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A High-Resolution UAV LiDAR Survey for Identifying Quarry Features in the Colli Euganei, Italy: Comparative Analysis and Case Studies of Two Breccia Quarries

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Abstract

This thesis presents an analysis of quarry features in the Colli Euganei, Veneto, Italy, focusing on the application of high-resolution UAV LiDAR surveys. The research identified and characterized 89 potential quarry sites through remote sensing, with a particular emphasis on quarries associated with breccia stone materials in the central and eastern regions of the Colli Euganei. A comparative analysis between high-resolution UAV LiDAR and publicly available, lower-resolution LiDAR data demonstrated significant advantages in spatial resolution, which enhanced the identification, visualization, and interpretation of quarry features. The methodology involved detailed UAV LiDAR surveys and point cloud processing to generate high-resolution digital terrain models (DTMs), allowing for more precise quarry identification and analysis.

The comparative study revealed substantial improvements in detecting subtle quarry features and interpreting their spatial context using high-resolution data. Fifty of the identified quarry features were further analyzed through statistical analysis, revealing clear distinctions between presumed modern quarries and a diverse range of historic sites. This statistical differentiation, supported by qualitative assessments of proximity and feature characteristics, underscored the variety in form and size of historic quarries. A smaller number of sites were validated through field surveys, which confirmed a high likelihood that the remotely identified features were indeed quarries.

Additionally, two prominent breccia quarries were selected for in-depth case studies to demonstrate the value of site-specific analysis using high-resolution LiDAR data. These case studies examined the physical characteristics, spatial distribution, and hypothesized functional roles of the quarries, suggesting that both were integral to Roman-period extraction activities, particularly for the collection of pozzolanic additives used in mortars.

This research highlights the significant advantages of UAV LiDAR in archaeological investigations, particularly in forested environments, for both regional landscape analysis and detailed site-specific studies. The results underscore the importance of high-resolution remote sensing for uncovering subtle anthropogenic features and enhancing our understanding of historical quarry landscapes.

Sommario

Questa tesi presenta un'analisi delle caratteristiche delle cave nei Colli Euganei, Veneto, Italia, con particolare attenzione all'applicazione di rilievi LiDAR UAV ad alta risoluzione. La ricerca ha identificato e caratterizzato 89 potenziali siti di cava attraverso il telerilevamento, con un'enfasi specifica sulle cave associate ai materiali lapidei costituiti da breccia vulcanica nelle regioni centrali e orientali dei Colli Euganei. Un'analisi comparativa tra i dati LiDAR UAV ad alta risoluzione e quelli LiDAR a bassa risoluzione disponibili pubblicamente ha dimostrato vantaggi significativi in termini di risoluzione spaziale, migliorando notevolmente l'identificazione, la visualizzazione e l'interpretazione delle caratteristiche delle cave. La metodologia ha previsto rilievi dettagliati con LiDAR UAV e l'elaborazione delle nuvole di punti per generare modelli digitali del terreno (DTM) ad alta risoluzione, consentendo un'identificazione e un'analisi più precisa delle cave.

Lo studio comparativo ha rivelato notevoli miglioramenti nell'individuazione di caratteristiche sottili delle cave e nell'interpretazione del loro contesto spaziale grazie ai dati ad alta risoluzione. Cinquanta delle cave identificate sono state ulteriormente analizzate attraverso analisi statistiche, rivelando chiare distinzioni tra le cave presunte moderne e un'ampia gamma di siti storici. Questa differenziazione statistica, supportata da valutazioni qualitative di prossimità e caratteristiche delle strutture, ha sottolineato la varietà di forme e dimensioni delle cave storiche. Un numero limitato di siti è stato verificato tramite rilievi sul campo, che hanno confermato l'elevata probabilità che le caratteristiche identificate da remoto fossero effettivamente cave.

Inoltre, due importanti cave di breccia sono state selezionate per studi approfonditi al fine di dimostrare il valore dell'analisi sito-specifica utilizzando dati LiDAR ad alta risoluzione. Questi studi di caso hanno esaminato le caratteristiche fisiche, la distribuzione spaziale e i ruoli funzionali ipotizzati delle cave, suggerendo che entrambe fossero essenziali per le attività estrattive nel periodo romano, in particolare per la raccolta di additivi pozzolanici utilizzati nelle malte.

Questa ricerca evidenzia i notevoli vantaggi del LiDAR UAV nelle indagini archeologiche, in particolare in ambienti forestali, sia per l'analisi del paesaggio su scala regionale che per studi dettagliati sito-specifici. I risultati sottolineano l'importanza del telerilevamento ad alta risoluzione

per scoprire caratteristiche antropiche sottili e migliorare la comprensione dei paesaggi di cava storici.

Chapter 1: Introduction

This chapter serves as an introduction to the research and an overview of the area's natural and social history. The first section is dedicated to a broad overview of the research, the second the objectives which influenced the research, the third the geology of the Colli Euganei, and finally the fourth which provides a condensed summary of the history and prehistory of quarrying activities.

1.1 Research Overview

The agenda of this work is firstly, to identify through a high-resolution unmanned aerial vehicle (UAV) LiDAR survey the locations, distribution, and characteristics of quarries in the Colli Euganei, the Euganean hills, and review the effectiveness of this research against publicly available data. These surveys produced high resolution orthophotos and digital terrain models allowing for the terrain to be reviewed and the characteristics of identified quarry sites to be analyzed.

The effectiveness of LiDAR surveys in forested, topographically varied, terrains like the Colli Euganei at identifying archaeological features within a landscape has been well established since the 2000's. It has since become a standard method in landscape archaeology and remote sensing where its capabilities to assess remote, difficult to access, or forested terrain have been corroborated by numerous publications across the world in multiple contexts (Bewley, Crutchley, and Shell, 2005; Chase and Chase, 2009; Doneus and Briese, 2011; Evans et al., 2013). LiDAR surveys have been traditionally conducted using plane mounted sensors where pilots traverse a large area, often hundreds of square kilometers, in transects at fixed elevations above ground level, producing incredibly valuable data for the assessment of landscapes. In recent years public and private research through this methodology has produced increasingly accurate and higher resolution data and in the case of northeastern Italy the Regione del Veneto produced 25 meter, 5 meter, and now 1 meter resolution LiDAR surveys produced by Ministero dell'Ambiente e della Tutela Del Territorio e del Mare, showcasing the ever-increasing quality and accessibility of LiDAR data for research purposes which has already been applied to a variety of archaeological and geomorphological research.

While modern plane mounted LiDAR surveys are certainly valuable resources in the analysis of broad landscapes, a more recent technique for targeted high-resolution surveys has been adopted over the last decade. The widespread accessibility and use of unmanned aerial vehicles (UAVs), often referred to as drones, has allowed for the same techniques of plane mounted LiDAR sensors to be applied to UAVs and have since produced exceptionally high-resolution targeted surveys which were previously unachievable through airplane mounted surveys (Risbøl and Gustavsen, 2018; Barbour et al., 2019; Ćmielewski et al., 2021). Given the availability of these two methodologies, several UAV projects have been conducted in the last several years which targeted areas of larger regional plane mounted survey where the density of ground points was insufficient. In these cases, targeting specific regions of forested terrain produced quality results that justified the effort of a high-resolution survey (Poitier, Baleux, and Calestranc, 2020). Ultimately, the development of this research method over the last decade, and the insights offered by the 1-meter resolution LiDAR data of the Regione del Veneto service, encouraged a high-resolution UAV survey to be conducted in seven targeted areas of the central-eastern Colli Euganei to assess the distribution of quarries in the region.

The archaeological and natural significance of the quarries in the Colli Euganei has not gone unnoticed: the area has received a large amount of archaeometric and geological investigations over the last several decades, primarily by researchers from the University of Padova. These projects have covered a wide variety of topics, most of which have been focused on the geographical distribution and provenance of trachyte resources with several recent publications expanding our understanding of how this prominent geological formation was utilized throughout various periods (Maritan et al., 2013; Zara, 2016; Germinario et al., 2018a). Despite this, there remain multiple geological and archaeological components of the Colli Euganei which comparatively have been under researched in comparison to the trachyte quarries of the region. In particular, the pre-modern exploitation of volcanic breccia.

The region hosts a variety of breccia deposits, a conglomerate stone typically composed of irregular sized inclusions cemented together by a fine-grained matrix. In the Colli Euganei many of these are volcanic in nature, with high amounts of amorphous silica, and capable of producing a high quality pozzolanic additive for hydraulic mortars and concrete. The distribution of these quarries is therefore an essential component of a region’s historical relationship with resource extraction and yet, limited research has been focused on the subject. This project was developed to address these potential insights through the high-resolution UAV survey and identification of breccia quarries, examining their attributes, and interpreting their function within the landscape.

1.2 OBJECTIVES

The objectives of this research are multifaceted and aim to advance the understanding of pre-modern quarrying activities in the Colli Euganei through the application of high-resolution UAV LiDAR surveys. The specific objectives are firstly the identification and mapping of quarry sites to accurately identify, document, and map the locations of quarries within the Colli Euganei using high-resolution UAV LiDAR data. This includes distinguishing between different quarry types and assessing their spatial distribution across the landscape in addition to conducting a detailed analysis of a sampled portion of the sites' physical and morphological attributes, focusing on the specific characteristics of the quarries identified. This involves examining the size, shape, and features of the quarries.

To evaluate the effectiveness of UAV based high-resolution LiDAR surveys in comparison to publicly available plane mounted LiDAR data, a comparative assessment of the survey methods is required. The increased resolution and targeted approach of UAV surveys must be assessed to determine to what degree the data contributed to a more nuanced understanding of the quarrying landscape and the general distribution of quarry features in comparison to that of the already available public data.

Additionally, this project identified multiple quarry sites with potential to expand the general understanding of the archaeology and history of quarrying activity in the Colli Euganei. To depict the benefits and capabilities of the high-resolution LiDAR data when paired with field survey and feature documentation, two locations of densely located breccia quarry features were selected as case studies with the goal to interpret the identified quarry sites within their historical and archaeological context, focusing on the function of the pre-modern quarrying activities. This involves correlating the survey and field data with previous geoarchaeological findings in the region to establish a clearer understanding of resource extraction in the region, particularly during the Roman period. By investigating the provenance of materials extracted from these quarries, particularly volcanic breccia, and their role in historical construction and manufacturing processes, quarrying activities may be linked to broader patterns of resource utilization in the region.

Lastly, the results of the analysis conducted across the attributes of quarries identified in the survey areas and in the site-specific review of the case studies can be reviewed to contribute to the development of remote sensing methodologies by refining techniques for identification and analysis of quarry sites in forested and topographically complex terrains. This includes proposing best practices for future UAV LiDAR surveys in similar landscapes and examining areas of improvement in survey methodology. Additionally, this research encompasses only a minor portion of the Colli Euganei, and the results of this work can provide recommendations for future archaeological and geological research in the Colli Euganei and similar regions. This includes identifying gaps in the current understanding and suggesting areas where further investigation is needed.

1.3 Geological Background

The Colli Euganei is a geologically unique region shaped by complex formative processes spanning several geological eras. The landscape, characterized by interconnected and isolated volcanic hills that rise above the surrounding plain, has been molded by a dynamic interplay of tectonic activity, volcanic eruptions, and sedimentary deposition. These processes have given rise to a diverse array of stone typologies, each with distinct characteristics that are geographically specific to the region. For more than two millennia, this geological diversity has made the Colli Euganei a renowned and highly exploited source of stone materials, contributing significantly to the region's cultural and economic history.

The major geological formations of the area can be broadly categorized under an extended period of marine sedimentation followed by volcanic activity. Marine sedimentation produced several important stone typologies during the Mesozoic Era. The first being Rosso Ammonitico Veronese, a limestone characterized by the presence of some amounts of clay dating to 150 – 135 million years ago, followed in the Cretaceous period by Biancone, an almost pure calcium carbonate from 135 – 90 million years ago, due to an increase in sea depth. As the sea became shallower by the end of the Mesozoic, sedimentation shifted to Scaglia Rossa, a marly limestone high in clay from 90 – 55 million years ago, and then Euganean marl from 55 – 33 million years ago, a regionally specific marl, containing high amounts of clay (Astolfi and Colombara, 1990). These earlier deposits would be shifted and influenced by the following volcanic activity.

Interspersed between deposits of Euganean marl, the earliest phases of volcanic activity began around 43 million years ago through effusive eruption of magma undersaturated in silica, creating submarine deposits of volcanic basalt. These deposits alternated with those of Euganean marl until the major phase of volcanic activity. Around 35 to 30 million years ago an eruption of effusive magma occurred which was formed in magmatic chambers in the earth's crust over 10 million years. This process created a distribution in the silica content with higher percentages concentrating at the top of the chamber. The eventual emission of the chamber produced a viscous lava high in silica which created the primary hill formations visible today in the form of conical volcanic deposits, uplifted and deformed sedimentary layers, and sedimentary strata breakage across the surface of lava cones. As the chamber of magma emptied, its composition in terms of silica content changed producing rhyolitic, trachytic, latitic, basaltic lava and breccia deposits, forming the distinct volcanic geological diversity of the Colli Euganei (Astolfi and Colombara, 2018).

To understand the quarried areas surveyed in this project, the formative process of volcanic breccias is essential. Through a combination of explosive processes related to the eruption of magma, and the super cooled effects of the submarine location, a large amount of fragmentation of volcanic material and often older sedimentary rocks like Euganean marl occurred. Over time these discontinuous masses of primarily volcanic aggregates were cemented together by a matrix of fine-grained volcanic debris typically high in amorphous content, creating volcanic breccias whose composition ranges in the Colli Euganei across all the typologies of volcanic materials present (Sedea and Lallo, 1973). Often, strata of breccia are deposited in the higher levels of the volcanic domes while the lavas are found at lower levels where cooling rates were slower. The fine-grained matrix and amorphous content of the volcanic breccia deposits of the Colli Euganei make many deposits ideal for the production of pozzolanic aggregates.

Throughout the Neogene period, uplifting continued to expose volcanic and sedimentary strata and erosional and depositional processes slowly began shaping the volcanic domes of the region, exposing outcrops of geological diversity. Millions of years of fluvial and lacustrine deposits accumulated throughout the low-lying areas, increasing the geological diversity of the region. The Quaternary period added additional erosional and sedimentary processes influenced by glacial and inter glacial cycles. The erosion of this period and the decrease in sea level created the present landscape of isolated and interconnected volcanic hills (Piccoli et al, 1976).

The result of these processes is a region rich in geological diversity that reflects the enduring legacy of its complex geological history. This background is crucial for understanding the quarried areas surveyed in this project, particularly the formation and utilization of volcanic breccias and trachytic lavas, which played a significant role in the region's development.

1.4 Historical Background

The Colli Euganei, with its rich geological diversity, has been a significant site for human activity since the Middle Paleolithic period. Early inhabitants were drawn to the region's abundant natural resources, particularly flints for tool production. Over millennia, the area's unique stone typologies became highly sought after, evolving from the targeted extraction of raw materials in prehistoric times to extensive quarrying during the Roman period. This quarrying reached its peak with the exploitation of Euganean trachyte, essential for constructing Roman infrastructure across Northern Italy. The region's strategic importance continued through the Medieval and Renaissance periods, with its stone materials being extensively used in the burgeoning cities of Padua and Venice. Modern quarrying practices, marked by industrial-scale extraction, peaked in the 19th and 20th centuries, ultimately leading to significant environmental concerns and the establishment of the Parco Regionale dei Colli Euganei in 1989 to preserve this historically and culturally vital landscape.

1.4.1 Pre and Protohistoric Activity

Human activity within the region of the Colli Euganei began as early as the middle paleolithic period. The region’s rich diversity of natural raw materials, especially flints for construction of stone tools, topographic visibility, natural shelters, and access to water made it an ideal location for both settlement and resource collection (Peresani, 2013). Archaeological research in the area has uncovered multiple sites of settlement, some of which are Monti Venda, Madonna, Mural, Ceva, Cinto, Lozzo, and Versa (Peresani, 2001) and analysis of various lithic typologies found dispersed across in the regions of the Colli Euganei and the Monti Berici date throughout the proto and prehistoric period (Pellegati and Visentini, 1997) (Duches and Peresani, 2009). Thus, the region can be defined as both a settled and prominent location within northeastern Italy for stone material procurement, tool production, and regional exportation, with typological evidence of stone tools dating up until the Mesolithic (Peresani, 2013)

Numerous settlements in the vicinity of the Colli Euganei date from the Bronze age and through the Iron Age. In many cases, they are believed to have been continuously occupied. Of particular importance is the site of Este, where multiple excavations have been conducted documenting the settlement and funerary practices of the site during this period. Indicating a continuity of occupation from the Bronze age until incorporation into the Roman Republic (Bortolami et al., 2022; Meadows et al., 2014). At Este, provenance studies on trachyte inclusions within the matrix of ceramics identified several locations within the trachyte formations of the southwestern Colli Euganei as viable matches, indicating a selective utilization of stone resources from the region by surrounding communities (Maritan et al, 2005). Grindstones formed from Euganean trachyte and dating to the 7th to 5th centuries BCE have been documented as far east as Trieste (Bernardini, 2005). Paleo-Venetian funerary stelae from the same period are an additional example of trachyte preference (Antonelli et al., 2004). Both are indicators of the unique quality of this material in the region and the extent of exportation and trade of Euganean resources by the end of the Iron Age.

While the occupation, use, and exportation of resources in the Colli Euganei can be established throughout the prehistoric period, the extent of quarrying activities remains an open question. Major sites of prehistoric stone resource collection have not been identified. This could be due to a dispersed extraction of resources, difficulties in identifying prehistoric quarries, or a lack of focused research on the subject. More likely it is due to settlements of the prehistoric period being concentrated on waterfronts and made of timber, reducing the demand for constructional stone and therefore the establishment of heavily extracted quarries in the pre-roman period (Meadows et al., 2014). Regardless, the extent of quarrying activity during the prehistoric period does not compare to those that follow and is best summarized through the targeted extraction of flints and latter trachyte for use in the construction of artifacts without any impactful demand for constructional stone.

1.4.2 Roman Quarrying

Quarrying activities during the Roman period are well documented within the Colli Euganei thanks to the preference of trachyte materials for the construction of a wide variety of public and private roman infrastructure projects and artifacts. This is particularly evident in the case of aqueducts, forums, and bridges, where the compressive strength and resistance to erosion made trachyte an especially sought after material (Maritan et al., 2013; Previato et al., 2014). A great deal of attention has also been paid to several major roman roads like the *Via Flaminia* and *Via Aemilia* and their exploitation of Euganean trachyte (Capedri, Grandi, and Venturelli, 2003; Renzulli *et al*., 1999) In the case of Italian peninsula, the trachyte resources of the Colli Euganei are by far the predominant source and have been found at sites hundreds of kilometers away (Di Bella, 2012).

The trachyte sources within the Colli Euganei have variations in major and trace element compositions which has allowed researchers to perform provenance studies of samples to suspected quarry sites. This has produced a considerable amount of research both into the use of Euganean trachyte in the roman world and more importantly the provenance of trachyte to specific historic quarries within the Colli Euganei (Capedri, Venturelli, and Grandi, 2000; Capedri, Grandi, and Venturelli, 2003; Zara, 2016; Germinario, 2017; Germinario *et al.*, 2018a; Germinario *et al*, 2018b). In one analysis of constructional stone samples, the quarry sites of Monte Merlo, Monte Oliveto, Monselice, and Monte San Daniele were identified as the four primary quarry sites of trachyte extraction for the use in constructional stone, with only one sample whose chemical composition did not correlate (Germinario *et al*, 2018a). This aligns with previous provenance research analyzing around 500 samples of roman trachyte artifacts like milestones, querns, mortars, and gravestones which identified the quarry sites of Monselice, Monte Oliveto, and Monte Merlo as the primary sites of extraction to produce trachyte artifacts (Zara, 2016). The geographic distribution of these sites and their relatively even provenance across the samples, as well as multiple quarries typically being identified in sampled sites, gives insights into the management and transportation networks of Roman quarries in the Colli Euganei. Firstly, that quarry extraction appears to have been subdivided by regions which were in their vicinity and zone of control. Monselice trachyte was primarily utilized in *Ateste* but is mostly absent in constructional samples from *Patavium*, where Monte San Daniele and Monte Oliveto appear to have been preferred

(Germinario *et al*, 2018a). This division of the territory of the Colli Euganei is supported by the establishment of *cippi* during the Republican period by the Roman senate demarcating the territorial limits of the communities of *Ateste* and *Patavium* (Buonopane, 1992). Considering the economic importance of quarries in the roman world this is unsurprising. Secondly, of the infrastructure projects analyzed only a small minority were entirely composed from one quarry suggesting that the constructional demands relating to infrastructure projects in the region required the simultaneous extraction of materials from multiple sites at the same time or alternatively that local communities such as *Patavium* relied on intermediaries to secure the sale, transport, and storage of quarried materials (Germinario *et al*, 2018a).

These provenance studies also have provided indicators on the extent and methods of transportation of the stone resources of the Colli Euganei during the Roman period, especially from dateable samples ranging from the 1st century BCE to through the 1st century CE, the height of monumental public work construction in the Roman empire (Zara, 2016). Fluvial routes in the vicinity of the Colli Euganei like the Bacchiglione, Adige, and Brenta alongside connecting canals and drainages are argued as the most likely methods of stone material transport for inland needs while a series of Roman harbors across the Adriatic coast and the major rivers like the Po are believed to have facilitated the transportation to even more distant locations (figure 1). The use of these fluvial routes has been confirmed by a roman shipwreck in the Bacchiglione containing quarried stone and likely travelling to *Patavium* (Previato and Zara, 2014). A series of publications relating to this distribution, transportation, and the proposed geographic position of fluvial channels during Roman times has allowed the potential routes of transport to be proposed (Mozzi et al., 2010; Piovan et al., 2012; Stefani & Vincenzi, 2005; Stefani & Zuppiroli, 2010; Zara, 2016) whose proximity to the eastern Colli Euganei indicates that Roman trachyte quarries, which primarily are located it the most eastern and lower elevation portions of the volcanic formation, were selected based on their accessibility to Roman fluvial transportation routes (Germinario *et al*, 2017).

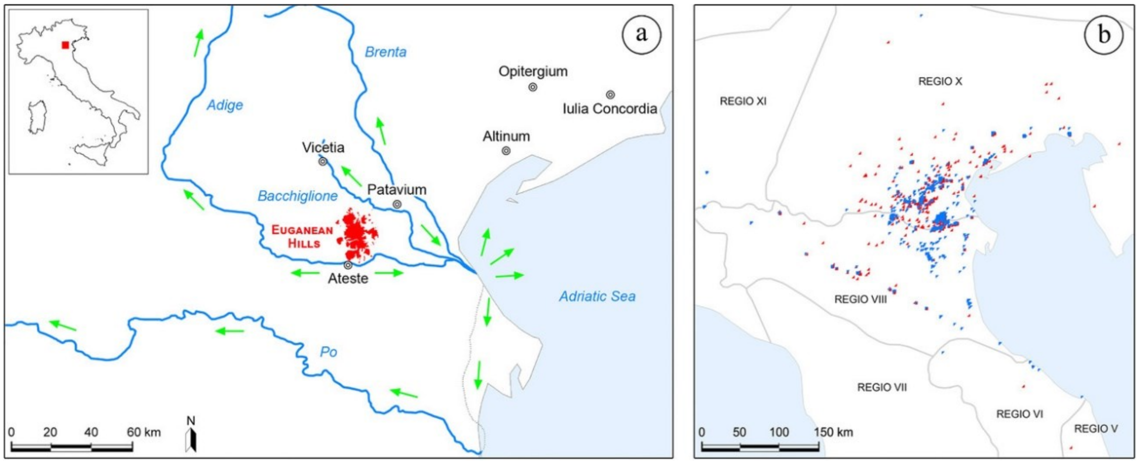


Figure 1 - *From (Germinario et al, 2018b) detailing compiled research of (Mozzi et al., 2010; Piovan et al., 2012; Stefani & Vincenzi, 2005; Stefani & Zuppiroli, 2010; Zara, 2016). A – Proposed locations and major fluvial routes during roman times and direction of transported quarried materials from the Colli Euganei. B – Distribution of known Colli Euganei trachyte from artifacts (red) and infrastructure works and structures (blue) across northern Italy (Regiones Augustee).*

The determination of the Monte Oliveto trachyte quarry as one of the most utilized Roman quarries in the Colli Euganei (Zara, 2016; Germinario *et al*, 2018a) has considerable implications on several of areas surveyed in this research. Monte Oliveto is in the immediate vicinity of areas one, four, five, and seven analyzed in this study (see chapter 3) and therefore it is a clear indicator that the quarries identified in this research are both geographically located in a region of well-established quarrying activities and accessible to fluvial routes of transport used during the Roman period.

While research on the distribution of breccia materials from the Colli Euganei in the Roman period has historically been limited in comparison to that of trachyte, recent provenance studies have been conducted with the aim of identifying samples of roman concrete to specific sites of extraction. The most important of these being a chemical composition analysis of samples collected from the Via Degli Scavi archaeological site in Montegrotto Terme using XRPD, SEM-EDS, and XRF methodology (Pilgrim, 2024). Some of these samples were conclusively matched based on their major and trace chemical composition to the Villa Draghi quarry site, a historic quarry complex identified and delineated through the high-resolution LiDAR data collected from this project's survey (see section 4.1). This is critical as it indicated the site quarried at a minimum from around the 1st to 2nd century CE (Pilgrim, 2024). This indicates that the Villa Draghi quarries, and presumably the wider region of breccia material surveyed in this project, were known locations utilized to produce *opus caementicium* at a minimum during this period. It also indicates the potential for more extensive mortars sampled from both roman archaeological sites located within the region of known trachyte distribution (figure 1) and from the numerous breccia quarries identified through our project's survey for quarry provenance studies.

The quarrying activities of the Colli Euganei during the Roman period which relate to this survey project are summarized as an extensive use of trachyte from the Colli Euganei highlighting the region's significant role in supplying durable construction materials for infrastructure projects across Northern Italy. The detailed provenance studies conducted have provided valuable insights into the specific quarry sites used and the transportation networks that facilitated the distribution of these materials. The findings underscore the strategic selection of quarry sites based on their proximity to fluvial routes, ensuring efficient transport of trachyte to various construction sites. Additionally, recent research on breccia materials, particularly in relation to Roman concrete production, further emphasizes the importance of the Colli Euganei as a vital resource area in the Roman world and validates multiple areas surveyed using high-resolution LiDAR in this research as ideal locations for the procurement of stone materials in the Roman period.

1.4.3 MEDIEVAL AND RENAISSANCE QUARRYING

The quarries of the Colli Euganei, particularly those of trachyte and to a lesser degree breccia, continued to be utilized throughout the Middle Ages, largely for the same reasons of the Roman period. The position of the hills in an increasingly populated region with relatively few formations with viable stone resources demanded its exploitation as a source for the growing population centers of Padova and Venice (Arnau, 2011). While relatively few articles have been published detailing research on specific quarrying sites during the medieval or Renaissance in comparison to the Roman period, the use of trachyte and other materials is well documented in a variety of constructional projects across Padova and Veneto as early as the 12^{th} century, and multiple historical sources cited the perceived quality and diversity of materials available in the Colli Euganei (Vergani, 1994). Additionally, the durability and slip resistance of trachyte saw it become a major resource in both cities during their mutual monumentalization during the Renaissance for the purposes of pavement stones known as *selici* or *masegni*. A wide variety of monumental structures were also constructed during these periods utilizing trachyte, including churches, fortresses, villas, walls, and bridges (Vergani, 1994). The Rialto Bridge in Venice is one example where increasingly elaborate architectural structures during the height of Venetian power employed trachyte for use as constructional stone.

For the purposes of this research, the key historical development during this period of interest is the system of Medieval canals and drainages which were constructed across much of the Po valley throughout the 11^{th} to 13^{th} centuries to facilitate trade and travel between surrounding communities with Venice and the larger Mediterranean as a whole. Near the Colli Euganei several of these, and their periods of construction, are important for understanding which regions and at what periods resources of the Colli Euganei could have been most extracted. The two most influential for the eastern Colli Euganei are the Bisatto canal which connected Vicenza to Este, Monselice, and Battaglia Terme and is dated to around 1139 CE, and the Battaglia Canal which connected the watercourses at Battaglia Terme to Padova around 1189-1201 CE for the purpose of transporting people, agricultural goods, and stone resources of the Colli Euganei (Aio, 2022). The relationship between Padova, Venice, and the Colli Euganei through this interconnected system of navigational canals continued well into the start of the 20^{th} century until automotive and train infrastructure surpassed it.

The quarrying of the hills for both trachyte and breccia materials was certainly extensive. Based on the dominance of trachyte usage in Padova and Venice as early at the 12^{th} century CE and the connection of fluvial routes during this period, it is reasonable to assume that many quarry sites belong to this period of extraction. Additionally, there is likely a relationship between quarries of this period and their ease of accessibility to navigational canals.

1.4.4 Modern Quarrying

The period of modern quarrying was characterized by the drastic increase in demand for stone materials, particularly trachyte, beginning in the second half of the 19^{th} century. Furthermore, the methods by which stone materials were extracted changed drastically. For millennia, quarry sites were primarily excavated by hand with the use of chisels, picks, and wedges. By the end of the 19^{th} century the use of dynamite to break large sections of quarry faces, together with the invention of the helical wire in the 20^{th} century allowed for quarries to become industrial enterprises. In the Colli Euganei, numerous quarries primarily of trachyte but also others of rhyolite, perlite, and limestone for use in the production of cement, were heavily exploited.

Quarries of this period are identifiable through their extreme size, the increased height of quarry faces, and large earthen access ramps.

By the second half of the 20th century the impact of the quarry activities on the environment, landscape, and cultural heritage of the Colli Euganei became so significant that in 1971 the law *Legge Regionale n. 11/1971* was passed, which forbade new licenses to be issued for the purposes of quarrying activities within the region and established a process for the closure of the remaining active quarry sites. In 1983 a census of the Colli Euganei documented a total of 170 quarries of which 18 were still active (6 of limestone material types and 12 of trachyte). Eventually these activities were phased out entirely except for limited quarrying at select sites for the purposes of historical restoration projects.

The region as we know it today began with the formation of the Parco Regionale dei Colli Euganei in 1989, a regional park encompassing 18,000 hectares of the Colli Euganei which established protections for the natural landscape, environment, and cultural heritage of the region. This has marked a drastic change in the use of the land, which consistently had been a critical source of stone materials in northeastern Italy for several thousand years to a region now celebrated for its biodiversity, natural beauty, history, and tourism.

Chapter 2: Survey Methodology

The following sections describe the various decisions and processes undertaken regarding the LiDAR and Orthophoto data collected and processed as part of this research, to accurately depict the methodology utilized. The sections describe the reasoning behind which areas were selected for UAV survey, under what parameters the data were acquired, how the data were processed, and how ground truthing field surveys were conducted.

2.1 Survey Area Selection

The UAV project was designed with the initial intention of providing high resolution DEMs (Digital Elevation Models) of an achievable sized portion of the Colli Euganei. When areas were determined for selection, there were three primary factors which influenced the decision making. Firstly, that the survey areas should be in the eastern portion of the Colli Euganei formation to investigate the relationship between the quarried materials of the Colli Euganei and their historical usage across archaeological sites in the region of Padova. Secondly, to investigate geological portions of the hills rich in breccia stone materials. While the quarried history of the trachyte resources of the Colli Euganei have received a wide variety of publications, research projects, and archaeological research (Capedri, Venturelli, & Grandi, 2000; Zara, 2016; Germinario et al. 2018a; Germinario et al., 2018b) there are a plethora of other materials found within this diverse geological region which were also extracted in historic and modern times, which have received less attention by comparison. In particular, this is the case of the regions of breccia stone materials. Lastly, publicly available LiDAR data at 1-meter resolution provided by the Ministero dell'Ambiente e della Tutela del Territorio e del Mare was reviewed to broadly identify quarry features in areas of interest based on the previous parameters. The DEMs provided by this data are valuable but lack the clarity at 1-meter resolution to identify moderate and small sized quarry features effectively. Additionally, larger features which are visible are pixelated and often their DEMs cannot provide detailed information on a quarry feature's morphology. The evaluation of these data indicated which of the potential regions of research required, or at least would benefit from, a higher resolution LiDAR data collection.

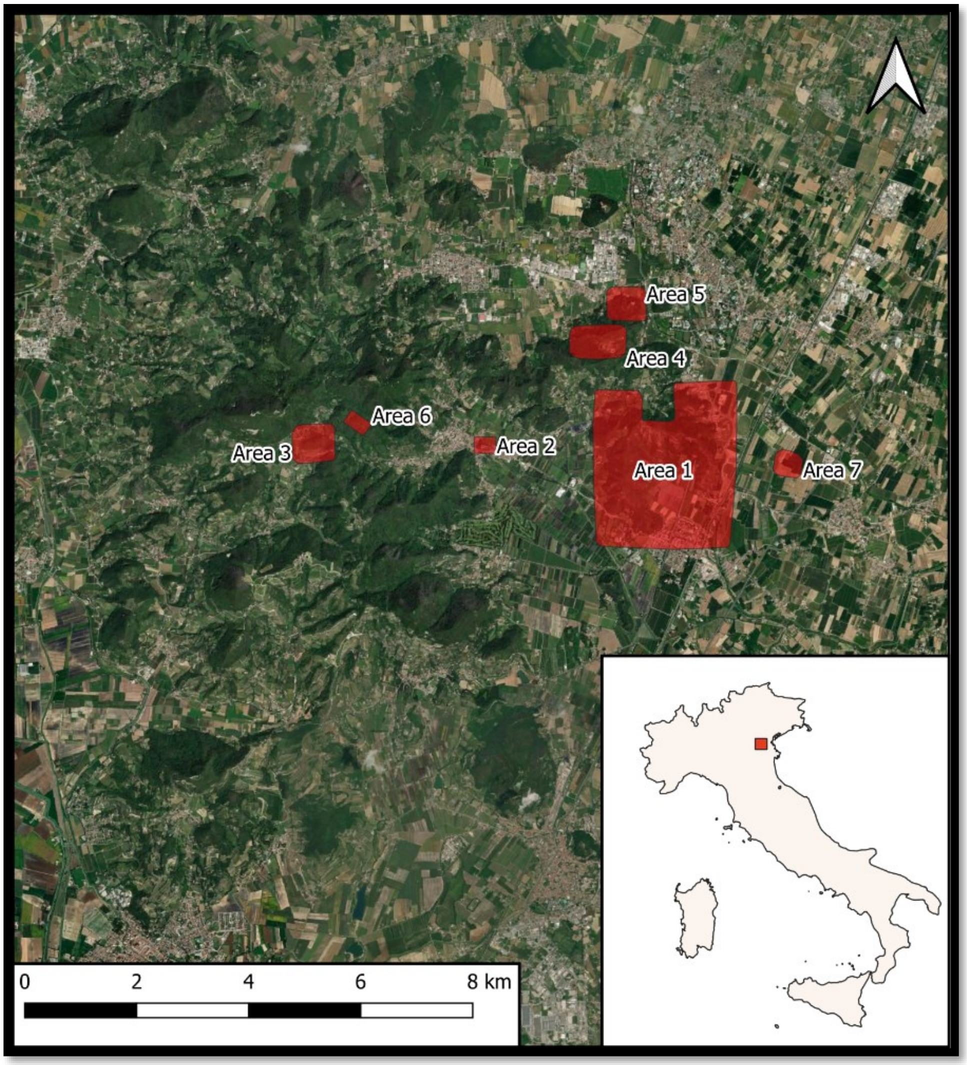


Figure 2 – ESRI satellite imagery map of the Colli Euganei depicting the seven regions dispersed across the central and east central regions of the hills surveyed through UAV LiDAR and Orthophotography

Based on these criteria seven separate areas of investigation were selected to receive a higher resolution UAV LiDAR and orthophotography survey. These survey areas are located throughout the central eastern and central portions of the Colli Euganei, with most of the areas surveyed being in the hillside terrains between the communities of Galzignano Terme, Battaglia Terme, and Montegrotto Terme (figure 2).

2.2 UAV Data Acquisition

The UAV survey conducted by Archetipo srl utilized sophisticated drone technology to capture detailed topographical data of the quarry features in the Colli Euganei region. The survey took place over multiple days between February and March of 2023, with flights conducted on 14th and 23rd February, as well as 3rd, 7th, 9th, 10th, 15th, 16th, and 28th March, for a total of 34 flights. Each flight adhered to the necessary regulatory constraints, such as maintaining a visual line of sight with the drone. This constraint, as well as the flight duration limits of the drone's battery life, which typically allowed for 40-50 minutes per flight, influenced the total number of flights required.

The UAV used in the survey was the DJI Matrice 300 RTK, a highly versatile drone known for its robust design and precision. The drone is listed at an approximate weight with two TB60 batteries at 6.3 kg, with a payload capacity of 2.7 kg. With RTK (Real-Time Kinematic) capabilities, this drone provided highly accurate geospatial data essential for mapping and analysis. Its RTK system enabled high-precision navigation, which was valuable for ensuring consistency across the multiple flights. The vertical flight accuracy in RTK mode is rated at ±0.1 meters, while the horizontal accuracy is ±0.1 meters, making it suitable for the detailed survey requirements in complex terrain.

The survey utilized two primary sensors, the DJI L1 LiDAR sensor and the Zenmuse P1 camera. The L1 LiDAR sensor, with a detection range of 450 meters and a point return rate of up to 480,000 points per second, enabled detailed terrain mapping with real-time colorization of point clouds based on reflectivity, real color, and elevation. It is rated at first return system horizontal and vertical accuracy of ±10cm and ±5cm at 50m in altitude. The Zenmuse P1 camera, featuring a 45 MP full-frame sensor, can capture high-resolution imagery with a Ground Sampling Distance (GSD) of 3 cm, and can achieve an absolute accuracy of 3 cm horizontally and 5 cm vertically under optimal flight conditions.

Flights were performed at a constant altitude of 90 meters above ground level and a speed of 7.5 m/s, ensuring consistent data collection. The flight plan incorporated 40% overlap between transects, balancing comprehensive coverage with operational efficiency. GNSS accuracy was ensured by utilizing the drone's RTK system in Network Real-Time Kinematic (nRTK) mode, connected to ItalPoS stations, resulting in precise positioning with ±0.1 m horizontal and vertical accuracy. By utilizing nRTK positioning the survey did not require the use of ground control points (GCP), a more accurate positioning method that would have required more resources, planning, and time to produce, allowing the surveys to be completed in a reasonable timeframe. This advanced UAV system, coupled with high-precision sensors and meticulous flight planning, facilitated the collection of accurate, high-resolution geospatial data over the survey period.

2.3 LiDAR Data Processing

2.3.1 Point Cloud Processing

The data processing of UAV LiDAR data began with the acquisition of survey data and the generation of raw point clouds using DJI Terra software. This initial step focused solely on building the point cloud without applying any further processing or classification. Following the creation of the raw point cloud, several software platforms were evaluated for processing, including Spatix and CloudCompare. However, TerraScan was ultimately selected due to its advanced automated capabilities, which provide efficient management and processing of LiDAR point clouds. TerraScan offers a variety of classification routines that enable the automatic filtering and classification of point clouds, making it the preferred tool for this project.

The processing workflow began with noise filtering and statistical outlier removal to enhance the accuracy of the point cloud. TerraScan's "Ground Macro" classification tool was then employed to identify ground points. While TerraScan offers user-adjustable settings, the default configuration was deemed adequate for this project. The results of TerraScan's classification were compared with manual classification performed using CloudCompare. Although CloudCompare was effective in classifying a substantial portion of the ground points, it encountered difficulties in areas with dense vegetation, leading to less accurate results. In contrast, TerraScan's automated classification produced more consistent and homogeneous ground point data. Minor errors were observed in specific locations, such as a modern terrace boundary at Monte Mussato in Survey Area 2, but overall, the automated classification provided a higher degree of accuracy for generating digital terrain models.

Following classification, digital terrain models were produced with resolutions of 0.5-meter, 0.25-meter, and 0.2-meter cell sizes. Any gaps in the data were filled using a standardized nearest neighbor interpolation method. While the interpolation increased as the resolution became finer, it was mostly concentrated in areas that already required interpolation at lower resolutions. The difference in resolution between the 0.2-meter and 0.5-meter cell sizes was significant, with the higher resolution providing a more detailed representation of the terrain.

The calculation of ground point density was complex, as it was influenced by factors such as vegetation cover, terrain characteristics, and the number of points collected during each flight. Despite these challenges, the average ground point density ranged from 21 to 49 points per square meter, equivalent to 0.82 to 1.95 points per 0.2-meter cell. Although this density is lower than what has been produced by some other UAV archaeological surveys in forested environments (Poirier, Baleux, Calastrenc, 2020) it is considered high resolution given the scope of the survey, which covered more than 8.5 square kilometers. The primary focus of the research was to document quarries with distinct elevation changes, and the resolution was more than adequate for capturing these features with limited interpolation.

In conclusion, the use of TerraScan's automated classification routines facilitated the efficient processing of UAV LiDAR data, allowing for the creation of accurate digital terrain models across a large landscape. The data processing approach succeeded in documenting key features with remarkably high resolution and sufficient ground point density, balancing the need for detail with the challenges of large-area surveying.

2.3.2 DTM Visualization

Raster data sets were visualized and investigated using the open-source mapping and spatial analysis software QGIS v. 3.34. The benefit of this application, or those similar to it like ArcGIS, is the availability of a suite of tools and programs preinstalled or developed through third parties available for download as plugins, which allow for incredible variability in the spatial analysis capabilities, data integration and management, advanced visualization of datasets, customized scripting, and geostatistical analysis (Lock, 2003; Ebert, 2004; Conolly and Lake, 2006). Due to these benefits, these programs are often utilized in the fields of geography, geology, urban planning, environmental science, and archaeology.

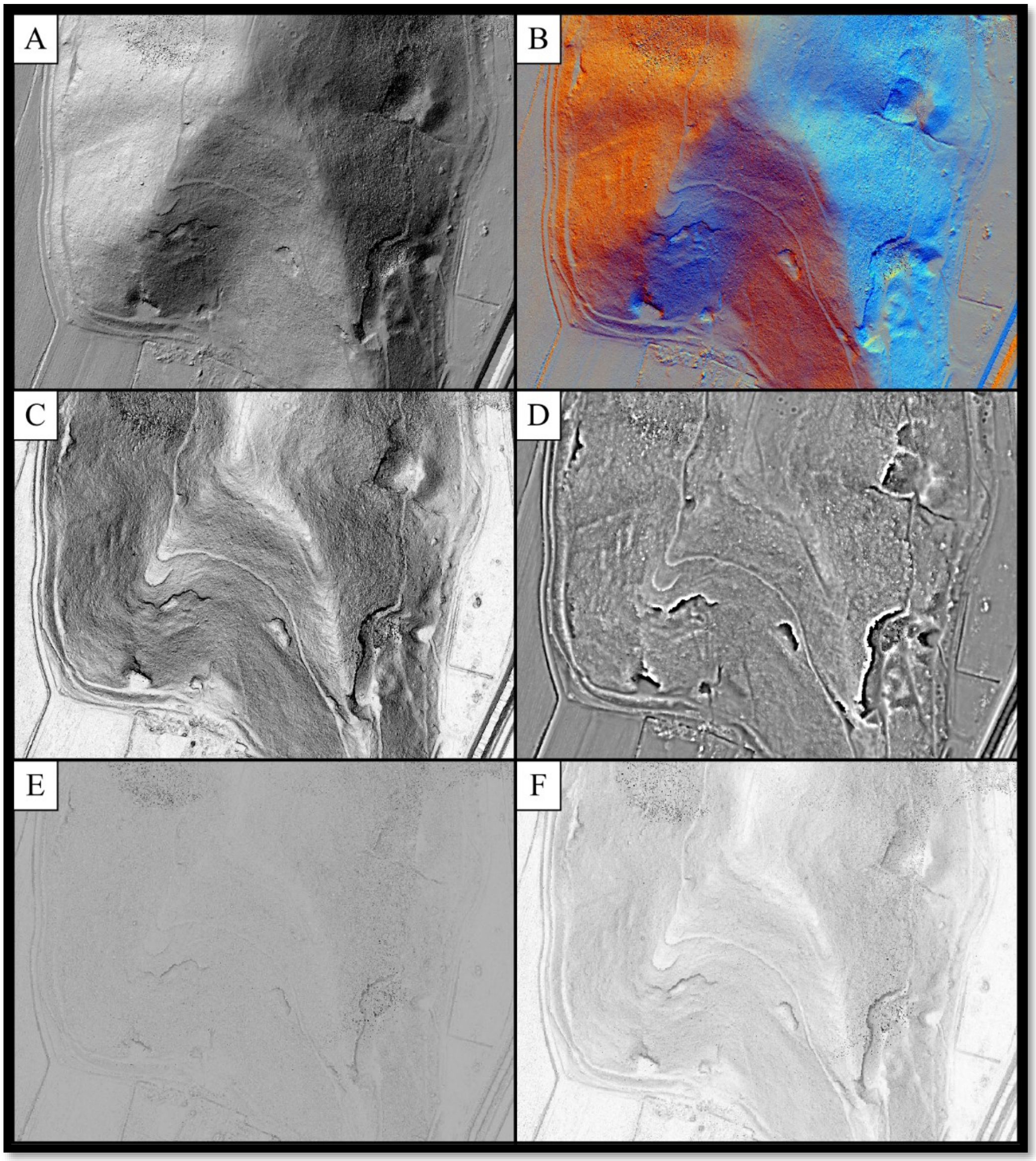


Figure 3 – Various methods utilized to examine DTM rasters of the survey areas with a portion of the hill formation just north of Catajo Castle visualized where several potential quarry features are visible. A – single direction hillshade model (Azimuth 315, Elevation degree 35). B – multi directional hillshade model (16 directions at elevation degree 35). C – Slope gradient. D – SLRM. E – Openness Positive. F – SVF. Note that each methods' effectiveness is influenced both on the characteristics of the feature and that of the surrounding landscape.

An additional open-source software, the Relief Visualization Toolbox (RTV v. 2.2.1), was used to produce standardized visualizations of topographic characteristics of each of the survey areas investigated (figure 3). RTV allows for a raster file to be input and series of visualizations and constraints, or settings to be selected to produce a variety of visualizations as additional raster files. Each typology of visualization selects different parameters of the base raster DTM file elevation data and provides extrapolated images. The visualizations utilized for this project, and those which are primarily employed for the identification and visualization of archaeological features (Kokalj, Zakšek, and Oštir, 2013) were Sky-View Factor (SVF), Openness – Positive, Simple Local Relief Model (SLRM), Slope gradient, and single and multiple Analytical hillshading. SVF is a measure of the amount a point is visible to the sky, and it is used in archaeology for visualizing features which interrupt this line of sight (Kokalj, Zakšek, and Oštir, 2011). Openness – Positive measures the amount of visibility a point has to the horizon, making it particularly useful in landscape archaeology to highlight elevated prominent features (Doneus, 2013). Both methods were produced through sixteen searched directions with a radius of ten pixels. SLRM allows for small topographic variations to be highlighted by a smoothing of a DEM evaluated against the original. This is particularly useful in identifying archaeological features in landscape with varied topography (Hesse, 2010). A radius of twenty pixels was applied for trend assessment. Slope gradient is simply a measure of the elevation change between a pixel and its surroundings and has obvious applications in measuring anthropogenic topographic variabilities. These visualizations, alongside the original DTM rasters, were utilized for the analysis of potential quarry features.

2.3.3 Orthomosaic production

The additional source of data collected through the UAV surveys, simultaneously with the LiDAR acquisition, were several hundreds of vertical photographs capturing the survey area. This allowed for the creation of high resolution orthophotography images as a supplementary source of data to evaluate the regions and potential quarried sites. An orthophoto is essentially a large, high resolution, aerial photograph which has been orthorectified (geometrically corrected to account for distortions of topography, camera angles, or anomalies), and therefore provides an accurate representation of distance and scale. This is done through the processing and compilation of multiple photographs to select for only the vertical representation of the terrain. Orthophotography is applied to archaeological investigations for the purposes of site documentation, management, visualization, and integration with geographical information system mapping.

This project utilized the software Metashape v.1.8.5, a software developed by Agisoft specifically for the processing of image data for photogrammetry, 3D models, and georeferencing. Aerial survey photos were processed in continuous “chunks” through a multistep process beginning with photo alignment with the project ESPG: 7791 coordinate system to produce a sparse point cloud. Standard parameters were applied for areas with dense vegetation such as 40,000 tie points, excluded stationary points, guided image matching, and adaptive camera model fitting. Noise points were selected and removed followed by the production of a dense point cloud with moderate depth filtering, a less time-consuming process typical for landscape analysis. Points were filtered by confidence and a compact dense cloud produced. From these, a DEM was produced and an orthomosaic built using that as its surface with hole filling and ghosting filter enabled. Finally, the orthomosaics were exported into TIFF files at both 2cm and 5cm resolutions. While the 2cm resolution was more detailed, the files were excessively large and necessitating less demanding orthomosaics for landscape analysis in QGIS.

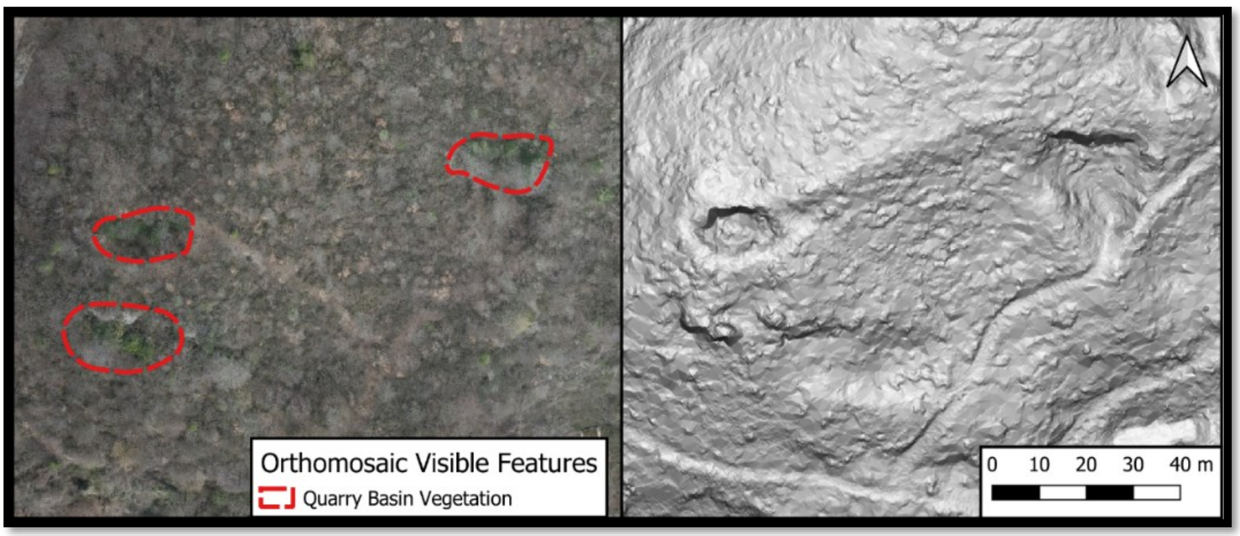


Figure 4 – Comparison of 5cm resolution orthomosaic results (left) and 0.2m resolution Slope DTM (right) of a western portion of Monte Marco in survey area 3 depicting QF 3.01 and 3.02. Note that the quarry faces and depressions visible in the slope map have easily visible differences in vegetation in the orthomosaic. 1:500 scale

These datasets were beneficial in their ability to depict the extent of vegetation and coverage for each quarry site at the time of the UAV survey, providing some context as to why, or why not, point cloud density may have decreased in specific portions or periods of the survey project. Additionally, the unique topographic depression of many large and small quarries has an influence in some locations on plant species due to variations in drainage or sunlight with the surrounding landscape (Bétard, 2013). In some cases, potential quarry sites had visible differences in their vegetation, a marker tool for future remote sensing projects in the Colli Euganei (figure 4).

However, the dense ground vegetation, particularly in the form of non-deciduous brush and overhead tree canopy dominate the visual data collected. Limited photographic data was produced that added to the understanding of quarry sites, except in the case of limited or nonexistent ground vegetation and forest canopies.

2.4 Quarry Feature Identification

The methodology for determining which features on the landscape were potential quarry features and which were natural formations was both quantitative and qualitative. In most cases, reviewing a combination of the DTM visualization that were produced (section 2.3.2) allowed for features to be easily differentiated from their immediate surrounding landscape. This is due to the fact the quarry morphologies are negative cuts in the landscape which create sudden and prominent topographic variabilities, allowing for visualizations of SVF, SLRM, slope, and hillshade models to depict the locations with clear variations in values. Often quarry faces, platforms, debris piles, access routes, ramps, or depressions were visible allowing for quarries to be both identified and a theoretical limit of the quarried area to be distinguished from the neighboring natural hillsides. This was particularly true for large, steeply sloped features.

Smaller features, those whose primary quarry face was only several meters long, required a standard to be established to both limit the possibility of error and allow for research to be focused on sites which had greater anthropological influence on the historical resource extraction of the region. However, several quarry features were identified which could be considered limited use extraction sites. These were selected based on a qualitative analysis of visibility in SVF, SLRM, slope, and hillshade models followed by a threshold of slope and exposed quarry face height using QGIS. If a portion of the quarry face had a slope of at least 66 degrees and change in elevation greater than 1.5 meters, and the collected ground points for the region allowed for the DTM to have limited interpolation, then the feature was selected as a potential quarry site.

2.5 Field Survey

For the purposes of feature documentation and ground truthing results obtained from the LiDAR data, a series of field surveys were conducted at the potential quarry features. These primarily occurred from January through March 2024. Features were located using a combination of GPS coordinates and georeferenced maps produced through QGIS and visualized on the mobile application QField. Upon arriving at a potential quarry site, the immediate vicinity was navigated to identify the extent and visibility of the quarry. In field documentation of quarries was standardized using quarry survey feature forms (appendix A7), which were subdivided for surveyors to broadly describe the contexts of the location of the quarry feature, the morphology, and physical characteristics of the quarry, and briefly summarize the stone material typologies found at the location.

A series of photographs collected on digital cameras or personal cell phones were collected highlighting the general location, the quarry faces, surrounding debris related to quarrying activities, and any physical evidence of quarrying such as tool marks on the quarry surface. In the case that quarries were densely covered in vegetation, bio colonization, or highly eroded through weathering, photographs were also collected. In most cases, geological samples were taken, with their location collected using a Garmin GPS device for the purposes of geological and mineralogical analysis of the material. However, this analysis is still in progress and laboratory analysis of material results were not available to provide a more specific context to geological variabilities between quarries with similar material types. The exception to this being several samples taken from the Villa Draghi quarry site.

In total, 30 potential quarries or areas of interest were investigated at the date of this work, with the expectation that many of the remaining features identified from the high-resolution LiDAR data will be investigated soon. Of these, more than 83% related to quarrying activities based on the presence of quarry faces and associated features like debris filled basins and scattered boulders of the same material type. The sites which were not confirmed as quarry features either were only partially acceptable to begin with based on the DEM selection methods employed on QGIS (see section 2.4). However, in all cases but one, the primary reason for failure to identify a quarry feature was dense vegetation or extensive soil deposition on the investigated slope, suggesting that in some of these cases the quarry morphology in the DEMs may be true, but unconfirmable without further research.

Chapter 3: Results

This chapter is designed to present the landscape, natural features, and anthropic features which are identifiable and measurable in the high-resolution LiDAR or orthophotography data acquired from the UAV survey and data processing. Each region of survey, a total of seven covering around 8.5 square kilometers of terrain, is described based on its location, general landscape, and associated features. In each case, features unrelated to quarrying activities, but which were identified through the high-resolution topographic data collected, are also described to fully depict the range of information the survey provides across the landscape.

Following the overview, all features identified within each region as potential quarry sites are presented, alongside visualizations of the landscape and quarry features and descriptions of their physical and morphological characteristics. The overall distribution across the landscape, size classifications, material types, morphology, and other standard topographic characteristics are discussed to summarize the data provided in each of the survey areas. A statistical analysis of potential correlations of the spatial attributes of 50 quarry features distributed across the most cohesive region, area 1, is presented to assess to what degree the quarries can be differentiated from remote sensing.

3.1 Survey Area 1: Battaglia Terme to Via Scagliara

Of all seven separate areas where UAV surveys were conducted, area 1 is by far the most comprehensive region. It extends across most of the major hill formations between Battaglia Terme and those south of Monte Oliveto and substantial portions of the surrounding low-lying plains, fields, and villages. The total area of high-resolution LiDAR data is about 664 hectares, more than 77% of the total area surveyed. This is the most extensive and cohesive representation of the quarrying landscape of the Colli Euganei.

The area is an essential region for the study of breccia materials found within the eastern Colli Euganei, comprising most of the breccia material types according to the available geological survey data (Bellati et al, 1976). However, multiple modern period trachyte quarries are also found in the region. The most notable is the massive Parco ex Cava beneath Monte Croce, on the outskirts of Battaglia Terme, which was excluded from analysis due to its extreme size and recent exploitation.

The landscape is well represented across the DEM which encompasses the major formations of this region. Specifically, the hills of Catajo Castle in the southeast, Montenuovo to the northeast, the southern slope of Monte Ceva to in the north central portion, Monte Castellone and the Via Scagliara quarry site (see chapter 4) to the northwest, and finally the entirety of the Monte Spinefrasse and Monte Croce hill systems as well as large portions of the plains in between.

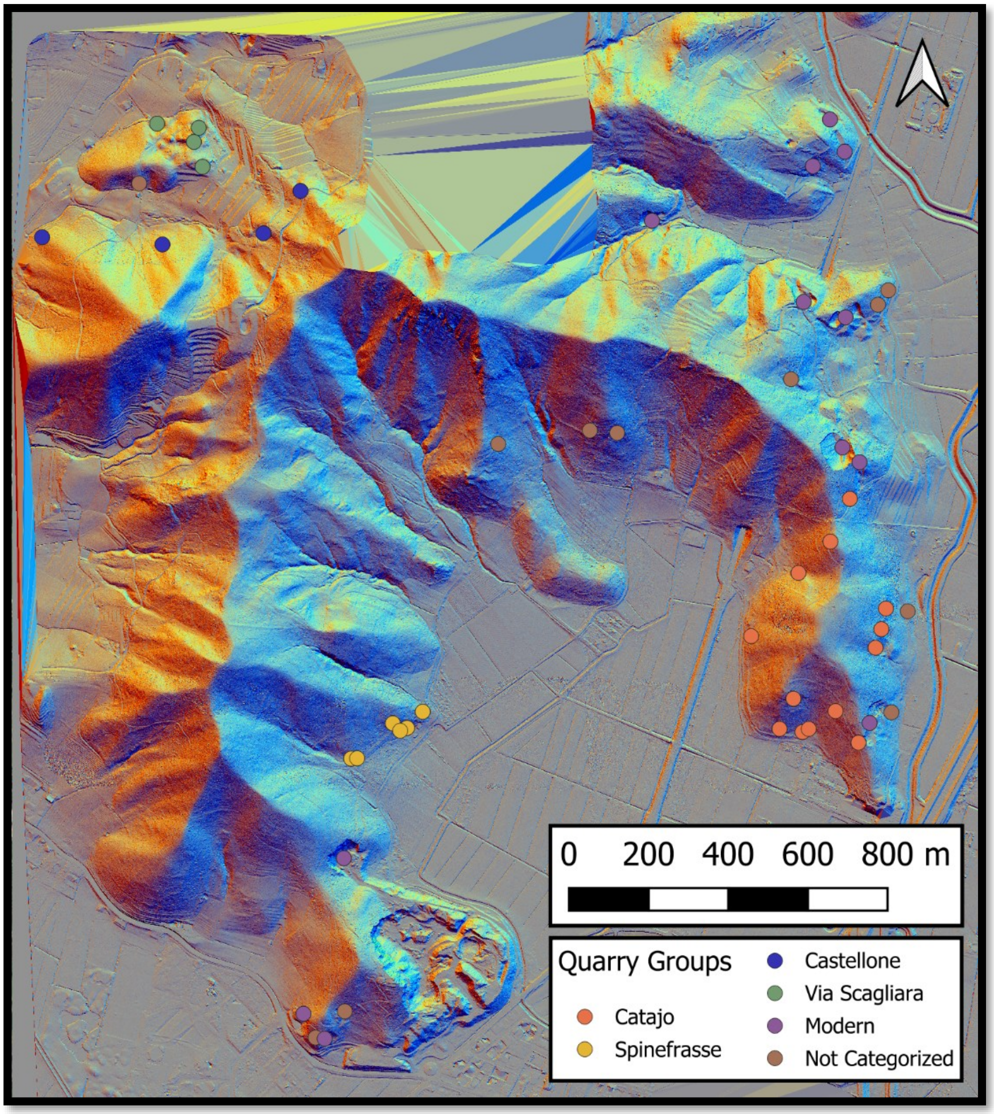


Figure 5 - multi-hillshade map of Area 1 quarries categorized in groups based on location and shared attributes.

3.1.1 ASSOCIATED FEATURES

In the plains, despite being of a secondary interest to the goals of the research, precise data on the location as well as the width and slope of several canals is visible. Many other expected features such as roads, smaller water management canals, and even the orientation and elevation of plow marks are also visible. While valuable, this data is unrelated to the research goals of this project except for the major canals. Across much of the easternmost side of the area 1 DEM the Battaglia Canal, the Rialto drain, the Bisatto Canal, and their convergence near Catajo Castle are visible. This is of particular interest as these watercourses were constructed from 12th century CE and their usage is directly tied to the exploitation and transport of stone materials quarried from the Colli Euganei (Aio, 2022). The data gathered from the plains surrounding the quarried hillsides allows for a clear determination on the size and position of presently existing canals and drains, roads, buildings, and the topographic manipulation of agricultural fields surrounding or encroaching on nearly all the hills' base slopes.

Within the terrain of the hills themselves several notable anthropogenic features unrelated to quarrying activities were identified through the high-resolution LiDAR data that were previously undetected. The most prominent of these are a series of craters formed from aerial bombings that are spread throughout the region of Montenuovo. In total 32 features were identified that have the morphological characteristics of craters formed from bombings. They are approximately 7 meters wide and 1 meter deep, however there is some variability in size. The majority are located on the northern and southern slopes of Montenuovo, near either entrance of the Venice – Bologna train line tunnel (figure 6). While unrelated to the objectives of this research, their visibility highlights the quality of the data gathered through the high-resolution LiDAR survey and the data may be of interest to future research dedicated to this period of conflict in Veneto.

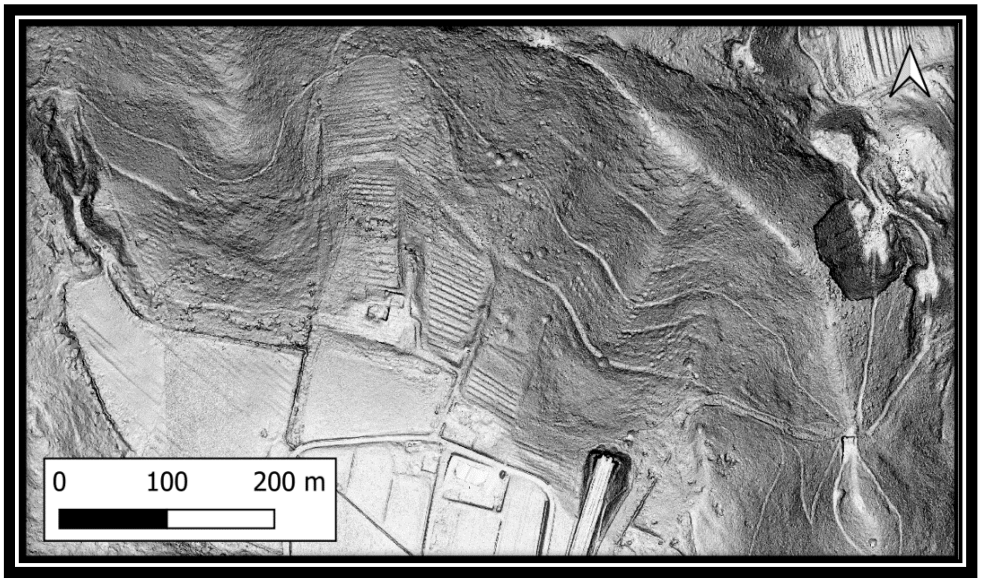


Figure 6 - Slope Map visualizing several clusters of bomb craters in the vicinity of the train tunnel on the south slope of Montenuovo and to the left an extensive series of agricultural terraces, now abandoned and obscured by tree coverage

Most of the human influence on the landscape that is distinguishable in the data, aside from quarrying activities, is agricultural. Much of the research area, especially at the lower slopes of the hills, have some form of terracing cutting into and reshaping the natural slopes of the hills (figure 6). In some cases, the usage can be hypothesized either by the presence of subtle undulations in the topography indicating uniformed rowed planting, possibly for vineyards, or in other case equally spaced, slightly raised, spherical features planted in a homogenous area along a slope, indicating an orchard.

Additional anthropogenic features across the hills of this area are primarily those of expected typologies in a continuously occupied and agriculturally utilized region. Trails, roads, and footpaths are clearly visible across the entirety of the surveyed hills, providing some information on the historical routes of access local inhabitants may have utilized to traverse the area. In some cases, these paths can be associated with the hypothetical routes of access for extracting quarried materials and in the case of more modern quarry sites wide, leveled roads are clearly distinguishable from the surrounding landscape, often built on large amounts of deposited materials to create an artificial slope or ramp to access quarried areas. This variety in anthropogenic features detectable in the region, while not strictly beneficial to the objectives of this research, showcases broad research application potential of high-resolution LiDAR surveys.

3.1.2 Quarry Features

This surveyed region contains most of the quarry features identified through the high-resolution LiDAR data. In total 50 quarry features were selected based on their visible characteristics. The majority being listed by single features and a small minority of quarry feature sites containing multiple near continuous quarry faces to better represent their supposed context. Of these features, a minority were investigated as part of ongoing field surveys in which photos, field descriptions, and evidence of quarrying activity were documented and geological samples collected. As this region was the largest continuous area of the UAV survey, it was chosen as the ideal sample set for analysis on spatial attributes of each potential quarry site and their relationships to each other and the landscape (see section 3.10). The attributes collected were those readily available and distinguishable through the collected elevation data, including hypothesized volume, primary quarry face morphology and sizes, proposed quarry typology, original slope, and distance to historical navigational canals (appendix A1 and A2).

The most easily distinguishable grouping is the modern quarries, of which 12 sites were differentiated (figure 5; appendix A3-A6). These quarries tend to have similar characteristics to each other making them easily distinguishable from premodern quarries excavated before the industrial revolution. In the Colli Euganei, these traits appear in the form of drastic differences in the physical attributes, especially those of area and hypothetical volume (table 1). Secondary features related to the quarrying activities are typically highly visible with limited erosion due to their age in the form of continuous access routes, large earthen ramps, and level platform extensions off the natural hill slope (QF 1.06 is the primary exception, showing eroded and poorly visible access routes). Many spatial attributes are indicators such as interpolated volume where the largest of the sites was measured at nearly 64,000 cubic meters. Secondary features related to the quarrying activities are typically highly visible with limited erosion due to their age. Continuous access routes, large earthen ramps, and level platform extensions off the natural hill slope are all indicators of modern activity. Many were composed of large irregular concave features with limited linear portions. The peaks of these quarry faces also tend to be composed of repetitive concave sections measuring approximately 3 to 8 meters wide, a trait absent from the remaining quarry features, representing a characteristic attribute of industrialized quarrying methods. Ultimately, these assertions and the characteristics of the sites need to be evaluated in future field research.

QF ID	Quarry Face Length (m)	Quarry Face Max Height (m)	Original Hill Slope (%)	Max Elevation (m)	Area (m^2)	Volume (m^3)
1.06	178.4	10.1	41.2	51.5	2217.5	11766.6
1.14	112	7.2	52.6	86.5	1403.5	6608.9
1.15	261.9	9.5	54.8	113.1	5847.6	63990.8
1.17	278	17.5	43.9	61.9	2385.4	18696.8
1.20	157.3	21.5	61.9	81.2	3478.6	39972.3
1.22	251.6	13.5	45.9	69.5	3404.5	23163.0
1.23	52.2	4.4	47.8	48.7	1424	3076.4
1.24	194.7	13.1	48.9	48.7	2454.3	8522.7
1.25	87.5	14	59.9	34.8	1202.6	5781.6
1.34	215.1	11.8	38.4	59.7	5604.7	60353.1
1.36	57	9.3	45.4	36.8	1004.3	3871.7
1.38	71.8	10.6	46.1	36.3	1816.1	9305.4

Table 1 - Quarry features in Area 1 designated as modern based on physical attributes. For a complete table of all measured attributes see appendix A1 and A2

Of the perceived premodern quarries detected in area 1, four groups comprising a total of 26 quarry sites were created based on shared characteristics in form, physical attributes, and their vicinity to each other (appendix A1 and A2). These groups were the quarries of the Catajo castle region, the Via Scagliara quarries (see section 4.2), four on the northern slope of Monte Castellone, and six on the eastern slope of Monte Spinefrasse (figure 5; appendix A3-A6**)**. The remaining quarries were not categorized, but further research is likely to reveal relationships to neighboring quarries. These groupings are based on a qualitative analysis of the spatial distribution, approximate size, morphology, and typology of the quarries. This subdivision serves as a tool for the analysis of these quarries in their respective landscapes.

The Catajo Castle cluster is the largest with 13 quarry features around the hill formation, descending from Montenuovo in the north and descending toward Catajo Castle to the south (figure 5; appendix A3-A6**)**. The majority of these are located on the eastern and southern sides of the hill and are characterized by their tendencies to be excavated along the natural contours of their respective slopes creating a variety of concave, convex, and linear quarry face morphologies with limited depth of excavation into the actual slope of the hill (table 2). A small number of quarry features in this region were excluded due to characteristics suggesting possible modern influence. The quantity and even distribution of these features may indicate that many are from the same period of extraction and based on their proximity to Catajo Castle and the navigational canals one hypothesis is that they date from the 12th century onwards (Aio, 2022). This is an assumption which should be evaluated by field and provenance analysis.

QF ID	Max Elevation (m)	Quarry Face Length (m)	Area (m^2)	Volume (m^3)	Morphology	Typology
1.01	26.9	38.1	629.3	1517.7	Linear	Open Pit
1.02	23.8	41.1	137.9	99.6	Semi-circular	Open Pit
1.03	53.1	66.2	484	764.6	Linear	Slope Quarry
1.04	51.2	46.8	406	693	Linear	Open Pit
1.05	48.9	46	199.4	237.7	Linear	Open Pit
1.08	24	50.9	327.9	349.2	Irregular	Open Pit
1.09	49.7	40.5	1347	6743	Linear	Open Pit
1.10	48	27.1	389.1	438.2	Concave	Open Pit
1.11	42.8	43.5	333.8	597.3	Irregular	Slope Quarry
1.13	86.6	19	122.8	145.6	Concave	Open Pit
1.21	41.3	15.3	75.3	70.2	Linear	Open pit
1.14.1	72.6	20.6	150.1	127.3	Linear	Open Pit
1.02.1	19.9	42.9	68.9	26.3	Linear	Trench

Table 2 - Catajo grouped quarries with attributes. For a complete list of measured attributes see appendix A1 and A2

The other three groups were selected for similar reasons, each indicating that their inter relationships are indicators of a shared quarrying activity (appendix A1 and A2). The Monte Spinefrasse group contains six quarry features in the direct vicinity of each other and isolated from the rest of the quarrying activity in the region, all except one of relatively small size, suggesting a limited but cohesive period of extraction. The four quarries of the Monte Castellone group are nearly equally distant, isolated, on the same geological formation, and most importantly have similar access routes, quarry face heights, and maximum elevations. This indicates a potential for being quarried in the same period with similar methods, likely close to the modern period based on the high visibility of their access routes. Lastly, the Via Scagliara quarries, examined here under four quarry sites, show obvious signs of an organized and extensive period of interconnected quarrying activities between the sites (section 4.2).

3.2 Survey Area 2: Monte Mussato

Survey Area 2 was a minor addition to the UAV survey at only 11.4 hectares. It is located within the town of Galzignano Terme and encompasses Monte Mussato, a small, isolated hill roughly 30 meters higher than the surrounding plain the town is built on. Most of its ridge has been incorporated into the driveway, walls, and structures of a now abandoned hotel. It was selected to be surveyed because of its position within the surrounding town, the irregular concaved slope morphology of Monte Mussato, and its expected geological composition of rhyolitic breccia formed through the explosion of diatreme necks (Bellati, 1976). This is a unique geological formation in comparison to the surrounding hills composed of rhyolitic lava.

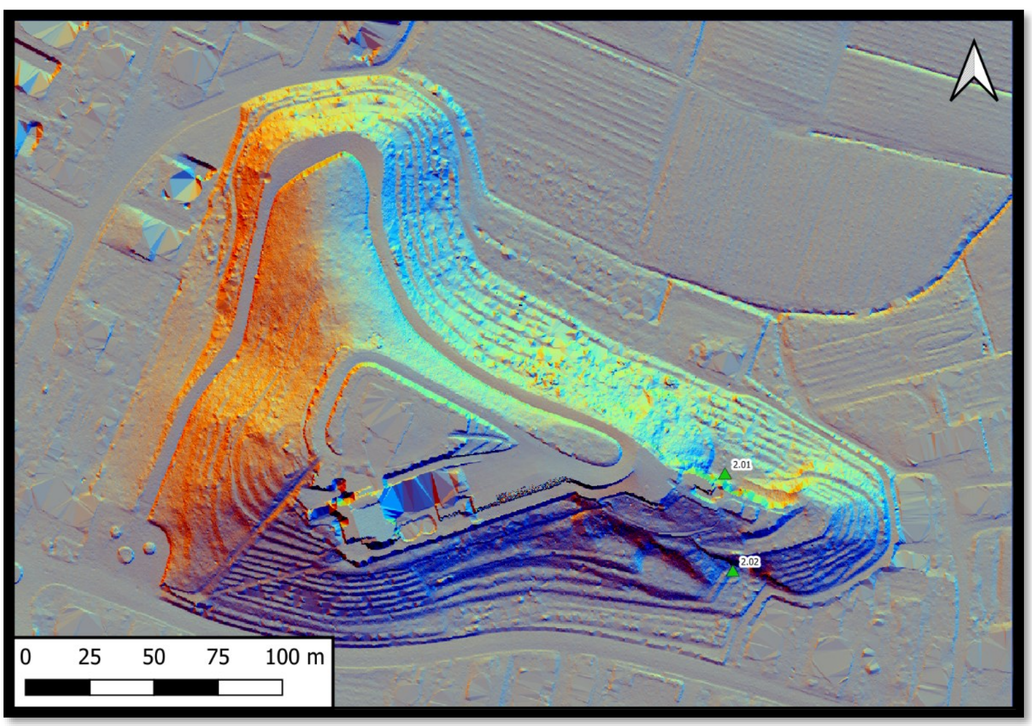


Figure 7 - multi-hillshade map of Area 2 depicting Monte Mussato and two potential but not yet surveyed quarry faces in Galzignano Terme, Veneto, Italy

The DEMs processed from the high-resolution LiDAR data allowed for determination of the hills shape to be established. In particular, the northern slope of Monte Mussato was intriguing due to its deeply convex form making the hill particularly narrow along its eastern half. However, ground elevations showed no shifts in slope across the surface which typically indicates extensive quarrying. Instead, on all sides of the hill, evidence of minor successive linear adjustments in elevation, and the modern presence of olive groves, indicate that historic agricultural terracing had the primary anthropogenic impact on the nature of the hill's morphology, alongside the construction of the hotel and its road.

Two potential quarries were identified, QF 2.01 and 2.02, located on the easternmost portion of Monte Mussato. QF 2.01 is the most probable of the two with a maximum quarry face height of 9.9 meters and presumed length of 61 meters. Its morphology is complicated by the presence of a terrace platform against it to the southwest and set of stairs scaling alongside the presumed quarry face to the east. QF 2.02 appears to be another quarry composed of three neighboring linear segments on separate terraced elevations. The largest is 25 meters long and with a maximum height of 6.3 meters. However, due to the hill's morphology being greatly influenced by agricultural and construction terraces it is necessary to complete a field survey of these two sites before assuming their function as quarries.

3.3 Survey Area 3: Monte Marco

Area 3 is in a central region of the Colli Euganei and encompasses the entirety of Monte Marco, its surrounding agricultural fields, and portions of the lower slopes of the Monte Venda, Orsara, and Peraro over an area of 50.1 hectares. The terrain visualized in the DTM's of the area allows for numerous hill slopes, agricultural fields, terraces, trails, roads, and eroded valleys to be examined with precise changes in elevation. The area was selected for survey due to its primary composition of rhyolitic breccia formed through the explosion of diatreme necks, but it also includes several trachytic and rhyolitic lava outcrops and a geological fracture transecting it (Bellati, 1976). In comparison to the surrounding geological formations, aside from Area 6, it is an isolated location of breccia deposits, and therefore a likely location for breccia quarries to be located.

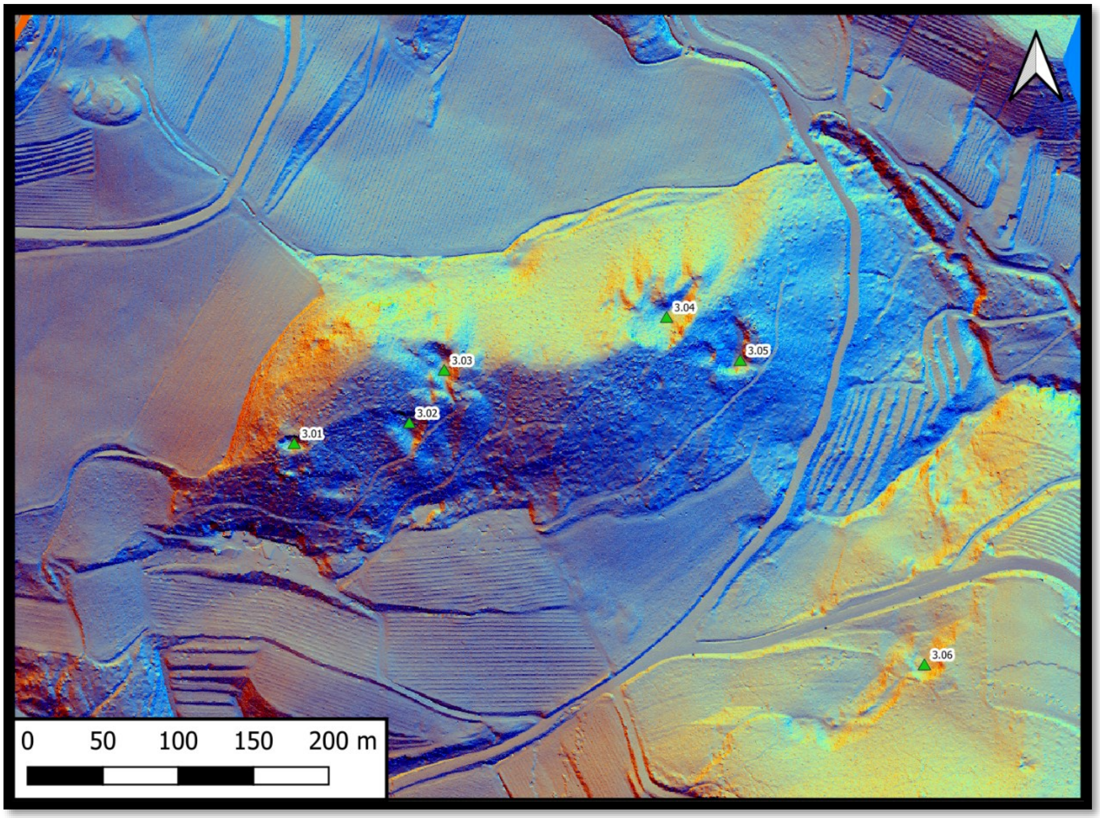


Figure 8 – multi-hillshade map of Area 3 centered around Monte Marco with labeled markers showing the six potential quarry features surveyed. Of which, four were validated in field as quarries.

Six potential quarry sites were identified in area 3, all of which were reviewed during field surveys. Of these six, four were confirmed to be quarry sites, while two could not be confirmed from consideration. QF 3.02 appears to be a potential quarry site. It is located on the ridge top of Monte Marco and resembles two semicircular depressions with a prominent change in elevation on its northeastern portion. Due to dense vegetation and soil deposition and no clear indicators of quarrying activities the field survey did not confirm its function, but from a spatial perspective quarrying is the probable cause for its formation. QF 3.06 is located southeast of Monte Marco at the base of a hill slope where there are noticeable depressions in the natural slope for a stretch of 150 meters. Field survey identified a portion of exposed rhyolitic lava but no signs of quarrying activities. The other four quarry sites (QFs 3.01 and 3.03-5) all showed obvious signs of quarry activities through the presence of quarry faces, substantial amounts of gravel sized quarry material debris, boulders of diverse sizes detached from the quarry. QF 3.01 and 3.03 are particularly interesting as both sites had quarry faces which were terminated at the near horizontal intersection of rhyolitic breccia and rhyolitic lava geological strata, indicating that both quarries were targeting the breccia materials and that excavation continued until contact with the lava.

QF ID	Quarry Face Length (m)	Max Quarry Face Height (m)	Material	Typology	Morphology	Survey Results
3.01	22.7	5.4	Rhyolitic Lava & Breccia	Open Pit: Depression	Linear	Valid
3.02	28.1	6.6	Rhyolitic Lava & Breccia	Open Pit: Sloped	Linear	Valid
3.03	28.3	3.4	Rhyolitic Breccia	Open Pit	Irregular	Uncertain
3.04	66.6	4.8	Rhyolitic Breccia	Open Pit: Sloped	Concave	Valid
3.05	36.9	4.2	Rhyolitic Breccia	Open Pit	Concave	Valid
3.06	143.7	4.6	Rhyolitic Lava	N/A	Concave	Unlikely

Table 3 - Potential quarry feature attributes of survey Area 3. All were evaluated in field surveys.

While this represents the total number of quarries analyzed in Area 3, it should be noted that across much of Monte Marco there are minor, limited in size topographic variations, primarily on the western half of the hills northern and southern slopes. These were not prominent enough to be added to this research but may be limited extraction quarries or quarrying-related features.

3.4 Survey Area 4: Monte Alto

Area 4 is focused primarily on the southern slope of Monte Alto's western ridge line and the high elevation valley spanning between this ridgeline and that of Monte Trevisan to the south. It spans a diverse geological area of approximately 58 hectares which includes known deposits of basaltic, trachytic, and perlitic lavas, rhyolitic and perlitic breccia, Euganean marl, rhyolitic obsidian, and mixed debris dispersed across the valley (Bellati, 1976). The area was of interest for survey partially due to the region's geological diversity, its proximity to known areas of Roman quarrying like Monte Oliveto (Germinario, 2018a), and geological interests in the large 20th century perlite quarry near the center of the survey area (QF 4.01). Aside from quarry features, the high-resolution LiDAR data collected allows for the identification, visualization, and spatial analysis of the area's road, hiking trials, topography of the surrounding hills, the network of fluvial eroded drainages formed in the valley's lower elevation to the west, and the areas' modern and historic agricultural terraces.

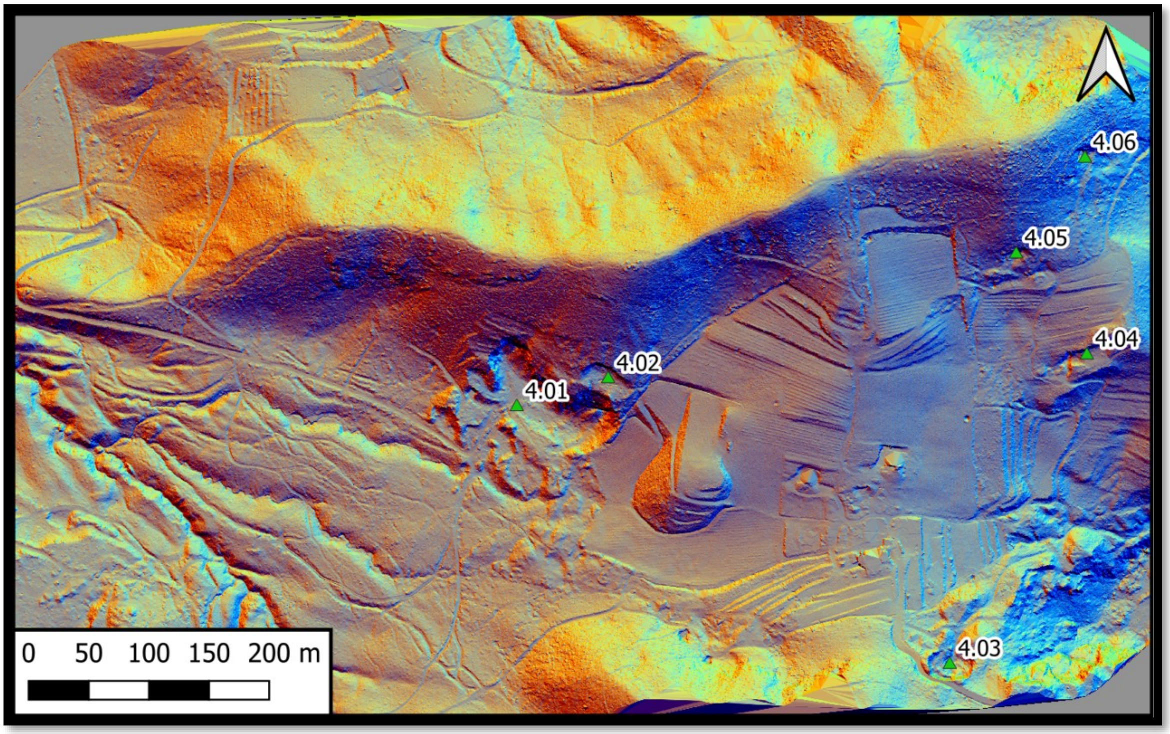


Figure 9 – multi-hillshade map of Area 4 covering the ridgeline of Monte Alto and the valley between Monte Trevisan. Six potential quarry features are highlighted of which two have been surveyed to date.

A total of six potential quarry sites were selected in Area 4 based on the project criteria. Two of these were known modern quarries, both of which were analyzed and documented during field surveys. QF 4.01, a known perlite quarry from the 20th century, is an irregular shaped modern quarry composed of multiple subsections of large, deeply concave cuts into the hill slope of Monte Alto. These sections occur dispersed over an area of about one hectare with the base of most of the quarry ranging from 95 to 100 meters in elevation, apart from a lower elevation quarry face with base at around 88 meters. Large boulders dispersed across the site suggest the use of dynamite and a series of ancillary buildings, scrap metal, equipment, and 20th century trash are representative of the extent of quarrying activities at the location. QF 4.02, located directly above QF 4.01 to the northeast, is an additional modern quarry with a semi-linear concave quarry face composed of columnar perlitic lava, a unique and visually impressive geological formation. Small linear features are detectable bordering the north face of QF 4.01 and west of QF 4.02, which may be indicative of a prospecting method for determining the location of the quarries, however this requires in-field ground truthing.

The other four features are dispersed across the eastern portion of Area 4. Two on the slope of Monte Alto (QF 4.05-6), One in the forested valley beside remnant agricultural terraces (QF 4.04), and the last on slope of Monte Trevisan (QF 4.03). All these features will require a field survey to document their true function, but from a morphology perspective most appear to be historic quarries. They have linear quarry face features of various lengths and access routes which are detectable but not clearly visible, however QF 4.06 has a uniquely tall quarry face in some portions and may be modern. QF 4.03 is the exception, being a near circular feature with some portions of its quarry face being 10 meters high and is most likely modern. Without in-field documentation, these features' periods of quarrying activity cannot be determined. Morphological indicators do provide insights into the function, but the accuracy of these assumptions can only be accessed through field surveys (table 4).

QF ID	Quarry Face Length (m)	Quarry Face Max Height (m)	Material	Typology	Morphology	Confirmed
4.01	261.1	23.1	Perlitic Breccia	Open Pit	Irregular	Yes
4.02	48.9	7.6	Perlitic Lava	Open Pit	Linear	Yes
4.03	91.8	11.4	N/A	Open Pit	Semi-Circular	N/A
4.04	59.4	5	N/A	Open Pit	Linear	N/A
4.05	33.3	5.5	N/A	Open Pit	Linear	N/A
4.06	57.6	15.5	N/A	Open Pit	Linear	N/A

Table 4 - Survey Area 4 Potential Quarry Feature Attributes – note 4.03-4.06 were not surveyed in the field.

3.5 Survey Area 5: Villa Draghi

Area 5 covers approximately 41.2 hectares of Monte Alto's northern slope, immediately west of the isolated Monte Castello on the outskirts of Montegrotto Terme and less than 100 meters northeast of Area 4 at its closest point. The most prominent feature of the area is the Villa Draghi in the northeast portion of the surveyed hill system. The region was chosen based on two primary characteristics. Firstly, analysis of the 1-meter resolution LiDAR data showed the presence of multiple large, irregularly shaped, quarry faces within the topography of the hill facing north, but the extent, morphology, and function of these features was impossible to discern. Secondly, like Area 4, the region was geologically diverse with substantial amounts of latitic and trachytic breccia and lava deposits (Bellati, 1976). It was also located in the vicinity of Monte Oliveto, a heavily exploited region of Roman quarrying especially by *Patavium* (Germinario et al., 2018a; Germinario et al., 2018b). For these reasons, area 5 was chosen as an essential region for understanding the history of breccia quarrying activities in the eastern Colli Euganei.

Aside from potential quarry features, the high resolution DTMs allowed for an excellent quality of visualization in most of the region and a large quantity and diversity of agricultural terraces and fields have been identified in the region, likely associated with the use of the land by the Villa Draghi and early periods. As most of these areas are now densely forested, and the 1-meter resolution LiDAR data was unable to visualize many of these features, this data is valuable for understanding the agricultural history and organization of the area. Roads, trails, footpaths, and fluvial erosion are all present as well.

The most prominent quarry features of the area are 13 quarry faces spanning from east to west from Villa Draghi to the opposite side of the hill with maximum elevations of the largest features around 70 meters (figure 10). These features are particularly unique for their density, interconnected nature, morphologies, and material uniformity. Many of them are likely related to the same period of quarrying activities. However, this information is described in depth through the case study on the Villa Draghi quarries and therefore will not be described here (see chapter 4).

There were three other potential quarry features which were identified through remote sensing and have not yet been field surveyed (figure 10). These are QF 5.14, an irregularly shaped deeply concaved feature with an apparent maximum quarry face height of 7.6 meters and an eastern gently sloping portion. This feature appears to be contemporary with the primary Villa Draghi access road and may be the result of its construction. QF 5.15 is an unlikely candidate for a quarry feature but may warrant further investigation. It is an apparent anthropogenic removal of material, cutting through historic agricultural terraces, and appears to have an exposed face in its northern section which could be between 2 to 3 meters high. This feature may also relate to the construction of the road. Lastly, QF 5.16 is a large, concave feature on the western side of the hill formation. Its slope is not as extreme as a traditional quarry site, but clearly more so than the rest of the natural hillside in the region and is approximately as high as 10 meters. The nature and function of these features will become clearer following a field survey.

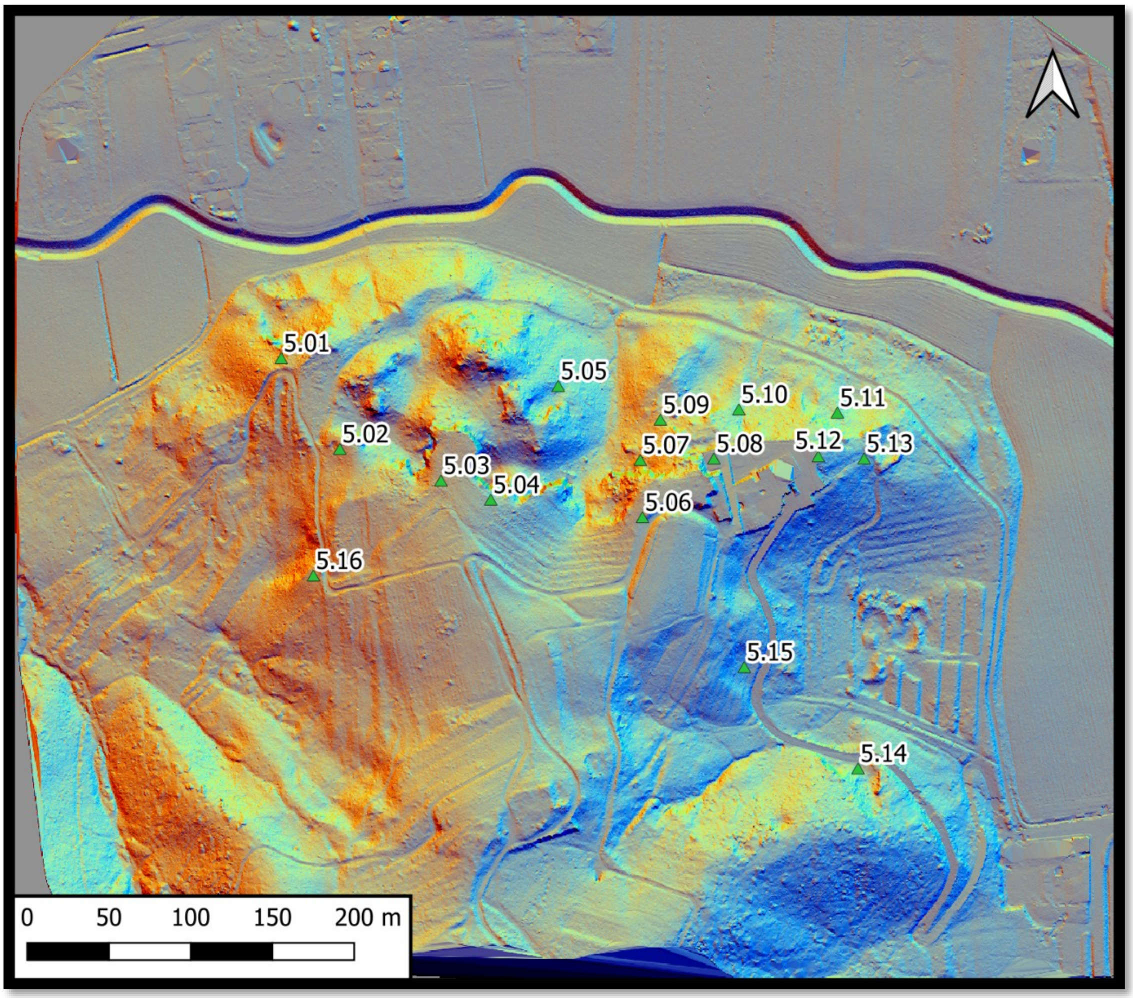


Figure 10 – Survey Area 5 multi-hillshade map depicting general locations QF 5.01 through QF 5.16

3.6 Survey Area 6: Monte Orsara

Area 6 is located on the ridge of Monte Orsara less than 200 meters northeast of Area 3 at its closest point. It is approximately 11.5 hectares in size. The DTMs produced in this region from the LiDAR survey encompass more than 400 meters of the ridge line of Monte Orsara, a section of the southwest slope, and a larger portion of the opposite northeast slope. The area was selected because, like Area 3, geological mapping of the area identified isolated outcrops of rhyolitic breccia formed through the explosion of diatreme necks, making the region essential for understanding the distribution of breccia quarries in the central Colli Euganei. These isolated formations are surrounded by rhyolitic lava alongside outcrops of trachytic lava and an apparent geological fracture (Bellati, 1976).

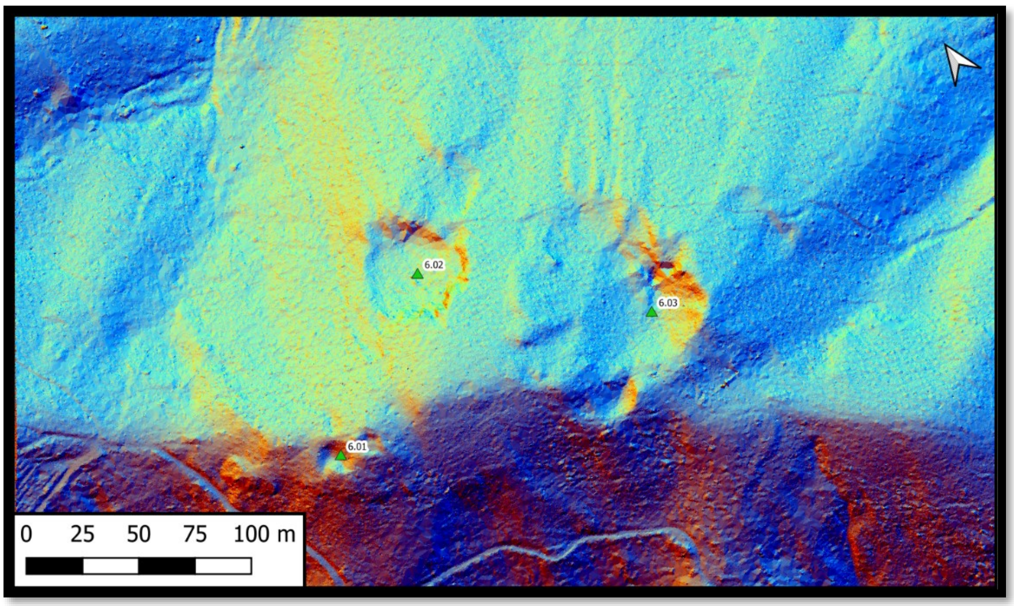


Figure 11 – multi-hillshade map of Area 6 covering a portion of the Monte Orsara ridgeline and highlighting the general locations of three potential quarry features surveyed. Only 6.02 and 6.03 had characteristics suggestive of quarrying activities.

Three areas of potential quarrying activities were identified through analysis of the LiDAR data prior to the field survey. The smallest of these, QF 6.01, is located on the ridge line of Monte Orsara and it is composed of two circular bowl-shaped depressions only several meters wide. No evidence of quarrying activity was visible and the most likely explanation for the formation of these depressions is an explosion, possible from aerial bombing during the Second World War. QF 6.02 and QF 6.03 were both determined to be quarries based on their morphology, exposed quarry faces, and substantial amounts of gravel and boulder-sized debris dispersed across their bases. QF 6.03 provides the most evidence for its function as a historic quarry with two small features located in the feature's primary depression at its base on the northeast slope. Both are clear indicators of historic quarrying, one as a narrow linear extraction into the rhyolitic breccia, and the other a minor feature, linear and excavated into the hillside.

However, there are unique characteristics to both potential quarries which complicate their function. Firstly, they are formed on surprisingly steep slopes and have no visible routes of access, other than a narrow hiking trail, which is surprising considering their sizes. Secondly, the composition of exposed stone, especially at QF 6.02**,** is very heterogeneous with large formations of rhyolitic lava interspersed in the exposed rock faces, and it has a unique morphology where the largest portion of the exposed rock face is oriented with the slope instead of against it. QF 6.03, while certainly having evidence of quarrying activity, is composed of two large depressions, one on the ridge top and the other large formation below it, but it has limited or no exposed stone faces across the ridges of either depression. Regardless, both potential quarry features have evidence of a huge amount of material being removed from them and their unique characteristics may warrant future review of Monte Orsara and its geomorphological characteristics.

3.7 Survey Area 7: Monticello

Area 7 is focused on Monticello, a small, isolated hill located in the plain east of Area 1 by about 650 meters. It is the only geological formation of the Colli Euganei in the immediate vicinity and is surrounded by agricultural fields, small drainages, and dispersed buildings in a relatively flat area. Its geological composition is apparently entirely latitic lava (Bellati, 1976) and it is the easternmost formation in the entire Colli Euganei. The area was included in the high-resolution survey to determine the extent of quarrying activities on the hill, some of which are partially visible in the 1-meter resolution LiDAR data and to map the surrounding fields to determine if there were topographic variations relating to historic routes of transport to and from the hill.

Ultimately, the UAV survey was unable to detect a historic route of transport in the surrounding agricultural fields, but it was able to detect and visualize the fields, drainages, and even the orientation of the plowed rows. Within the hill itself a total of six quarry features were identified, together with an access route along the western and northern slopes which begins in the southwest corner of the formation. Of these, five (QF 7.01-5) are located directly off the access route and spaced equally across the northern slope. They have two separate morphologies in shape and size. Two (QF 7.02 and 7.05) are trench quarries and appear to have been used for determining the quality of stone at the location before being abandoned. The other three (QF 7.01, 7.03, and

7.04) were excavated and are similar irregularly shaped depressions with multiple concave quarry faces, elongated, and access through trench cuts from the access route. The final quarry feature (QF 7.06) is located on the southwest portion of the hill and is a large, open pit quarry which has removed an entire section of the hill and morphologically appears to have been excavated with modern equipment.

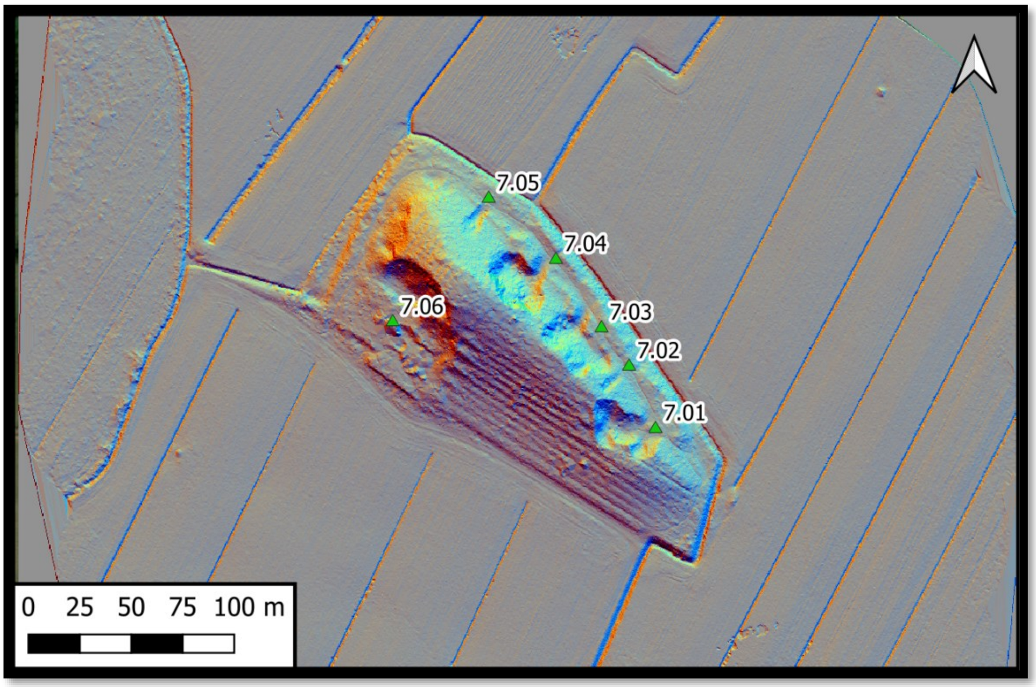


Figure 12 - multi-hillshade map of Area 7, the isolated hill formation Monticello, and the surrounding plain. The not yet surveyed quarry features have been categorized under six separate potential quarry features.

The differences in both location, morphology, and typologies of QF 7.01-5 to QF 7.06 suggest two separate phases of quarrying activities at Monticello. Based on size and morphology, the first five features appear to be historic quarries excavated before the 19th and 20th centuries. Additionally, across the entire unquarried portions of southern and western slopes, equal distant linear terraces, less than 2.5 meters wide, are easily distinguishable while on the northern slope the topographic data shows that, aside from these five quarries features, the slope is unmodified. On the western and southern slopes of Monticello these terraces appear to be directly cut by the QF 7.06. This serves as a temporal indicator for the two periods of quarrying, the terraces being created *post quem* the historic quarries QF 7.01-5, as evidenced by the exclusion of the north slope from terracing**,** and *ante quem* the presumed modern quarry QF 7.06. Ultimately, a field survey and access to the private property will be necessary to determine the function of these sites and fully document their attributes.

QF ID	Quarry Face Length (m)	Quarry Face Height (m)	Material	Typology	Morphology
7.01	90.5	7	Latite*	Open Pit	Semi-rectangular
7.02	11.4	1.2	Latite*	Trench	Linear
7.03	74.1	2	Latite*	Open Pit - sloped	Semi-rectangular
7.04	83.6	8.8	Latite*	Open Pit - sloped	Semi-rectangular
7.05	14.8	2.1	Latite*	Trench	Linear
7.06	99.1	8.6	Latite*	Open Pit	Concave

Table 5 - Survey Area 7 potential quarry feature attributes. Note that the area has not been field surveyed and material type is not confirmed.

3.8 Comparative Analysis

A primary objective of this research was to understand to what degree the addition of high-resolution LiDAR data collected through a UAV survey in the Colli Euganei at 20cm resolution would benefit the identification, documentation, and analysis of quarry distribution. Considering that this region, as well as large portions of northern Italy, have already received an extensive LiDAR survey through the Italian government, through the Regione del Veneto geographic service and the Ministero dell'Ambiente e della Tutela Del Territorio e del Mare, a comparison of results is necessary. These can be publicly accessed at 25 meter and 5-meter resolutions, and at 1 meter by request. The availability of these LiDAR datasets allows for a comparison of their results and to determine if additional high-resolution UAV surveys in the Colli Euganei are justified and necessary for documenting the quarrying activities in the region.

To discern the extent of additional data provided, the 89 potential quarry sites identified through the UAV survey were compared against the 1-meter resolution LiDAR in terms of which sites were visible in the lower resolution data. These were categorized as either partially visible (topographic variations were present that could be interpreted as quarry features but with considerably poor visibility), discernable (enough clarity to identify the function of a feature as a potential quarry), or not discernable in the data set (areas which had little to no topographical indications or poor visibility). This resulted in 48 potential quarry sites being discernable, 19 partially visible, and 22 not discernable in the data set across the seven surveyed regions. This indicates that without the aid of submeter resolution LiDAR data it would have been impossible to complete a topographic survey of quarry locations in the region with any degree of confidence as about 46% of potential quarry sites chosen for investigation identified through the 0.2 meter UAV survey were only able to be detected in the 1 meter resolution LiDAR data in the form of heavily interpolated features without clear boundaries or attributes or worse, not able to be clearly distinguished from the surrounding landscape at all.

The primary influence on the results was both the overall size of the quarried area and especially the extent of elevation and slope change in the feature compared to that of the surrounding natural landscapes. The primary difference between those which were clearly discernable versus only partially visible or not detectible being elevation change in the apparent quarry face, where potential quarries of 4 meters or less in height were generally poorly visualized. Features which were completely or practically not visible in the 1-meter resolution data were of the smallest sizes, not necessarily in length but especially in the elevation change or the height of quarry faces.

These results indicate that while the lower resolution LiDAR is capable of prospectively identifying areas of interests and identifying the locations of the most topographically visible quarries, it is unable to accurately visualize moderate and small sized sites leading to the possibility that even at 1 meter resolution essential sites would be missed in a landscape analysis (figure 13). This validates the benefits of conducting a targeted high-resolution UAV survey in a landscape of varied topography and dense ground and tree coverage vegetation, where not only minor quarry sites were able to be detected but every site was able to be clearly visualized. The application of UAVs in LiDAR research for the remote sensing of archaeological features is an expansion to a series of published research over the past decade (Risbøl and Gustavsen, 2018; Barbour et al., 2019; Ćmielewski et al., 2021). The benefits of conducting a UAV survey in forested environments with dense areas of evergreen has been conclusively proven in multiple research projects, including this work, that while less obstructed regions can be well surveyed through plane mounted LiDAR surveys, forested environments where the identification of archaeological features in necessary greatly benefit by the increased accuracy of a targeted UAV survey (Casana et al., 2021; Dainelli et al., 2021; Schroder et al., 2021; Poirier, Baleux, and Calastrenc, 2020).

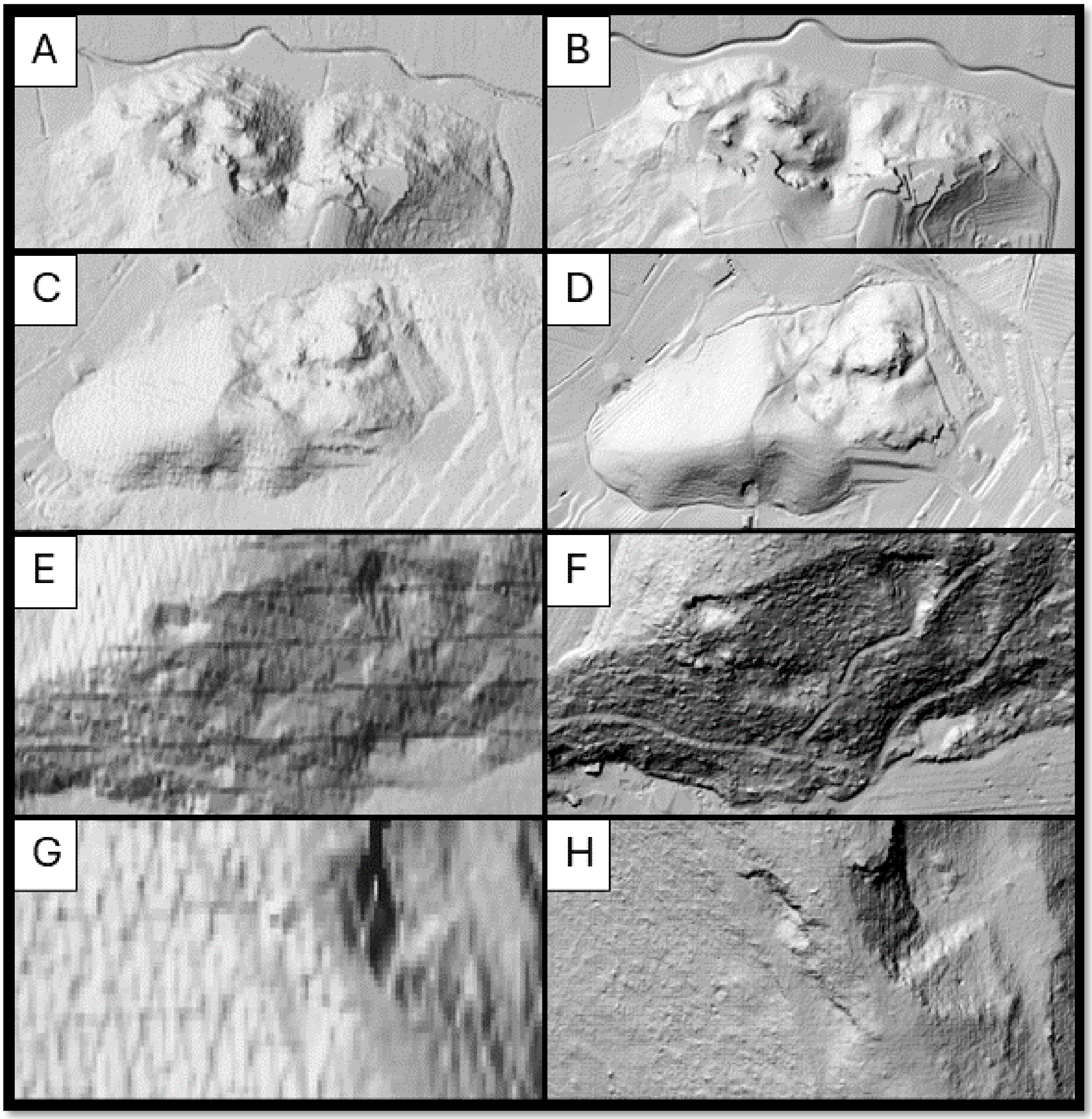


Figure 13 – Hillshade DTM comparisons: left column is 1-meter resolution and right column is 0.2-meter resolution. (A-B) Villa Draghi Quarry Site and (C-D) Via Scagliara Quarry Site are visible in both data sets, however at 0.2-meter resolution several more features are visible and quarry attributes relating to size, shape, and typology are detectable (1:2500). (E-F 1:1000) The SW portion of Monte Marco and (G-H 1:500) QF 1.05 are practically non-detectable at 1-meter while the UAV 0.2-meter resolution clearly defines them, the surrounding terrain, and their access routes. A clear advantage not just in the analysis of the features but for the identification of quarry sites in general.

However, the benefits are enhanced even further if the objective of the LiDAR data set analysis goes beyond identifying areas of interest for field research. In this research the quality of quarry visibility was so great that a large variety of attributes could be measured or assessed through the remote sensing data alone. While 1 meter resolution LiDAR is already considerably high quality in comparison to previous decades, the high-resolution UAV survey produced DTMs with 25 times more resolution, so the identified quarries could be measured, evaluated, and assigned according to typologies under a variety of visible attributes. This allowed for a deeper level of documentation, statistical analysis, and overall, an enhanced understanding of the quarried landscape of the Colli Euganei.

3.9 Quarry Attributes

Potential quarries in Area 1 were selected for sampling of spatial, morphological, and typological attributes in order to determine the range of these characteristics. Area 1 was selected, and the other areas excluded, being the largest of the areas covering 77% of the survey. It also contained most of the quarry locations, with 50 sites selected for analysis and because it is a large, continuous, region of survey with multiple regions of quarrying dispersed across it, with a relevant variability in geological materials and topography. This made these 50 samples ideal for interpreting quarry attributes, also considering that a complete field survey of most of the potential quarry sites has not been completed.

Attributes were restricted to those which could be directly measured or reasonably estimated at each of the sampled locations. These were the length of the primary quarry face feature at a site, the estimated maximum height of the exposed portion of quarry wall, the estimated slope of the natural hillside (based on averages of the surrounding slopes), the maximum elevation, the elevation gain from the base of the feature to peak, the orientation of the quarry, geological material type (if field surveyed), distance from known 12th century transportation canals, an estimated area, and finally a hypothetical volume (appendix A1 and A2). These attributes primarily correlate to decisions in the quarry process that lead to the location selected and the method of extraction.

Hypothetical volumes were produced through a grid interpolation technique in the application QGIS known as Inverse Distance to a Power (IDP), with a weighting power of 2 and vector points restricted to the perceived perimeter area of each quarry feature, to produce an interpolated raster at 20-centimeter resolution creating a surface covering the quarry which represents an estimate of the elevation of the natural hillside prior to excavation. While several interpolations formulas were experimented with, IDP produced the best results based on the uniformity of contour lines produced in comparison to the surrounding natural hillslopes. IDP is essentially a method by which values are restricted to the minimum and maximum of the true elevation vectors used, and in which the influence of each vector on an interpolated cell is weighted against the proximity to the known vector point. From these, volume was calculated using the QGIS Raster Calculator to measure the difference between elevations collected from the survey and those interpolated.

Measuring volume, even an interpolated estimate, was necessary as it is the only collectible attribute of a quarry feature that can represent the true size of the quarry, and the extent of material extracted from the site (appendix A1). Additionally, volume was beneficial for measuring the differences in perceived modern quarry sites from those of pre-modern, besides simply relying on morphological characteristics. These distribution and correlations between these values were then analyzed.

3.10 Statistical Distribution

To evaluate the extent to which attributes identifiable through high-resolution LiDAR data could be analyzed, Area 1, the largest and most comprehensive survey area, was selected as the focus of this study. This area encompasses a diverse range of modern and premodern quarry sites, offering a robust dataset for analysis. Within Area 1, a total of 50 quarry sites were sampled, providing a representation of the region's quarrying activities. By selecting this extensive and varied dataset, the analysis aims to push the limits of LiDAR-derived data in identifying and characterizing quarry attributes. This analysis was conducted through the program R (R Core Team, 2023), a well-recognized and heavily supported program designed specifically for the purpose of statistical analysis of data sets.

A correlation plot was created to explore the relationships between continuous variables measured across the 50 sampled quarries. This indicated that the selected attributes relating to the size of a quarry feature showed strong correlations with each other (length of a quarry face, quarry face maximum height, elevation change within a feature, assumed area, and hypothetical volume), an expected and unsurprising result. Interestingly, attributes related to the site selection of a sampled quarry feature, natural hill slope or the maximum elevation of a feature, showed positive but limited correlation to all other attributes which suggest these characteristics may have had a minor, but mostly irrelevant effect on the amount excavated from a quarry. Distance to navigational canals on the eastern border of Area 1 showed almost no correlation to the size of quarries and a moderately positive correlation with direction, indicating that unsurprisingly quarries facing east also tend to be on the eastern portion of Area 1. Lastly, the only attribute which produced primarily negative, albeit minor, correlations was the direction the quarry faces were oriented (figure 14).

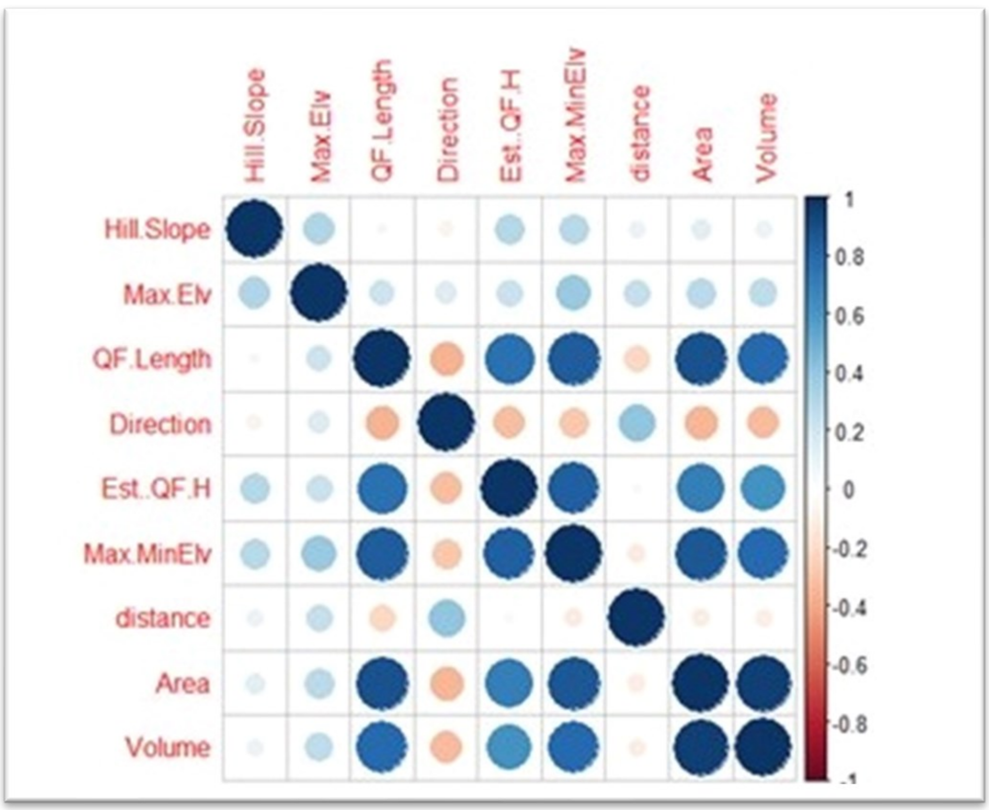


Figure 14 - Correlation Plot: intensity of the colors represents the strength and direction of the correlations: dark blue indicates a strong positive correlation, while dark red represents a strong negative correlation. The diagonal line in the plot reflects perfect correlations (a variable correlated with itself). See Appendix A1-2 for an explanation of attributes.

To explore potential groupings within the data, it was necessary to determine the optimal number of clusters. The elbow plot method was employed to identify the optimal number of clusters. This method involves calculating the within-cluster variance (sum of squares) for varying numbers of clusters. The "elbow" point, where the reduction in variance begins to diminish significantly, suggests the optimal number of clusters. For this dataset, the elbow plot indicates that two clusters provide an ideal balance between minimizing variance and the number of clusters (figure 15). Silhouette analysis was also performed to assess the quality of clustering. This method evaluates how similar each observation is to its assigned cluster compared to other clusters, with values close to +1 indicating good clustering and values close to -1 indicating poor clustering. The silhouette analysis corroborates the elbow plot, also suggesting that two clusters are optimal (figure 15).

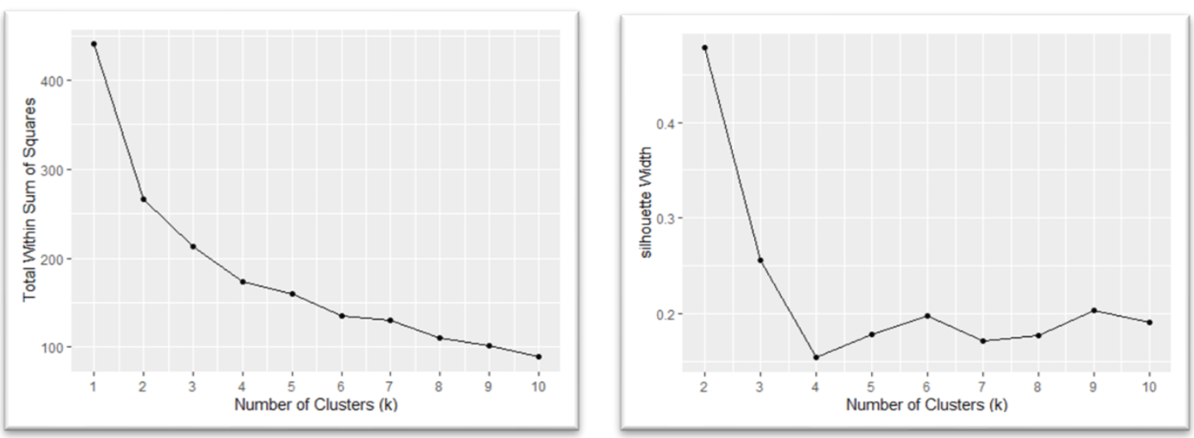


Figure 15 – Elbow Plot (left) and Silhouette Plot (right) Both indicating 2 optimal clusters.

The gap statistic was utilized as a final method to determine the optimal number of clusters. This method compares the observed within-cluster variation to that expected under a null reference distribution with no clustering. Contrary to the previous methods, the gap statistic suggests that three clusters are optimal (figure 16)

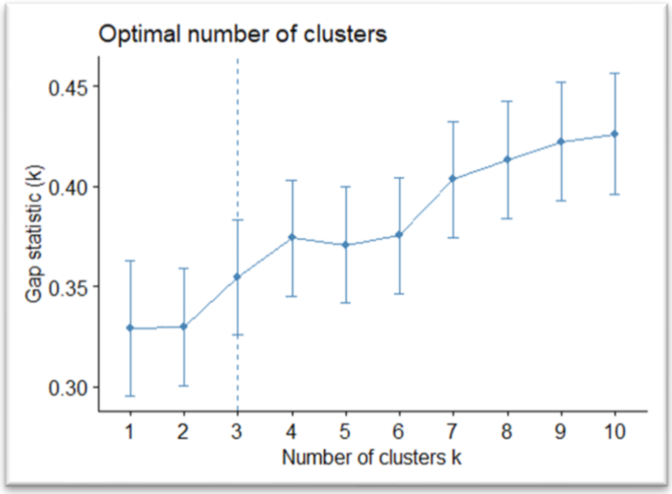
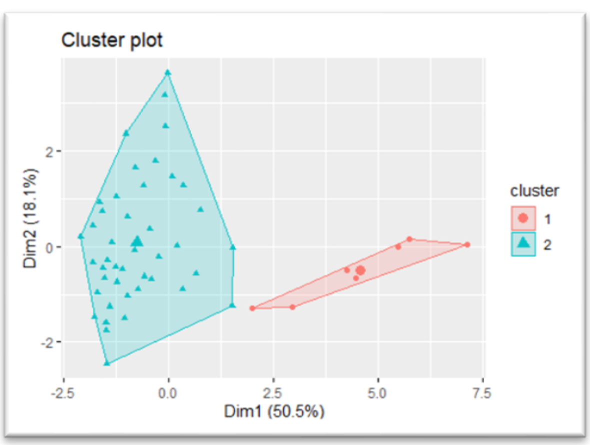


Figure 16 – Gap Statistic Plot indicating 3 clusters as optimal.

To visualize the clustering, Principal Component Analysis (PCA) was used to reduce the dimensionality of the data (figure 17). The first two principal components account for 50.5% and 18.1% of the variance, respectively, capturing 68.6% of the total variability. The two-cluster solution shows distinct separation between the clusters in the two-dimensional PCA plot, indicating a good degree of separation. The three-cluster solution also shows clear separation in two dimensions and the clusters are more spatially logical, despite being less supported by the statistical tests.



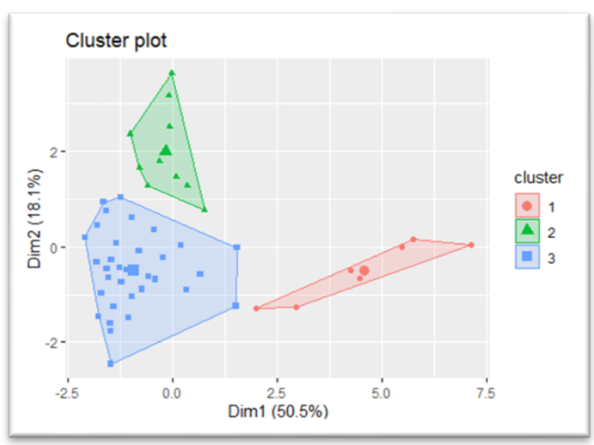


Figure 17 – Two Cluster plot (left) and Three cluster plot (right)

When reviewing the spatial distribution of these sites to their assigned clusters, cluster 1 is composed of the largest of the modern quarries and is therefore spatially unconsolidated, while cluster 2 is composed of the remaining quarries including some minor proposed modern quarries. However, when viewed with three clusters, the additional cluster separates multiple moderate and some especially small quarries, and the spatial distribution appears to have produced more geographically logical clusters, despite the statistical evidence supporting a two-cluster model more strongly (figure 18).

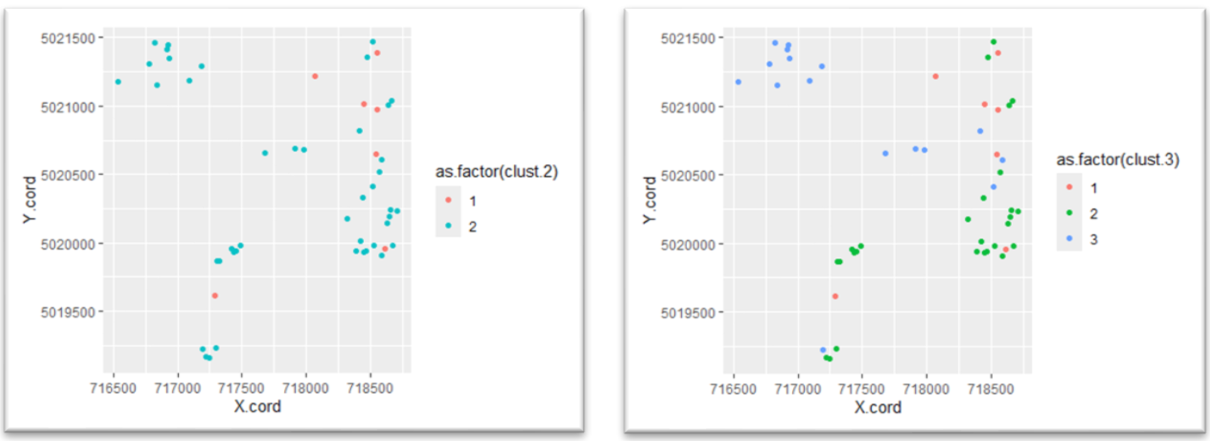


Figure 18 – Spatial Distribution of Two Clusters (left) and Three Clusters (right)

The means of the groups were examined under both the two-cluster and three-cluster models. Cluster 1 remains consistent across both models as it retains the same sampled sites in both the two and three cluster models. The means are centered around zero, with values below the mean represented as negative (figure 19). Essentially, the two-cluster model, which is supported the most statistically, has clustered the largest quarry sites according to the variables relating to size within cluster 1 and the rest of the sites under cluster 2, and combined they have values mostly just below the mean. On the other hand, the three-cluster model separates cluster 2 by most values being well below the mean, and cluster 3 as a collection of sites which are primarily characterized by above mean values of natural hill slope, max elevation, distance from navigational canals, and direction of quarry faces.

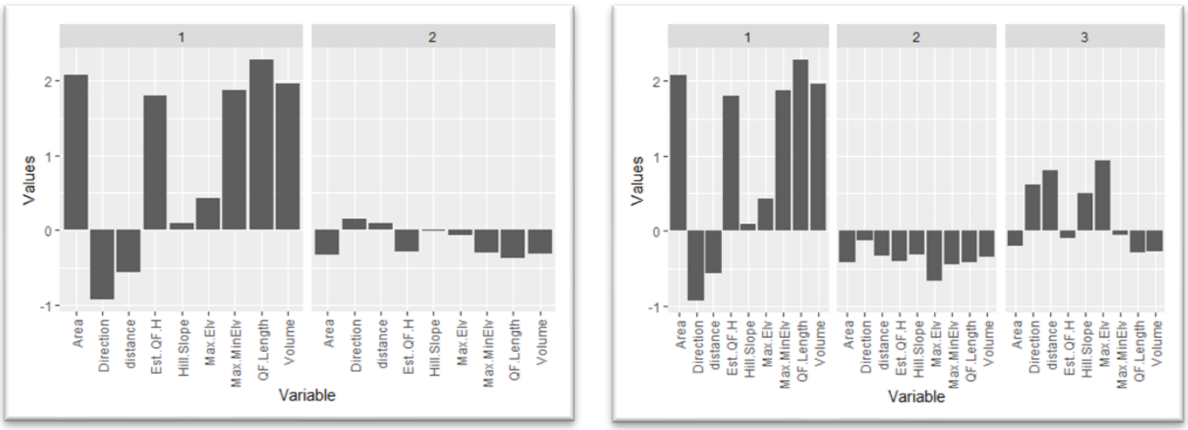


Figure 19 – Two cluster (left) and three cluster (right) values of variables according to the mean.

A statistical analysis was conducted to investigate whether the distance between quarries can predict the likelihood of them belonging to the same cluster. This was assessed using a generalized linear model with a binomial outcome, where the model predicted whether a pair of quarries was in the same cluster (1) or not (0). For the two-cluster model, no significant relationship was found between the distance and cluster membership ($p = 0.4$). However, in the three-cluster model, a significant negative relationship was observed ($p < 2 \times 10^{-16}$), indicating that as the distance between quarries increases, the likelihood of them being in the same cluster slightly decreases. In more general terms there is a correlation between the proximity of quarry locations and their likelihood to have similar attributes, which may be an indicator that the qualitative groups outlined in section 3.1.2 are partially supported by this statistical analysis, even though less clusters were produced. Despite this, the effect size was small and accounted for only about 6% of the variance, suggesting that while distance does have some predictive value, it is not a strong determinant of cluster membership.

The analysis provides a comprehensive understanding of the statistical relationships and clustering patterns within the dataset. While the two-cluster model is statistically supported, the three-cluster model aligns better with spatial patterns, highlighting the importance of considering both statistical and spatial factors in the interpretation of quarry data. These results indicate that in terms of evaluating only physical attributes of potential quarry sites through remote sensing, statistical clusters within the Colli Euganei are present. However, the results are mostly representative of the comparably massive size of the largest modern quarries included in this sample set, which produced cluster 1.

These values may have overly influenced the results of this analysis and renewed statistical analysis excluding cluster 1 may be beneficial. Alternatively, the statistical support for the two-cluster model suggests that the premodern, and some smaller modern quarries, found across the entirety of Area 1, are evenly distributed in their variables without any exceptionally distinct groups visible. This suggests that the extended period of quarrying activities, across the whole region, produced an even distribution of quarry features, at least according to the variables analyzed here. Interestingly, the three-cluster model does distinguish several quarry sites, which were proposed on qualitative analysis of shape and proximity, to the Via Scagliara and Monte Castellone groups (section 3.1.2), a statistical indicator that these sites have attributes which distinguish them from the rest of the survey area and supporting the hypothesis that either group could be the result of organized and planned quarrying activities from a distinct period.

Chapter 4: Quarry Case Studies

Throughout the spring of 2024, multiple field surveys documented numerous findings first identified in the LiDAR data. Among these findings there were two distinct breccia resource collection areas, each containing multiple quarry features, referred to here as the Villa Draghi quarry site and the Scagliara quarry site. This chapter complements the larger thesis by showcasing the depth of analysis achievable when focusing on individual, dynamic quarry systems using data collected through remote sensing surveys and in-field ground truthing and feature documentation. Various degrees of analysis, including evidence-based hypotheses on the function, dating, and interconnectivity of quarries, are presented for these case studies.

Each of these quarry systems exhibits desirable characteristics such as well-preserved quarry walls, quarry marks, negative traces of block excavation, unique topography, and similarities in form and apparent function. These characteristics warranted a dedicated section within this work to describe and analyze these two case studies.

The objectives of this chapter are to present each quarry site within its geographical context, describe and analyze various features related to quarrying activities using high-resolution LiDAR data and field survey information, hypothesize the function of each site based on collected data, and interpret the apparent similarities between these sites. Additionally, this chapter will discuss potential future research that could confirm any connection in age or function and consider the implications these sites might have for interpreting breccia quarries across the Colli Euganei. By addressing these objectives, this chapter aims to provide a detailed examination of the Villa Draghi and Scagliara quarry sites, enhancing our understanding of quarrying activities in the region and laying the groundwork for future research.

4.1 The Villa Draghi Quarries

The first case study is focused on a series of quarry features that are in the vicinity of Villa Draghi, a 19th century villa built on the northern slope of Monte Alto on the western outskirts of Montegrotto Terme, Italy. The quarry site, for the purposes of this case study, is an assemblage of quarry features located within the geomorphological region of the northern slope of Monte Alto, below 70 meters in elevation. All quarry features are extracted from the same geological material type, a loosely compacted trachytic breccia with large clasts containing a high amount of amorphous silica and distinctive mineralogical characteristics (Pilgrim, 2024). All features identified in this location are presented here as one quarry site with the goal of depicting their characteristics and inter relationships.

4.1.1 Site Description

The area of the quarry site has a varied topography of quarry walls, isolated hills, undulating slopes. Much of it has been anthropologically influenced by the extensive quarrying of the hillside, extraction routes, and especially through the erosional deposition of debris from the northern slope of the Monte Alto hill which have been deposited at the base of all quarry walls. Notably, the slope of the Monte Alto hill south of the quarried areas is particularly gradual for the general landscape of the Colli Euganei. This difference between the gently sloping upper hillside and the vertically cut quarry walls makes the Villa Draghi quarries especially prominent features in the general landscape (figure 20).

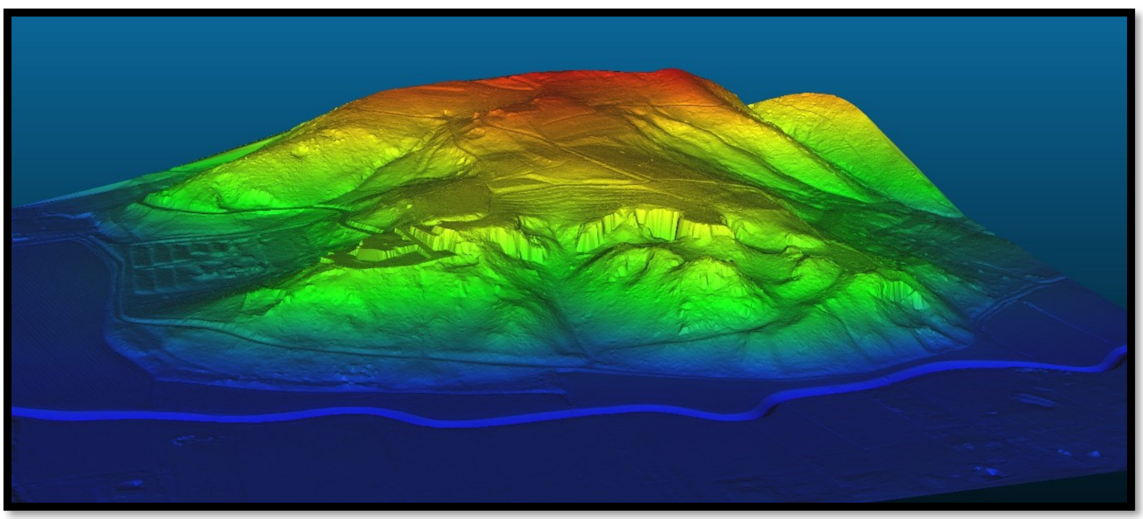


Figure 20 – 3D visualization of the Villa Draghi quarry site and survey area 5. Produced through Could Compare TIN (Triangular Irregular Network) mesh processing of ground classified point cloud from UAV survey. Color ramp represents elevation change. View based perspective with standard lighting at natural scale.

Geologically, most of the quarry walls demarcate a shift in material types between the quarried breccia and that of a rhyolitic lava. The limits of most of the quarry walls appear to represent a transition in the purity of desirable breccia materials to those of more mixed composition with large and irregular inclusions of rhyolitic lava. This is also supported by geological surveys of the Colli Euganei (Bellati, 1976). Additionally, the area's geology is complicated by the presence of rhyolitic lava conical formations downslope of the major quarried walls by several dozen meters. These formations are indicative of the geological variability in this region of the Colli Euganei, formed through a complex history of stratified volcanic materials and cemented debris. In this case the conical formations of lava are indicative of the submarine volcanic activity forming several minor cones in the vicinity of each other. The breccia materials appear to have had a considerable depth, filling the voids between the conical volcanic mounds, burying them, and forming a continuous slope with limited topographic variations. While this is impossible to confirm considering the extent of material which has been excavated, it is probable considering the surrounding undisturbed slopes of Monte Alto which lack severe topographic variations like steep slopes (figure 20).

Aside from the unique and densely located quarry features found at this quantity only at this site, the Villa Draghi quarries were selected for case study analysis due to the wide variety of associated research, recent findings, and artifacts found at the site that provide a clear understanding of its Roman period of use. Recent provenance analysis comparing samples collected from the quarries found a clear match with the Roman mortars used in construction of a bath complex located in Montegrotto Terme (Pilgrim, 2024). This finding is supported by the presence of Roman roof tiles fragments, *tegulae*, within QF 5.03. Previous research indicated the neighboring Roman trachyte quarry at Monte Oliveto was not only heavily utilized in the Roman period, but also was preferentially selected for constructional projects in *Patavium*, and it was geographically located in the vicinity of proposed Roman fluvial routes for transportation (Germinario et al, 2018b**)**. Combined, this indicates that Villa Draghi quarries were clearly exploited, ideally located, and in a region of known quarrying infrastructure to perhaps be the principal location for breccia material quarrying in the region, particularly for use by ancient *Patavium*.

4.1.2 IDENTIFIED FEATURES

Through a combination of remote sensing analysis of various DTM maps produced from the high-resolution LiDAR data and in field surveying, a total of 13 quarry features were documented as part of the Villa Draghi complex (figure 21, table 6). The quarry faces are diverse, some no more than a few meters long and a couple meters high and others of comparably monumental size to the rest of the survey areas premodern quarries. The largest continuous quarried face measures 220 meters in length. Typologically they appear as primarily open pit quarries but are unique in that several features have quadrangular quarry face segments, an attribute mostly absent from the rest of the surveyed areas. Additionally, there is a moderate sized subterranean quarry extracted beneath a portion of QF 5.04. Most of its volume is obscured by a deep infill of soil and sediment caused by erosion, an indicator of the potential age of the quarry system. It is the only subsurface quarry identified in the Colli Euganei. Essentially, the Villa Draghi quarry site is entirely unique in terms of the quantity and density of quarry features, morphology, typology, and overall size.

Quarry Feature ID	Quarry Face Length (m)	Quarry Face Max Height (m)	Morphology	Typology	Material
5.01	56.8	11.1	Linear	Open Pit - Sloped	Trachytic Breccia & Lava
5.02	17.9	6	Linear	Open Pit	Trachytic Breccia
5.03	n/a	n/a	Irregular block extraction	Underground Quarry	Trachytic Breccia
5.04	221.2	18.8	Rectangular, Linear	Open Pit	Trachytic Breccia
5.06	25.4	6.1	Concave	Open Pit	Trachytic Breccia
5.05	53.7	7.2	Rectangular	Open Pit - Sloped	Trachytic Breccia
5.07	63.8	13.9	Linear	Open Pit - Sloped	Trachytic Breccia
5.08	26.9	9.9	Linear	Open Pit - Stepped	Untyped Breccia
5.09	12.1	3.6	Concave	Open Pit - Sloped	Untyped Breccia
5.10	13.4	6.5	Linear	Open Pit - Sloped	Untyped Breccia
5.11	57	2.6	Concave	Open Pit - Sloped	Untyped Breccia
5.12	14.8	2.8	Linear	Open Pit - Sloped	Untyped Breccia
5.13	20.6	4.3	Concave	Open Pit - Sloped	Trachytic Breccia

Table 6 – Villa Draghi quarry feature attributes

One area of exemption, but of certain quarrying activities is the site of the Villa Draghi itself. Based on the Villa platform's shape being confined to multiple quarry faces in its western, northwest, and eastern extent, and on the fact that masonry wall terraces above the villa are a facade meant to cover and stabilize quarry walls, some of which are clearly visible in the northwest portion of the Villa complex, it is likely that the Villa's location was previously an additional breccia quarry site and that the Villa itself was built upon an a flattened processing area which cleared and leveled the slope of the hill. However, aside from the portions of visible quarry faces, the area has been so heavily modified by the Villa terraces, walls, and buildings that an accurate interpretation of these features' shape or function is unlikely (figure 20 and 21).

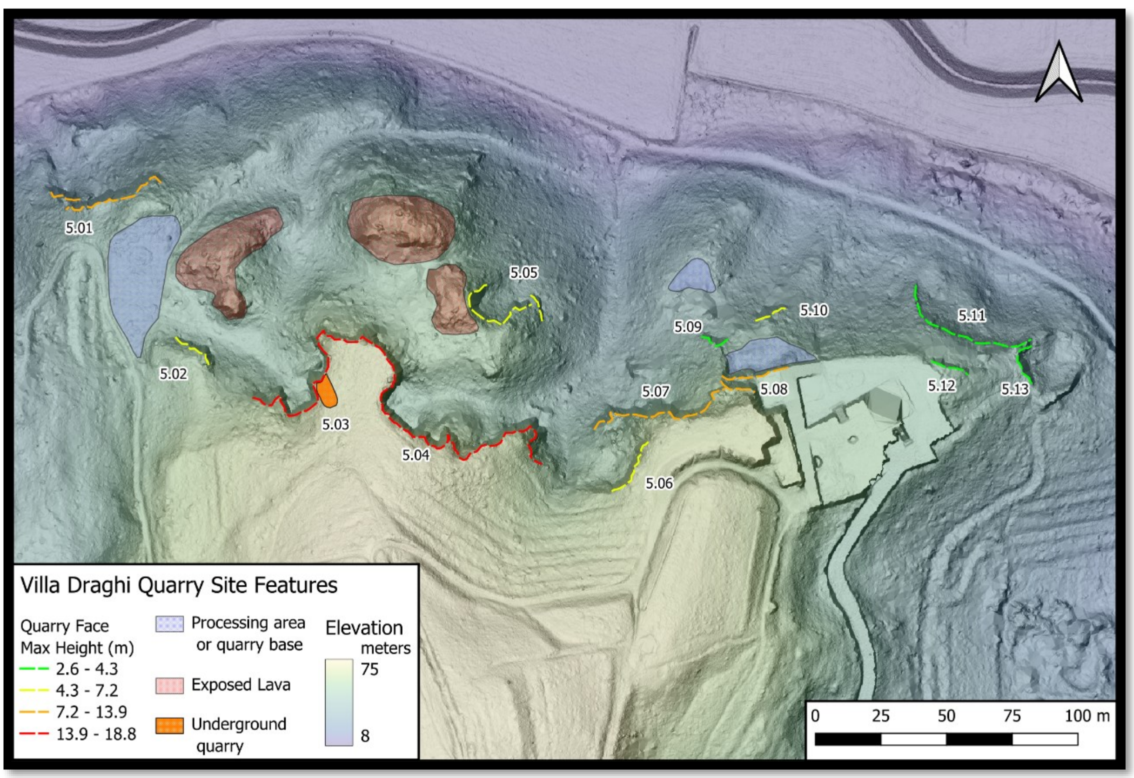


Figure 21 – Villa Draghi quarry site feature map depicting the quarry faces and associated features relating to quarrying activity identified at the site. Map is composed of Slope values overlayed by transparent hillshade and elevation color ramp values.

Of particular importance to the nature of the Villa Draghi site quarries is the quantity and quality of preservation of quarrying marks. This is especially important considering the erosive granular nature of the breccia materials which are especially susceptible to weathering. Within the Villa Draghi site most of the identified quarried features have undergone intense bio colonization and weathering, however, in several locations, traces of quarrying activities like tool mark indentations and negatives of excavated blocks are well preserved and offer insights into the techniques utilized to quarry the materials. The areas with the greatest preserved traces are features QF 5.03, 5.04, and 5.05. QF 5.04, the major quarry face of the site, contains three separate areas of dense quarry traces, two of which are located directly west and east of subterranean quarry feature QF 5.03. Many of these features have been digitized using high-density laser scans, allowing for a high accuracy of measurement and digital modeling (figure 21).

Field surveys of these locations allowed for the documentation of many of these areas, which revealed multiple typologies of quarrying marks and an overall standardization of these in size or repetition in multiple quarry mark locations. These quarry face surface marks appear mostly in the form of pickaxe marks which range in size and quality of preservation across the location but overall are located near vertical quarry faces in uniform horizontal bands depicting layers of excavation from the peak of the quarry faces to their unexcavated base elevation. In general, the marks have a noticeable but limited curvature, a spacing of around four centimeters apart, and a length of around 40 centimeters, though this varies. At the corners of quarry walls, pick marks change orientation to either vertical along the corner or short and horizontal. The eastern quarry face of the rectangular cut shows the approximate height of each layer of excavation, and a tendency for the orientation of the pick marks to alternate with each layer, suggesting a change in direction of excavation.

Additional tool marks are visible at feature QF 5.03, the underground quarry, where the surface is entirely composed of the negative traces of block excavation of the breccia material. At multiple locations near the entrance and inside of the quarry, there are indentations on either side of the blocks of excavated stone showing the use of chisels and wedges to separate and detach the material. These traces appear in the form of linear cuts in the face of the quarry on either side of the block and are approximately 2.5 cm deep and as much as 7 cm wide.

The negative traces of block excavation are dispersed across at least four locations and appear in two distinct morphological typologies, the first being standard block excavation which gives the underground quarry feature QF 5.03 its morphology of sloped, irregular walls and ceiling, and the second being smaller concentrated block excavation which is focused on rectangular sections composed of multiple courses.

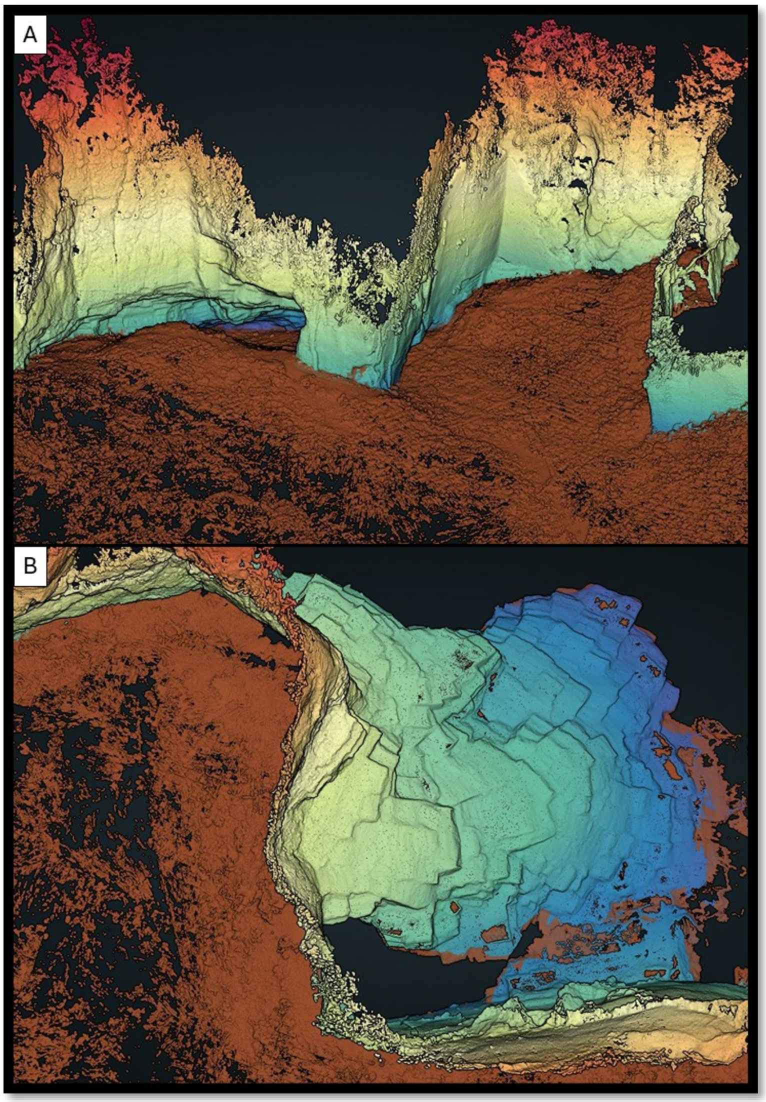


Figure 22 – Laser Scan depicting QF 5.03 and surrounding rectangular portions of QF 5.04. A – View of entrance to 5.03 and quarry faces of 5.04. B – Aerial view of 5.03 ceiling morphology. By Filippo Carraro.

Standard block excavation is found at all major quarry mark locations and appears in a variety of dimensions. The largest of these are around 130 cm wide and as much as 45 cm high but can range in size to 80 cm wide and 25 cm high. In all areas there is apparent overlap in dimensions with blocks quarried around it, creating an uneven surface of overlapping negative traces making standard dimensions difficult to calculate and the length of the negative traces partial as there are no complete cuts of an individual block visible. However, on the ceiling of feature QF 5.03 maximum depths are around 40 cm. This allows for an estimate of the largest blocks extracted being greater than 40 cm in length with widths reaching 130 cm and heights of 45 cm (figure 23e and f). In general, these characteristics are typical of premodern quarry methods and are expected in a Roman context (Ward-Perkins, 1972; Bessac, 1988; Gracia-M, 2011; Wotton, Russel, and Rockwell, 2013).

The second typology of quarry block negatives is differentiated by its size range and especially the regularity of its quarried method. These traces are found in grouped rectangular or near rectangular incisions at the current elevation of the quarry wall bases in location across QF 5.04 and the entrance of 5.03, displaying a coordinated use of the technique as opposed to the larger typology which appears irregularly planned. These traces of excavation range in length from approximately 45cm to 55cm, with heights of around 13cm to 17cm. In most cases the traces of block excavation are grouped two or three columns wide and multiple courses high (figure 23c and d). There are no sections of meaningful depth at their locations to form an estimate. This technique may be representative of a need to quarry blocks of a smaller and more easily moveable size alongside more typical large quarry blocks seen at Roman quarries (Rockwell, 1993; Coli et al, 2011**)**, or it could be representative of a method of targeted excavation in which smaller and more regularly sized blocks were removed to create rectangular cuts into the geological stratum, either to investigate the quality of the material or to create tunnels.

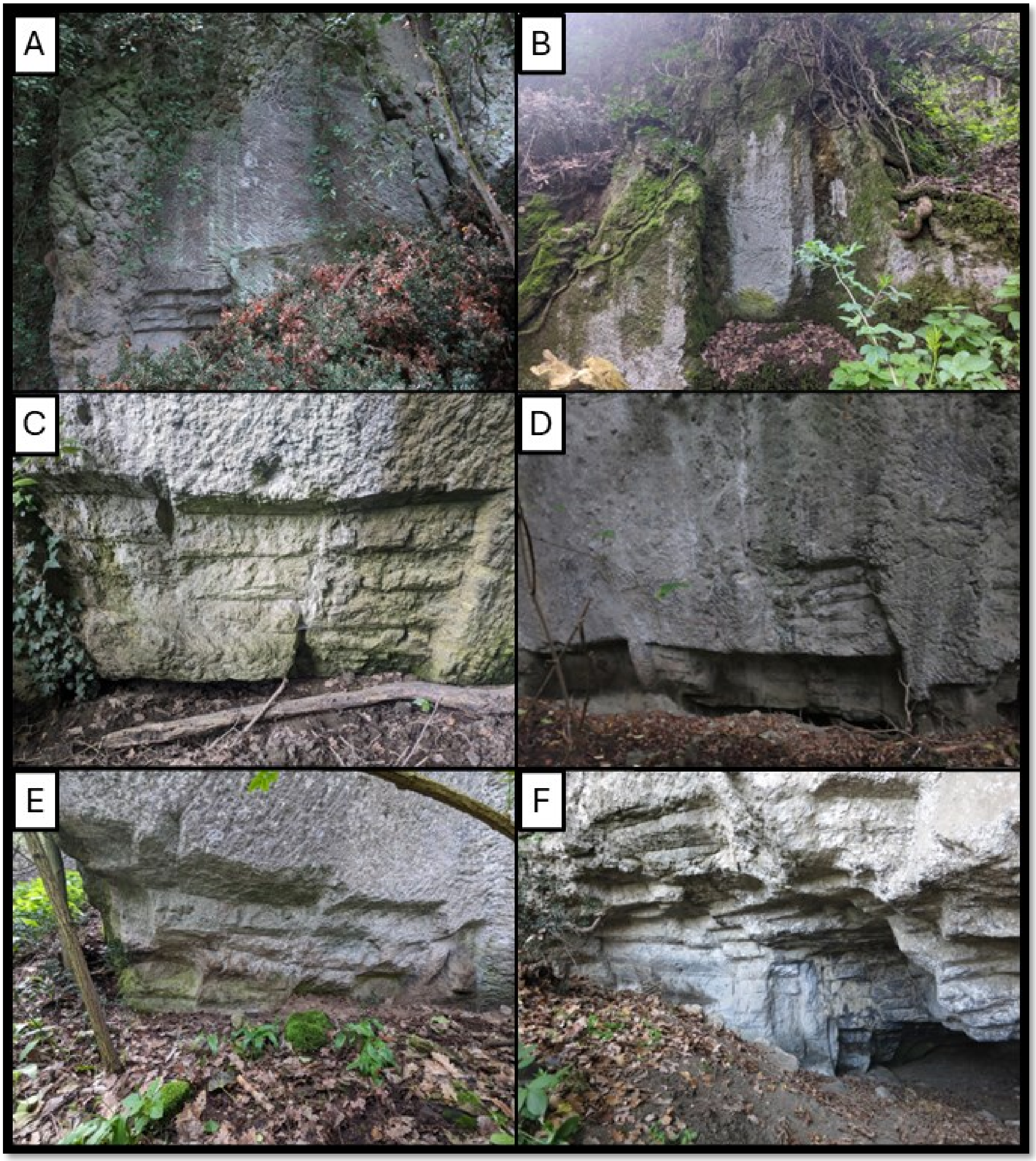


Figure 23 – Photographs of traces of pick marks and block excavation from QF 5.03 and 5.04. A – Quarry wall with pick marks and small typology of block extraction. B – Unique elongated quadrangular cut from eastern portion of QF 5.04. C & D – examples of small, coordinated, typology of block extraction from western and central portions of 5.04. E & F – examples of the large, typical, and irregular block extraction from easternmost portion of 5.04 and entrance to 5.03.

4.1.3 Function Analysis

The morphologies, typologies, and various evidence of quarrying activity found across the identified quarry features of the site testify the extent to which the area was utilized. However, as quarrying activities have been conducted in the Colli Euganei for more than two millennia, it is necessary to examine the area to determine to what degree the formation of these quarry features relate to the same phase of extraction and what evidence is present to indicate interconnectivity between features.

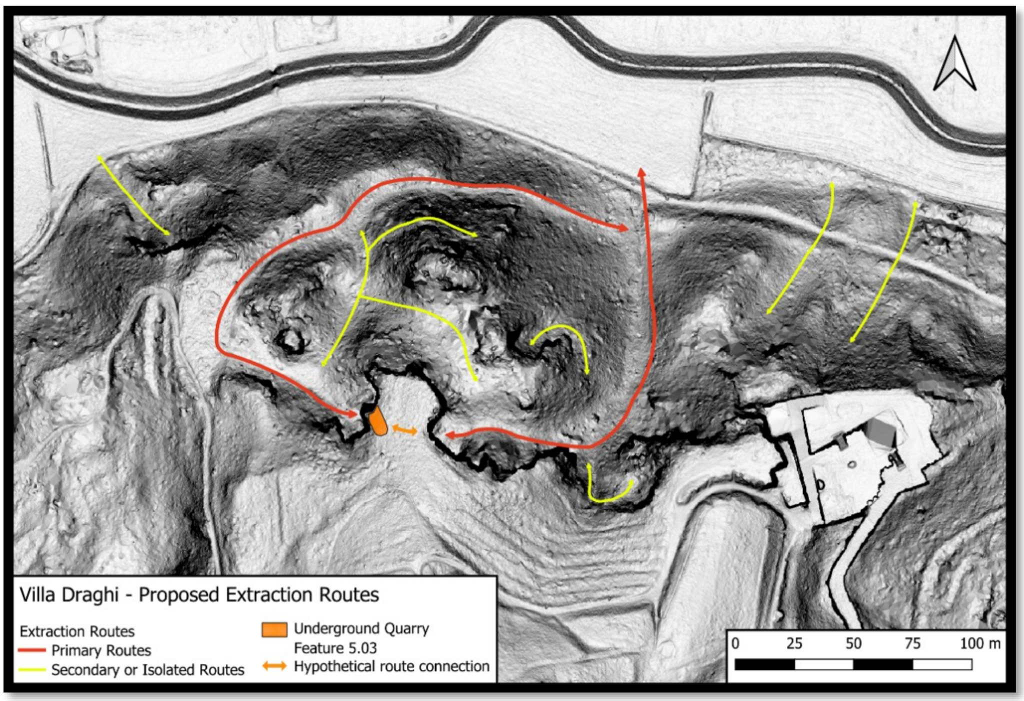


Figure 24 – Slope map of the Villa Draghi quarry site depicting primary, isolated, and secondary extraction routes and the proposed hypothetical connection which the unexcavated underground quarry 5.03 may create.

The primary evidence for the function of this area as a cohesive area of planned quarrying related to one temporal period are topographical indications of roads used to access the quarries and transport their materials. At the Villa Draghi site there are several areas which indicate the existence of ancient trails through the landscape. Two primary routes are proposed here which were identified through slope analysis of the region (figure 24). For the purposes of site connectivity these routes suggest that the center of QF 5.04, the irregular portion exposed from the otherwise semi linear quarry face and which the subterrain quarry QF 5.03 is located beneath, was the epicenter of quarrying activities. Two primary access routes are proposed, which suggest access around the northern slope to one of the conical hills of rhyolitic lava suggesting the presence of further, yet undocumented, quarrying activity. The secondary proposed routes indicate from what direction individual features may have been accessed (figure 24).

The confluence of these two primary routes ending on either side of the topographical outcrop which QF 5.03 is quarried beneath may also be indicative of a greater interconnectivity of the area than presently visible. QF 5.03 is filled with erosional sedimentation except for a couple meters from the ceiling of the subterrain portion. However, a small segment only several centimeters wide on its western extent connects with the eastern rectangular quarry face of QF 5.04 at its present base elevation. These surface marks show targeted quarrying activity in the direction of QF 5.03 (Figure 24). The same evidence of block extraction is found directly west of the subterrain quarry and increases in depth as elevation decreases. This is an indicator that the subterrain quarry may tunnel through the entire width of its geological strata and that the termination points of the major access routes of the quarried region are indicative of multiple entrances to this subterranean quarry. However, in all these locations sedimentation has prevented the true extent of quarrying activity from being understood. With the addition of further research in the form of targeted excavation and geophysical survey methods like electro resistivity, the true depth and extent of feature QF 5.03 and the base quarried elevations of the surrounding portions of QF 5.04 may be discerned.

Additionally, A large 1,200 square meter artificially flattened area to the west of QF 5.02 and transected by the western access route (figure 21), may be the result of a processing area where quarried blocks were collected, shaped, and stored before being transported down the hill slope and into the plane to the north. Processing areas are typical features of extensively quarried premodern quarries, especially during the Roman period, and they are indicative of a planned management of quarry sites in areas undergoing lengthy periods of extraction (Rockwell, 1993).

These features support the idea that the quarry features dispersed around them are related to a well-planned and managed extraction of breccia materials across multiple, densely located, quarry locations, particularly the quarry features QF 5.02 – 5.07 which are dispersed across the vicinity of the proposed extraction routes. While the remaining features may relate to the same period of extraction, they are individually accessed directly from the base of their slopes.

4.1.4 SUMMARY

The review of the features, distribution, size, surface characteristics, and the function of the interconnected sites indicates that this complex of densely dispersed quarry faces are related to an extensive period of organized quarrying. The recent provenance matching of samples collected at QF 5.04, which found materials from the quarry were utilized in the production of Roman concrete at the Via Degli Scavi site, provides a clear indicator for the period of extraction of these interconnected quarry features (Pilgrim, 2024). This is supported by the consistency of surface characteristics found at multiple locations, the geographic proximity of sites, the uniformity of breccia material type across all quarries, and importantly the compatibility of these characteristics to known Roman quarries across the Mediterranean and northern Italy (Bessac, 1988; Coli et al, 2011; Garcia-M, 2011; Previato, 2018). There is the possibility of multiple periods of extraction, especially considering the eastern quarry features at Villa Draghi which are heavily weathered and more isolated. The heavily extracted and interconnected nature of most of the quarries at Villa Draghi suggest that additional sampling of Roman concrete samples in the area of *Patavium* is likely to produce additional sites with provenance to the Villa Draghi quarry complex and expand our understanding of local material selection for concrete in Northeastern Italy during the Roman period.

4.2 THE VIA SCAGLIARA QUARRIES

The Via Scagliara quarry site is a collection of open pit quarry faces located on a minor hill formation north of Monte Castellone and northwest of Monte Ceva (figure 25). It is directly south of the via Scagliara road which traverses east-west through the valley between the Monte Oliveto ridges to the north and those of Monte Ceva to the south. Due to the road's proximity to the site and the etymological route of name "Scagliara," being a reference to the flacking and debris of stone materials, it was chosen as the name for these quarries.

4.2.1 SITE DESCRIPTION

The site is composed of six quarry features which were verified through field surveys and additional two features which have clear topographic indicators for associations with quarrying activities but were either unable to be confirmed during the survey due to erosional deposition and vegetation or require further analysis and documentation. The verified features have similar characteristics as they are composed of multiple exposed sections of convex and linear quarry wall faces which follow the topographic curvatures of their surrounding hill formation and cut into it with linear, rectangular, or stepped sections.

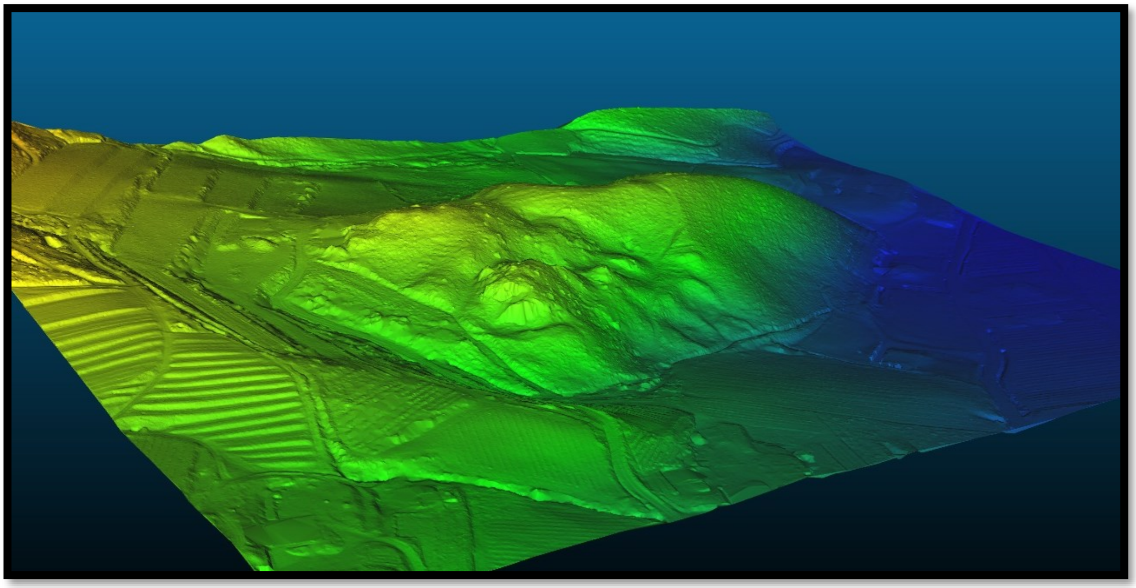


Figure 25 – 3D visualized of the Via Scagliara quarry site and hill formation. Produced through Cloud Compare TIN (Triangular Irregular Network) mesh processing of ground classified point cloud from UAV survey. Color ramp represents elevation change. View based perspective with standard lighting at natural scale.

From a geological and topographical perspective, the site represents a targeted extraction of an isolated hill formation, a trend seen through the survey, especially in areas 3 and 7. The formations' current topography has been heavily modified by anthropogenic activities but it was almost certainly composed of a primary east-west oriented ridge line to its south, a second peak to its northeast, and interestingly a minor valley formation between the two in the center. Here, as well as at the Villa Draghi quarries, there is unambiguous evidence of the targeted excavation of rhyolitic breccia which is superimposed or intermixed in geological strata of rhyolitic lava. The rhyolitic lava appears either in the exposed sections of quarried sections of the hills or as two conical formations in the center of the hill. These features, and the distribution of breccia materials intermixed above and between the slopes of lava are indicative of the stereotypical volcanic formations of the region where emissions of magma during the Eocene produced multiple neighboring conical formations of rhyolitic lava which are covered in earlier deposits of volcanic breccia dislodged, fragmented, and cemented together through a process of submarine rapid cooling. The isolation of the hill features of the Via Scagliara site are a characteristic of these formative processes and from a resource extraction perspective, they allow for a more direct extraction of materials with less effort than similar resources within the larger hills.

From a historical perspective, the Via Scagliara quarries are in the immediate vicinity of known Roman regions of extraction as well as the 12th century navigational canals. Like the Villa Draghi quarries, this densely quarried hill is located only one kilometer from Monte Oliveto, the most researched and most utilized Roman trachyte quarry of ancient *Patavium* (Capedri, Venturelli, and Grandi, 2000; Zara 2016; Germinario et al, 2018a). The key distinguishing factor of the known Roman quarry sites of Monte Oliveto and Villa Draghi (Pilgrim 2024) from the Via Scagliara site is the fact that its location is within the hill formations, instead of adjacent to the eastern exterior of the Colli Euganei formations and the central Veneto plain. The Via Scagliara quarries are nestled within the depression between Monte Castellone, Ceva, and Oliveto with a base elevation more than 25 meters higher than the nearest portion of the central Veneto plain and in a valley where the present road rises more than 80 meters above the plain and nearly 1.8 kilometers from the site. Based on the quantity of quarry faces in the location, this indicates the resources were valuable enough to extract them from an interior location for an extended period of use. However, these distances and elevation gains are minor when considering the entirety of the Colli Euganei.

4.2.2 Identified Features

By reviewing various raster terrain models like SLRM, Slope, and Multi-hillshade produced through the high-resolution LiDAR data and conducting a limited field survey of the sites, several features were identified relating to quarrying activities which are categorized under two distinctions. The first being quarry features which were identified and documented, with samples collected in the field. Features VS 1 - 6 were all validated in the field as areas of evident quarrying (in the statistical analysis and results of Area 1 these are grouped under QF 1.43, 1.44, and 1.44.1 to better represent quarried areas instead of independent features). These quarry faces have a variety of morphologies including a rectangular cut, linear segments, and substantial portions of convex irregularly quarried faces (table 7). When grouped, these indicate a quarrying method which prioritized following the breccia stratum around the main hillslopes, with several areas of a greater depth of extraction where the material was most available (VS-3, 4, and 5). Typologically, these features are all open pit quarries, however feature VS-2 is a stepped variety with two clear quarry faces (figure 27a) and features VS-4 and 5 appear to be part of a larger area of quarrying activity and are the stepped remnants of a major quarry (figure 26).

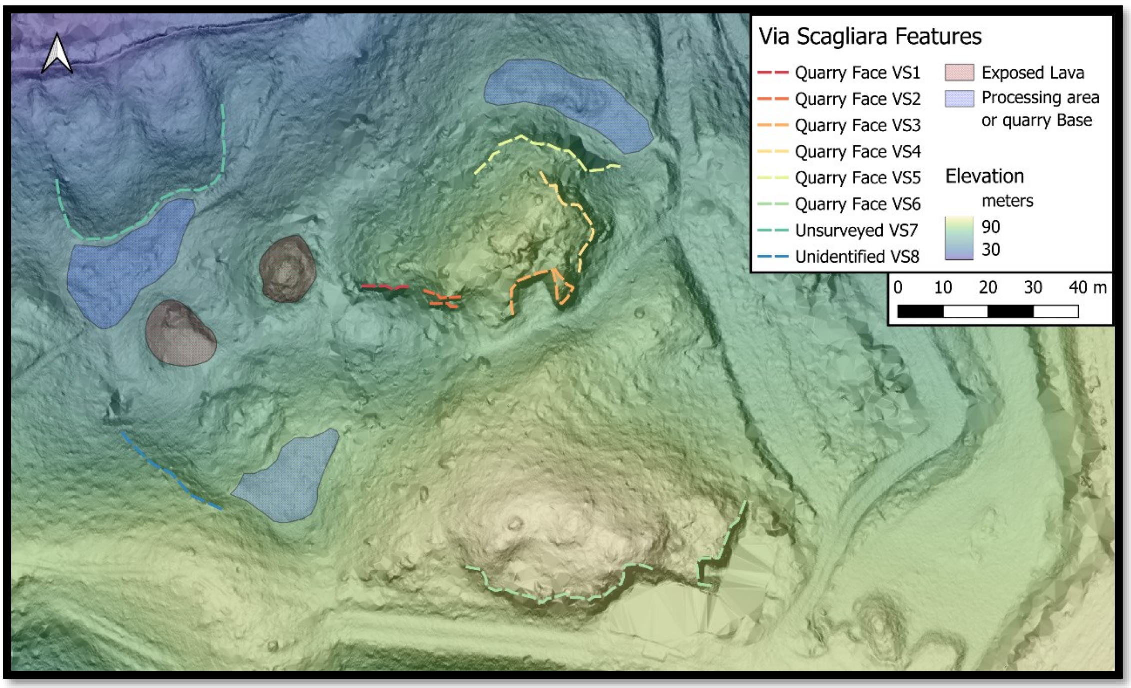


Figure 26 – Via Scagliara Quarry Site map depicting the quarry faces and associated features relating to quarrying activity identified at the site. Map is composed of Slope values overlayed by transparent hillshade and elevation color ramp values.

The second category of quarrying activity are two features which are clearly indicative of quarrying from a topographic perspective, but which were unable to be confirmed during field surveys. Feature VS-7 is a large double basin concave depression with a moderate slope, but an obvious anthropogenic formation, and feature VS-8 is in the center of the formation, with a visible but shallow slope, and boarded by apparent processing areas or remnant bases of quarries. In both contexts field surveys did not disprove the function of these features as quarries. Instead, a surprising amount of soil and vegetation obscured the ability to identify faces. However, it is likely that limited excavation or geophysical survey would identify the extent of anthropogenic activity in the regions as their morphology is clearly related to quarrying (figure 26).

The surface characteristics of quarrying activities across these faces are more weathered than those at Villa Draghi but are identifiable across several of the features. The most widespread are pick marks which are found in various degrees of quality across features VS1-5 (figure 27d, e, and f). Measurements of their sizes are difficult to approximate, however, in the best-preserved location, VS-3, each pick line is about 4 centimeters apart, diagonal, and slightly curvilinear in shape, measuring about 40 cm long. Intersections of horizontal bands of quarry marks suggest, like at Villa Draghi, that the direction alternated at times with each layer of excavation. Additionally, at the base of VS-5 there are apparent chisel or pick trench marks, about 7 centimeters wide and 2.5 centimeters deep, demarcating the width of an unexcavated quarry block about 80 centimeters wide. The marks were partially buried by soil sloping against the base of the quarry wall. An indicator that the true base of the quarry wall is buried, by meters of deposits.

QF ID	Quarry Face Length (m)	Quarry Face Max Height (m)	Morphology	Typology	Material
VS 1	10.6	4.0	Linear	Open Pit	Rhyolitic Lava & Breccia
VS 2	8.4	5.9	Linear	Open Pit - Stepped	Rhyolitic Breccia
VS 3	33.7	3.5	Rectangular	Open Pit	Rhyolitic Breccia
VS 4	29.9	6.4	Convex	Open Pit (Stepped?)	Rhyolitic Breccia
VS 5	37.1	8.3	Convex, Rectangular	Open Pit (Stepped?)	Rhyolitic Breccia
VS 6	74.8	4.4	Convex	Open Pit	Rhyolitic Breccia
VS 7	N/A	N/A	Concave	Open Pit - Shallow	N/A
VS 8	N/A	N/A	Linear	N/A	Rhyolitic Lava & Breccia

Table 7 – Quarry attributes of features proposed or identified at the Via Scagliara Quarry Site

Unlike at Villa Draghi, negatives of quarry block extraction are not clearly defined or visualized. Other than the partially buried demarcated block (figure 27e), the best evidence for block size are several partial portions found at VS-2 and 5 where multiple sections of rectangular wall face intersections are visible. At VS-5, one segment shows numerous levels of semi-irregular block extraction throughout its height, however the depth is only several centimeters at most. Combining these traces, it suggests a typology of semi-irregular sized block extraction, like those at Villa Draghi, with a preference to excavate until the formation of complete quarry wall faces, without additional quarrying into the faces. However, this may be the result of a high depth of sedimentation obscuring the visibility of quarry bases, where this technique primarily occurred at Villa Draghi.

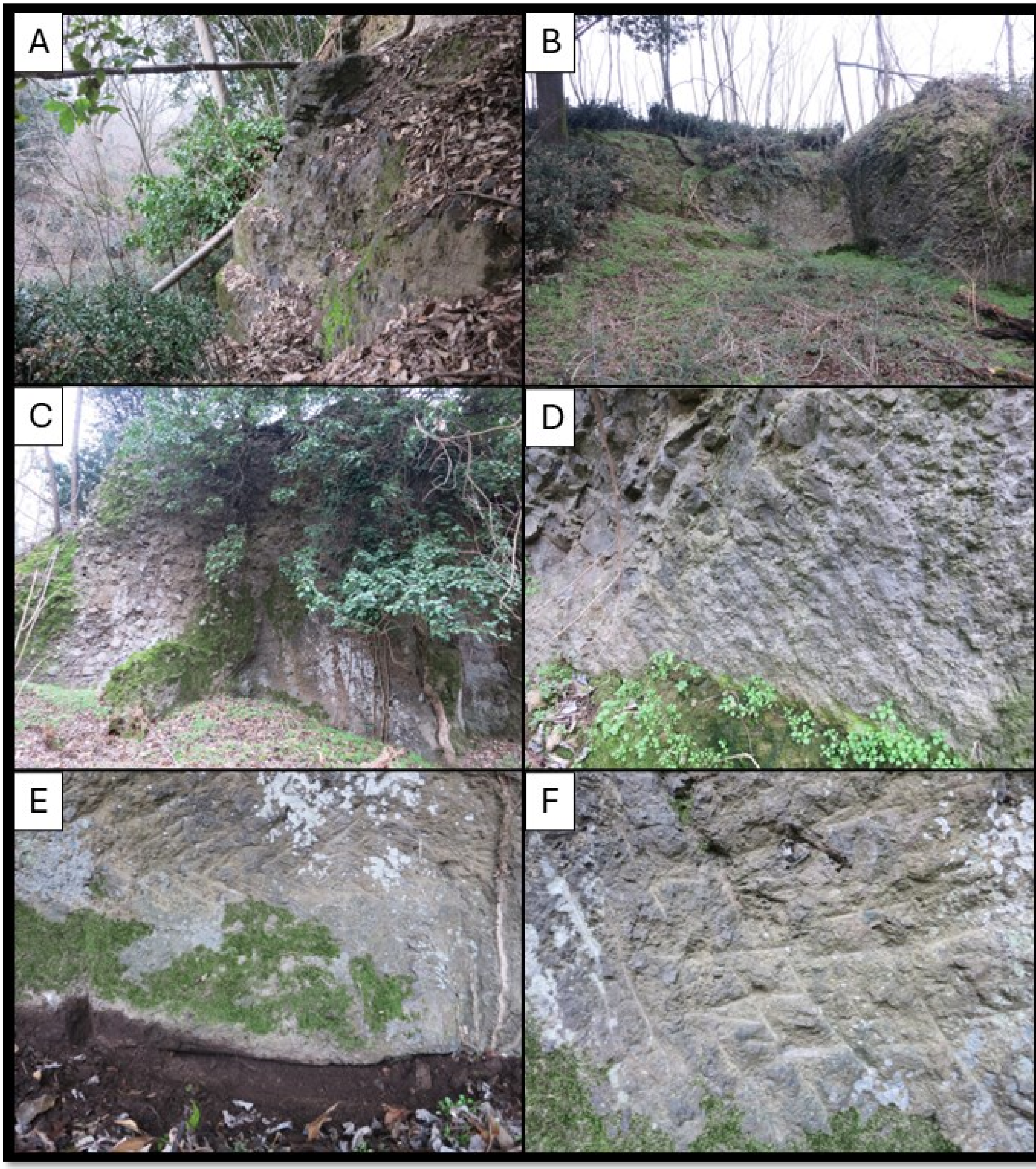


Figure 27 – Survey photos of Via Scagliara features and quarry marks. A (VS2) shows the partial stepped nature of the quarry wall and negative cuts of block extraction. B & D (VS3) photos show the rectangular cut of the feature and uniform pick marks. C, E, & F (VS5) shows some of the linear and rectangular faces found across the feature, overlapping pick marks (F), and the incised boundaries of an unexcavated block (E). Photos by J. Olah

4.2.3 Functional Analysis

Here, as at Villa Draghi, the density of quarry faces and features are indicators of a coordinated and prolonged period of quarrying activities. To assess the function of the area as an interconnected group of quarries associated features must be examined. At the Via Scagliara site, a series of access routes to travel within and out of the quarry complex, as well as probable processing areas, are indicators of the interconnected function of these features.

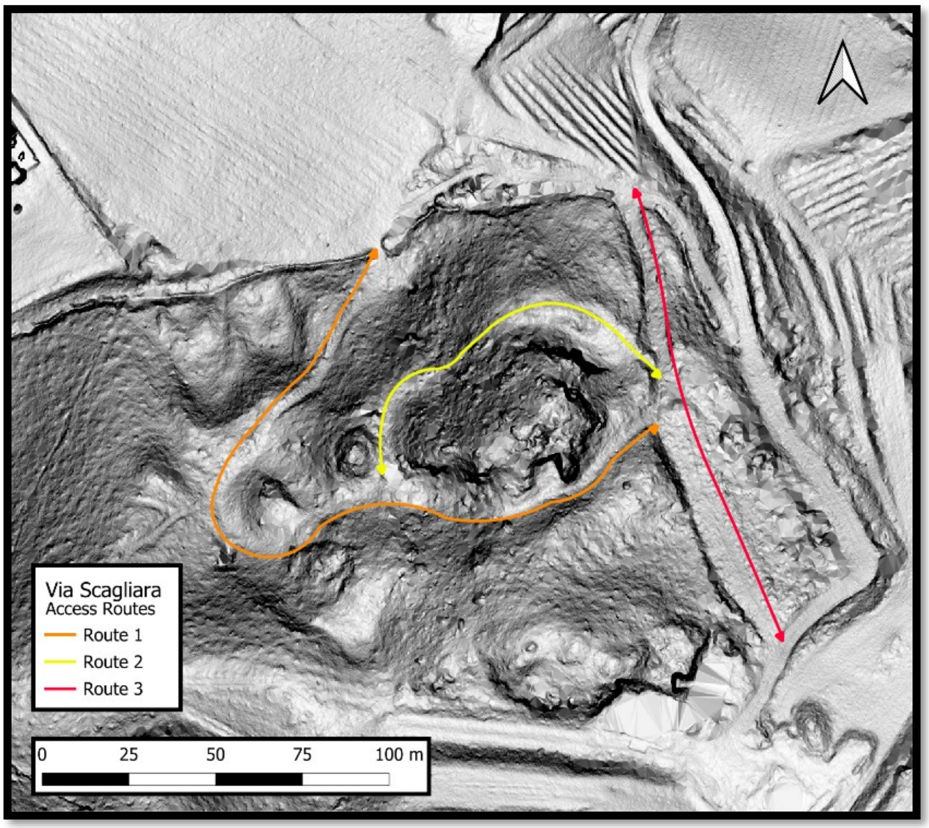


Figure 28 – Slope Map of the Via Scagliara Quarry site depicting three possible routes of access/resource extraction. Note that Routes 1 and 2 are similarly poorly defined in their limits while Route 3 is clearly defined, indicating a probable difference in periods of use.

Through the examination of SLRM, slope, SVF, and multi-hillshade DTMs produced through the high-resolution LiDAR survey, in particular slope visualizations, three primary access routes have been identified, which affected the natural topography of the Via Scagliara hills. Route 1 appears the primary route of the quarry complex, entering the formation from the northern plain in SSW direction, skirting the heavily extracted hill to its east, and turning uphill to the east across a minor valley between two hill formations and intersecting with route 2. In doing so it passes directly adjacent to features VS1 through VS3 and may represent a probable route of extraction for VS4 and VS5, as its profile is mostly a gradual downhill slope until reaching the plain (figure 28). Route 2 skirts the primary hill of extraction along the western and northern slopes and appears to have functioned as an access between the two heavily quarried regions near VS4 and VS5 to the northeast and VS1 and VS2 to the southeast. It may also indicate that minor quarry activity was conducted on these slopes. Its slope is less dramatic change in elevation than the central valley of the quarried areas and it may have been a method to transport materials to the cleared base of VS5. Route 3 is a linear feature, oriented SSE, wide, and cut into the hillside itself. The anthropogenic levelling ranges from 5 meters to 12 meters wide and the cut of the hillside is as deep as 3 meters. These characteristics distinguish it from other access routes identified at either case study raising the possibility that it may be related to another period of activity unrelated to quarrying activities. However, the interconnectivity it provides to the Via Scagliara Road valley, VS4 and VS5 in the center, and VS6 to the south, makes it a candidate. Additionally, the cuts in the hillside need to be investigated and may represent minor quarrying activities, and the road is overgrown and abandoned showing an extended period of disuse. Another road exists just to the east, which is better positioned for servicing agricultural needs, while route 2 appears to be designed for access within the hill formations. For these reasons it is assumed to be dated to the same period of activity as the quarries, though this requires further investigation.

Additional features that require further investigation are three particularly flat regions dispersed across the quarried areas. Each is clearly the product of anthropogenic activity and have minor changes in elevation. They may have functioned as processing and storage areas for the collection of quarry blocks before transportation out of the hill formation and to navigational canals in the central Veneto plain. Additionally, they could be produced through the excavation of quarries and are representative of the remnant bases. The most particular of these is the central feature which is raised in elevation and slightly isolated. Its location near the proposed quarry face of VS8 may indicate that the area was quarried despite limited physical evidence. This location, as well as the bases of most of the quarry features, would benefit from further research in the form of targeted excavations or geophysical surveys to determine how the large amount of soil deposition in the area has obscured our understanding of the quarry complex.

Combined, these features indicate that there is a clear association between these quarry features. Their extraction of the same material type, morphology, and surface marks are all indicators of a shared methodology in quarrying activity. The density of the features, their concentration in one isolated hill formation, and their interconnectivity visible through multiple access routes and proposed processing areas indicate that the area functioned as a consolidated region of planned quarrying of volcanic breccia for an extended period.

4.2.4 Summary

In conclusion, the Via Scagliara quarry complex represents a concentrated and prolonged effort to extract rhyolitic breccia from an isolated hill formation within the Colli Euganei. The site's numerous quarry faces, interconnected by access routes and probable processing areas, reflect a well-coordinated operation, driven by the valuable nature of the resources despite the challenging terrain. The distinctive geological features of the area, including the targeted rhyolitic breccia intermixed with lava, underscore the strategic significance of this quarrying activity in the broader context of the region's volcanic landscape. The evidence suggests that the Via Scagliara quarries played an integral role in the resource extraction history of the Colli Euganei. Expanded research in the form of targeted excavation, geophysical surveys, and provenance matching of samples to archaeological sites in the region will greatly improve our understanding of the site.

4.3 Site Comparison

The original incentive for choosing the Villa Draghi quarry site and the Via Scagliara for case study analysis were their apparent topographical similarities first made evident in the high-resolution LiDAR data. Following the successful provenance analysis of Villa Draghi to the Roman period site Via degli Scavi in Montegrotto Terme, the site's function as a heavily utilized quarry for the manufacturing of Roman concrete has been well established (Pilgrim, 2024) and further supported by the sherds of roman roof tiles found within the quarry, and its location within a known area of Roman quarrying (Germinario et al., 2018a). The multiple levels of comparability with the Via Scagliara quarries in the form of typologies, morphology, surface marks, topography, and overall function supports the hypothesis of this site belonging to a Roman period of extraction, either simultaneously or one preceding the other.

The typologies of the quarry features at both sites are similar, with both displaying a combination of open-pit and stepped quarry faces. These features suggest a shared methodology in extraction, focusing on following the natural contours of the landscape to maximize resource yield. Both sites have quadrangular quarry face features, and they present a unique morphology in comparison to the rest of the survey areas that only appears, to this level of similarity, at these sites. The sites share another unique morphology in the form of large double basin excavated open pit quarries which in both locations have gradual slopes and poorly visible quarry walls, but with large amount of breccia gravel or boulders dispersed within them (figure 29). These features, QF 5.10 and VS7, have morphologies which are the most comparable to each other than any other feature identified in this survey. The shared morphology, typology, and material properties between the sites is a valuable indicator of a shared period and methodology of quarrying (Rockwell, 1993; Garcia-M, 2011, Garcia-M and Rouillard, 2018). While the morphology of Roman quarrying techniques has been well documented as non-standardized and therefore difficult to determine through survey, Roman quarries have been shown to share characteristics when quarried in the same region the same material, and therefore morphological similarities within the same geological region are often an indicator for shared provenance (Rockwell, 1993).

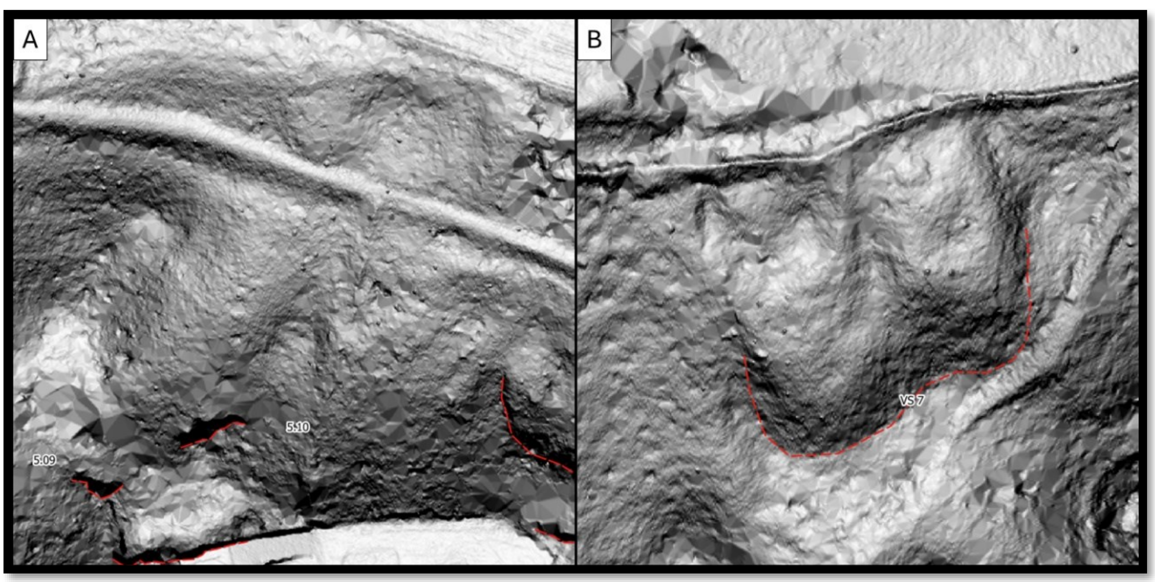


Figure 29 – Slope maps of similar shallow sloped double basin depressions related to quarrying activity at 1:500 scale. A – from the north slope of Villa Draghi, probably related to quarry face QF 5.10, note that the lower portion is cut by a more modern trail. B – feature VS-7 from the Via Scagliara quarry site.

Surface marks across both sites, particularly the pick and chisel marks, also exhibit consistent patterns. The spacing and orientation of these marks indicate a mostly unstandardized technique for larger stone blocks. This too has been established at multiple roman quarry sites where most materials, except for precious decorative stones and project oriented constructional stones, tend to be sized according to the natural bedding and vertical faults present in the material (Bessac, 1988; Rockwell, 1993; Coli et al., 2011). These similarities in quarrying methods between the sites point to a similar period of quarrying activity likely of Roman origin.

Topographically, the sites are situated in distinct yet comparable environments. The Villa Draghi quarries are positioned on a prominent hill formation with a broader view of the surrounding landscape, offering easily accessible transportation in the Roman period (Germinario et al., 2018b). In contrast, the Via Scagliara site is nestled within a more secluded, less accessible area but still within the general vicinity of the well-established Monte Oliveto Roman trachyte quarry. Despite these differences, both locations feature ridges and valleys that would have influenced the placement and extent of quarrying activities, with both quarries heavily exploiting their associated hill slopes to the point of exposing multiple conical hills composed of lava (figures 21 and 26). This extent of quarrying created the unique exposed geological features of their areas, in a form which has only been identified at these two quarry complexes, again indicating a shared methodology of extraction, and implying both sites were extensively quarried for extended periods of time.

The extraction routes at both sites are indicative of a strategic approach to transporting materials. Villa Draghi shows evidence of direct routes leading to the central Veneto plain and therefore navigable waterways, which would have facilitated the movement of the stone blocks (Germinario et al., 2018b), and it shows that most of the quarries functioned as one large enterprise with shared routes. Via Scagliara, while more isolated, also features carefully planned routes that connect the quarry faces with each other and to a broader regional network. These routes, while difficult to interpret (Jimenez et al., 2020), combined with the general topography of their areas, support the interconnectivity between quarry features and the high degree of comparability found across these two case studies.

Given the similarities in quarry feature typologies, morphologies, surface markings, and the strategic planning of extraction routes, Via Scagliara exhibits many characteristics associated with Roman quarrying operations. The parallels in the functional aspects of both sites strongly support the hypothesis that Via Scagliara served a similar role as a Roman quarry, despite its more challenging location. The consistency in quarrying methods and evidence of transportation networks further reinforce this conclusion.

4.4 Summary of Findings

In conclusion, the comparative analysis of the Villa Draghi and Via Scagliara quarry sites has provided substantial evidence supporting their classification as Roman-period quarries. The similarities in quarry feature typologies, extraction methods, and transportation networks between the two sites indicate a shared methodology and operational period. This not only underscores the significance of these sites within the broader context of Roman industrial activity in the Colli Euganei, but also enriches our understanding of the technological and logistical approaches employed by Roman quarrymen in this region.

This analysis shows the extent to which high-resolution LiDAR surveys combined with field surveys and site documentation can be utilized to characterize the features of quarried regions, determine their function with their region, and expand our understanding of the ancient quarrying activities in the Colli Euganei, especially those composed of volcanic breccia and the extent of local pozzolanic material utilization in Roman world. These indications have the potential of expanding our knowledge of this period and with the addition of thorough petrographic and chemical analysis of geological samples from both sites against archaeological sites dispersed across the greater *Patavium* area, knew indicators of the extent of this material utilization in the Roman period will be gained.

Chapter 5: Discussion

This chapter interprets and reviews the research conducted, contextualizing the methods, quality, and significance of the results. First, the findings are evaluated in terms of their benefits. Then, the limitations of the data and methods of analysis are considered, along with recommendations for improvement. Finally, current objectives for continuing this research are outlined, and future projects related to the historic quarries of the Colli Euganei and the application of high-resolution UAV LiDAR surveys in forested environments are suggested.

5.1 Interpretation and Analysis of Findings

The primary objective of this research was to evaluate the advantages of high-resolution UAV LiDAR in identifying quarry features in the Colli Euganei and compare it with 1-meter resolution aerial LiDAR data. The results confirmed that the added labor and expense of conducting UAV LiDAR surveys were justified due to the significant improvement in the accuracy and resolution. The Digital Terrain Models (DTMs) produced by the UAV LiDAR were 25 times more detailed than those generated from the 1-meter aerial data, which suffered from considerable interpolation, particularly in areas with dense vegetation. The UAV LiDAR data provided a clearer representation of quarry features, with less interpolation. For example, of the 89 potential quarry sites identified using the 0.2-meter UAV LiDAR data, a sizable portion (approximately 46%) were either difficult to distinguish or entirely obscured in the 1-meter aerial data. This highlights the substantial difference between the two methods, particularly for identifying smaller or more concealed quarry features.

Even for larger quarries, the 1-meter data had notable limitations. The lower resolution resulted in several meters of interpolation between the highest points of quarry faces and their bases, distorting the sites' overall morphology. In contrast, UAV LiDAR data reduced this interpolation to a few dozen centimeters, providing a far more accurate depiction of the quarries' spatial and morphological attributes. These findings underscore the value of high-resolution UAV LiDAR surveys in forested environments for accurately visualizing and measuring anthropogenic features. While 1-meter aerial LiDAR may be appropriate for broad landscape analysis it fails to detect smaller features and conduct detailed morphological analysis in heavily vegetated areas. For projects requiring precise documentation of feature morphology or in-depth site analysis, UAV LiDAR is indispensable.

Traditionally, LiDAR has been used primarily for large-scale landscape analysis, major feature identification, or site documentation alongside methods like orthophotography and total station measurements. However, recent advances in UAV technology, LiDAR sensors, and point cloud processing have made high-resolution surveys more accessible and capable of producing detailed results. The 89 potential quarry sites identified in this study range from large, easily detectable features to complex, interconnected quarry systems, such as the Villa Draghi and Via Scagliara quarries, or smaller, isolated quarry features such as QF 1.26 and QF 1.27. Without the high resolution of UAV LiDAR, many of these sites would not have been detected.

At the Villa Draghi and Via Scagliara quarries, the UAV LiDAR data enabled a comprehensive visualization of interconnected features, including multiple quarry faces, platforms, and extraction routes. Field surveys enriched this analysis by collecting geological samples, photographs, and detailed descriptions allowing the sites to be interpreted as integrated systems with shared morphologies and spatial relationships. Comparisons with other quarries identified through the UAV surveys revealed a high degree of similarity in their attributes to each other, supporting the hypothesis that the Via Scagliara quarries date to the Roman period, like the Villa Draghi quarries. This underscores UAV LiDAR's capability to enable detailed site-level analysis, even in challenging environments.

This research also demonstrated the potential for using high-resolution LiDAR to perform statistical analysis on quarry features. By measuring physical and spatial attributes from the UAV data, statistical analyses explored relationships between quarries. Clustering analysis suggested two to three distinct groups of quarries within the dataset. These findings aligned with qualitative groupings based on region, morphology, and size. The analysis distinguished a cluster of presumed modern quarries with significantly different attributes, particularly in size, from the historic quarries. This demonstrates the value of combining quantitative methods like clustering analysis with traditional qualitative approaches to refine the classification of quarry sites. However, the inclusion of modern quarries might have influenced the clustering results due to their enormous size and more extreme attribute values. Nevertheless, this analysis highlights the potential of high-resolution LiDAR data for statistical analysis of quarry features, offering another dimension to landscape analysis beyond basic feature identification.

5.2 Limitations

Despite the meaningful contributions of this research to understanding the quarry landscape of the Colli Euganei and the premodern use of pozzolanic breccia materials, several limitations are worth acknowledging. These relate to the self-imposed constraints on quarry identification, the methods used in the UAV survey, and the early stage of this larger research project, including the inability to assess all features through field survey documentation, geological sample analysis, and provenance studies.

In terms of identifying potential quarry sites, remote sensing was the sole factor in the initial determination, with plans for subsequent field surveys. While the 1-meter resolution LiDAR struggled to clearly identify moderate, complex, and small quarries, the UAV LiDAR data faced its own challenges. The high resolution captured even minor anthropogenic disturbances, and some quarries, initially appearing continuous, were revealed as multiple closely spaced faces. Due to the impracticality of fully surveying all potential features, constraints on feature size (section 2.4) were applied to focus the investigation. Additionally, several areas with modern houses built directly against apparent quarry cuts, such as those at Catajo Castle, require future investigation. Additionally, the 89 identified potential quarry feature sites often grouped closely related features under a single identification number to better represent areas of quarrying activity, and individual features were examined separately only in specific cases, like with the Via Scagliara quarries.

The UAV survey methods also presented challenges. Although GNSS-nRTK positioning achieved acceptable accuracy for the landscape survey, the most precise method would have involved deploying multiple ground control points (GCP), providing sub-centimeter accuracy. However, this approach was deemed impractical due to the time and cost required in the forested and hilly terrain of the Colli Euganei, especially since the nRTK positioning was already highly accurate. Another issue is that some regions were not surveyed. Expanding the UAV survey to cover these additional areas, particularly the absent north-central portion of area 1, would further enhance the understanding of the region’s quarrying landscape.

Lastly, the field surveys and geological sample collection are currently incomplete, with only 30 of the proposed features examined. Future fieldwork will deepen this analysis by providing more detailed geological, typological, and archaeological context for the identified quarries. However, the data gathered from the UAV LiDAR surveys were still sufficient to conduct meaningful spatial and morphological analysis.

5.3 Future Research Suggestions

This study marks the beginning of a larger project aimed at addressing deeper questions about the quarry landscape in the Colli Euganei, with a specific focus on the morphological, spatial, and geological diversity of historic quarries, particularly those associated with pozzolanic breccia materials. Answering these questions will require extensive future research spanning several disciplines, particularly petrographic and chemical analysis, historical material provenance, and archaeological field studies.

One promising area of future research is the detailed petrographic and chemical analysis of geological samples collected from the quarries identified in this study for the purpose of provenance research. By comparing these quarry samples with archaeological materials from nearby historical sites, it will be possible to trace the provenance of the stone and better understand how and where breccia materials from the Colli Euganei were utilized (Pilgrim, 2024). This approach could reveal critical information about regional exploitation patterns, trade distribution, and the temporal periods during which specific quarries were actively used (Capedri, Venturelli, and Grandi, 2000; Capedri, Grandi, and Venturelli, 2003; Zara, 2016; Germinario, 2017; Germinario *et al.*, 2018a; Germinario *et al*, 2018b).

A key component of future work will involve expanding provenance research on the breccia quarry case studies of Villa Draghi and Via Scagliara quarries. Initial research has already linked materials from the Roman Via degli Scavi site in Montegrotto Terme to the Villa Draghi quarries (Pilgrim, 2024). This suggests that the Villa Draghi quarries were used during the Roman period, and further research may uncover additional Roman-era sites that sourced their construction materials from this location. By analyzing the extensive material extracted from the Villa Draghi quarries, it will be possible to determine specific temporal periods of quarry activity, shedding light on the broader Roman exploitation of the Colli Euganei's resources. Similarly, the Via Scagliara quarry site has yet to be analyzed. Given the morphological, typological, and surface mark similarities between this site and Villa Draghi, it is hypothesized that Via Scagliara was also exploited during the Roman period. Provenance research here could confirm this hypothesis, expanding the understanding of Roman-period quarrying activities in the region.

The UAV high-resolution LiDAR surveys conducted in this study covered 8.5 square kilometers, but additional areas remain unexplored, particularly in the north-central portion of Survey Area 1. Expanding these surveys will allow for a more comprehensive analysis of the quarry landscape. This method could also be applied to other regions with dense vegetation or rugged terrain, where traditional methods may fall short. Additionally, Future research should incorporate statistical analyses, such as multivariate clustering, to refine quarry classification when applicable as this integration of quantitative and qualitative approaches will deepen our understanding of quarry systems and the completion of the planned field surveys will provide additional insights into quarrying methods and associated artifacts, contributing to a richer interpretation of the region's historical use.

In summary, future research should build on the methodology of this study, focusing on expanding UAV coverage, enhancing provenance studies, and integrating statistical analyses. These efforts will deepen our understanding of the quarry landscape in the Colli Euganei and inform broader archaeological inquiries.

Chapter 6: Conclusion

This research was conducted to address several research questions regarding the breccia quarries of the Colli Euganei, aiming to identify their locations, evaluate the effectiveness of publicly available LiDAR data, and determine the benefits of high-resolution UAV LiDAR surveys. The results presented in this study clearly demonstrate the advantages of UAV LiDAR for identifying and analyzing anthropogenic features, such as quarries, in the forested and varied terrain of the Colli Euganei. The superior quality of data from these surveys enabled enhanced visualization, identification, measurement, and analysis of quarry features across the landscape. As a result, dozens of previously undetectable quarry features were revealed, regional statistical analysis was possible due to the data's improved accuracy and resolution, and localized case studies, like those of the Villa Draghi and Via Scagliara quarries, showcased the potential for high resolution LiDAR data to be utilized at regional and site-specific interpretations of quarrying activities.

The comparison with publicly available aerial LiDAR data highlights the significant improvements offered by UAV technology in terms of accuracy, resolution, and interpretability. While 1-meter resolution data is sufficient for detecting large features, the UAV LiDAR data's finer resolution revealed new quarries, clarified poorly defined areas, allowed the visualization of ancient extraction routes, and significantly improved the ability to measure and categorize features remotely. Beyond feature identification, this research demonstrates that high-resolution LiDAR can be used to conduct advanced statistical analysis, providing a more nuanced classification and interpretation of landscape features. These results strongly suggest that high-resolution LiDAR enhances the understanding of archaeological landscapes, especially forested environments. These advantages complement and expand on lower resolution datasets and should be considered by researchers conducting both site-specific documentation and broader regional analyses.

The examination of the Villa Draghi and Via Scagliara quarry site case studies further underscores the advantages of high-resolution LiDAR data. In both cases, feature identification and classification were assisted by resolution and visualization capabilities of UAV LiDAR. When combined with in field surveys and feature documentation, the data allowed for comprehensive documentation of both breccia quarry complexes, revealing that these sites were extensive quarrying areas composed of interconnected features, likely exploited over an extended period.

The comparability between the two case study sites, evident through shared quarry morphologies, extraction techniques, and surface markings, strongly suggests that these quarries employed a common methodology. The site selection of both indicates a shared preference for large loosely compacted breccia deposits within topographically complex systems. While most quarry features identified in this project are located along the extreme borders of the Colli Euganei, both case study sites involve extensive quarrying within the hill systems, requiring considerable effort for material extraction. These findings suggest that Via Scagliara and Villa Draghi quarry sites are more closely related to each other than to any other features identified in this project. Therefore, it is reasonable to hypothesize that these sites were selected, managed, and exploited during the same general period using similar technologies and methods. Given that the Villa Draghi quarry site has been confirmed as the source of pozzolanic additives for a nearby Roman archaeological site, this has large implications for understanding the local Roman exploitation of pozzolanic resources, particularly in northeastern Italy and the greater *Patavium* area.

Both case studies hold significant potential for future research, particularly through provenance analysis of mortars, which could inform on the extent of Roman utilization, trade, and distribution of these materials. Future studies could explore how the transport of breccia materials compared to the widely distributed trachyte during the same period, and whether these quarries served different regions or operated simultaneously. The outcomes of such research would expand our understanding of Roman resource exploitation in the Colli Euganei.

There are, however, limitations to the current phase of this research. As this work represents early findings in a larger project, the conclusions are based on what has been completed so far. While the UAV survey covered more than 8.5 square kilometers and identified 89 areas of interest, only 30 of these locations have been surveyed in the field. As a result, the broader regional analysis was primarily limited to attributes derived from the UAV LiDAR data. A complete field survey will allow for a deeper exploration of quarry relationships, particularly in terms of geological composition, surface markings, and other evidence of quarry activity that can provide insights into the function and periods of operation. Similarly, there are other areas in the Colli Euganei that could benefit from UAV LiDAR surveys, potentially revealing hundreds of unknown or poorly visualized quarries. With the addition of provenance analysis and the completion of the field surveys, the history and extent of breccia extraction in Colli Euganei will be greatly expanded.

In conclusion, this research has made valuable contributions not only in its ability to identify new quarry features, improve visualization, and preform regional statistical analysis as well as localized functionality determinations, but in general to the field of UAV LiDAR applications for archaeology. The convincing results of this project support the increasingly accessible and applied technique of performing high resolution LiDAR surveys in environments where either minimal elevation differences in features must be detected or where complex and forested landscapes can benefit from the improved data quality.

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Appendix

The following tables and figures pertain primarily to the attributes, measurements, and locations of the 50 quarry features analyzed in Survey Area 1, along with a sample of the field forms used during the field surveys. While these documents provide key insights into the study, several additional datasets and resources are not included in this appendix. These include the complete set of field survey forms, the full album of photographs from the fieldwork, and a significant amount of raw and processed data related to the LiDAR and Orthophotography UAV surveys. Additionally, files associated with the QGIS project used for remote sensing analysis and visualization are also excluded from this appendix. For further information regarding these datasets or to access any of this material, interested parties should contact Professor Michele Secco at the Università degli Studi di Padova.

All maps, images, tables, and figures in this work which do not have an author cited were produced during this research by the author, Josiah Olah.

Survey Area 1 Quarries: Locations and Attributes Utilized in the Statistical Analysis

Quarry Feature ID	X cord (E) UTM 32N	Y cord (N) UTM 32N	Hill Slope (%)	Highest Elevation (m)	Quarry Face Length (m)	Direction (azimuth°)	Quarry Face Height (m)	Elevation change (m)	Canal Distance (m)	Area (m^2)	Volume (m^3)
1.01	718386.5953	5019939.027	36.6	26.9	38.1	214	6	14.7	328.2	629.3	1517.7
1.02	718444.2772	5019931.167	20.7	23.8	41.1	179	1.9	12.4	279.0	137.9	99.6
1.02.1	718459.7279	5019938.93	33.4	19.9	42.9	185	1	5.9	272.0	68.9	26.3
1.03	718421.4429	5020014.914	43.2	53.1	66.2	159	4.5	11	303.6	484	764.6
1.04	718527.201	5019983.753	40.2	51.2	46.8	240	3.1	6.8	214.2	406	693.0
1.05	718584.8013	5019904.434	43.3	48.9	46	128	3.9	7.1	131.3	199.4	237.7
1.06	718612.8933	5019954.008	41.2	51.5	178.4	100	10.1	18.1	104.1	2217.5	11766.6
1.07	718667.6609	5019980.448	49.6	21.3	24.8	100	3.4	8.2	90.3	355.5	717.5
1.08	718315.2718	5020172.252	46	24	50.9	284	2.9	7.6	439.1	327.9	349.2
1.09	718627.7065	5020142.98	56.7	49.7	40.5	110	7.6	19.9	106.5	1347	6743.0
1.10	718642.2837	5020189.692	59.7	48	27.1	85	2.1	18.7	109.7	389.1	438.2
1.11	718653.7919	5020241.568	77	42.8	43.5	96	4.1	13.5	97.3	333.8	597.3
1.12	718708.589	5020234.692	28.8	14.9	34.9	83	1.9	6.5	40.6	191.5	80.4
1.13	718514.3132	5020409.926	46.7	86.6	19	289	2.3	4.5	277.4	122.8	145.6
1.14	718587.3563	5020609.717	52.6	86.5	112	102	7.2	26.6	224.2	1403.5	6608.9
1.14.1	718563.1167	5020517.497	35.5	72.6	20.6	124	2.9	6.7	263.6	150.1	127.3
1.15	718544.5494	5020646.858	54.8	113.1	261.9	38	9.5	45.2	242.8	5847.6	63990.8
1.16	718415.3814	5020818.263	54.2	98.1	34.1	105	2.3	11.4	417.2	590.2	1305.4
1.17	718552.2413	5020974.087	43.9	61.9	278	146	17.5	35	297.6	2385.4	18696.8
1.18	718633.7828	5021005.484	48.1	28.7	21.3	106	2.7	3.9	255.7	168.6	152.7
1.19	718659.5928	5021041.838	42.4	20.1	21.1	109	2	5.7	219.3	196.3	247.2
1.20	718446.9751	5021012.487	61.9	81.2	157.3	35	21.5	42.8	357.9	3478.6	39972.3
1.21	718433.8733	5020331.094	45.7	41.3	15.3	335	1.5	3.7	332.1	75.3	70.2
1.22	718066.0611	5021216.631	45.9	69.5	251.6	42	13.5	34.8	520.7	3404.5	23163.0
1.23	718470.385	5021354.179	47.8	48.7	52.2	109	4.4	21.6	118.7	1424	3076.4
1.24	718549.9396	5021390.534	48.9	48.7	194.7	57	13.1	27.7	58.1	2454.3	8522.7
1.25	718513.2706	5021471.426	59.9	34.8	87.5	28	14	17.9	35.4	1202.6	5781.6

1.26	717978.9052	5020683.319	53.9	88.7	20.4	190	2	7.4	832.8	89.2	60.1
1.27	717910.1186	5020689.496	45.4	87.8	15.6	218	2.1	2.8	904.2	53.9	29.3
1.29	717680.0049	5020655.442	42.5	94.1	25.1	108	3	8	1129.8	261.7	418.5
1.30	717451.0201	5019941.419	38.7	24.7	23.6	123	6.2	11.2	1230.4	51	15.3
1.30.1	717433.8642	5019934.505	45.3	23.8	7.3	146	1.2	2.3	1191.2	552.1	1130.8
1.31	717490.358	5019982.223	36	20.8	16.7	86	3.1	3.8	1196.7	43	30.8
1.32	717415.3634	5019952.961	47.4	36.9	24.2	144	3.3	8.4	1252.1	121.6	67.0
1.33	717310.6703	5019864.303	33.3	38.2	19.5	115	2.8	5.6	1329.0	259.3	416.9
1.33.1	717325.7843	5019865.035	31.2	36.1	34	106	2	6	1306.5	299.7	252.3
1.34	717292.3272	5019613.926	38.4	59.7	215.1	123	11.8	32.3	1242.7	5604.7	60353.1
1.35	717294.6357	5019228.783	31.2	46.7	53.6	187	6.9	11.9	1161.7	360.3	401.6
1.36	717244.0674	5019159.903	45.4	36.8	57	143	9.3	17.6	1161.6	1004.3	3871.7
1.37	717221.3101	5019162.757	47.1	32.7	20.3	240	2.3	6.4	1206.3	72.9	53.7
1.38	717190.9878	5019222.84	46.1	36.3	71.8	262	10.6	21.7	1231.2	1816.1	9305.4
1.39	716836.752	5021157.124	73.2	101.9	27.9	320	7.9	21.2	1723.4	513.7	1719.4
1.40	717090.4204	5021185.427	42.7	137.3	42.3	235	6.6	17.8	1470.7	588.2	1887.4
1.41	717183.5086	5021291.783	45.3	139.1	35	346	6.5	21.6	1358.8	762.3	2456.7
1.42	716778.3795	5021310.75	61.5	65.4	47.6	179	8.4	13.5	1749.7	248.6	662.2
1.43	716915.7241	5021415.069	53.6	79.3	74.5	165	6.1	14.8	1570.4	1080.8	1985.4
1.44	716928.036	5021450.466	72.1	72.9	43	34	7.7	11.2	1569.9	1045.3	2564.2
1.44.1	716937.3893	5021352.41	43.3	89.7	52.8	166	4.3	9.4	1561.6	839.8	1593.1
1.44.2	716823.3388	5021461.011	42	53.4	72.9	344	2.5	16.2	1663.3	1331.9	1561.5
1.47	716534.5927	5021175.239	64.6	38.3	35.4	314	5.7	13.5	2010.4	392.9	881.4

Table A1 – Survey Area 1 Quarries: Locations and Attributes Utilized in the Statistical Analysis. Hill Slope: represents an estimate of the original natural slope of the area by averaging the surrounding slope. Quarry Face Length: measures longest continuous or nearly continuous quarry face of a QF. Canal Distance: measured from Battaglia canal and Rialto drain. Dimensions used to calculate Area and Volume is based on a remote sensing estimate of the feature limits.

Survey Area 1 Quarries: Qualitative Attributes, Grouping, and Clustering

Quarry Feature ID	Morphology	Typology	Material	Field Surveyed	Grouping	Clustering
1.01	Linear	Open Pit	n/a	No	Catajo	2, 2
1.02	Semi-circular	Open Pit	n/a	No	Catajo	2, 2
1.02.1	Linear	Trench	n/a	No	Catajo	2, 2
1.03	Linear	Slope Quarry	n/a	No	Catajo	2, 2
1.04	Linear	Open Pit	n/a	No	Catajo	2, 2
1.05	Linear	Open Pit	n/a	No	Catajo	2, 2
1.06	Concave	Slope Quarry	n/a	No	Modern	1, 1
1.07	Concave	Open Pit	n/a	No	Not Categorized	2, 2
1.08	Irregular	Open Pit	n/a	No	Catajo	2, 2
1.09	Linear	Open Pit	n/a	No	Catajo	2, 2
1.10	Concave	Open Pit	n/a	No	Catajo	2, 2
1.11	Irregular	Slope Quarry	n/a	No	Catajo	2, 2
1.12	Concave	Open Pit	n/a	No	Not Categorized	2, 2
1.13	Concave	Open Pit	n/a	No	Catajo	2, 3
1.14	Linear, Concave	Open Pit	Latitic Lava	Yes	Modern	2, 3
1.14.1	Linear	Open Pit	Latitic Breccia	Yes	Catajo	2, 2
1.15	Semi-circular	Open Pit	Latitic Lava	Yes	Modern	1, 1
1.16	Concave	Open Pit	Latitic Breccia	Yes	Not Categorized	2, 3
1.17	Irregular, Concave	Open Pit	n/a	No	Modern	1, 1
1.18	Rectangular, Linear	Open Pit	n/a	No	Not Categorized	2, 2
1.19	Linear	Open Pit	n/a	No	Not Categorized	2, 2
1.2	Concave	Open Pit	n/a	No	Modern	1, 1
1.21	Linear	Open pit	n/a	No	Catajo	2, 2
1.22	Irregular, Concave	Open Pit	n/a	No	Modern	1, 1
1.23	Irregular	Open Pit	n/a	No	Modern	2, 2
1.24	Convex	Open Pit	n/a	No	Modern	1, 1
1.25	Concave	Open Pit	n/a	No	Modern	2, 2
1.26	Linear	Open Pit	Latitic Lava	Yes	Not Categorized	2, 3
1.27	Semi-rectangular	Open Pit	Latitic Lava	Yes	Not Categorized	2, 3

1.29	Semi-circular	Pit	Rhyolitic Breccia	Yes	Not Categorized	2, 3
1.3	Linear	Open Pit	n/a	No	Spinefrasse	2, 2
1.30.1	Linear	Open Pit	n/a	No	Spinefrasse	2, 2
1.31	Concave	Open Pit	n/a	No	Spinefrasse	2, 2
1.32	Concave	Open Pit	n/a	No	Spinefrasse	2, 2
1.33	Concave	Open Pit	n/a	No	Spinefrasse	2, 2
1.33.1	Convex	Open Pit	n/a	No	Spinefrasse	2, 2
1.34	Concave	Open Pit	n/a	No	Modern	1, 1
1.35	Irregular	Trench	n/a	No	Not Categorized	2, 2
1.36	Concave	Open Pit	n/a	No	Modern	2, 2
1.37	Concave	Open Pit	n/a	No	Not Categorized	2, 2
1.38	Concave	Open Pit	n/a	No	Modern	2, 3
1.39	Irregular	Open Pit	n/a	No	Castellone	2, 3
1.4	Concave	Open Pit	n/a	No	Castellone	2, 3
1.41	Concave	Open Pit - Trench	n/a	No	Castellone	2, 3
1.42	Semi-rectangular	Open Pit - Stepped	Rhyolitic Lava	Yes	Not Categorized	2, 3
1.43	Rectangular, Linear	Open Pit - Stepped	Rhyolitic Breccia	Yes	Via Scagliara	2, 3
1.44	Convex	Open Pit - Stepped	Rhyolitic Breccia	Yes	Via Scagliara	2, 3
1.44.1	Convex	Open Pit	n/a	Yes	Via Scagliara	2, 3
1.44.2	Concave	Open Pit	n/a	No	Via Scagliara	2, 3
1.47	Concave	Open Pit	n/a	No	Castellone	2, 3

Table A2 - Survey Area 1 Quarries: Qualitative Attributes, Grouping, and Clustering. Note that material types are based on field observations (n/a indicates it was not typed or not surveyed) and that the morphologies and typologies were primarily categorized through remote sensing. Clustering values are presented in the form of (X, X) with the first value representing the value for the two-cluster model and the second the value the three cluster model.

Northwestern quadrant of Survey Area 1: Labeled and Categorized Quarry Features

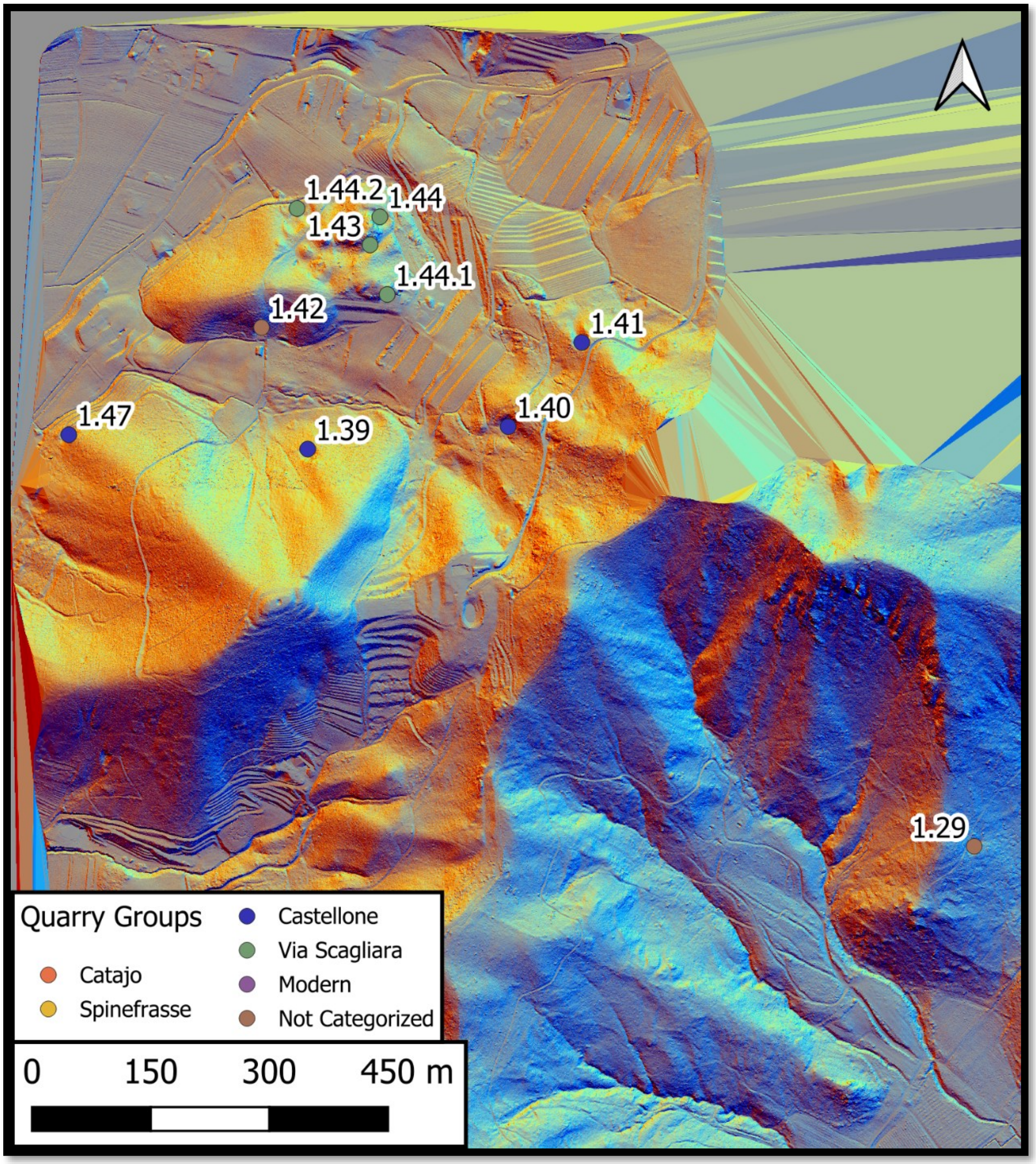

Figure A3 – multi-hillshade map of Northwestern quadrant of Survey Area 1 with labeled and Categorized Quarry Features. Hill formations are Monte Castellone, Ceva, and the Via Scagliara quarry site hill formation.

Northeastern quadrant of Survey Area 1: Labeled and Categorized Quarry Features

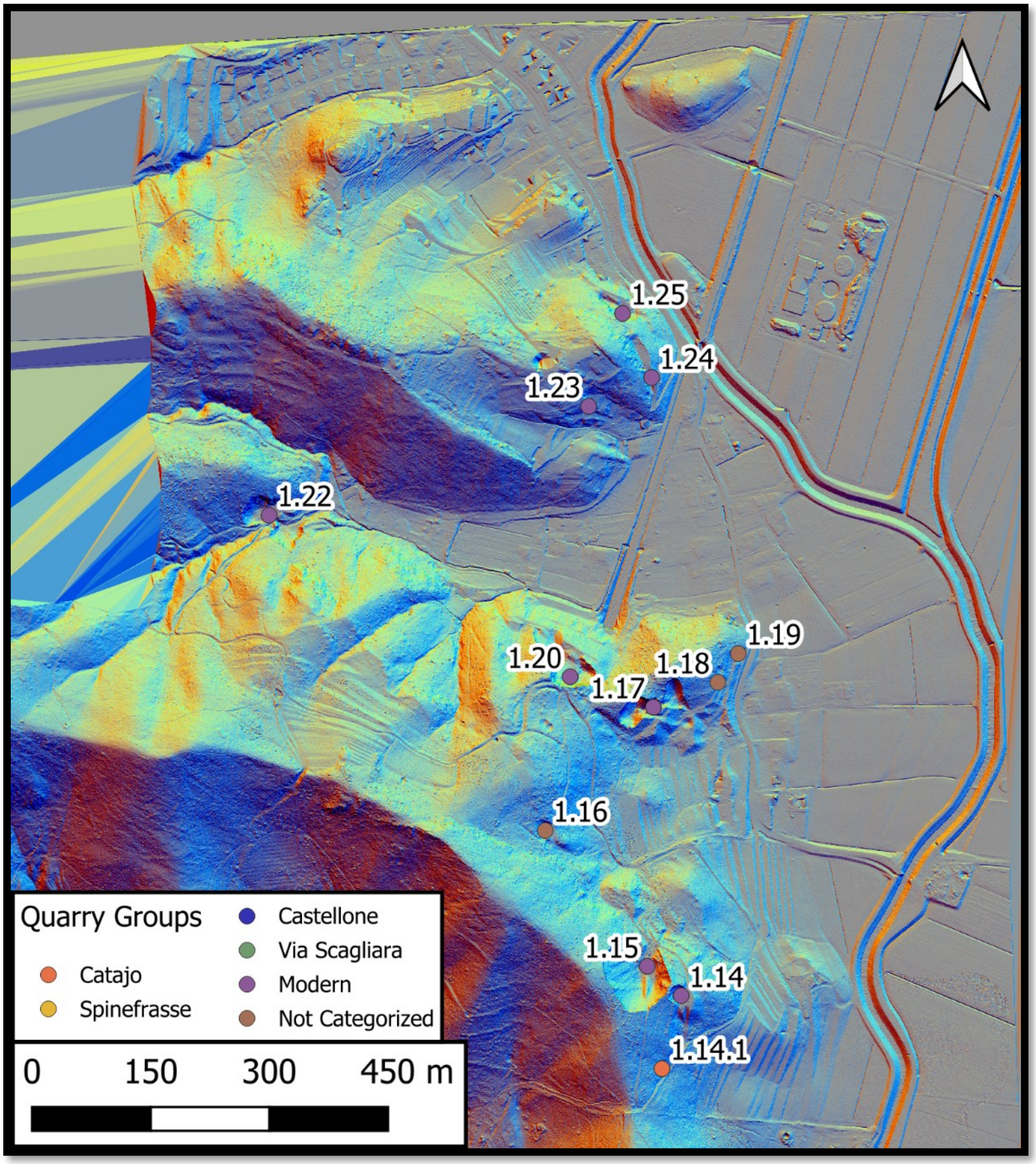

Figure A4 - multi-hillshade map of Northeastern quadrant of Survey Area 1 with labeled and Categorized Quarry Features. The principal hill formation is Montenouvo.

Southwestern quadrant of Survey Area 1: Labeled and Categorized Quarry Features

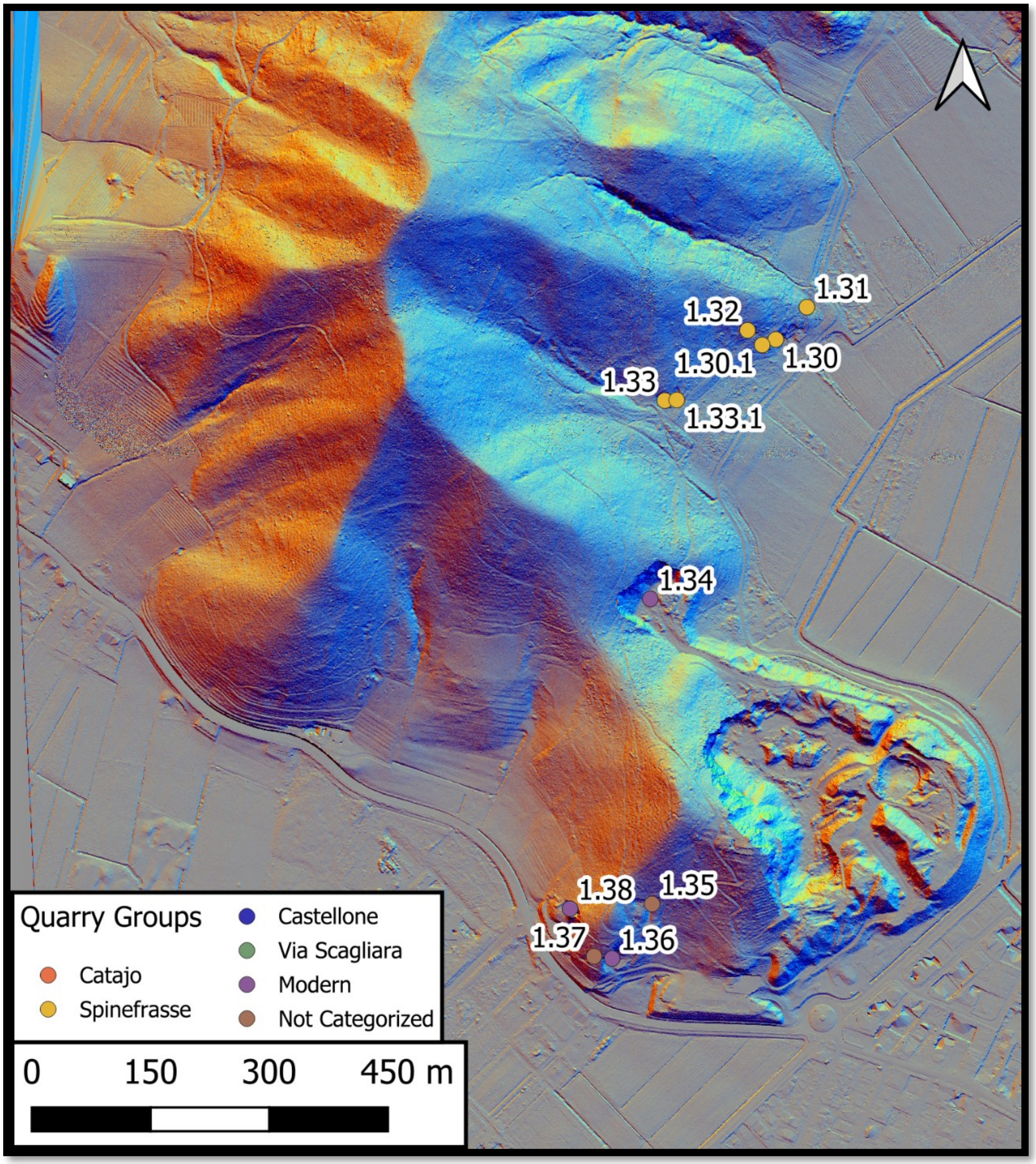

Figure A5 - multi-hillshade map of Southwestern quadrant of Survey Area 1 with labeled and categorized quarry features. The principal hill formations are Monte Croce and Spinefrasse.

Southeastern quadrant of Survey Area 1: Labeled and Categorized Quarry Features

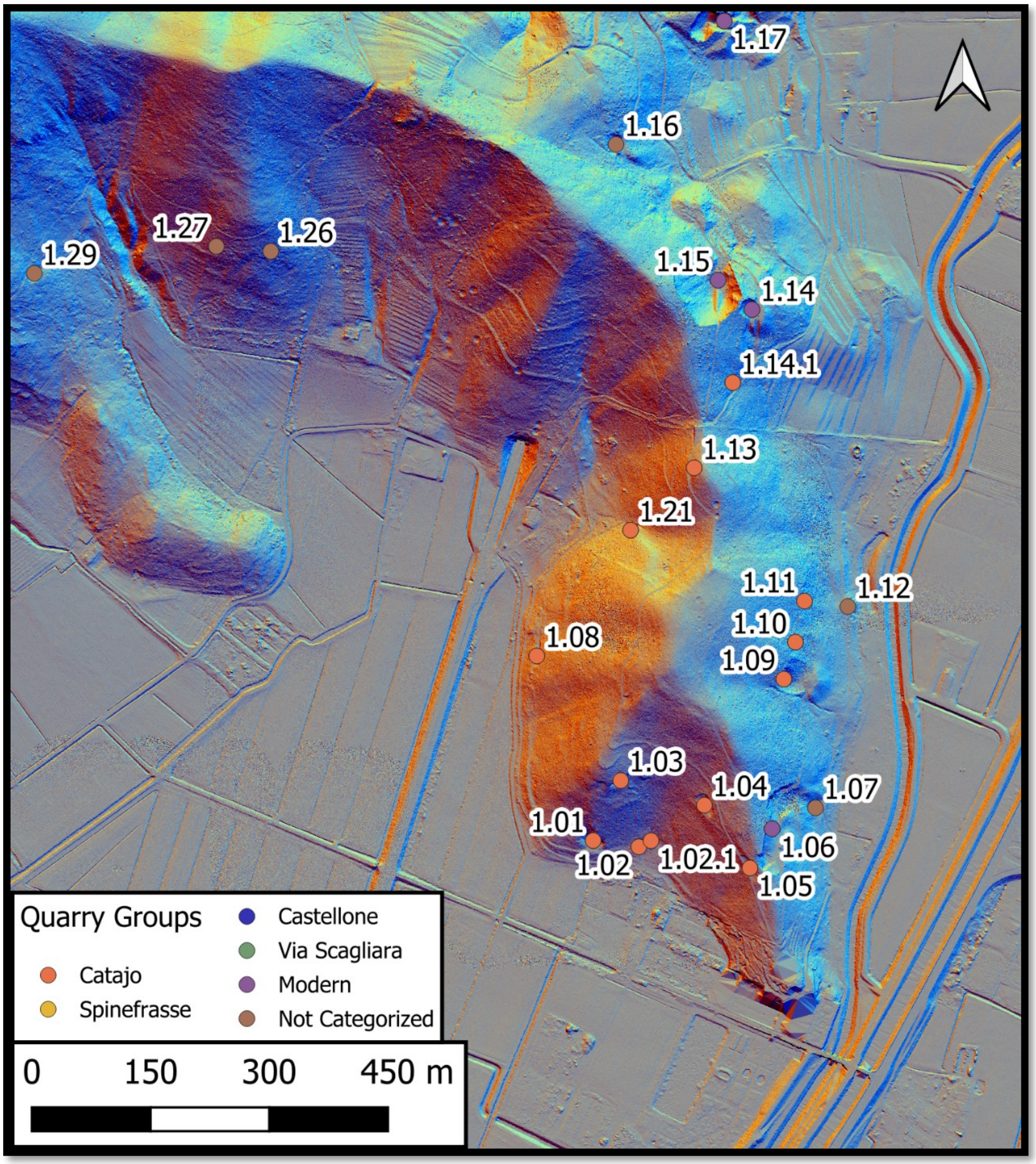

Figure A6 - multi-hillshade map of Southeastern quadrant of Survey Area 1 with labeled and categorized quarry features. The principal hill formations are the Catajo Castle ridge and Montenuovo.

Field Survey Form

Quarry Feature:
Survey Area:
UTM / Lat Long:
Elevation:

Surveyors:
Date/Time:
Weather Conditions:
Photos:

Location
Description:______

Vegetation:______

Is the QF adjacent to other QFs: (Y/N)

QF IDs:______

QF Information
Feature Morphology (shape/orientation/continuity):______

Evidence of Quarrying Activity: (Y/N)

Pre-Modern Quarrying Activity: (Y/N)

Description of Quarrying Activites:______

Visible Resource Collection Route: (Y/N)

Route Description:______

Associated Anthropogenic Features/Artifacts: (Y/N)

Feature/Artifact Description:______

Geological Information
Quarried Rock Typology/Classification:______

Samples Collected: (Y/N)

Sample ID:______

Associated Non Quarried Rocks: (Y/N)

Type & Relationship to QF:______

Figure A7 – Field survey form utilized during the project to document visual attributes and observations of analyzed quarry features. Made by J. Olah