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OPTIMIZING ORNAMENTAL STONE QUARRYING AND COMMERCIAL EXPLOITATION THROUGH SEDIMENTOLOGICAL AND UAV-BASED 3D MODELLING

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EXTENDED ABSTRACT

L'estrazione di pietre ornamentali da successioni sedimentarie rappresenta un settore produttivo strategico, caratterizzato però da complessità geologiche e gestionali rilevanti. In molti contesti sedimentari, la forte variabilità laterale e verticale delle litofacies determina la presenza alternata di porzioni di roccia ad alta resa commerciale e di unità meno pregiate che generano volumi significativi di scarto. Ciò comporta difficoltà nella programmazione delle attività, aumento dei costi operativi, maggiori rischi per la stabilità dei fronti e un impatto ambientale più elevato in termini di suolo occupato, rifiuti estrattivi elevati e morfologie artificiali residuali. Per ottimizzare l'impiego delle risorse geologiche e minimizzare l'impronta ambientale delle cave è quindi necessario un approccio multidisciplinare e data-driven, capace di fornire un quadro dettagliato della continuità interna dei giacimenti e del reale potenziale estrattivo.

In tale contesto si inserisce lo studio condotto presso il giacimento di Poggio la Vecchia, nel comune di Manciano (Grosseto), dove si estrae dalla formazione miocenica "Arenaria di Manciano", la pietra ornamentale commercialmente nota come "Santafiora". L'analisi di facies condotta su questa formazione indica che essa fu deposta nell'ambito di un sistema deltizio dominato dall'azione del moto ondoso; come tale, essa presenta un'elevata eterogeneità sedimentaria, che ne influenza l'aspetto e il comportamento meccanico, con forti ripercussioni sulle sue caratteristiche merceologiche. Per gestire tale variabilità è stato sviluppato un protocollo integrato che combina un'analisi sedimentologica dettagliata e una modellazione tridimensionale ad alta risoluzione mediante rilievi fotogrammetrici da UAV (*Unmanned Aerial Vehicle*) georeferenziati tramite punti di controllo GNSS (*Global Navigation Satellite Systems*).

Il lavoro ha previsto la misura di due sezioni stratigrafiche dei fronti di cava, con descrizione di litologia, granulometria, strutture sedimentarie, paleocorrenti e colore della roccia. Questo ha consentito di identificare otto facies principali riferibili all'ambiente di fronte deltizio e, più in particolare, ai subambienti di spiaggia sommersa superiore e inferiore. A ciascuna facies è stata associata una specifica qualità commerciale definendo così un chiaro legame fra interpretazione sedimentaria e valore estrattivo.

Parallelamente, sono stati eseguiti voli UAV con elevata sovrapposizione fotografica e risoluzione centimetrica (3–5 cm/pixel), elaborati tramite software fotogrammetrici per ottenere ortofotomosaici, modelli digitali del terreno e un modello 3D accurato del giacimento, con errori medi su GCPs (*Ground Control Point*) e CPs (*Check Point*) inferiori a 5 cm. Le immagini ravvicinate scattate sui fronti sono state poi integrate nel software "LIME" come texture di dettaglio, migliorando la leggibilità delle superfici rocciose e la distinzione di facies simili. L'insieme dei dati è stato trasferito in un ambiente tridimensionale in cui interpretazioni sedimentarie e informazioni spaziali si supportano reciprocamente.

Questo *workflow* ha permesso di mappare con maggiore precisione la continuità delle litofacies di pregio anche in porzioni non ancora esposte, stimando con maggiore affidabilità i volumi di roccia estraibile e la quantità di scoperta da rimuovere. I risultati indicano una potenziale riduzione degli scarti di circa il 20-25% grazie a una pianificazione selettiva delle fasi estrattive. Inoltre, fondamentale è stata anche la caratterizzazione tridimensionale delle discontinuità strutturali del massiccio roccioso, che costituisce un importante supporto alla sicurezza operativa e al controllo dei rischi in cantiere.

Dal punto di vista ambientale e autorizzativo, l'uso di questa metodica, che rende disponibili modelli 3D aggiornati, ha consentito un monitoraggio continuo delle variazioni morfologiche della cava, facilitando la definizione di scenari di ripristino coerenti con i vincoli paesaggistici e con le normative vigenti. Il protocollo proposto ha così fornito una base oggettiva per l'interazione con enti pubblici e stakeholder locali, migliorando la trasparenza del processo decisionale.

In conclusione, l'integrazione tra analisi sedimentologiche e fotogrammetria UAV applicata alla Arenaria di Manciano ha evidenziato come questa indagine costituisca un metodo efficace e trasferibile ad altri giacimenti sedimentari, contribuendo a un modello estrattivo più efficiente, sicuro e sostenibile. Futuri sviluppi includeranno l'impiego di sensori multispettrali e tecniche di riconoscimento automatico delle facies per aumentare la capacità predittiva del modello.

ABSTRACT

Quarrying ornamental stone involves extracting lithoid materials that are often variably fractured and heterogeneous, resulting in commercial products of different qualities. This variability poses challenges in planning and managing efficient quarrying processes. Traditionally, efforts have prioritized extracting the most commercially valuable materials, often neglecting less profitable portions of the deposit. Over time, such practices can lead to safety risks and environmental issues, including complications in restoring and integrating the landscape post-extraction.

Sedimentological studies in quarries, particularly facies analysis, offer valuable tools for identifying high-value lithotypes during the initial stages of site development. This supports the creation of effective mining plans that optimize resource use, enhance occupational safety, and address environmental considerations, including post-quarry landscape integration.

Adopting unmanned aerial vehicles (UAVs) combined with accurate Global Navigation Satellite Systems (GNSS) surveys facilitates the development of high-resolution 3D terrain models with centimeter-level accuracy. When integrated with detailed photographic data using specialized software, these models simplify the application of facies analysis, enabling precise estimation of the location and volume of lithofacies of commercial interest. This integrated methodology improves extraction efficiency, reduces operational costs, and promotes more sustainable quarrying practices.

This study demonstrates the experimental application of this approach at the Poggio la Vecchia quarry in the municipality of Manciano (Grosseto Province). Here, the Manciano Sandstone, commercially known as "Pietra Santafiora," is extracted, showcasing the potential for sustainable resource exploitation through advanced sedimentological and modeling techniques.

Keywords: *facies analysis, UAV, 3D model, sandstone, quarry*

INTRODUCTION

The quarrying of rocks of different origins is an important economic activity, allowing access to resources for construction-related activities, although this has several impacts on the environment. These materials can be used in various applications, from buildings to fine ornamental stones. The remaining material from this type of quarrying can then be used for road works, projects requiring environmental rehabilitation of degraded areas, or to restore the areas where the quarries were developed, striving as much as possible to restore the area's original morphological profile. Generally, quarrying is carried out according to a plan defined in a project. This plan, especially for new quarries, must consider environmental and landscape constraints, site safety, and the commercial purposes of the material. These aspects can be better defined by understanding the geological characteristics of the rocks involved in the quarrying process. This is especially true for sedimentary rocks, which are deposited in different depositional contexts, show a major variability of aspects and, consequently, different economic values. However, the exploitation of quarries where sedimentary rocks are used as ornamental stones poses a series of problems closely related to how these rocks appear, a characteristic connected to the type of sedimentary environment where they were originally deposited. The result is that within the same quarry, such rocks can drastically change their appearance even in sectors relatively few meters apart, thus giving rise to different commercial products. The variability in appearance present in sedimentary rocks is evident in the case of the Manciano Sandstone (the subject of our investigation), a lithostratigraphic unit of the Middle-Upper Miocene that crops out very discontinuously along the Tyrrhenian margin of Tuscany and Latium regions. This formation, which shows a thickness of about a hundred meters in the territory of the Municipality of Manciano, is extracted from three quarries, Poggio la Vecchia, Scarceta, and Gamberaio, that are aligned in a N-S direction and separated by a few hundred meters. Our work particularly focused on the Poggio la Vecchia quarry, where the commercial variety of Manciano Sandstone known as "Pietra Santafiora" is extracted. In this quarry, one can observe types of deposits with different facies that show variations over distances of just a few tens of meters, whose genesis is attributable to local depositional processes, as there are no tectonic elements (*e.g.*, faults) that could juxtapose deposits with different characteristics. Although more markedly accentuated in the Poggio la Vecchia quarry, this depositional heterogeneity is also found in the other two quarries, where the sedimentary successions show similar depositional environments. As can be easily imagined, the heterogeneity of these deposits means that a high volume of detrital material is produced to extract the stone with more commercial value. It turns out that some types of facies have a higher market value than others, although extracting them requires quarrying other types of facies of lower commercial value. The resulting problem is the disposal of a large amount of material for which no precise production timeline is planned, and whose management poses a series of environmental, landscape, and workplace safety issues at the extraction sites. A major difficulty in estimating the production and volume of material to be extracted is due to several characteristics such as: *i*) the areal extent of the quarries; *ii*) their multi-level arrangement; *iii*) the heights of the excavation fronts; and *iv*) the inaccessibility of some areas because of quarrying. The resolution of these issues can be initiated by combining studies of sedimentology, structural geology, and 3D reconstructions of the investigated sector based on photogrammetric models in specific areas of a particular quarry. Recent advances in UAV photogrammetry and virtual outcrop modeling have enabled centimeter-scale 3D reconstructions that support stratigraphic and facies mapping in active quarries. These methods, when integrated with sedimentological approaches, provide robust datasets for analyzing heterogeneity and guiding selective extraction (Colomina & Molina, 2014; Buckley *et alii*, 2019; Rossi *et alii*, 2017; Gentili & Madonna, 2024). Sedimentological studies, particularly facies analysis, combined with stratigraphic studies, allow for the identification of deposits with similar facies within the same quarry. They also enable prediction, based on the vertical evolutionary trends of the examined succession, of where it is most likely to find facies with higher commercial value. At the same time, structural geological analysis and the recognition of the degree of rock fracturing and displacement can better define areas with a greater degree of uniformity. This is important for evaluating potential offsets of the most valuable materials caused by fault movements that occurred over geological time. The 3D reconstruction of quarry fronts is a handy tool that provides a complete overview of the investigated area. Despite the related issues, thanks to the use of textured 3D models derived from UAV photogrammetric surveys, appropriately integrated with photos taken near the quarry fronts, it is possible to define better the distribution of the various facies within the quarry, thereby maximizing the exploitation methods of the different fronts to extract facies with different commercial values. All these elements are also essential for helping to define the safety of the construction site. The use of these different approaches has therefore proven to be fundamental. The purpose of this paper is to propose this methodology as a working tool when dealing with the quarrying of valuable stone materials. This approach also provides a real estimate of the volumes (metric scale) of the quarried material, allowing for better commercial planning and more precise cultivation with a view towards both production and environmental respect.

GEOLOGICAL AND STRATIGRAPHIC SETTING

The landscape of Tuscany, the region where the Manciano Sandstone predominantly crops out, has been influenced by various selective geomorphological processes connected with regional tectonic uplift that has affected the entire Tyrrhenian margin of the Italian peninsula since the end of the Miocene. This process, which accelerated during the Quaternary, produced a geomorphological structure characterized by mountain ridges consisting of lithotypes dating from the Paleozoic to the Miocene, predominantly oriented in the NNW-SSE direction, alternating with lower depressed areas forming basins filled mainly with Miocene to the Quaternary clayey, sandy, and conglomeratic sediments of marine and continental environments. In general, the geological-stratigraphic (Figure 1) data of the Tuscan area indicate that the outcropping rock successions belong to different paleogeographic domains that were involved in the Oligo-Miocene tectonic phases responsible for the construction of the northern Apennines (Stampfli *et alii*, 1991, 1998; Scrocca *et alii*, 2003; Pascucci *et alii*, 2007; Marroni *et alii*, 2010; Carminati & Doglioni, 2012).

More specifically, the deposits of the Manciano Sandstone are part of the succession, defined as neo-autochthonous by the Authors, which developed along the Tyrrhenian margin of Tuscany between the Miocene and the Pleistocene. This neo-autochthonous succession was unconformably deposited above older terrains belonging to the Ligurian, Subligurian, and Tuscan units, as described in several studies (Elter *et alii*, 1964, 1991; Plesi, 1974; Elter, 1975; Montanari & Rossi, 1982; Fazzuoli *et alii*, 1985; Ricci Lucchi, 1986; Ciarapica & Passeri *et alii*, 1994, 1998; Bortolotti *et alii*, 2001; Carmignani *et alii*, 2013; Conti *et alii*, 2022, with references therein). These units are organized in a complex geological structure resulting from the superimposition of several tectonic units forming the framework of the northern Apennine chain.

THE MANCIANO SANDSTONE

The Manciano Sandstone constitutes a fossiliferous unit originally dated to the Langhian by Dessau (1951), Giannini (1957), and Alberti *et alii* (1970) and later to the Burdigalian-Serravallian by Fazzini (1972), and Martini *et alii* (1995). Compositional analysis on this unit (Rossi, 2019), indicated that this stone consists mainly of fine- to coarse-grained sandstones with moderately to well-sorted, sub-angular to rounded grains cemented by calcite and subordinate silica. The detrital framework is dominated by monomineralic quartz and plagioclase, with minor K-feldspar, muscovite, and opaque Fe-Ti oxides. Lithic fragments are scarce and include volcanic, low-grade metamorphic, and sedimentary (siliciclastic and carbonate) clasts. The rock typically shows a compact texture with a brownish to reddish hue and a low clay content. These compositional and textural features suggest a mixed sediment supply derived from rocks belonging to Ligurian and Tuscan domains and suggest a provenance from a continental block to recycled-orogen (*e.g.*, the Ligurian allochthonous successions) . Moreover, recent stratigraphic-sedimentological investigations based on facies analysis (Rossi, 2019) have better defined its depositional, paleogeographic, and tectonic setting, which differ from the conclusions proposed by Martini *et alii* (1995). This new interpretation, is supported also by other regional studies (Elter, 1995; Pascucci *et alii*, 1999; Carmignani, 2004, 2013; Cornamusini *et alii*, 2011, 2014), and indicate a deposition of the Manciano Sandstone on the Tyrrhenian side of the Apennine Chain in a context of extensional tectonics

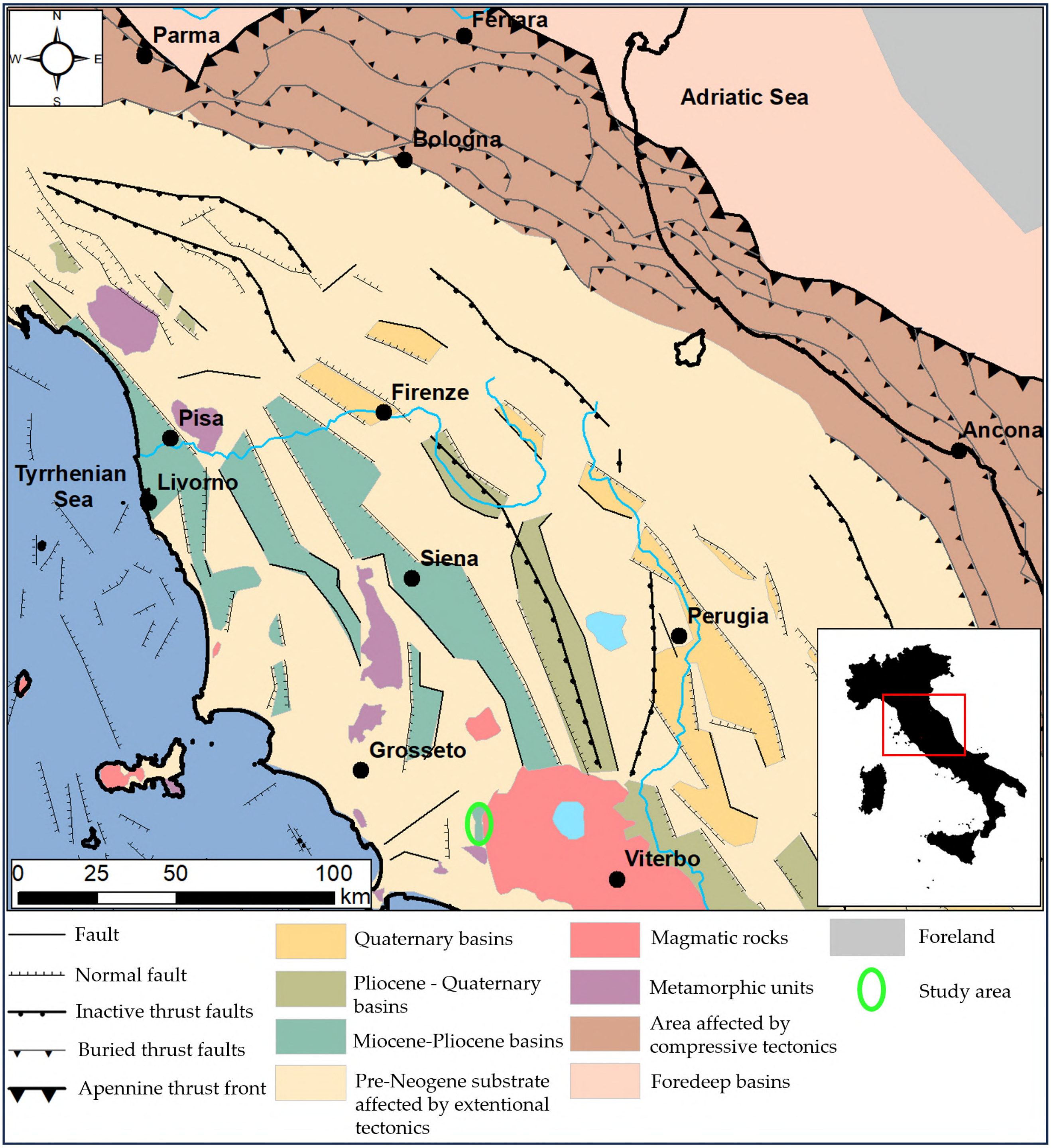


Fig. 1 - Generalized tectonic scheme of the Northern Apennines showing the main extensional and compressive elements, the Neogene sedimentary basins, and the outcrops of magmatic and metamorphic rocks. Modified from Conti et alii (2022)

associated with the opening of the Tyrrhenian back-arc basin. In the investigated quarrying sites, the Manciano Sandstone lies, in fact, unconformably on the deformed Upper Cretaceous-Paleocene successions and is capped by the Upper Tortonian fluvial-lacustrine deposits. About the age of this stratigraphic unit, the integration from two independent datasets: 1) the most

Fig. 2 - Deltaic clinostratified deposits of the "Poggio la Vecchia" quarry showing local erosional surfaces (see yellow arrows), probably formed due to the hyperpycnal flows moving towards the deeper portion of the basin in supercritical conditions. The hammer for scale (28 cm)

recent paleontological data (Néraudeau, 2007; Néraudeau & Masrour, 2008) that indicate an age extending to the Tortonian for the main echinoderm forms originally used by Giannini (1957) to define the age of this formation, and 2) the new geochemical data based on the strontium isotopic ratio (Rossi, 2019), it is suggested that the deposition of the Manciano Sandstone occurred between the Serravallian and the Tortonian. This result disagrees with the data presented by Barbieri *et alii* (2003), who indicate a late Messinian age for this unit.

About the depositional environment, the recent stratigraphic and sedimentological analyses (Rossi, 2019) suggest that this unit was deposited in a coastal depositional context, specifically in upper to lower shoreface environments that were integral parts of a wave-dominated deltaic system. This interpretation is supported by the physical and biogenic sedimentary structures occurring in these deposits as well as by their stratigraphic organization, characterized by the presence of large-scale clinostratification typical of a deltaic apparatus (Figure 2). Furthermore, the various preserved bedforms have been attributed to the wave processes and the action of hyperpycnal and hypopycnal flows associated with river floods occurring at the mouth of the deltaic system. In the analyzed deposits, there is no evidence of shelfal facies nor any structures suggesting a possible tidal influence, as proposed by Martini *et alii* (1995).

MATERIALS & METHODS

Field data, stratigraphic logs, and GIS

We applied the previously suggested work method to the Poggio la Vecchia quarry (Figure 3).

Initially, a geological survey of the area around the quarry was conducted, followed by a more specific geological-technical survey to assess the stability of the quarry's rocky fronts and obtain information on the fracturing of the rock mass and the frequency of the existing fractures. To get detailed stratigraphic data, we measured two stratigraphic-sedimentological sections, approximately 100 meters apart and 100 m thick, using the numerous steps occurring in the quarry. Every step of the quarry was measured and described utilizing the procedure related to facies analysis. We obtained several detailed stratigraphic logs (Figure 4) containing data on the thickness and texture of the sediments, type of bedding, physical and biogenic sedimentary structures, paleocurrent directions, fossils, and colors. All this allowed us to recognize several facies (*i.e.*, beds or bedsets having similar features in terms of sediment texture and physical and biogenic structures) whose association was used to define the depositional context of the Manciano Sandstone. A grid survey was utilized, moving from the lowest floor up to the top of the quarry, to photograph all the quarry steps where the single logs were measured. The photos were taken approximately 3-5 meters away from each front and every 20 meters. A handheld device (Figure 4), specifically an Honor 6 Plus with a HiSilicon Kirin 925 Octa-core chip (4×1.8 GHz Cortex-A15 & 4×1.3 GHz Cortex-A7) with 32 GB of memory, 3 GB of RAM, and an 8MP f/2.4 camera, was used to capture these images. The camera was mounted on an OSMO MOBILE stabilizer to improve image quality. The scaling of the photos was achieved by placing a metric scale directly on the front. Pictures, logs, and other data were collected and organized with GIS software (QGIS) for steps and positions. Ground photographs were acquired at approximately 3-5 m from the quarry faces along the extraction benches, with the camera positioned at about 1.5-1.7 m above ground level. The approximate azimuth and position of each image were recorded from embedded GNSS/EXIF metadata and verified in QGIS before integration into LIME. High-

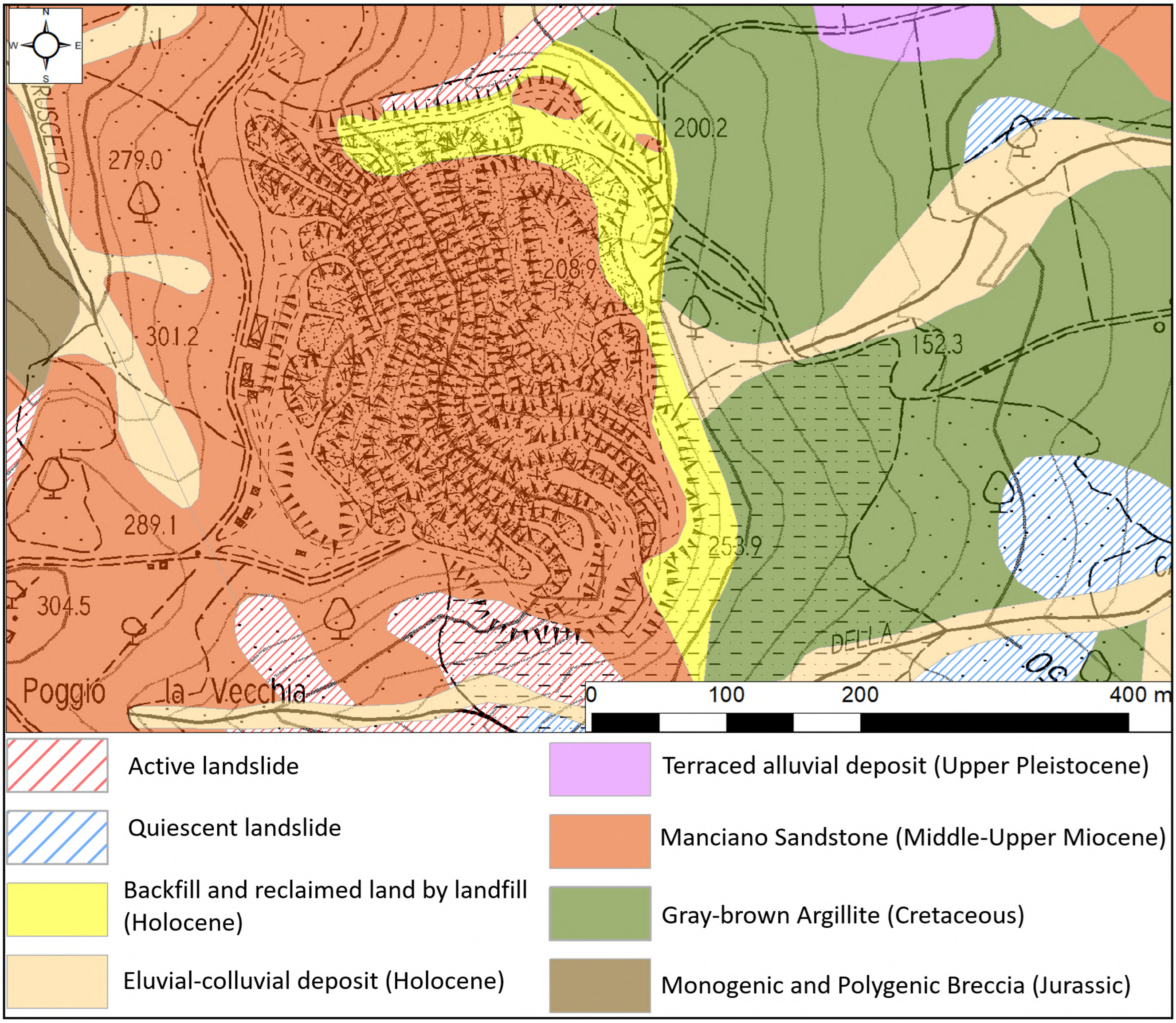


Fig. 3 - Geological map of the "Poggio la Vecchia" quarry

resolution images were adjusted (fisheye effect, perspective transformations, *etc.*) and merged with graphic software. We obtained 25 columns for each sampling site, including detailed photographic data. A representative example summarizing the integrated stratigraphic and photographic dataset obtained through this procedure is shown in Figure 7.

UAV data

The photogrammetric survey of the Poggio la Vecchia quarry was carried out on December 7, 2019, to monitor progress in the quarry's cultivation plan. The UAV model Italdron Evo 4hse, with a maximum takeoff weight of approximately 9 kg, was equipped with a Sony Alpha 7R Mark II camera with a 35 mm lens (Figure 5).

Before conducting the flights, markers were placed on the ground, and their centers were surveyed using the Leica GNSS station. This station, consisting of the GS08 Plus rover and CS 10 Controller, was connected to the Leica Smartnet network and acquired data in ETRF2000 geographic coordinates (EPSG 7930) and ellipsoidal height. These points were divided into GCPs (Ground Control Points) for correct scaling and georeferencing of the model and CPs (Control Points) for estimating the survey positional accuracy. During processing, the data collected were transformed into plane coordinates WGS84 UTM 32N (EPSG 32632), planar coordinates, and geoid height using the ConveRgo

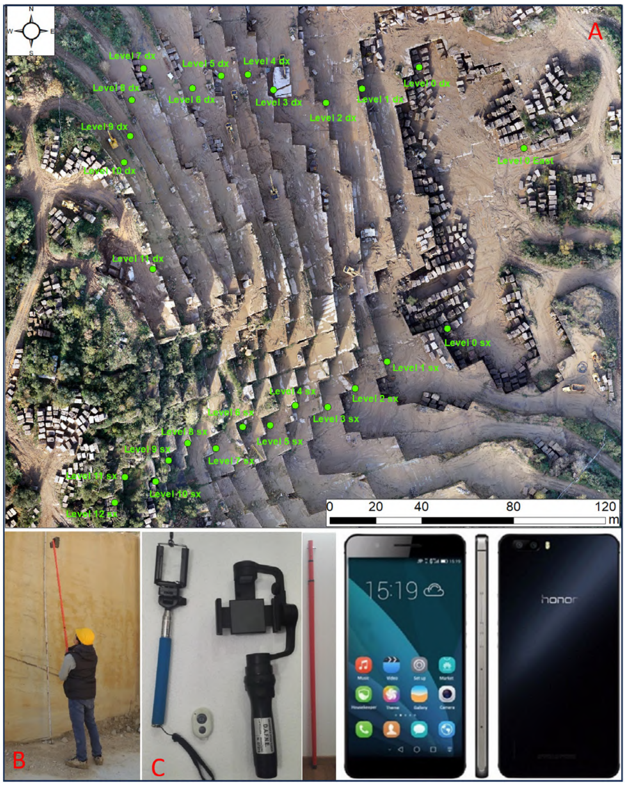


Fig. 4 - (A) Localization of survey zones in a GIS environment; the green writing indicates the several steps of the quarry utilized to measure the stratigraphic-sedimentological sections; (B) field survey operations; (C) instrumentation used; modified from Rossi et alii (2017)

software. This transformation was carried out using the IGM GK2 grid no. 343. The flights were conducted with a planned photographic overlap of 75% at an altitude varying between 90 and 100 m to achieve a nominal ground resolution of approximately 1.5-2 cm/pixel. Given the purpose of the survey, no flights with an angled camera were planned to obtain detailed images of the faces. Thanks to the high photographic overlap and the high-quality camera, it was possible to reconstruct the mining fronts even without these types of images. Images and coordinates were processed using the Agisoft Metashape software. The workflow included image alignment, dense cloud and mesh generation, and the subsequent creation of a textured 3D model, which represents the final step of the photogrammetric reconstruction. The following steps were carried out:

- checking the images and assessing their quality, with the elimination of low-quality images;
- image alignment and obtaining the sparse cloud;
- attributing a reference system (EPSG 32632) and placing markers in photographic images, divided into GCPs and CPs;
- optimizing the alignment process and gradual selection to reduce errors;
- generating the dense cloud at high quality and constructing the 3D model;
- textured 3D model: the final textured 3D surface was generated by projecting high-resolution RGB images onto the mesh to enhance the visual realism and lithological detail of the quarry fronts.

3D model improvement

To improve the texture definition, in some areas of the 3D model, LIME software by VOG was used. This software is the result of a collaboration between the Norwegian Research Centre (NORCE) in Bergen, Norway, and the University of Aberdeen, UK (Buckley *et alii*, 2019). All detailed images taken on the ground in immediate proximity were then checked. The shooting points were easily found thanks to the geolocation information contained in the photographs themselves. After a careful selection of the photos, selected portions of these images were inserted into LIME and positioned on the model. As a final operation, these images were locally merged within the model's texture (Figure 6). The same procedure was followed for entering the stratigraphic logs. Using the improved model, it was possible to recognize and trace the limits of the facies previously found through field analysis.

RESULTS

Field results

The field analysis allowed the measurement of stratigraphic logs for each acquisition point (Figure 7), and through a detailed facies analysis, it was possible to recognize eight main facies, whose characters are reported in Table 1.

UAV results

The photogrammetric process resulted in typical products such as the orthophotomosaic with a definition of 3.5 cm/pixel, DTM (Digital Terrain Model) obtained from the point cloud classified into terrain points with a definition of 2.6 cm/pixel, and the textured 3D model enhanced in LIME (Figure 6A). The errors associated with GCPs and CPs are shown in Table 2.

Result from the enhanced 3D model

For a better expression of the results, what was found in the improved 3D model was exported into the open-source software Cloud Compare (Cloud Compare 2024), which allowed the spatial trends of the facies to be better understood as well as their positions in the quarry (Figure 8).

Overall, the integration of field facies analysis with UAV-derived photogrammetric data produced a detailed three-dimensional reconstruction of the Manciano Sandstone within the Poggio la Vecchia quarry. The orthomosaic (3.5 cm/pixel) and DTM (2.6 cm/pixel) resolved decimetric-scale features

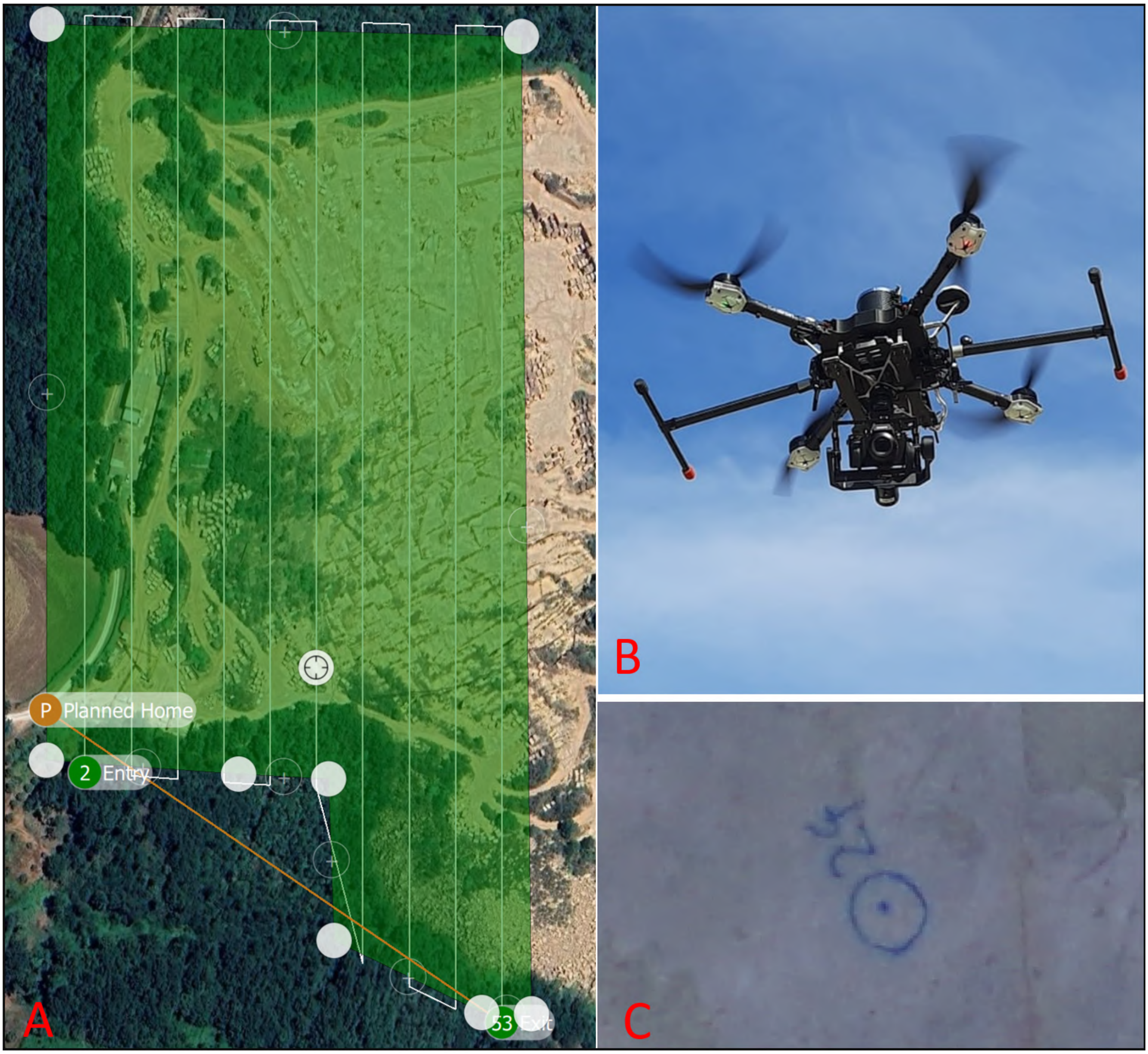


Fig. 5 - (A) Survey mission planning; (B) UAV used Italdron Evo 4hse equipped with Sony Alpha 7R II camera; (C) example of GCP detected and measured by a GNSS station

along quarry faces, while CP-validated RMSEs remained within a few centimeters (Table 2). Integrating enhanced textures in LIME significantly improved discrimination between visually similar facies, constrained their lateral continuity (Figure 6D), and enabled volumetric estimates of extractable units (Figure 8). These results provided a high-resolution quantitative basis for selective extraction planning, optimization of overburden removal, and reduction of waste material, demonstrating the practical and methodological effectiveness of the proposed workflow.

DISCUSSIONS

Facies analysis is a methodology for studying and interpreting the different depositional environments of sediments and sedimentary rocks. Facies refers to a set of distinctive characteristics of a rock body, such as composition, texture, sedimentary structure, colour, and fossil content, which provide information on the environment in which it was formed. This method of study, together with a detailed physical stratigraphic analysis of the investigated sedimentary succession, has been widely applied in the oil industry to investigate sedimentary

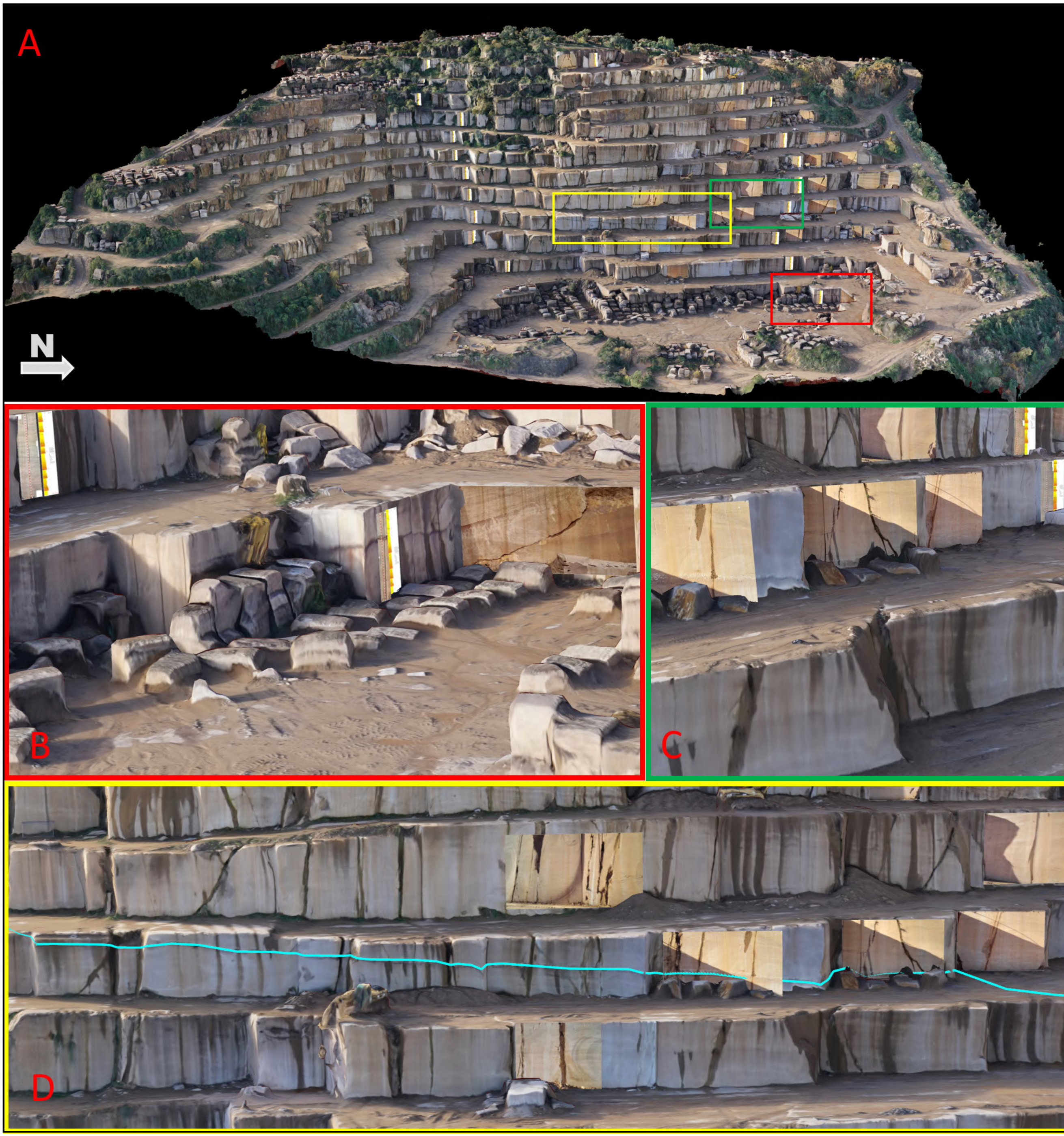
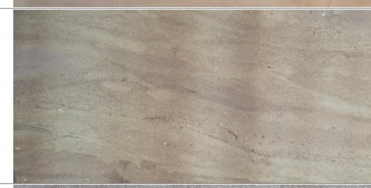
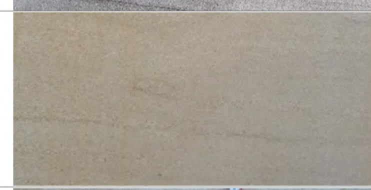
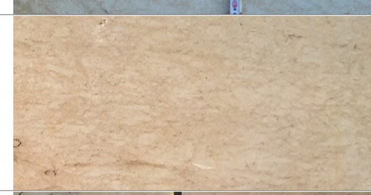
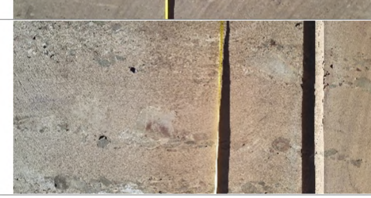


Fig. 6 - (A) Panoramic view of the quarry with high-definition images merged into the 3D model; (B, C), High-definition details showing the 3D stratification along the quarry steps, whose deposits have been attributed to the facies recognized through the field analysis; (D) Lateral extension of a ostrea layer along the quarry front constituting a particular facies type of commercial significance

basins that may host hydrocarbon reservoirs (Bynum, 2024). In this work, facies analysis was applied to problems related to the extraction of ornamental stone materials derived from sedimentary rocks. The studies conducted within the Poggio la Vecchia quarry in the Municipality of Manciano in the Province of Grosseto led to the identification of no less than eight different

Name	Description	Commercial stones	Example
A1	This facies consists of coarse to very coarse sands with small pebbles. Beds are 20/30 cm thick and show internally a cross lamination with foresets having tangential basal contact, generated by the migration of three-dimensional dunes	Santafiora Venata	
A2	This facies consists of medium and coarse sands showing a discontinuos curved subparallel lamination forming a classical trough cross-bedding, generated by the migration of three-dimensional dunes	Santafiora Venata	
A3	This facies consists of medium and coarse sands showing a planar cross bedding that forms tabular sets, generated by the migration of two-dimensional dunes	Santafiora Venata	
A4	This facies consists of medium-fine sands showing undulating subparalled bedding produced under the action of wave oscillation	Santafiora Leopard	
A5	This facies constis of medium to fine sandstones showing sets of curving lamination with convex-up (hummocks) and concave-up (swales) geometry	--	
A6	This facies consists of poorly to strongly bioturbated sandstones having different colours, variable from grey to yellowish to reddish colours	Santafiora Flower, Santafiora Uniforme, Santafiora Fiorito, Santafiora Perla	
A7	This facies consists of medium to very coarse-grained sands showing a variable concetration of whole or fragmented ostrea shells	Santafiora Ostrea	
Cg	This facies consists of well washed to poorly and well sorted conglomerate, having very rounded pebbles of variable dimension	Santafiora River	

Tab. 1 - List of the main facies recognized in the "Poggio la Vecchia" quarry with their commercial names (modified from Rossi *et alii 2017 and* Rossi *2019)*

Name	Error (m)
GCP	0.035
CP	0.048

Tab. 2 - Errors associated with the photogrammetric survey

facies in the quarry site that covers an area of approximately 12 hectares over a difference in height of approximately 100 meters.

The abundance in commercial varieties of ornamental

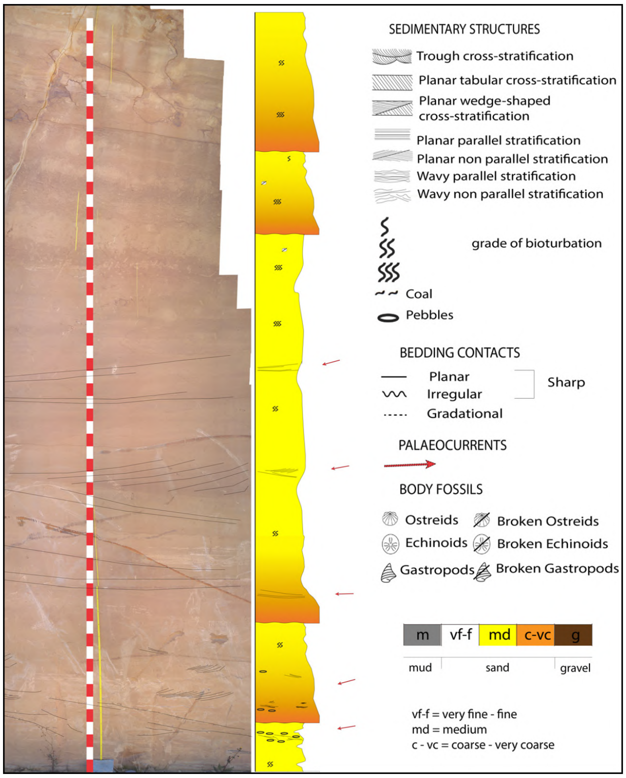


Fig. 7 - Representative stratigraphic log from the northern quarry steps. Scale bar = 10 cm; symbol key shown on the right. Modified from Rossi (2019)

stones is due to the intrinsic features of sedimentary rocks and is strictly related to the deposition environment. Geometries, colours, fossils, or fossil traces give every stone a uniqueness that can hardly be categorized as a commercial product. These peculiarities can be used in the extractive sector for the valorisation of products, understanding their kind of use, up to the choice of the trade name. For example, Ostrea facies can be described as the result of a storm event and the subsequent non-viable deposition of molluscs ripped from the substrate. "Fiorito" facies, in turn, is the result of a deep bioturbation with a poor abundance of ichnofacies but with a high level of ichnodensity. The next step was attempting to study the development of these facies in three-dimensional space, using photogrammetric surveys from UAVs supported by a GNSS survey. The highly accurate 3D model obtained from the photogrammetric process using rigorous techniques that are well-known in professional practice and also in the scientific bibliography (Colomina & Molina, 2014; Tufarolo *et alii*, 2017; Lanciano *et alii*, 2021) makes it easy to observe, study, and measure lengths, surfaces, and volumes with considerable time and cost savings while maintaining a high degree of precision. Photogrammetric flights are mostly performed for topographic purposes to monitor mining progress and for regulatory purposes. Not infrequently, even if textured, these models do not allow for the detailed study of facies and their exact spatial location in the quarry environment unless flights are planned from the outset with this purpose in mind, utilizing flights at reduced altitude (but always depending on the UAV's on-board camera) and with manual acquisitions. This type of acquisition requires many images, which have repercussions on fieldwork times and, above all, on processing times, generating models and point clouds of a certain weight in terms of gigabytes, which may not be easy to use if adequate workstations are not available. For this reason, high-definition images acquired at close range from the fronts during field reconnaissance were inserted and merged with the 3D model using special 3D model editing software (LIME). The operation was also facilitated by using common markers and step boundaries. This operation greatly facilitated the localization of the previously identified facies by allowing their spatial arrangements, extensions, dip directions, and dips to be studied, making it possible to hypothesize with good certainty the extent of the deposits and their position in the quarry area, such as those shown in Figure 9. The use of this information, combined with commercial quarry data, makes it possible, at least in theory, to improve extraction processes, planning, and, if necessary, modifying cultivation plans within the limits of authorization to extract valuable and easily marketable material more sustainably, increasing safety in the workplace, avoiding further compromising the qualities of the local landscape and containing the high costs of extracting material. This methodology is also applicable to mining aspects and problems, where 3D models of mining tunnels, realized using ground-based LiDAR, can be used for the definition of rock mass characteristics and sedimentological analyses, especially if improved through the introduction of high-definition images. Another field closely related to mining and quarrying aspects is that of the census of anthropogenic cavities from a sinkhole hazard perspective, where these techniques are being applied and developed to mitigate this important and mining-related, but often overlooked, geological risk (Gentili & Madonna, 2024).

CONCLUSIONS

This study highlights the value of integrating sedimentological analysis with UAV-based photogrammetric modeling to advance the understanding and sustainable management of ornamental stone quarries. The combination of traditional field-based geological methods with high-resolution remote sensing provides a robust framework for characterizing lithofacies, identifying structural heterogeneities, and optimizing resource exploitation. This integrated approach enables more precise mapping of extractive units and helps reduce waste by improving the selectivity of quarrying activities.

Fig. 8 - Examples of facies extension A7 (A), and A6 (B) along the quarry front

From an environmental perspective, the use of UAV-derived 3D models contributes significantly to monitoring the morphological evolution of quarry sites, allowing for the detection of landscape modifications over time. This is particularly relevant for planning reclamation strategies, assessing visual impact, and evaluating ecosystem disturbances. Moreover, the ability to generate spatially accurate, up-to-date digital terrain models supports more informed decision-making in terms of land-use management and environmental compliance.

By fostering a deeper understanding of the geological and morphological characteristics of extractive sites, the methodology proposed in this work promotes a transition toward more sustainable quarrying practices. These results are transferable to other contexts involving surface mining or geomorphologically sensitive landscapes, and they align with broader goals in environmental geoscience aimed at balancing resource use with ecological preservation.

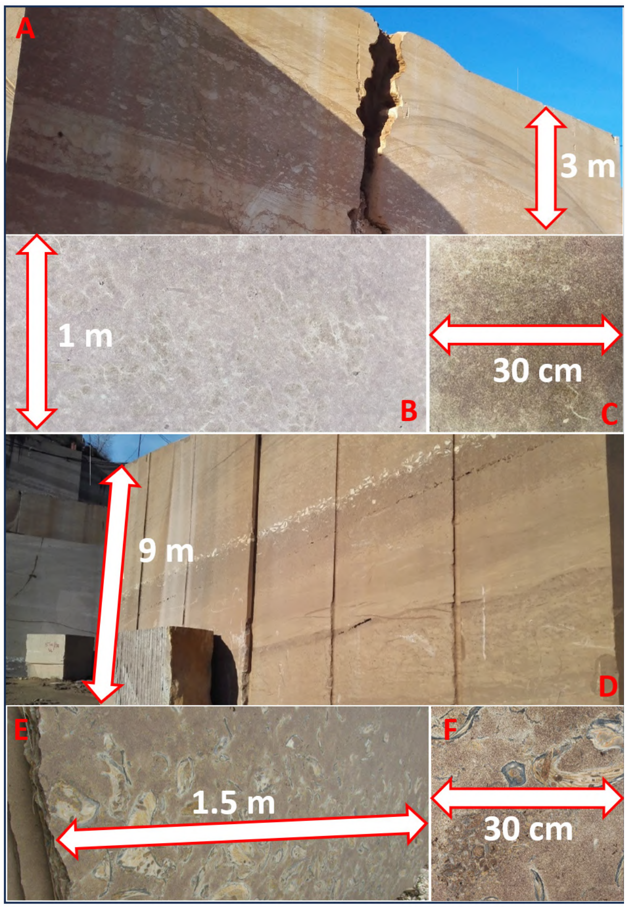


Fig. 9 - Specific commercial products: (A) Santafiora Uniforme, facies A6, in the quarry, (B) on a worked slab, and (C) on tile. (D) Ostrea commercial variety in the quarry, (E) on worked slab, and (F) on tile

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Declaration of competing interest

F.R. has been involved as a consultant and expert witness in Company Santafiora S.r.l. The other authors declare no conflicts of interest.

Author Contributions

The following statements should be used "Conceptualization, F.G.R., S.M.1, S.M.2 and F.G.; methodology, F.G.R., F.G, S.M.1; software, F.G.R., F.G.; validation, S.M.1, and F.G.R.; formal analysis, F.G.R.; investigation, F.G.R. and F.G.; resources, F.G.R. and F.G.; data curation, F.G.R.; writing-original draft preparation, F.G.R., S.M.1, S.M.2 and F.G.; writing review and editing, F.G.R., S.M.1, S.M.2 and F.G.; visualization, F.G.R.; supervision, S.M.1.; project administration, F.G.R.; funding acquisition, S.M.2. All authors have read and agreed to the published version of the manuscript.". Authorship must be limited to those who have contributed substantially to the work reported. (S.M.1=Salvatore Milli, S.M.2= Sergio Madonna).

Data Availability Statement

The data is available from the authors and may be consulted with permission. For information and requests please contact francesco.rossi@gmail.com.

REFERENCES

Alberti A., Bertini M., Del Bono G.L. & Salvati L. (1970) - *Note illustrative della Carta Geologica d'Italia alla scala 1:100.000. Foglio 136 «Tuscania» e Foglio 142 «Civitavecchia»*. Servizio Geologico d'Italia, **141**.

Barbieri M., Chiocchini U. & Madonna S. (2003) - *Nuovi dati sull'età dell'Arenaria di Manciano (Miocene) sulla base dei valori di rapporto isotopico 87Sr/86Sr (Italia centrale)*. Bollettino della Società Geologica Italiana, **122**: 351-354.

Bortolotti V., Fazzuoli M., Pandeli E., Principi G., Babbini A. & Corti S. (2001) - *Geology of the central and eastern Elba Island,Italy*. Ofioliti, **26**: 97-150.

Buckley S.J., Ringdal K., Naumann N., Dolva B., Kurz T.H., Howell J.A. & Dewez T.J.B. (2019) - *LIME: Software for 3-D visualization, interpretation, and communication of virtual geoscience models*. Geosphere, **15**: 222-235.

Bynum J., Pashin J. & Wethington C. (2024) - *Mississippian (Lower Carboniferous) facies heterogeneity and distribution within the mixed carbonate-siliciclastic reservoirs of the Midcontinent STACK Play, Oklahoma, USA*. SPE Journal, 29: 4094-4107. Conti P., Conticelli S., Cornamusini G. & Marroni M. (2022) - *Guide Geologiche Regionali, Volume 15, Toscana*. Società Geologica Italiana.

Carmignani L., Conti P., Cornamusini G. & Meccheri L. (2004) - *The internal Northern Apennines, the northern Tyrrhenian Sea and the Sardinia-Corsica block*. In: Crescenti U., D'Offizi S., Merlino S., Sacchi L. (Eds.), *Geology of Italy*, Special Volume of the Italian Geological Society for the International Geological Congress 32 Florence -2004: 59-77.

Carmignani L., Conti P., Cornamusini G. & Pirro A. (2013) - *Geological map of Tuscany (Italy)*. Journal of Maps, **9**: 487-497.

Carminati E. & Doglioni C. (2012) - *Alps vs. Apennines: The paradigm of a tectonically asymmetric Earth*. Earth-Science Reviews, **112**: 67-96.

Ciarapica G. & Passeri L. (1994) - *The Tuscan nappe in northern Apennines: data, doubts, hypotheses.* Memorie della Società Geologica Italiana, **48**: 7-22.

Ciarapica G. & Passeri L. (1998) - *Evoluzione paleogeografica degli Appennini*. Atti Ticinensi di Scienze della Terra, **40**: 233-290.

Colomina I. & Molina P. (2014) - *Unmanned aerial systems for photogrammetry and remote sensing: A review.* ISPRS Journal of Photogrammetry and Remote Sensing, **92**: 79-97.

Cornamusini G., Foresi L. M., Massa G., Bonciani F., Callegari I., Da Prato S. & Ielpi A. (2011) - *The Miocene successions of the Fiora Hills: Considerations about the development of the minor basins of Southern Tuscany*. Italian Journal of Geosciences, **130**: 404-424. DOI:10.3301/IJG.2011.17.

Cornamusini G., Foresi L.M., Dall'antonia B., Bossio A., Mazzei R. & Salvatorini G. (2014) - *The Miocene of Pianosa Island: key to understanding the opening of the Northern Tyrrhenian back-arc basin (Central Mediterranean).* Journal of the Geological Society, **171**: 801-819.

Dessau G. (1951) - *Geologia dei depositi di antimonio e d'altri minerali nel Gruppo dei Monti Romani. (Comune di Manciano, Maremma Toscana).* Bollettino della. Società Geologica Italiana, **70**: 1-64.

Elter P., Gratziu C. & Labesse B. (1964) - *Sul significato dell'esistenza di una unità tettonica alloctona costituita da formazioni terziarie nell'Appennino settentrionale*. Bollettino della Società Geologica Italian, **83**: 373-394.

Elter P. (1975) - *L'ensamble ligure.* Bulletin del la Société Géologique de France, **17**: 984-997.

Elter P. & Marroni M. (1991) - *Le Unità Liguri dell'Appennino Settentrionale: sintesi dei dati e nuove interpretazioni.* Memorie Descrittive della Carta Geologica d'Italia, **44**: 121-138.

Elter F.M. & Sandrelli F. (1995) - *La fase post-nappe nella toscana meridionale: nuove interpretazioni sull'evoluzione dell'Appennino settentrionale.* Atti Ticinesi di Scienze della Terra, **37**: 137-193.

Fazzini P., Gelmini M., Mantovani M.P. & Pellegrini M. (1972) - *Geologia dei Monti della Tolfa (Lazio settentrionale, Provincie di Viterbo e di Roma)*. Memorie della Società Geologica Italiana, **21**: 65-144.

Fazzuoli M., Ferrini G., Pandeli E. & Sguazzoni G. (1985) - *Le formazioni giurassico-mioceniche della Falda Toscana a Nord dell'Arno: considerazioni sull'evoluzione sedimentaria.* Memorie della Società Geologica Italiana, **30**: 159-201.

Gentili F. & Madonna S. (2024) - *Photogrammetry from UAV and low-cost lidar for sinkhole hazard mitigation in urban areas: Applications and evaluations*. Geographies, **4**: 343-362. Doi:10.3390/geographies4020020.

Giannini E. (1957) - *I fossili dell'Arenaria di Manciano*. Palaeontographia Italica, 51: 97-103.

Lanciano C., Vanneschi C., Tufarolo E. & Salvini R. (2021) - *Distributed optical fiber sensors and terrestrial laser scanner surveys for the monitoring of an underground marble quarry.* Italian Journal of Engineering Geology and Environment. Special Issue, **1:** 117-125.

Marroni M., Meneghini F. & Pandolfi L. (2010) - *Anatomy of the Ligure-Piemontese subduction system: Evidence from Late Cretaceous-middle Eocene convergent margin deposits in the Northern Apennines, Italy.* International Geology Review, **52**: 1160-1192. DOI:10.1080/00206810903545493.

Martini I.P., Cascella A. & Rau A. (1995) - *The Manciano Sandstone: a shoreface deposit of Miocene basins of the Northern Apennines, Italy.* Sedimentary Geology, **99**: 37-59.

Montanari L. & Rossi M. (1982) - *Evoluzione delle unità stratigrafico-strutturali terziarie del nord Appennino: 1. L'Unità di Canetolo*. Bollettino della Società Geologica Italiana, **101**: 275-289.

Néraudeau D. (2007) - *Les bioaccumulations néogènes (calcaires à algues, faluns) d'Europe occidentale et leurs relations avec la crise messinienne.* Comptes Rendus Palevol, **6**: 59-71.

Néraudeau D. & Masrour M. (2008) - *Évolution de la biodiversité et de la distribution paléobiogéographique des échinides sur les côtes atlantiques du Marocdu Tortonien à l'Actuel.* Geodiversitas, **30**: 211-232.

Pascucci V., Merlini S. & Martini I.P. (1999) - *Seismic stratigraphy of the Miocene-Pleistocene sedimentary basins of the Northern Tyrrhenian Sea and western Tuscany (Italy).* Basin Research, **11**: 337-356. Pascucci V., Martini I.P., Sagri M. & Sandrelli F. (2007) - *Effects of transverse structural lineaments on the Neogene–Quaternary basins of Tuscany (inner northern Apennines, Italy)*, in: Nichols, G., Williams, E., Paola, C. (Eds.), Sedimentary Processes, Environments and Basins: *A Tribute to Peter Fried*. International Association of Sedimentologists, Special Publication, **38**: 155-182.

Plesi G. (1974) - *Unità di Canetolo nella struttura di Bobbio (Val Trebbia), Montegroppo (Val Gotra) e lungo la trasversale Cinque Terre - Pracchiola.* Atti della Società Toscana di Scienze Naturali, Memorie, Ser. A, **81**: 121-151.

Ricci Lucchi F. (1986) - *The Oligocene to Recent foreland basins of the Northern Apennines*, in: Allen, P.A., Homewood, P. (Eds.), Foreland Basins. International Association of Sedimentologists, Special Publication, **8**: 105-139.

Rossi F. G., Madonna S. & Milli S. (2017) - *Facies analysis applied to quarrying: A review of the possible use of sedimentology to increase knowledge and use of ornamental sandstones.* Procedia Engineering, **208**: 136-144.

Rossi F. G. (2019) - *Le Arenarie di Manciano: valorizzazione delle attività estrattive attraverso indagini stratigrafico-sedimentologiche*. Ph.D. Thesis - Università della Tuscia, Viterbo. http://hdl.handle.net/2067/45881.

Scrocca D., Doglioni C. Innocenti F., Manetti P., Mazzotti A., Bertelli L., Burbi L. & D'offizi S. (2003) - *CROP Atlas: Seismic reflection profiles of the Italian crust.* Memorie Descrittive della Carta Geologica d'Italia, **62**.

Stampfli G. M., Marcoux J. & Baud A. (1991) - *Tethyan margin in space and time*. Palaeogeography, Palaeoclimatology, Palaeoecology, **87**: 373-409.

Stampfli G.M., Mosar J., Marquer D., Marchant R., Baudin T. & Borel G. (1998) - *Subduction and obduction processes in the western Alps*. In:

Vauchez, A., Meissner, R. (Eds.), *Continents and Their Mantle Roots*. Tectonophysics, **296**: 159-204.

Tufarolo E., Salvini R., Seddaiu M., lanciano C.,Bernardinetti S., Petrolo F., Carmignani L.,massa G. & Pieruccioni D. (2017) - *Structure from motion technique of proximal sensing airborne data for 3d reconstruction of extraction sites.* Italian Journal of Engineering Geology and Environment. Special Issue, **2**: 97-107.

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