Geological characterization and stability analysis for Salerno test site

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1. ABSTRACT

Landslides are one of the most critical natural hazards in the world and can be extremely destructive. Campania region (southern Italy) is particularly susceptible to these phenomena, in particular to the flowslides, due to the presence of pyroclastic deposits, related to the eruptions of volcanic complexes (Vesuvius and the Phlegraean Fields), on steep slopes made of carbonate or volcanic bedrock.

This study deals with experimental site in Salerno; it was chosen as it is geologically and geotechnically representative of the Lattari Mts, an area historically affected by this type of landslides. Furthermore, this choice allows for bridging the knowledge gap on these landslides between the northern slope, which has been extensively studied, and the southern slope, which has been less investigated.

This study proposes the geological characterization of the site through a multidisciplinary approach integrating boreholes, thickness logs and Electrical Resistivity Tomography (ERT) surveys; it is possible to define the stratigraphic section of the area and to determine the pyroclastic thickness, information that will then be crucial for a slope stability analysis.

In addition, the site will be equipped for the measurement and monitoring of soil hydraulic parameters (suction and volumetric water content), as they are preparatory factors for the triggering of these landslides. In fact, continuous monitoring of hydraulic and mechanical soil parameters is an important tool to improve the Early Warning Systems (EWS) and, thus, the risk mitigation.

Finally, preliminary results of UAV remote sensing data, using thermal and multispectral cameras, will be shown to estimate the hydraulic soil parameters measured in situ.

2. STUDY AREA

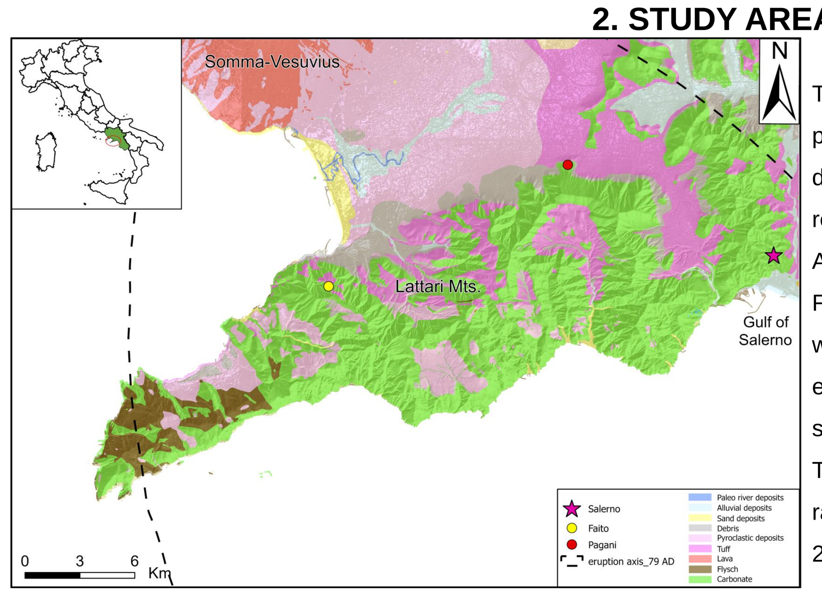

Figure 1: Study Area

The test site is in Salerno (Figure 1), in the southern part of Lattari Mts. The area is characterized by a dolomite bedrock overlain by pyroclastic deposits resulting from the eruption of Somma-Vesuvius (79 A.D).

Flowslides are typical of these contexts; however, while the northern part of Lattari Mts has been extensively studied (such as Faito and Pagani test sites), the southern slope has not.

The study area is characterized by a slope gradient ranging from 28° to 35°, with an average elevation of 238 meters above sea level.

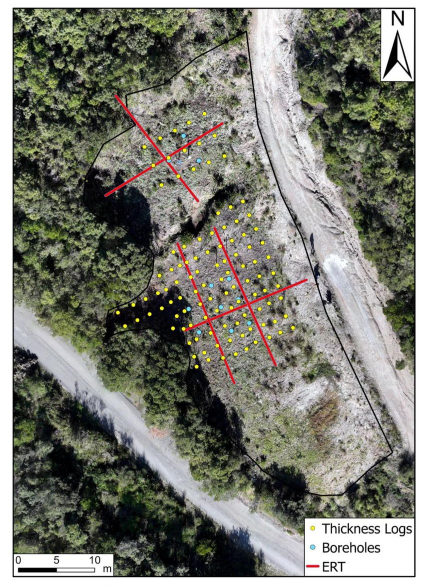

Figure 2: Surveys map

After vegetation removal, a UAV flight was conducted as part of the geological survey, resulting in the creation of study area orthophoto and DTM.

As shown in Figure 2, the investigations carried out are:

- 107 Thickness logs
- 11 Boreholes
- 5 ERT

The boreholes were strategically located to characterize the experimental site and a corresponding control area. These stratigraphic investigations have been synthesized into 11 stratigraphic columns, consisting of a pyroclastic cover from the 79 AD eruption, resting on a dolomitic bedrock (Figure 3).

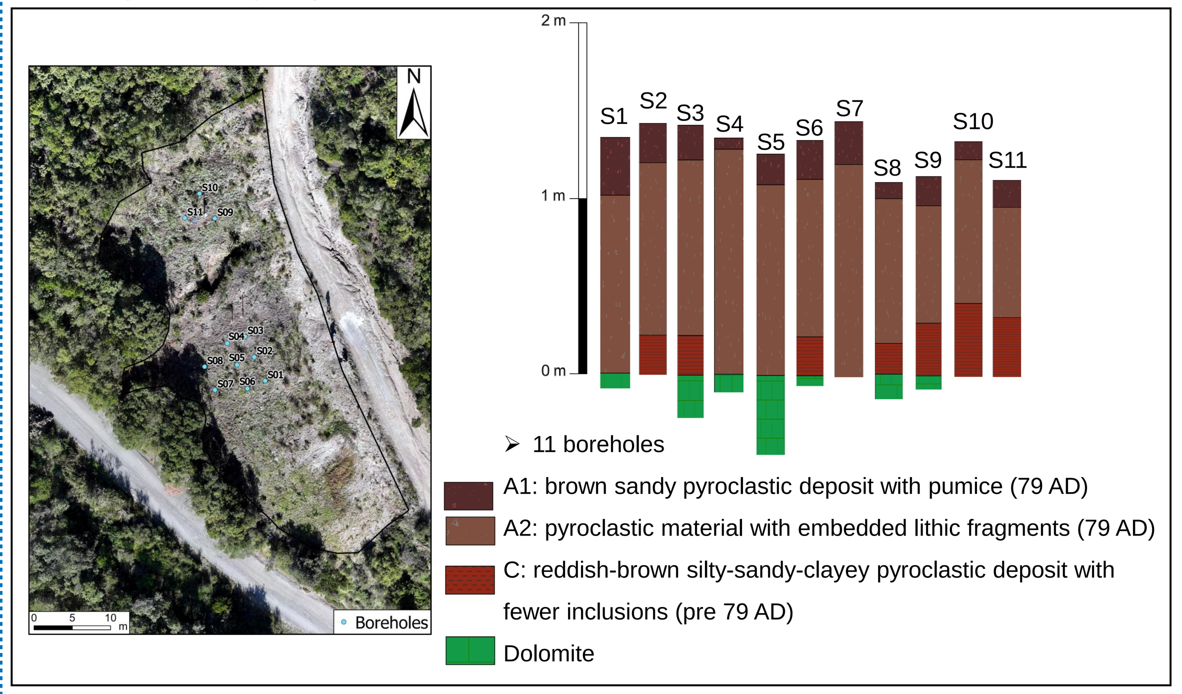

Figure 3: Location of boreholes and stratigraphic columns

3. MULTIDISCIPLINARY APPROACH FOR GEOLOGICAL MODELLING

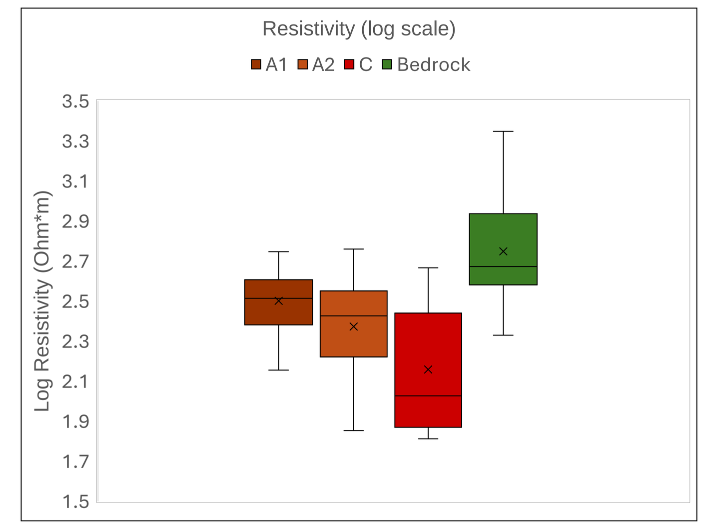

Figure 4: Box plot of resistivity ranges for each soil layer

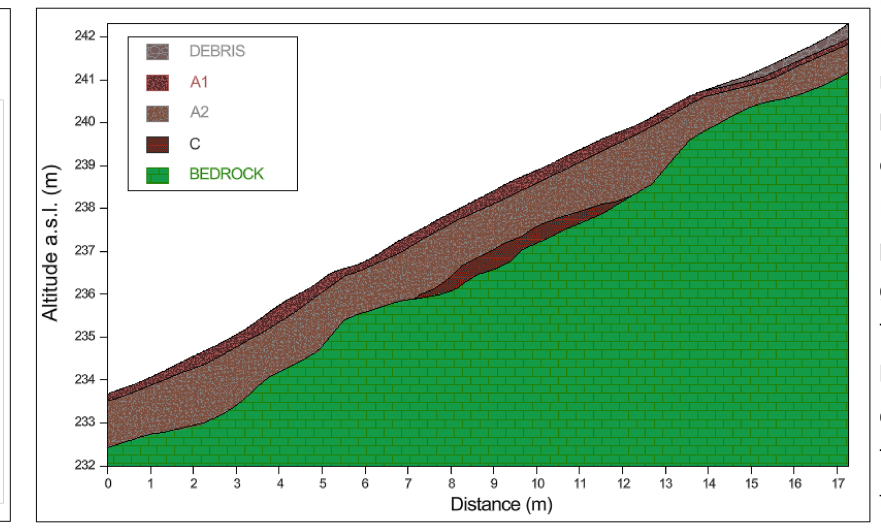

Figure 5: Geological cross-section

Five electrical resistivity measurements were also carried out.

Resistivity is a physical property of soils and rocks, measured in Ω*m, and indicates the resistance encountered by electrical current as it passes through a lithotype. It can therefore be related both to the characteristics of the soil skeleton of the materials and to their water content.

By knowing the position and thickness of the lithological layers from the boreholes, it was possible to associate a range of resistivity values with each lithotype. Box plots were generated to represent this data, as shown in the Figure 4.

The cover materials exhibit similar resistivity values, whereas the bedrock is characterized by higher resistivity. Although the cover materials share comparable values, they display a decreasing median from A to C.

This trend, combined with boreholes data and stratigraphic information, enabled the transition from resistivity distributions to the construction of geological cross-sections (Figure 5).

The thickness dataset enables to generate thickness maps for layers A1 (Figure 6), A2 (Figure 7), and C (Figure 8), with spatial interpolation techniques in ArcGIS Pro software.

Figure 6: A1 thickness map

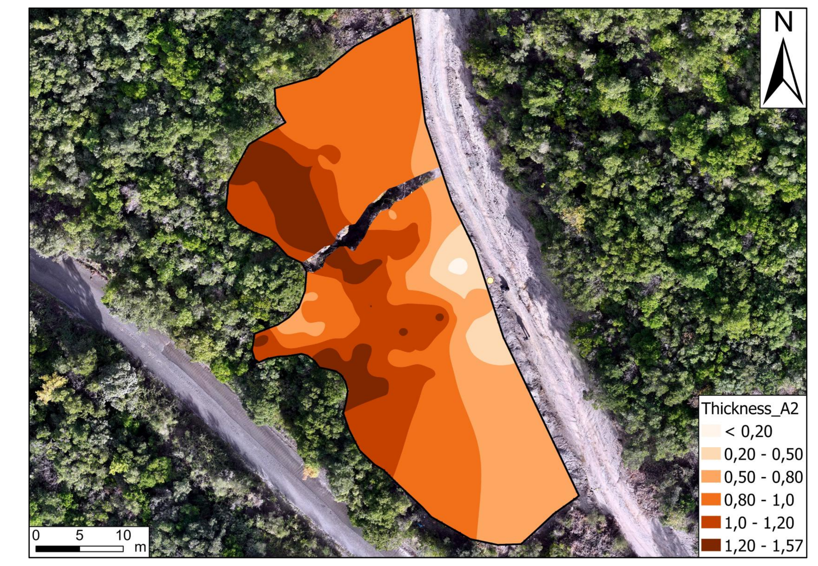

Figure 7: A2 thickness map

Figure 8: C thickness map

4. MONITORING EQUIPMENT

The site was equipped for the measurement and monitoring of soil hydraulic parameters (suction and volumetric water content), as they are preparatory factors for the triggering of these type of landslides.

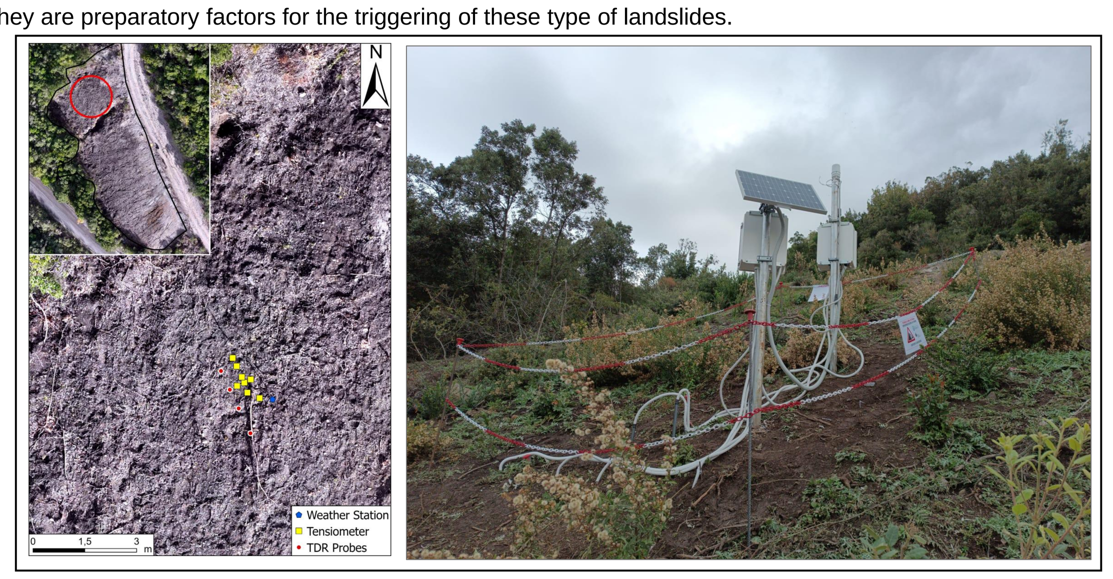

Figure 9 shows:

- 4 TDR Probes (DICEA + Tecno In) (November 2024)
- 5 Tensiometer (DICEA +Tecno In) (November 2024)
- 1 Weather Station (Tecno In) (November 2024)

Figure 9: Monitoring equipment

Figure 11: Cover thickness map

Figure 12: A1+A2 thickness map

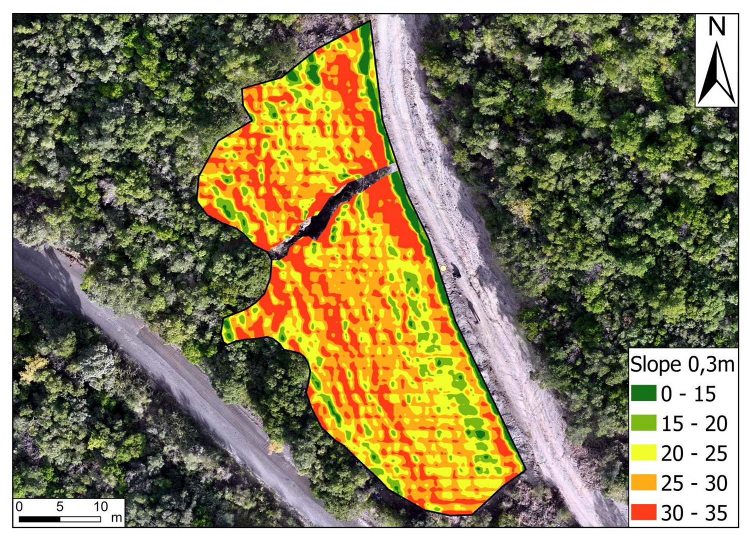

Figure 10: Slope map

The geotechnical characterization was carried out at the DICEA laboratory. Table 1 reports the preliminary geotechnical parameters of A2 soil, which are useful for the calculation of the Factor of Safety (FS).

Table 1: Geotechnical parameters for slope stabilty analysis

$SOIL$	A2
$\gamma\ [kN/m^3]$	17.8
$\varphi'\ [°]$	37
$c'[kPa]$	0

5. SLOPE STABILITY ANALYSIS

Based on the geological model and the geotechnical parameters, the Factor of Safety (FS) was calculated using the infinite slope model. Specifically, the analysis was conducted by modeling the area as a grid, with 0.3 × 0.3 m cell size, according infinite slope conditions, assuming a slip surface located below the A2 soil layer.

By adopting the Mohr-Coulomb failure criterion and applying the limit equilibrium method, the Safety Factor (SF) according to Bishop's effective stress approach for infinite slope conditions is given as follows:

$$F.S. = \frac{tan\varphi'}{tan\alpha} + \frac{S_r \cdot s \cdot tan\varphi'}{\gamma \cdot h \cdot sen\alpha \cdot cos\alpha}$$

In this equation φ' (friction angle) and γ (unit weight of the soil) are reported in Table 1; h is the depth of the assumed slip surface and α (the slope angle) was replaced by the slope map (Figure 10) derived from the Digital Terrain Model (DTM); S_r and s are the degree of saturation and suction, respectively.

The study area is characterized by a pyroclastic cover reaching a maximum thickness of about 2 meters (Figure 11). According to the literature, the A2 layer is the most susceptible to landslide; therefore, a sliding surface was hypothesized to develop below this layer, with an average depth of h = 1,50 m (Figure 12).

Two scenarios were analyzed: with and without suction.

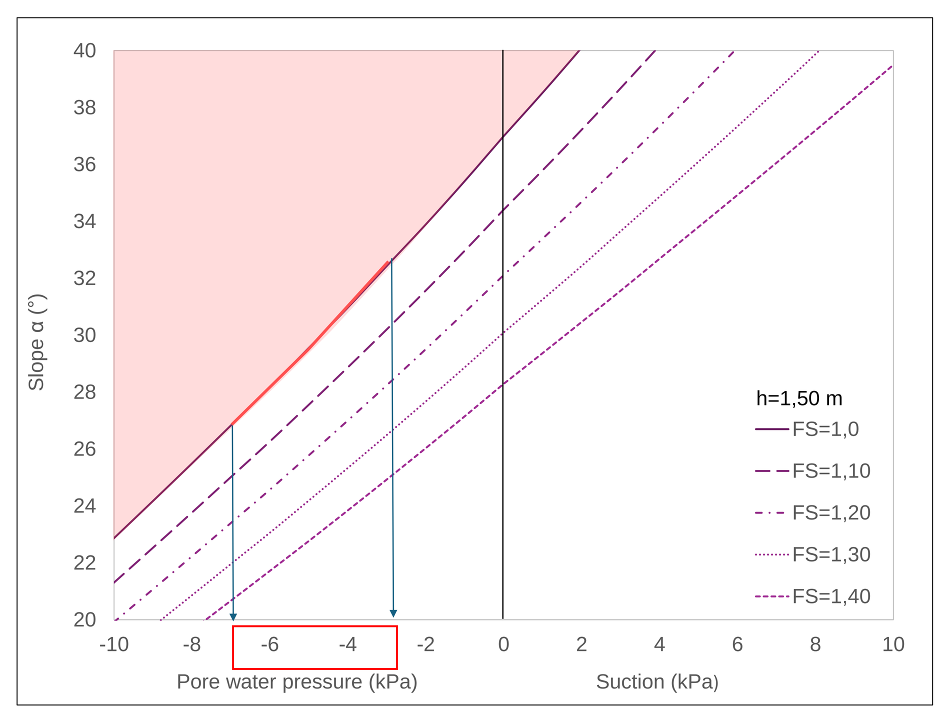

Figure 14: Stability chart

The safety factor obtained for the scenario "s = 0" indicates stable conditions across the entire study area (Figure 11). In this case, the Factor of Safety (FS) is a function only of the slope and the internal friction angle.

$$F.S. = \frac{tan\varphi'}{tan\alpha} + \frac{S_r \cdot s \cdot tan\varphi'}{\gamma \cdot h \cdot sen\alpha \cdot cos\alpha} \qquad HP:\ s = 0 \rightarrow F.S. = \frac{tan\varphi'}{tan\alpha}$$

Therefore, to identify critical conditions, parametric analyses were conducted, varying both suction and pore water pressure.

As shown in the stability chart (Figure 14; in this context positive suction and negative pore water pressure were assumed), for the slope angles present at the site, a pore water pressure of at least 3,0 kPa is required to reduce the Factor of Safety (FS) below 1. This corresponds to a water table located approximately 30 cm above the slip surface.

Figure 15 shows the result of the stability analysis considering a pore water pressure of 3 kPa. It can be observed that the presence of the water table leads to an increase in unstable areas.

Figure 13: Safety Factor map (s=0)

Figure 15: Safety Factor map (pwp=3kPa)

6. FUTURE DEVELOPMENTS: VOLUMETRIC WATER CONTENT BY REMOTE SENSING

Volumetric water content (VWC) can be measured using traditional techniques, such as TDR and FDR probes and tensiometers. Although these methods provide highly accurate measurements of water content, they are point-based and therefore limited, failing to capture the spatial heterogeneity of this hydraulic parameter.

Remote sensing techniques represent a promising approach for the estimation of surface VWC. The use of satellite imagery allows for broad and temporally continuous spatial coverage, improving the ability to monitor spatial variations in VWC. Furthermore, to achieve higher spatial resolution, Unmanned Aerial Vehicles (UAVs) equipped with multispectral and thermal cameras can be used, enabling detailed mapping of VWC.

One of the limitations of UAV-surveys is that UAV systems do not measure VWC directly. In fact, UAV data are primarily used to assess crop condition and their water stress. Crop health assessments are typically based on vegetation indices (Table 2), which derived from algebraic combinations of reflectance measurements collected by multispectral sensors, particularly using the red, green, blue, red-edge, and near-infrared spectral bands.

Figure 16 is the NDVI map of the experimental site: from an initial analysis, supported by the available orthophoto, the study area appears to be predominantly characterized by sparse vegetation.

MULTISPECTRAL CAMERA

- Flight date: January 30, 2025
- Drone: Phantom 4 Multispectral
- Sensor resolution: 1600x1200
- Flight altitude: 50 m
- h: ~12:15 PM

THERMAL CAMERA

- Flight date: January 30, 2025
- Drone: Autel Dual EVO II 640 T
- Sensor resolution: 640x512
- Flight altitude: 50 m
- h: ~12:45 PM

PRELIMINARY PROCESSING SOFTWARE

- Agisoft Metashape
- Pix4D Mapper
- ArcGIS Pro

Radiometric calibration of the multispectral images was carried out using, at present, only the sunlight sensor spectral (integrated into the drone), improving the accuracy of the collected data and making them comparable in time and space.

About the thermal elaboration, the drone is equipped with a high-resolution thermal camera designed to capture thermal data in the thermal infrared band (λ = 8–14 μm). Sensors operating primarily in the thermal infrared (TIR) collect radiation (heat) emitted directly from the Earth's surface.

Once the thermal data processing is done and the orthomosaic is constructed, the thermal map (Figure 17) using Set Raster Transform in Agisoft Metashape.

Table 2: Multispectral Vegetation Indices

INDEX	EQUATION
NDVI (*Normalized Difference Vegetation Index*)	NDVI= (NIR-Red)/(NIR+Red)
NDWI (*Normalized Difference Water Index*)	NDWI=(Green-NIR)/(Green+NIR)
VARI (*Visible Atmospherically Resistant Index*)	VARI= (Green-Red)/(Green+Red-Blue)
NDRE (*Normalized Difference Red Edge Index*)	NDRE=(NIR-RedEdge)/(NIR+RedEdge)
GNDVI (*Green Normalized Difference Vegetation Index*)	GNDVI= (NIR-Green)/(NIR+Green)

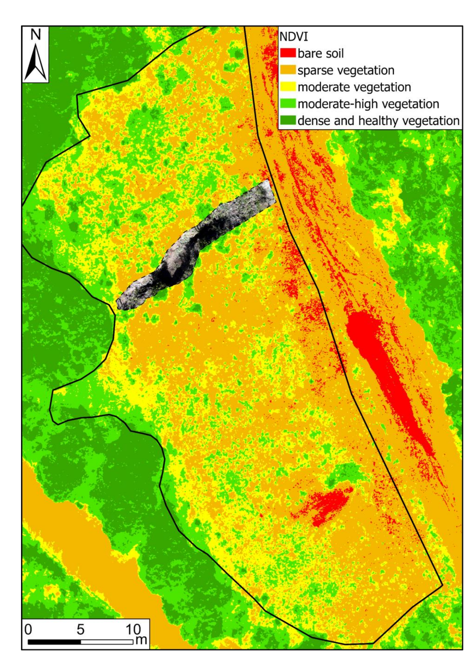

Figure 16: NDVI Index

Spatial resolution: 5 cm/pixel

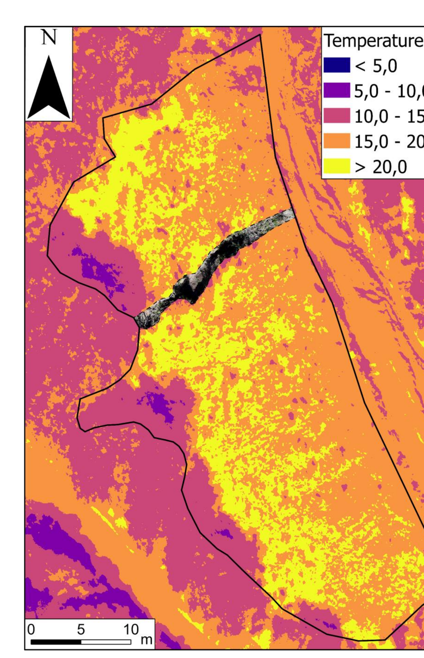

Figure 17: Temperature map

Spatial resolution: 5 cm/pixel

7. CONCLUSIONS

- The geological model reveals that the investigation area is predominantly characterized by A1 and A2 pyroclastic soils, while the C layer is localized within certain morphological depressions of the bedrock.
- Identifying the location of layer C is of critical importance, as its lower permeability compared to the overlying soils could lead to the development of pore water pressures and, consequently, the formation of a perched water table.
- This study will serve to calibrate the numerical simulations for the developments of the project.
- Continuous monitoring of hydraulic parameters and slope stability management improve early warning systems, thereby reducing risks.
- Future aims: to estimate Volumetric Water Content using satellite data and high-resolution unmanned aerial vehicle (UAV)-based multispectral and thermal images to generate spatial maps of VWC through machine learning algorithms.

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