 doi:10.20944/preprints202211.0357.v1

Freely available LiDAR-based digital terrain model (DTM) uncovers the heart of the Dacian World

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Abstract

Throughout history, the unique Dacian landscape has aroused the imagination of many. For decades, researchers have been fascinated by the magnificent structures the Dacians built and how they altered the mountains to their advantage. Dacian sites, despite their grandeur, remain mostly unknown due to their position deep within Romania's vast forests, generally in remote regions and hidden from the naked eye. Ground exploration in densely forested mountain regions is extremely difficult, and even if such campaigns existed, they would be insufficient to provide a comprehensive picture of the Dacian world. The lack of high-resolution remote-sensing data for wide areas made big-scale assessments of the landscape impractical. This is about to change, as new large datasets of LiDAR-derived digital elevation models, covering the entire heart of Dacian world, are now freely available. This paper reports on one of the most recent freely available LiDAR-based high-resolution digital elevation models in Romania, its impact on Romanian mountain archaeology, and how this can shape future research directions in understanding the Dacian landscape.

1. Introduction

The Dacian power centre located in south-western Transylvania (Fig. 1) emerged during the first half of the first century BC and lasted until the Roman conquest in AD 106. Its most distinctive architectural features were the impressive strongholds built high in the mountains, with walls and towers made of shaped stone, which held opulent aristocratic houses located near religious sites.

Fig. 1. Top: LiDAR-based DTM coverage area is shown in grey. The study area is represented by the blue rectangle. Bottom: The most important archaeological sites in the study area and in the vicinity of the Dacian capital, Sarmizegetusa Regia. The sites are classified as Dacian fortresses, hillforts, linear fortifications, Roman camps, or Dacian settlements.

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Extensive settlements sprang up around these fortifications, usually dispersed but occasionally clustered in dense neighbourhoods, arranged on numerous artificial terraces carved into the slopes of hills. The entire ensemble occupied an area spanning approximately 200km^2 in the Șureanu Mountains (Orăștiei) on elevations ranging between 500 and 1500m and was traversed by networks of ridge roads that linked the fortresses and settlements, as well as the entire centre, to the major trade arteries of the time.

Sarmizegetusa Regia, the capital of the Dacian Kingdom and a Hellenistic-type city, was at the heart of this ensemble (Stefan 2001). It is one of the most remarkable cities of temperate Europe's antiquity, situated around 1000m above sea level, with a scenic location and complex architecture resulting from the combination of local traditions and external influences. No significant archaeological remains originating before the Dacian era were discovered in this area. The surrounding fortifications were elite residences rather than military forts (Lockyear 2004); five of them (Costești-Cetățuie, Costești-Blidaru, Piatra Roşie, Bănița, Căpâlna), together with Sarmizegetusa Regia, are part of the serial site *Dacian Fortresses from the Orăştie Mountains*, which was inscribed on the UNESCO World Heritage List in 1999.

The effort required to establish this power centre indicates the existence of a central authority that possessed substantial economic and human resources. Strabo (VII, 3, 11) attests to its existence and dates its genesis to the reign of King Burebista (82/81–44 BC). The kingdom's second phase of flowering occurred during the reign of King Decebalus and was followed by the Roman conquest of the Dacian Kingdom under Emperor Trajan and the transformation of a significant part of it into a Roman province.

After the conquest, the central region was deserted, and evidence of subsequent human occupancy is extremely rare. The formerly developed region were now overgrown, and the entire infrastructure had disintegrated. The vast collection of strongholds, towns, fortifications, and roads was rendered nearly inaccessible by the forest. This explains not just the years of obscurity that followed, but also the preservation of Dacian monuments, which have not been destroyed or looted (Fig. 2).

Not until the early nineteenth century did the ruins of the fortifications come to the attention of the Habsburg officials who administered Transylvania at the time and who initiated the first field searches, prompted by the discovery of gold treasures in this region (Petan 2021a).

Fig. 2. A. Drone image of Costești - Blidaru; B. Terrestrial image of Costești - Blidaru (entrance tower); C. Terrestrial image of Sarmizegetusa Regia (temple area); D. Drone image of Alun - Piatra Roşie.

Since then, a genuine treasure-hunting craze has spread throughout the Dacian Mountains, a trend that has sadly still not fully subsided. Despite this, the extremely difficult access has always deterred enthusiasts and scholars from exploring the ruins (Pețan 2018). The first systematic archaeological research began during the interwar period, and the great campaigns of archaeological excavations of the Dacian fortifications occurred in the 1950s and 1960s, focusing almost exclusively on the monumental structures (walls, temples) in the central areas. Despite several decades-long field surveys that led to the identification of several dozen places with remains of habitation, the true extent of the settlements surrounding these fortifications, the number of terraces, the road network, and other elements have remained mostly unclear. Today, archaeological excavations are limited to the capital's central district (Florea 2017). Some other sites (such as Alun-Piatra

Roșie and Costești-Cetățuie) are undergoing small-scale excavations. However, results have not yet been published.

The detailed structure of the settlement system has remained a mystery to both specialists and the public due to the huge area in which the sites are distributed, challenging topography, high level of afforestation, and lack of well-articulated research projects. There is no published data on potential topographic or geophysical surveys, thus the information that is now available is, with very few exceptions, presented only in sketches from the middle of the twentieth century. However, some aerial photographs have revealed new information about Dacian fortifications and Roman army camps close to the Dacian capital (Stefan 2005).

The use of LiDAR sensors has resulted in a previously unheard-of revolution in archaeological prospection. Airborne LiDAR surveys have helped researchers better understand archaeological landscapes in unprecedented ways over the last two decades. The development of this technology has most likely had the greatest impact in tropical and subtropical areas, as it has assisted archaeologists in identifying sites in very remote and inaccessible areas. The impact of airborne surveys on establishing settlement patterns in the ancient Mayan landscape (Chase *et al.* 2014) and revealing a network of historical cities in Cambodia (Evens 2016) is already widely known, Across Europe's various landscapes thousands of sites were discovered and analysed with the help of LiDAR surveys (Bewley *et al.* 2005; Schindling & Gibbes 2014; Grammar *et al.* 2017; Masini *et al.* 2018). Today, a plethora of LiDAR sensors, mounted on airplanes or drones, are used for archaeological purposes. Some countries (e.g. Poland) have had LiDAR data generated for their entire territories and provide free access to high-resolution purged digital elevation models.

In Romania, the only systematic LiDAR surveys were conducted in the context of flood prevention in specific areas, particularly large river basins such as the Mureș, Siret, and Timiș. This data is not widely available and can only be accessed on special request. Several archaeological sites in Romania, however, have benefited from full LiDAR surveys (Szentmiklosi *et al.* 2011; Opreanu & Lăzărescu 2014; Vizireanu & Mateescu 2018; Gogâltan *et al.* 2019), and more archaeological studies have recently emerged in which LiDAR DTMs were used (Asăndulesei 2017; Asăndulesei *et al.* 2020; Berzovan *et al.* 2020; Niculiță 2020).

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The first LiDAR scan within the Dacian Mountains was conducted in 2011 and covered 72km^2, with a density of 9–12 points per square meter and Sarmizegetusa as its focal point. The data, which was commissioned by the BBC for use in a public documentary, was used for scientific purposes in the years that followed. This data enabled the identification of previously unknown fortifications in the center of the Dacian Kingdon and of potential Roman marching camps (Oltean & Hanson 2017). Oltean & Fonte (2020) analysed the settlement aggregation in the rural area of the capital. They also proposed various routes the Roman army could have taken to the Dacian capital using least cost path analysis and some derived analyses (Oltean & Fonte 2021). A new LiDAR data set made available to us by Primul Meridian (a company specialized in remote sensing data) led to a better understanding of how the land was used at the Alun-Piatra Roșie fortress (Pețan 2021b).

Several characteristics make the area under discussion an appropriate subject for LiDAR-based research: 1. The large surface area and the degree of forest cover have severely hampered research so far; 2. The human interventions in shaping the landscape are fairly easily traceable on DTMs; 3. For most of the area, the absence of human remains from periods other than the Dacian era allows a certain chronological classification of anthropic interventions, even in the absence of excavations; 4. With few exceptions, the difficult access to the area ensured a pristine state of conservation of the sites. All these are arguments in favour of the huge scientific potential of LiDAR-based research in the Dacian Mountains, which is of great importance not only at a local but also European level.

2. Data and study area

The current digital terrain model (DTM) was created as part of the LAKI II (Land Administration Knowledge Improvement) project – Geographical Information for the Environment, Climate Change, and European Union Integration (Informații geografice pentru mediu, schimbări climatice, și integrarea UE) and is the property of ANCPI (National Agency for Cadastre and Land Registration of Romania). The digital terrain model is LiDAR-based, with all data collected between 2017 and 2018. The point-cloud used to generate the DTM had a resolution of 8 points per square meter. The overall error

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for altimetry is 0.30m and 0.20m for planimetry—the resolution of the final DTM being 1m.

The data, identified as LAKI 2 MNT, can be downloaded for free from ANCPI's geoportal (geoportal.ancpi.ro). The current digital elevation model covers four counties (Fig. 1) in western Romania (Hunedoara, Arad, Alba and Bihor). The web geoportal supports data retirement by using a predefined mask such as a county polygon or a specific administrative unit. Additionally, the data can be retrieved by using built-in tools to create an irregular mask.

For the purpose of this study, we have downloaded the data by administrative units' polygons related to an area that encompasses the most important Dacian fortifications in Romania. The separate tiles were put together into one master grid file so that basic visualisation and analysis could be done on the whole dataset. The visualisation was performed by multidirectional illumination of a created hillshade layer. The DTM illustration in this paper was produced in ArcGIS Pro (GIS software).

3. A sneak peek under the canopy

It is well known that the Dacians shaped the mountains to their advantage, and as a result, a complex habitational system arose alongside their fortifications. Consequently, multi-terrace settlements sprang up everywhere. In most cases, the forest has reclaimed the terraces, making comprehensive field mapping nearly impossible (Fig. 3). In this context, the existence of the free LiDAR-derived DTM presented in this paper facilitates an overview of the landscape.

It has already been noticed that the number and density of terraces in the capital area is much higher than previously thought; almost 2000 anthropogenic terraces were identified on the DTM in an area of 100km^2 (Oltean & Fonte 2019: 259). For the whole area in question, this figure is much higher and remains to be determined by future research. It is expected that this will lead to a major reconsideration of the number of inhabitants in the capital area and, as a result, of the complexity of Dacian society.

A great novelty is the way the land is organised around the fortresses. Until now, the attention of archaeologists has been directed towards these hilltop fortifications, often regarded as isolated structures with a military role. LiDAR data attests to the existence of settlements organised in groups of terraces around these centres.

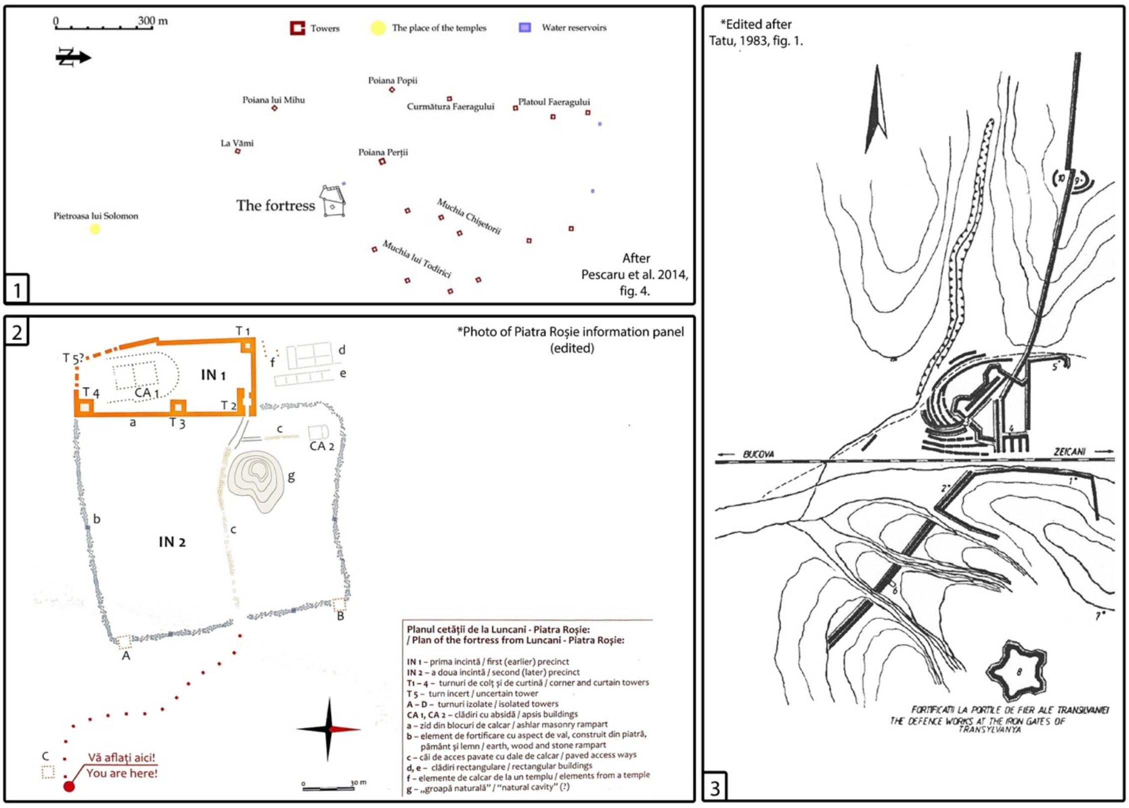

Fig. 3. 1 The most recent Costești area plan described by Pescaru et al. (2014) (the image was edited after Pescaru et al. 2014, fig. 4); 2 Information panel at the Alun - Piatra Roșie site entrance (photo by Aurora Peţan, edited); Hristache Tatu's 1982 drawing of Fortifications at the Transylvanian Iron Gate Pass (Bucova-Zeicani, Hunedoara County) was published in 1983. (edited).

A very good example is the fortress at Costești-Blidaru (Fig. 4). The visualisations of the LiDAR DTM reveal a complex system of terraces (Fig. 5) on the lower elevations descending from the highest elevation to the Grădiştea Valley as well as on almost all the ridges around the fortress and along the nearby river. On a simple slope generated raster (Fig. 8) the terraces, having a flat surface, can be easily spotted. At least 17 rectangular buildings have already been identified on these terraces (Pescaru *et al.* 2014), but the logic of their topographic location and consequently their functionality (military towers or dwellings) have remained unclear (Fig. 3:1). The DTM unveils a higher number of such structures (Fig. 5, 6), as well as unique constructions with a circular plan (Fig. 5 B, C) and previously unknown earth fortifications (Fig. 9) and ancient roads. Future study of the whole ensemble, as revealed by LiDAR data, may finally lead to the clarification of the nature of this site and its relationship with the very close fortress at Costești-Cetățuie.

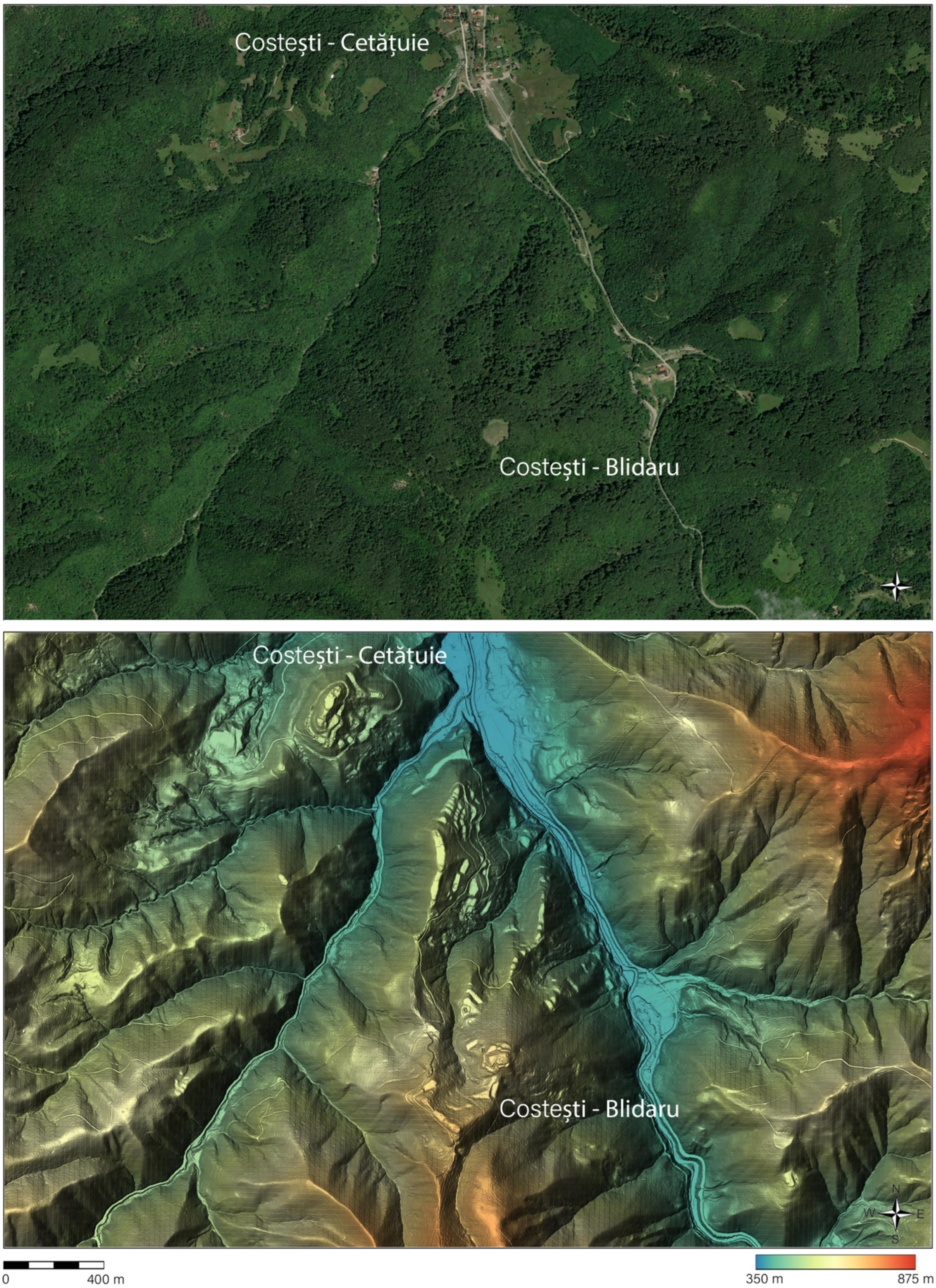

Fig. 4. Costești area: Top: CNES / Airbus satellite image from 9.11.202; bottom: LiDAR DEM, hill shaded.

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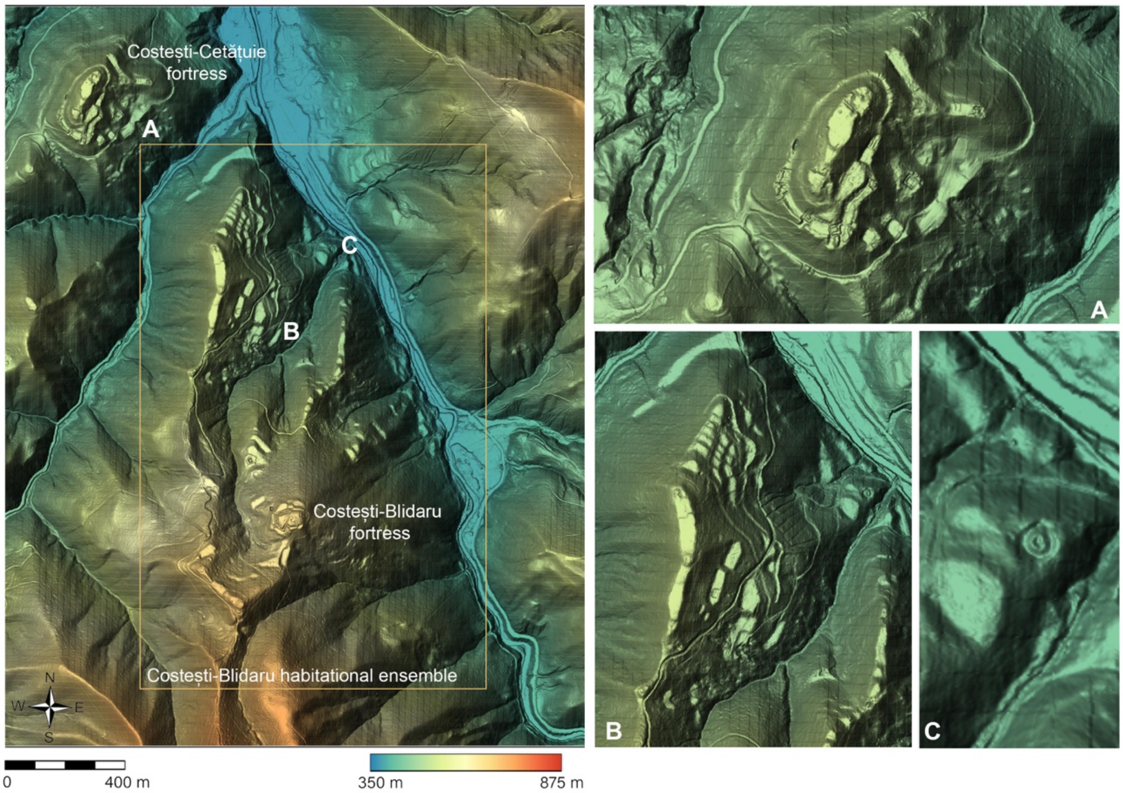

Fig. 5. Hill shaded LiDAR DEM in the Costeşti area - details of the Costeşti - Blidaru habitational ensemble (B, C) and the Costeşti - Cetăţuie habitational ensemble (A).

Both Costești-Blidaru and Costești-Cetățuie have established terraced settlements on east- and south-facing hillsides (Fig. 5). This can be clearly demonstrated by a straightforward slope direction analysis undertaken with any GIS software (Fig. 8 top). The same may be argued for other fortifications, such as Alun-Piatra Roșie (Fig. 8 bottom) and Sarmizegetusa Regia.

Another excellent example of how the mountain was shaped to create a habitational area is the site at Alun-Piatra Roșie (Fig. 6). The only archaeological excavations here took place in 1949 (Daicoviciu 1954), with a small-scale excavation follow-up in 2004. For decades, archaeologists believed these fortified constructions were primarily used for military purposes. It was only recently proven based on an accurate LiDAR analysis that the site was more than that: in reality, the core of this site consists of a spectacular ensemble (Fig. 7), made up of large terraces arranged in steps on the eastern slope of the hill (Pețan 2021b). At the highest point was an elite residence, and on the neighbouring hills one can easily identify previously unknown groups of terraces, which revolve around this core (Fig. 7). Therefore, it is obvious that functionality needs to be re-discussed in this case as well.

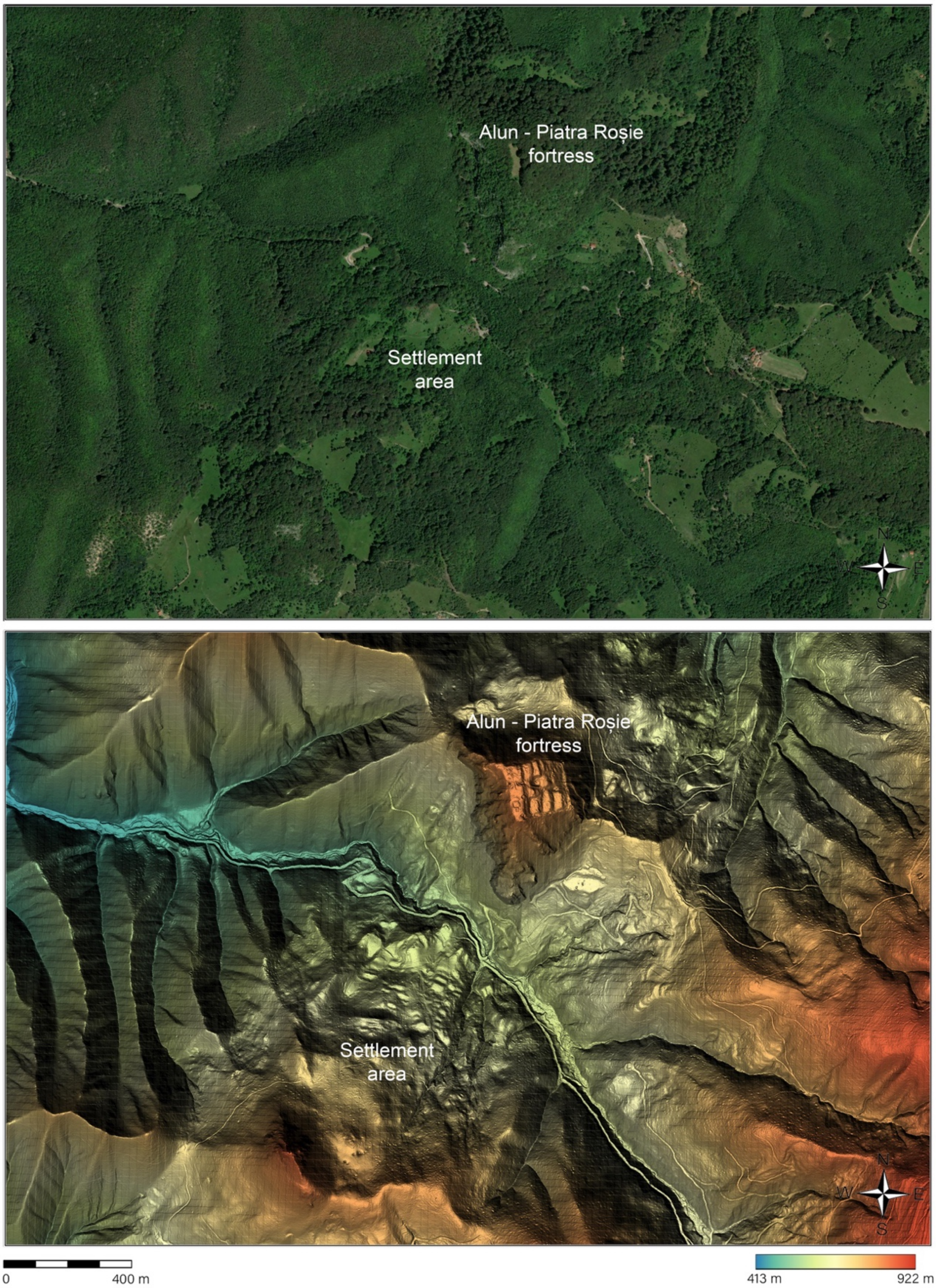

Fig. 6. Area of Alun - Piatra Roşie: Top: CNES / Airbus satellite image from 9.11.202; bottom: LiDAR DEM, hill shaded.

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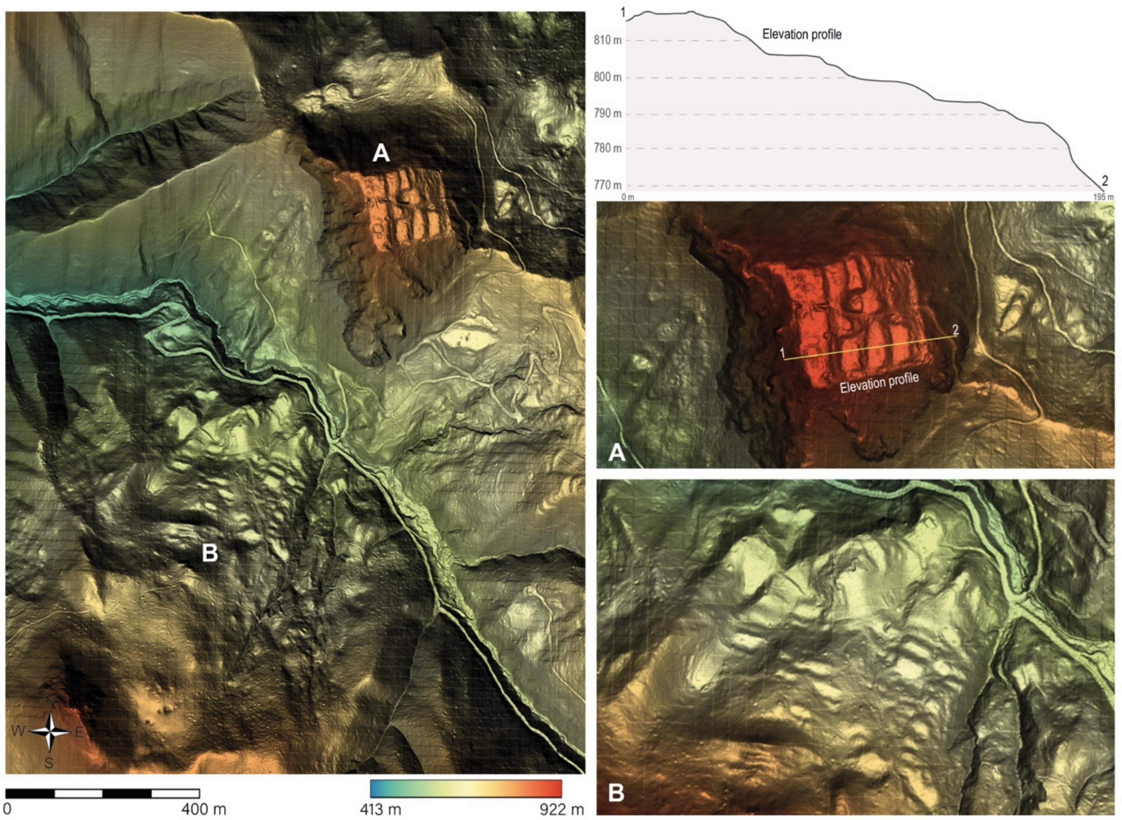

Fig. 7. LiDAR DEM with hill shading within the Alun - Piatra Roșie fortress: A. the fortress and B. the settlement.

In addition to revealing the high degree of complexity of these fortresses and settlements, the analysis of the DTM also brings to light numerous previously unknown fortifications, often located on the access roads to this centre of power. Being located in intensively inhabited areas in all epochs, they must be checked in the field, so that the period to which they belong can be determined without a doubt.

The most important of these is the intricate set of fortifications at the Transylvanian Iron Gate Pass (Bucova-Zeicani, Hunedoara County), which many historians identify with the ancient Tapae, the place where strong confrontations took place between the Dacians and Romans in AD 87 and 101 (Dio Cassius LXVII, 10; LXVIII, 8). This pass was in all epochs an important point of entry into Transylvania, and during the Dacian period one of the main access roads to the capital of the kingdom. Due both to many fortification works in this area throughout the ages and to the land covered by forest, it has not been possible to clarify so far the real extent and planimetry of these fortifications. The only existing plan was drafted four decades ago and is incomplete and quite confusing (Tatu

1983) (Fig. 3:3). The analysis of the DTM throws light on this complex field situation and in addition reveals new elements of the fortification (Fig. 9). The main known element is a linear barrier fortification of almost 2 km, which blocked the entire valley on both sides, most likely dating back to the Dacian era (Glodariu 2004: 539), with partial reuse in the Middle Ages or modern times (Fig. 9 top). Our analysis shows that the defence system was much longer and blocked not only the access through the valley, but also to the ridge road, which was protected in this way for a length of at least 2.8km (Fig. 9 top). Hence, at the moment the known length of the fortification is 4.8km, but its real dimension and route remain to be determined in the future.

In addition, the LiDAR data shows two novel enclosures, one located on the Cătanelor Hill, the other 250m further north (Fig. 9 bottom, marked with number 3 and 4). The first one encloses an area of 1.5ha with two concentric ramparts forming an irregular shape. The discovery of prehistoric ceramic shards in this area (Tatu 1983: 168) could indicate that it belongs to this era. The second one protects the edge of the hill with a pair of small enclosures that must be prior to the Dacian ditch, as they are cut by it. The barrage goes tangentially to the first enclosure, suggesting a possible integration of it into the blocking system. A fourth, already known fortification with bastions obviously dates to a later epoch, since it overlaps the Dacian rampart and the prehistoric enclosure (Fig. 9, marked with number 1). This complex picture is now much clearer and more spectacular than was expected and urges the initiation of field research in this area, promising results of great importance for understanding the strategies used by the Dacians in the wars with the Romans.

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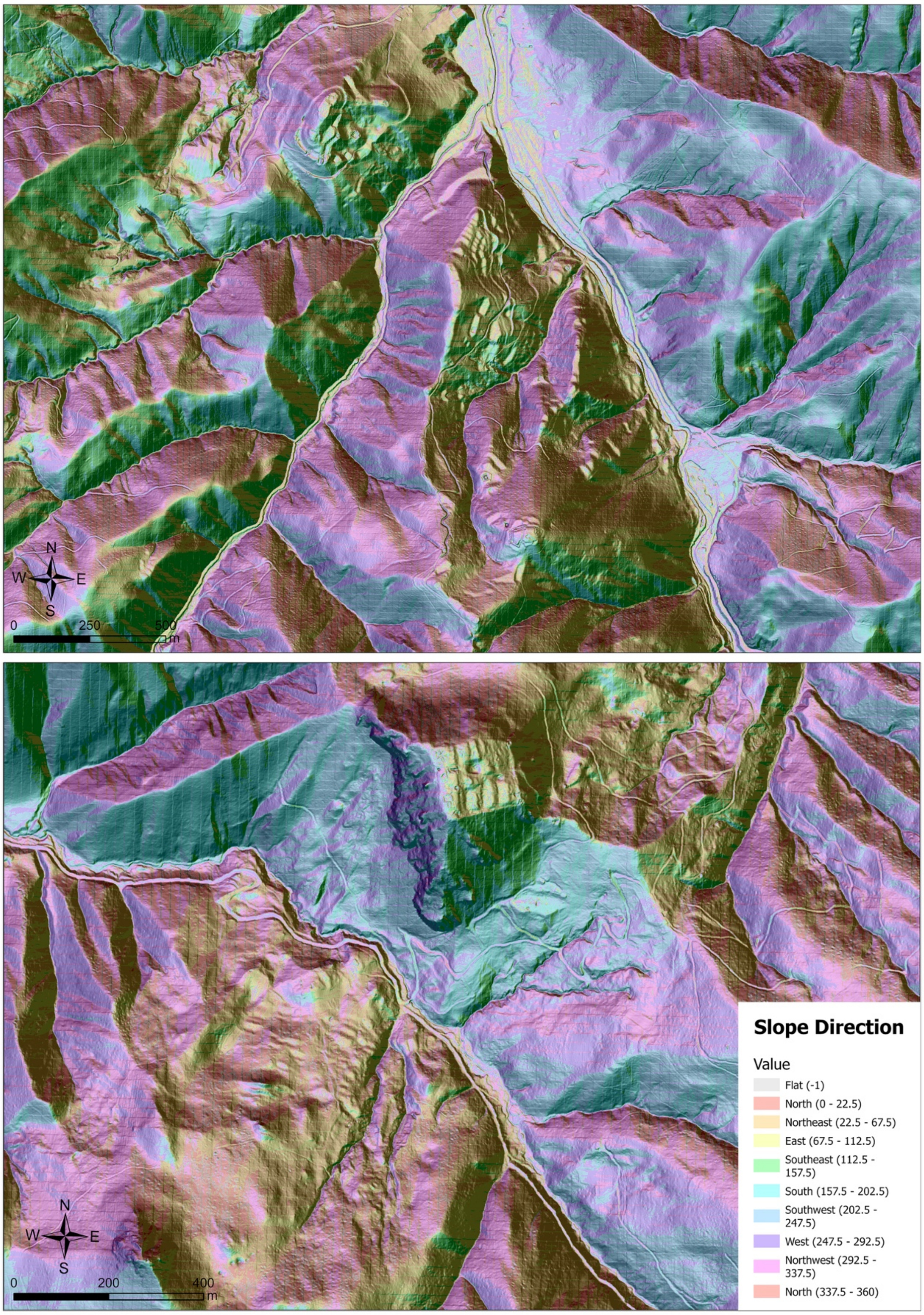

Fig. 8. Direction of the slope: Costești area (top), Alun - Piatra Roşie (bottom).

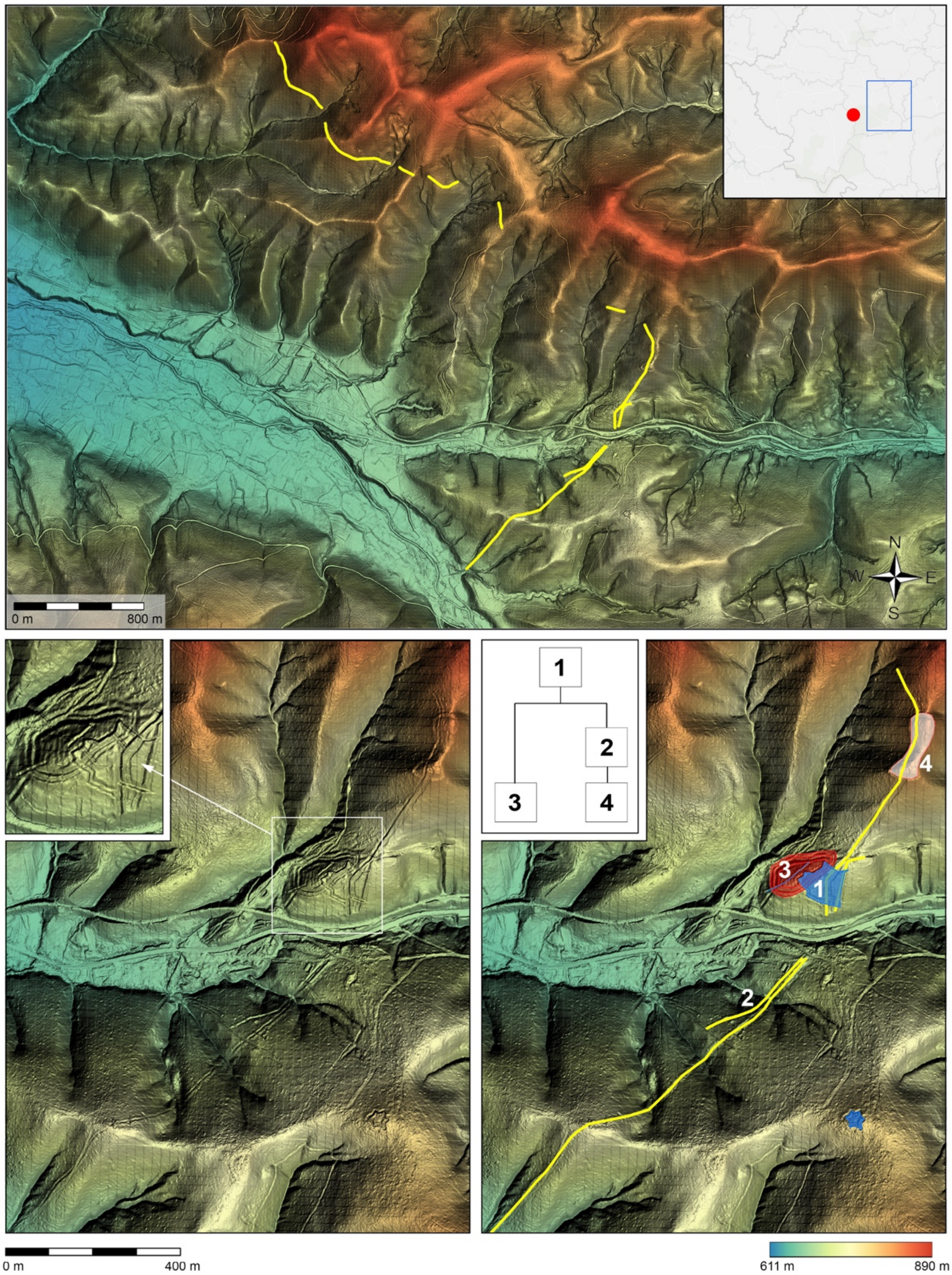

Fig. 9. Transylvanian Iron Gate Pass fortifications (Bucova-Zeicani, Hunedoara County): The yellow line represents a fortification system that is assumed to be Dacian. The LiDAR DEM reveals a system that is much longer than previously thought and has blocked access not only to the valley, but also to the ridge road. Bottom left: fortification details; Bottom right: chronology of the structures visible on the LiDAR DEM (1 – Habsburg fortifications, 2 – Linear Dacian fortification system, 3 and 4 – prehistoric fortifications)

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4. Perspectives

The availability of an open-access LiDAR based digital elevation model opens the door to a wide range of derivatives in terms of research and administration. It opens up new research directions in fields other than archaeology within the area. Geology, geomorphology, forestry, hydrology, and a variety of others stand to benefit. The gain is expected to be even greater in archaeology. Now, archaeologists and archaeology enthusiasts can manually explore the vast area in search of new man-made structures using only simple visualisation techniques already established in archaeological literature (Štular *et al.* 2012; Thompson 2020). Because this mountainous area is mostly devoid of archaeological sites from other historical eras, most new discoveries are likely to be Dacian or Roman.

This quantity of high-resolution data will contribute to more precise assessments in archaeology-related GIS work, since the geomorphometric calculations will provide a very low degree of uncertainty. Prior to this time, the resolution of the only accessible digital elevation models was insufficient for combining geomorphometric information for in-depth site study. Now, precision can be added to the calculation of terrain properties such as slope, slope aspect, coverage, rugosity, and many other parameters. Multi-criteria or geostatistical techniques can be enhanced by the more precise geomorphometry of each site. The geomorphometry computation and the broad area for which a free DTM derived from high-resolution LiDAR data is readily available will allow for more accurate prediction models.

Specific research directions can also be implemented in other subfields of remote sensing, particularly machine learning and deep learning for automatic object detection. Detection algorithms have been successfully used for archaeological purposes, and methodologies for object identification on LiDAR data are continuously developing (Fiorucci *et al.* 2022). Considering the nature of Dacian settlements, which developed by shaping the local terrain through successive terracing works, and the size of the habitational areas, we believe that pattern recognition and object classification would be essential to better comprehending the habitational dynamics within the area. Training algorithms to detect each individual terrace visible on the digital elevation model will make it possible for the first time to comprehend the extent of settlement development and the true size of the

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Dacian world. Deep learning, pattern recognition, and advanced geomorphometry calculations could provide, for the first time, numbers that can be considered for more sophisticated analysis and interpretation. For instance, rough habitational density maps and broad demographic estimates could be constructed.

Even more dynamic human interactions, such as the Dacian-Roman battles, could be explored by combining these methodologies in various ways. A better understanding of Dacian defences and settlements would lead to a better comprehension of the Roman military machine created to conquer these untamed lands. With such approaches Roman military strategies could be better explained.

In terms of future research design, the current data collection will make a substantial difference. Archaeological campaigns in the mountains are arduous and must be meticulously planned in order to give the desired outcomes. Archaeologists can now investigate the optimal location for future archaeological excavation units. The range of newly discovered structures will undoubtedly present new archaeological challenges that should be explored.

Local authorities in charge of the UNESCO World Heritage site in the Dacian Mountains could also benefit greatly from using and exploring this data set. Conservation strategies for fortifications and terrace-like settlements could emerge, as could assessments of site threats. As a result, each site's most vulnerable areas could be identified and addressed. This area is well-known for being a magnet for treasure hunters, and looting activity still occurs. Digital elevation models based on LiDAR have been successfully used to map archaeological looting (Danese *et al.* 2022). This data set could be used to identify and delineate older looted zones, as well as highlight areas that looters prefer. Once these areas have been identified and assessed, better protection strategies can be implemented.

5. Conclusions

Without a doubt, the emergence of this freely accessible LiDAR-based digital elevation model will redefine the face of Dacian archaeology by allowing for more targeted investigations and the development of new research directions in this region. Already, the initial exploration of this collection enables us to better comprehend the complexity of Dacian features (e.g., architectural features). Even the fortifications, which have been thoroughly researched, are more intricate than previously believed. Only by scrutinizing the LiDAR DTM were totally new additional fortification lines, towers, and other buildings observed. In addition, the greater awareness of the structure and development of the terrace-like habitation zones provide for a deeper understanding of Dacian civilization and may provide incredibly valuable data regarding demographic dynamics. The military techniques employed during the massive Daco-Roman conflicts can also be better comprehended.

In addition to archaeology, numerous other disciplines can benefit from this resource. Using it, local administration may develop more effective site protection measures.

The dataset reported in this paper will offer up new avenues for understanding the landscapes and social interactions at the heart of the Dacian world.

We expect that by making these tools available, archaeologists conducting systematic research in the region will be more encouraged to publish their findings locally and worldwide.

Acknowledgements

We would like to acknowledge the National Agency for Cadastre and Land Registration of Romania (Agenția Națională de Cadastru și Publicitate Imobiliară) and the LAKI II (Land Administration Knowledge Improvement) project – Geographical Information for the Environment, Climate Change, and European Union Integration (Informații geografice pentru mediu, schimbări climatice, și integrarea UE).

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