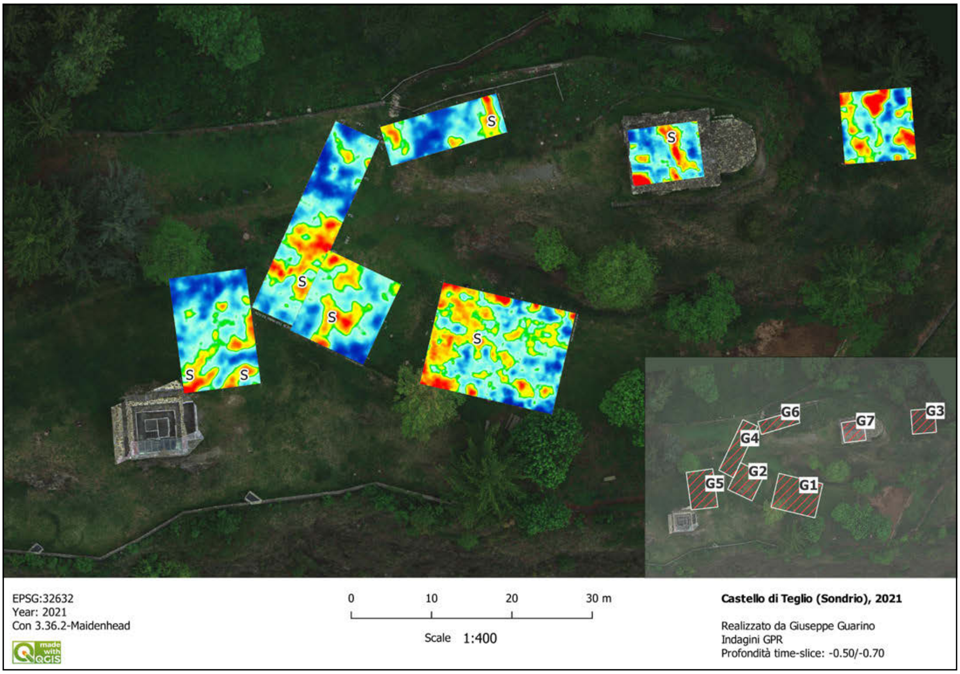

Fig. 2 – GPR Survey grid at Teglio castle. Depth: -0.5/-0.7 cm.

The GPR data revealed the presence of highly reflective anomalies, identified as wall structures comprising pebbles and earth. These structures were situated above the underlying bedrock, which was observed to lie at a relatively shallow depth. The bedrock was distinguishable in vertical radargrams due to its strong reflection, and it appeared that this bedrock had been intentionally carved in places to create functional rooms or structures (Fig. 2). In general, the wall structures, indicated in the figure by the letter S, have a north-south orientation in the area close to the church. Similarly, the structures carved directly from the rocky bank exhibit a north-south orientation. In the tower's vicinity, however, the structures appear to have a southwest/northeast orientation. Some anomalies in the GPR data can also be detected in the vegetative indices obtained by processing the multispectral data (Fig. 3).

The results obtained from the IHS processing were particularly noteworthy. A sector to the east of the tower exhibits anomalies that are not discernible with the NDVI, SAVI, and OSAVI indices. Unfortunately, due to the challenging terrain conditions, which are difficult to access with GPR, no measurements were acquired for possible comparison with this technique.

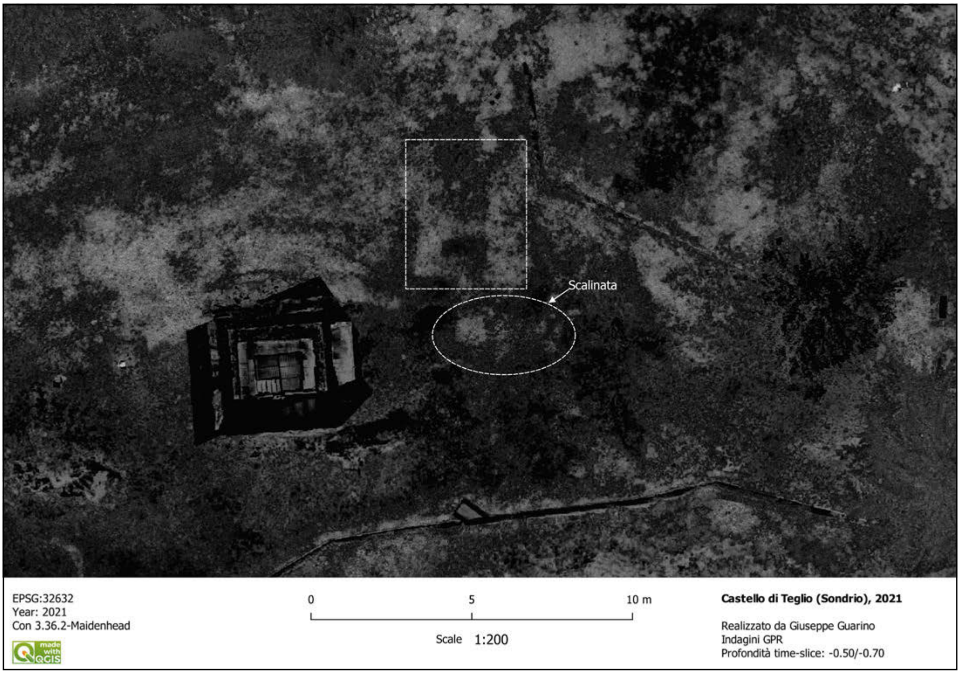

Fig. 3 – Saturation imagery obtained through the IHS process.

Nevertheless, the excavation, as described in the following paragraphs, definitively confirmed the presence of a monumental staircase that led to the tower.

G.G.

5. Excavations and evaluations of the results

In order to confirm the anomalies identified through non-invasive surveys, a series of exploratory archaeological excavations were conducted in May 2021. A total of ten exploratory trenches (S1-S10) were dug, eight of which yielded positive results, indicating the presence of masonry structures or archaeological stratigraphy. Trench 1, situated at the southern limit of the GPR-GR5 grid, explored anomalies detected by both the multispectral camera and the ground-penetrating radar, revealing the presence of a masonry wall (Fig. 4). This wall, originating at the northeastern corner of the tower, continued in the same direction for approximately 7 meters, with an elevation preserved for just a few decimeters. North of this wall, a second stone building was discovered, likely constructed during the final occupation of the castle. In the southeastern corner of the excavation, another wall was found,

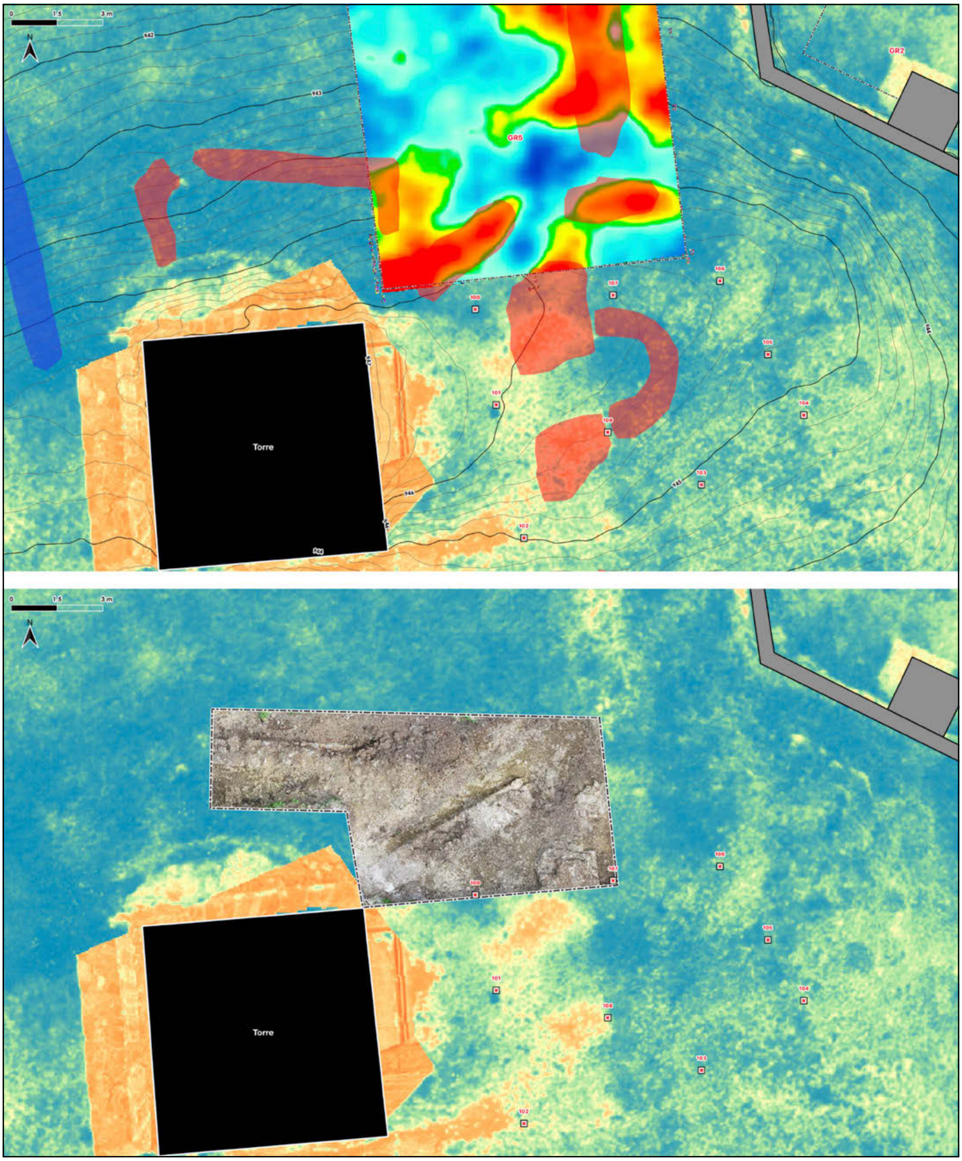

Fig. 4 – Overlap of GPR and multispectral SAVI index with the structures found in Trench 1.

measuring approximately 1.9 meters in thickness and oriented north-south. This wall extended beyond the southern limit of the exploratory excavation.

Additional walls were identified in Trenches 2, 7, and 10, with Trench 10 confirming the anomaly previously identified in GPR Grid GR6. Trench 3 yielded positive results, intercepting archaeological soils with a silty matrix and black coloration, arranged on two levels. This suggests the presence of terraces on the northern slope of the hillock on which the tower is built. Trench 4 was conducted on a plateau located just behind the rocky hilltop where the church stands. Here, the rock appears to have been cut in a regular manner, and the excavation uncovered a significant deposit of splinters from the same cut rock. This is likely waste material from the stone quarry used for constructing the late-medieval castle.

At least two ancient burials were discovered in Trench 9, near the church façade. Some bones were recovered from these graves, probably lost or ignored when they were relocated (no skeletons were found in the graves). This trench also revealed other materials that could be attributed to early medieval and protohistoric periods, providing evidence of ancient occupation in this area. The burials were situated close to a wall structure oriented east-west. Only the south elevation of this wall was uncovered. While further investigation is required to ascertain the pre-existence of this structure, its continuity with the present church suggests it may be part of the original religious building.

Trench 5, oriented northeast to southwest and traversing a significant portion of the meadow between the church and tower, uncovered a circular pit measuring approximately 2.3 meters in diameter at a depth of approximately 1 meter. The bottom of this pit was covered with a thick layer of lime mortar. Although it is challenging to ascertain the specific function of the pit, similar evidence is often associated with the construction phases of medieval castles, such as pits for slaking lime and mixing mortar. Among various artifacts with no chronological significance, the excavation yielded one soapstone spindle reworked from an older (early medieval) soapstone pot.

The preliminary investigations have yielded data indicating the presence of a well-articulated site in terms of both spatial organization and continuity of use. The materials, although decontextualized, provide evidence of long-standing and continuous occupation of Dos del Castel from the protohistoric period to the end of the Middle Ages. In ancient times, the castle likely comprised numerous structures developed near the main buildings, including the church and tower. Some of these structures are confirmed by the walls found during the exploratory excavations and by various cuts in the rock emerging throughout the castle, delineating rectangular rooms still visible today to the northwest of the church and the southwest of the tower.

Another noteworthy discovery was made during the initial stages of the extensive stratigraphic excavation of the castle of Teglio. The multispectral

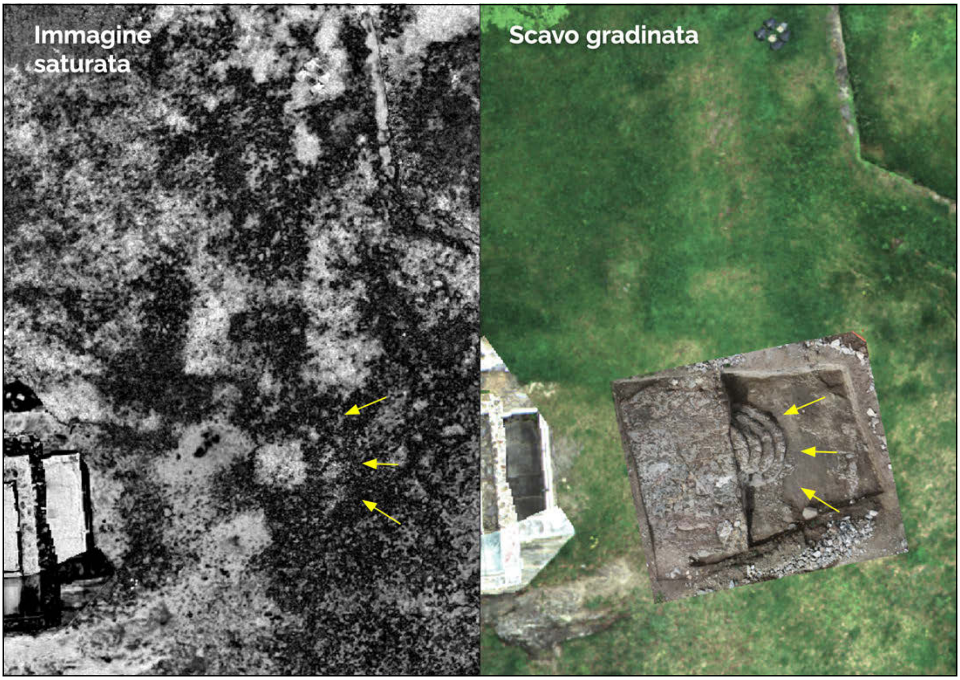

Fig. 5 – The staircase found in front of the Teglio tower, corresponding to the anomaly detected trough IHS process (left).

survey, through IHS processing, indicated the presence of a significant semicircular anomaly near the east wall of the tower. This anomaly was subsequently investigated during the first archaeological campaign, which unearthed a well-preserved staircase carved into the natural rocky bank (Fig. 5).

F.Z.

6. Conclusions

In conclusion, the correlation of various datasets revealed significant recurrences between the anomalies identified in the vegetation indices of the ground cover and those detected by the geophysical surveys. However, the anomalies observed in the vegetation indices did not always perfectly align with the characteristics identified in the geophysical surveys.

Particularly noteworthy was the evidence at GPR Grid G5, where the vegetation indices, especially the SAVI index, appeared to confirm the existence of largely overlapping alignments. Trench 1, excavated in correspondence with these anomalies (both the GPR and SAVI anomalies), confirmed that their origin is due to the presence of masonry structures in the subsoil. The integrated approach proved highly effective in elucidating the archaeological potential of the Dos del Castel area, prompting the decision to invest in an extended archaeological excavation of the site. This commenced in the summer of 2022 and is currently ongoing.

The clear visibility of the traces highlighted in the vegetation indices was favored by several factors, including the morphological and pedological characteristics peculiar to high-altitude sites, the season and type of vegetation present at the time of the surveys, as well as the depth of the archaeological deposit. During the surveys, the turf, being in the middle of its vegetative phase, had an average height of between 10 and 20 cm. Furthermore, the elevated site likely favored the formation of a thin archaeological deposit, characterized more by erosive phenomena than by significant soil accumulation. In this manner, the wall ridges, discovered at a depth of a few tens of centimeters, between -20 and -40 cm from ground level, were more clearly visible than in other contexts where the subsoil exhibited significantly greater density.

Similarly to the multispectral surveys, those conducted by GPR yielded significant traces, despite the soils being predominantly wet due to the snowfall at the time. It is probable that the presence of wet soil, although not particularly saturated as in the case of continuous rainfall, facilitated better delineation of the structures, enabling them to be distinguished from the surrounding background.

The initial application of this investigative method to the archaeological contexts of the Valtellina mountains appears promising, paving the way for new perspectives in the field of archaeological prediction. The outcomes of these investigations indicate the potential for further systematic applications in stratigraphically and morphologically distinct contexts, thereby facilitating a more expansive and adaptable approach to archaeological research.

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ABSTRACT

The Alpine settlement of Teglio, Italy, offers a commanding view of the Adda River and nearby passes, pivotal in early medieval times. The 'Dos del Castel' hillock, with its medieval structures including the S. Stefano church and 'Torre de li beli miri' tower, had remained unexplored archaeologically until recent non-invasive surveys using Ground-Penetrating Radar (GPR) and UAV multispectral analysis. These methods were applied to detect buried structures and analyze vegetation indices, revealing the presence of walls and possible functional spaces carved into the bedrock. The GPR surveys identified high-reflectivity anomalies indicating masonry structures, while multispectral analysis, despite sparse vegetation, highlighted significant areas of possible archaeological interest. Subsequent excavations confirmed these findings, uncovering walls, a monumental staircase, and other structures, suggesting a long-standing and well-organized occupation of the site. This integrated approach has proven effective, paving the way for new approaches in archaeological prospection.

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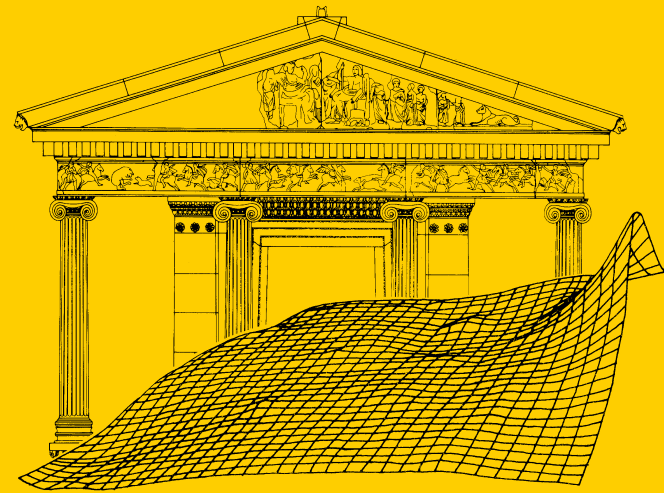

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