



Method

An interdisciplinary workflow for the comprehensive study of ancient quarried landscapes

Rebecca Levitan¹ , Evan Levine² , Demetrios Athanasoulis³, Irini Legaki³,
Jessica Paga⁴, Rosie Campbell^{5,7} , Hallvard Indgjerd⁶ ,
Jean Vanden Broeck-Parant⁷ , Vasiliki Anevlavi⁸ , Thorsten Jakobitsch⁸ &
Florence Liard⁷

¹ Department of Classics, King's College London, UK

² Faculty of Theology and School of Archaeology, University of Copenhagen, Denmark

³ Ephorate of Antiquities of the Cyclades, Athens, Greece

⁴ Department of Classical Studies, College of William and Mary, Williamsburg, USA

⁵ Faculty of Arts and Philosophy, Vrije Universiteit Brussel, Brussels, Belgium

⁶ Museum of Cultural History, University of Oslo, Norway

⁷ Institut des Civilisations, Arts et Lettres, Université Catholique de Louvain, Louvain-la-Neuve, Belgium

⁸ Austrian Archaeological Institute, Austrian Academy of Sciences, Vienna, Austria

Author for correspondence: Rebecca Levitan ✉ rebecca.levitan@kcl.ac.uk



Quarries are information-rich anthropic landscapes, but their unique characteristics often limit the effectiveness of traditional archaeological documentation strategies. Here, the authors present a novel interdisciplinary method for the documentation and analysis of these landscapes, focusing on two ancient marble quarries on the Mediterranean island of Naxos. The workflow, combining lidar, photogrammetry, sculptural and architectural study, geoscience, ecological study and archaeological survey, provides a means for the systematic documentation of quarry landscapes in the Mediterranean and beyond, and aims to promote an understanding of premodern extractive activities not as isolated occurrences but as important aspects of interconnected, evolving landscapes.

Keywords: Mediterranean Europe, Naxos, lidar, quarrying, photogrammetry, marble, sculpture

Introduction

Quarry studies in Mediterranean archaeology have experienced recent advances in field-work methodology, digital documentation and scientific analysis have facilitated the generation of a rich assemblage of data from these long-neglected spaces. Recent regional

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studies have focused on quarries in Greece (Russell 2017), Turkey (Scardozzi 2012), Sicily (Calderone *et al.* 2024) and the Andes (Earle & Cruz Quiñones 2023), while catalogues and gazetteers of ancient quarries (Russell 2013; Kokkorou-Alevras *et al.* 2014) offer substantial updates in our knowledge of their locations and distributions, accompanied by the integration of archaeometry and other quantitative approaches including chemical and petrographic analysis (Bloxam 2011).

Robust contextualisation of these quarries within their broader landscapes and sociohistorical settings is, however, often lacking and there is a growing awareness of the need for more theoretically informed frameworks around the study of stone extraction (Lyes 2023). Nuanced treatments of ancient quarries in the pre-Roman Aegean are particularly uneven, and most studies focus on quarrying as a means of engagement with artistic and architectural output. While interest in ethnographic and anthropological approaches to stone working is growing, most notably as these approaches relate to the development of architectural energetics (e.g. Taelman 2021), quarry studies have so far minimised their potential for addressing larger archaeological questions, notably in sociological, economic, industrial and environmental terms (Barker *et al.* 2023).

This article presents one novel, interdisciplinary and low-cost method for the study of quarried landscapes in the Cycladic region of the Mediterranean undertaken by the Naxos Quarry Project (NQP), including proof of concept at the marble quarries of Apollonas and Melanes on the island of Naxos (Figure 1). In contrast to most quarry studies, which rely on singular methods of documentation, our integrated approach combines lidar, photogrammetry, architectural and sculptural study, geochemical sampling, ecological study and regional archaeological survey to offer a new workflow for the systematic documentation of quarries and the integration of these data within broader, ongoing archaeological discussions in the Cyclades and beyond.

Naxos and project overview

Naxos is the largest island in the interconnected Cycladic archipelago, offering a resource-rich landscape that has long set it apart from its smaller, more arid neighbours. As such, the island presents a deep history of occupation from the Pleistocene (*c.* 200 000 BP) to the present, illuminated by archaeological fieldwork at the Stelida Peninsula (Carter *et al.* 2019) and the south-east coast (Renfrew *et al.* *in press*), evidence for prehistoric occupation near Chora (Foutou 1983; Cosmopoulos 1998; Vlachopoulos 2016), monumental Archaic temples at Portara (Gruben 1997), Sangri (Lambrinoudakis & Ohnesorg 2020) and Yria (Lambrinoudakis 1991), and the medieval fortified settlement of Kastro Apalirou (occupied eighth–thirteenth centuries AD) (Hill *et al.* 2018) (Figure 1). Naxos is perhaps best known for its role as the earliest site of systematic marble extraction in Greece, beginning in the Early Bronze Age (*c.* 3200 BC, Dixon 2013). Naxian artists and architects of the Archaic Period (*c.* 700–480 BC) fundamentally reshaped the materiality of Aegean art and architecture at home and abroad (Sheedy & Pike 2025).

The island is home to several sources of coarse-grained white marble as well as the only Aegean source of emery, a natural abrasive that played a critical role in marble working (Palagia 2006: 260). In the Archaic Period, Naxian marble workers were

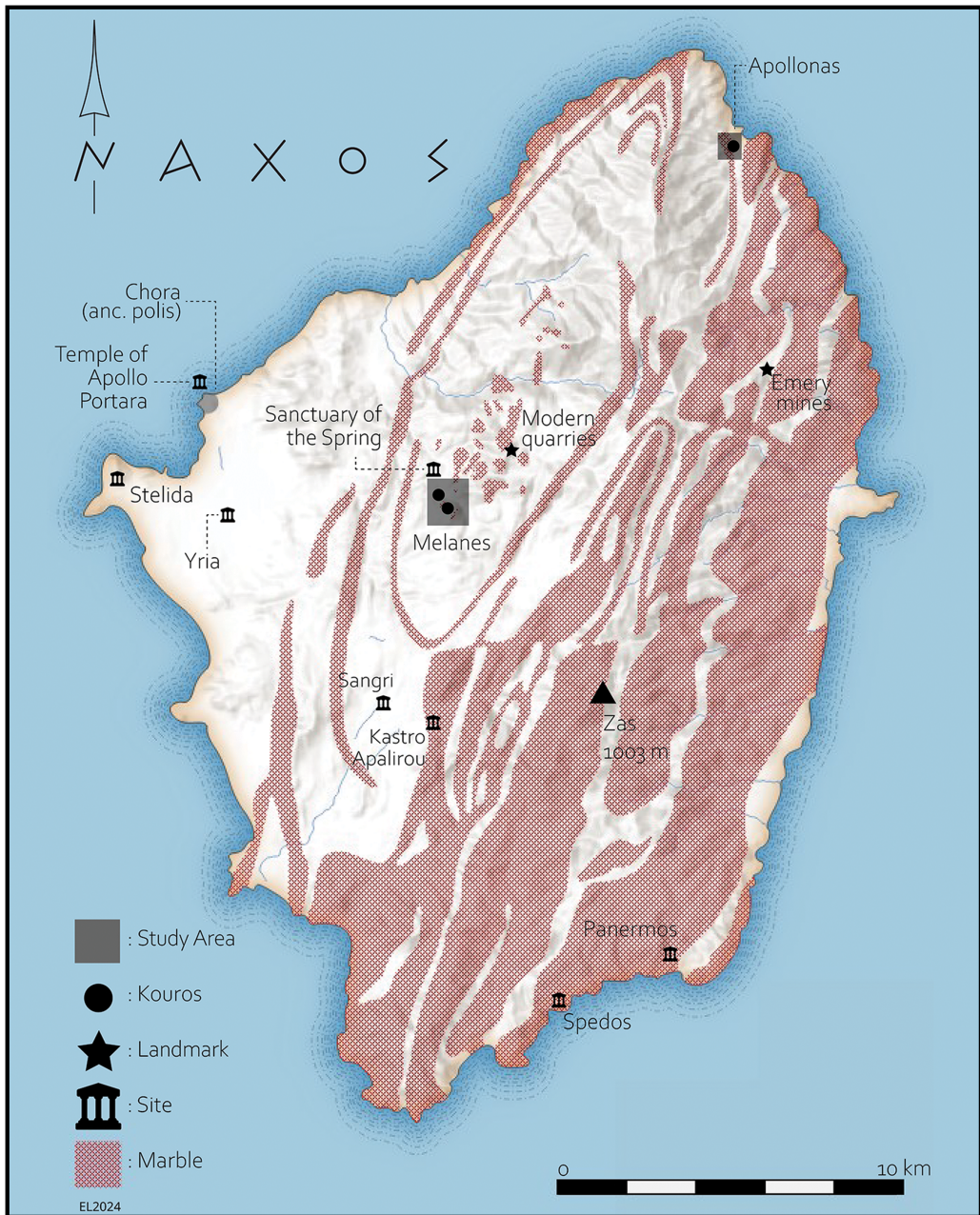


Figure 1. Map of Naxos showing study areas, major sites, kouros (archaic sculptures) and marble geology (figure by E. Levine).

technological and artistic pioneers who developed techniques to harness and exploit their local natural resources (Figure 2). While scholars have explored and studied the quarries of Melanes and Apollonas, significant questions regarding the relationship between the

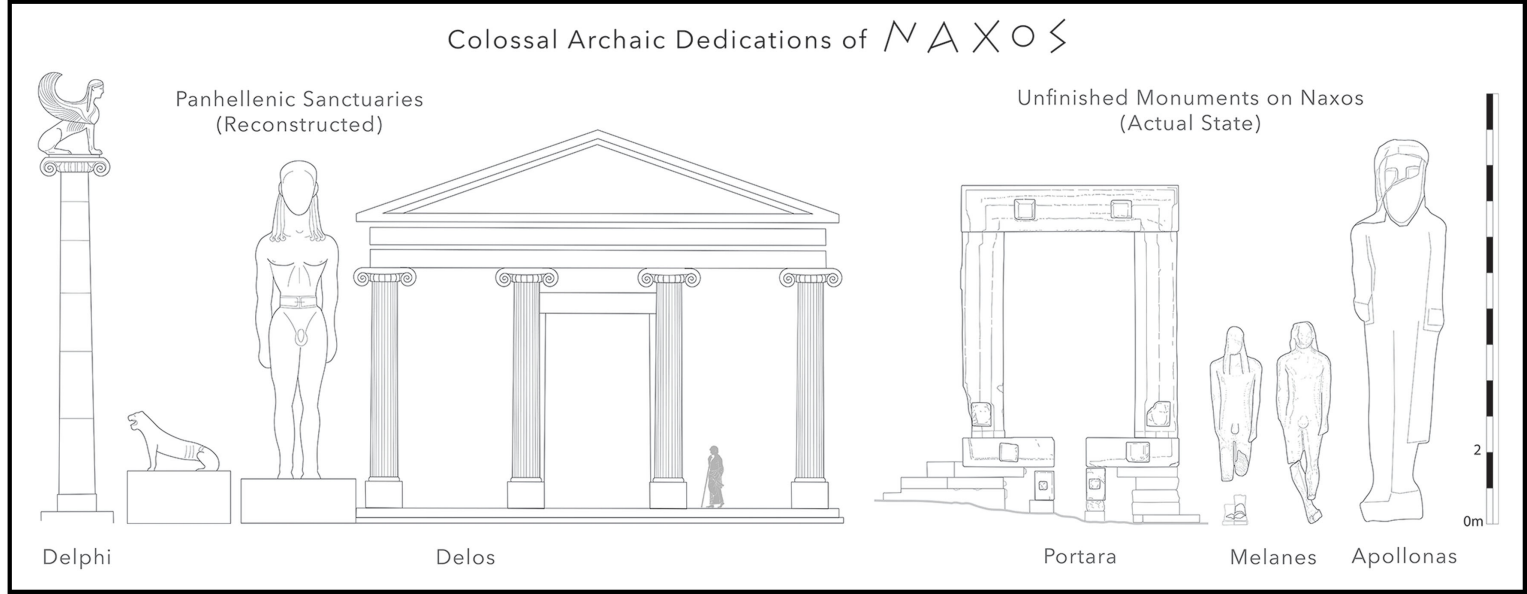


Figure 2. Elevations of Archaic marble Naxian dedications at Delphi (left) and Delos (centre) and local monuments on Naxos (right) (figure by R. Levitan).

ancient quarries, settlements and nearby sanctuaries, the routes by which extracted marble was transported and the chronology and sequence of quarry use remain unanswered (Alevras 2013: 116).

Previous work on Naxos has illustrated the presence of quarrying and stone working within a complex network of interrelated anthropic features (Kokkorou-Alevras 1992; Lambrinoudakis & Sfyroera 2010; Kokkorou-Alevras 2013, Kokkorou-Alevras *et al.* 2014, 1992; Korres 2021). No intensive or extensive survey work had, however, taken place at either site that could claim to understand the full extent of quarrying activity, nor the particular material records of this practice. This article presents the approach developed by NQP to address these challenges and lacunae, offering an avenue for the archaeological documentation of quarries as features within complex diachronic landscapes.

Methods

Recording strategy

Since large quarries are fundamentally negative or extractive features that challenge traditional archaeological documentation techniques designed for the built environment, we developed a multiscalar method to document evidence for both ancient stone working and the reuse of these spaces over time (Figure 3). We follow Heldal and Bloxam's (2008) concept of a 'quarryscape': an area of at least 1m² with clear signs of quarrying activity. Such signs include cuttings in the rock for the insertion of posts or splitting wedges (with spade-shaped, triangular and rectangular types predominating), channelling and *pointillé* (closely placed circular punch strokes). In many cases, multiple methods for stone extraction were identified within the same quarry area. Each identified quarry area was numbered, photographed and surveyed with a real-time kinematic differential GPS (RTK DGPS), and resultant data were recorded in a project database alongside a detailed description of the area. Several complex quarry areas were earmarked for further low-altitude drone lidar survey and photogrammetry to facilitate interpretation, alongside traditional autopsic approaches.

Organisation of these data necessitated a recording strategy that unified collection, storage and analysis in a single database. Rather than simply acting as a data repository, the NQP database was designed to promote reflexive interpretation and collaborative analysis (Taylor *et al.* 2015; Boyd *et al.* 2021: 62). The entire project—from data collection, to GIS, to analysis—is housed in a bespoke PostgreSQL relational database accessed through a browser-based frontend for ease of access in both the field and laboratory. The system is open source and can be modified for other archaeological projects (Indgjerd 2025).

Regional study

The topographic profile and spatial extent of open-air quarries make them well suited for 3D modelling and remote-sensing documentation, although the correct scale and resolution depends on the type of quarry, topography and vegetation. For the purposes of

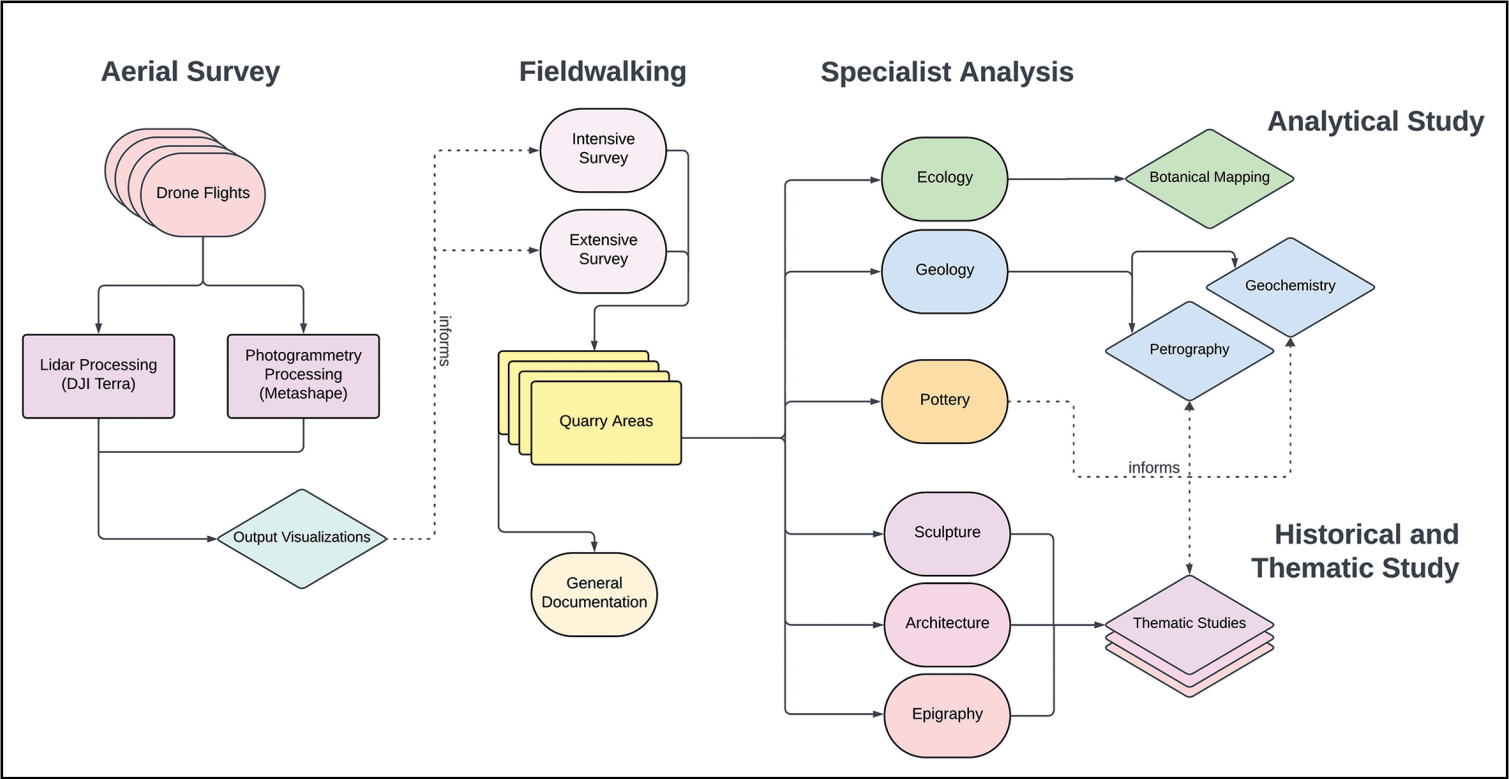


Figure 3. NQP workflow for the documentation of quarried landscapes (figure by R. Levitan).

NQP, manned airborne lidar scanning (ALS) provided insufficient resolution to penetrate local vegetation and record subtle evidence for human activity (see similar complexities in Calderone *et al.* 2024). Instead, drone lidar and photogrammetry documentation was employed to create topographic overviews of two study areas, around the Melanes quarries in the centre of the island and the Apollonas quarries at the north-east coast (see Figure 1). Flights were performed at a range of altitudes and parameters, and several data classification methods were employed to maximise vegetation penetration and surface documentation (Levine *et al.* *in press*).

The use of two aerial documentation methods—lidar and photogrammetry—allowed for a combination of processing techniques and a comparison in their efficacy. In the employment of lidar, the most substantial gains were seen in areas of higher and more open vegetation, while the differences in efficacy between the two methods were smaller in areas with dense, low vegetation. At both the Melanes and Apollonas quarries, we found that enhanced detail could be extracted from photogrammetry using point-cloud processing and visualisation otherwise reserved for lidar data, offering the opportunity to highlight subtle changes in surface topography, like toolmarks, necessary for the documentation and interpretation of quarry areas (Kokalj & Somrak 2019). Aerial recording produced orthomosaics, which were used to identify areas for intensive or extensive fieldwalking.

Documentation

Fieldwalking was used to identify diachronic evidence of human activity, including agricultural terracing, field walls, quarry areas, sculpture, architecture and surface ceramics (Figure 4). Both study areas were segmented into 100 × 100m tracts, with field walkers spaced 20m apart, walking in a cardinal direction and documenting all archaeological evidence along a 2m-wide transect (offering a 10% sample). Each transect was subdivided into five segments of 20m in length, gridding each tract into 25 smaller survey units.

Three-dimensional digital documentation offered an accurate and efficient recording strategy for features of particular interest, including structures, sculptures and fragments of worked marble (Figure 5, nos. 1–3). Handheld lidar scans for 31 architectural and sculptural fragments were collected with an iPhone 13 Pro and processed with the free Scaniverse application. Data were exported as georeferenced .las files and processed .obj textured meshes. This method was effective at documenting objects at various scales, including a large (> 7.5m) architectural fragment, greater than double-life-size (> 5.5m) sculptures abandoned at the Melanes quarry and a colossal (> 11m) sculpture in the Apollonas quarry. Focused studies of these objects are currently in preparation.

Lidar scans were particularly useful to test data collection accuracy in comparison to photogrammetry models of the sculptures, which we were able to ground-truth via close visual examination. Similarly, both photogrammetry and lidar modelling were effective in clarifying the iterative reinscription of a known boundary inscription in Apollonas (IG XII 5, 43; Figure 5, no. 4). Further processing and analysis of the dense point clouds from aerial recording resulted in useful visualisations, and we found that slope



Figure 4. Examples of the topography and vegetation at Apollonas (top) and Melanes (bottom) (figure by E. Levine).

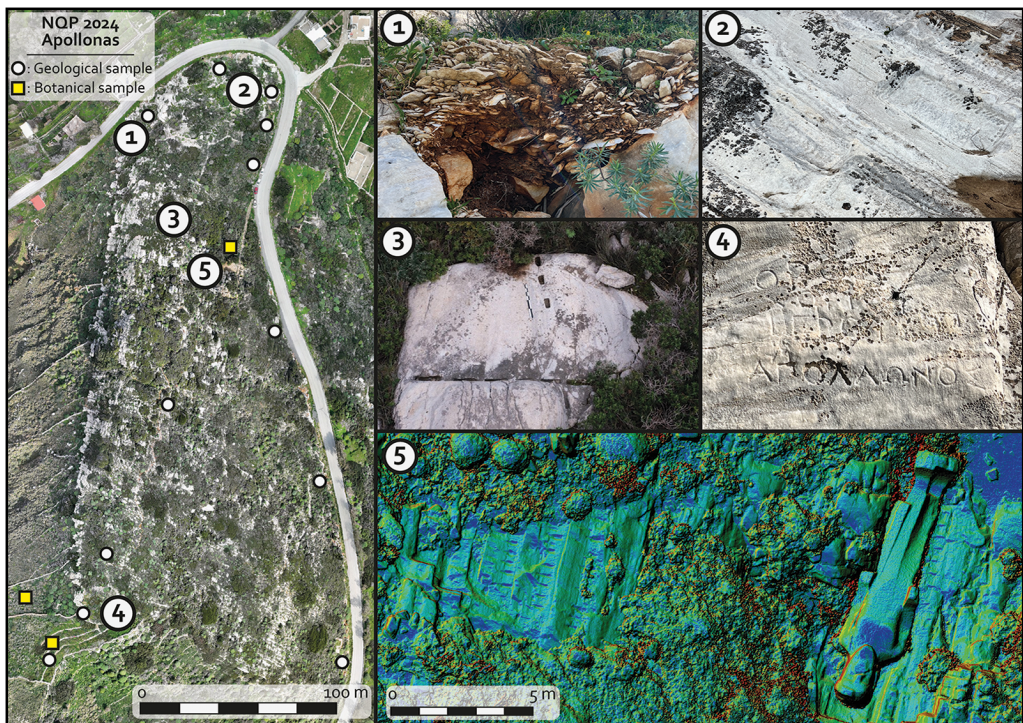


Figure 5. Areas of geological sampling and ecological study (left) and recorded features (right) at Apollonas: 1) slipways; 2) quarry beds; 3) wedge cuttings for block extraction; and 4) inscriptions. Photogrammetry (5, visualised as a slope index) and lidar assisted in the identification of these features (figure by authors).

analysis of high-resolution digital terrain models proved effective at highlighting evidence for quarrying (Figure 5, no. 5).

Surface ceramics underwent *in situ* macroscopic analysis and recording, focused on establishing both their spatial distribution and macroscopic characteristics (fabric, shape and decoration). In-field ceramic documentation was used to establish the range of chronological and functional activities in a given area, modelled on previous survey projects with similar datasets (Haggis & Mook 1993; Knodell *et al.* 2017).

Environmental study proved particularly effective in understanding the afterlives and reuse of these quarries. NQP undertook geobotanical investigation following the Braun-Blanquet (1964) method, a phytosociological recording that estimates the abundance and dominance of species within a *relevé* (vegetation sample plot). The quarry area of Apollonas presented diverse vegetation, and two *relevés* were investigated at different elevations to ensure representative results. In Melanes, where the vegetation is mostly homogenous, two *relevés* were also investigated to facilitate comparison between the two quarries. For each *relevé*, a plot between 9 and 20m² was documented with DGPS and all identifiable plant taxa within the designated area were recorded. After creating this list of plant species, the cover-abundance of each species was estimated using the Braun-Blanquet scale, allowing identification of the range of plant communities present. These results form the basis for a full description of each study area, including climate, soil pH

and soil hydration. Comparison of these data to broader trends on the island highlights the long-term environmental and botanical implications of intensive quarrying, abandonment and subsequent transition to agricultural landscapes, illustrating how premodern extractive industries continue to impact local environments and drive both micro- and macro-environmental change.

The final stage of documentation was a systematic geological sampling of each quarry. In total, 136 samples were collected from Apollonas and Melanes for petrographic and chemical analysis, using inductively coupled plasma mass spectrometry (ICP-MS) and stable isotope analysis (oxygen and carbon). Across the Mediterranean, macroscopic and isotopic studies have been used to build robust databases that illuminate marble provenance (e.g. Craig & Craig 1972; Attanasio *et al.* 2006). As Naxian marble deposits display a heterogeneous chemical signature (Herz 1988), we used petrographic and geochemical analyses to develop a detailed understanding of the geological profile of each Naxian quarry, allowing for the more precise identification of provenance for objects documented during survey and for objects in museum collections (Anevlavi & Prochaska 2021).

Results and discussion

Fieldwork verified that the topography, vegetation and archaeological evidence were markedly different between Apollonas and Melanes. The former displayed lower vegetation, steeper slopes and more visible worked bedrock, while Melanes, as an area of active cultivation, contains both ancient and modern cultural landscapes with a larger variety in vegetation zones. Approaching these industrial zones as complex and diachronic quarrying areas engendered a more robust analysis, thereby enriching our overall understanding of the quarries, as well as the tools and techniques of stone extraction.

At Apollonas, this method allowed the NQP team to identify and study eight large areas of intensive quarrying, offering a clear definition of the extent and limits of extraction along an exposed spine of marble bedrock. In addition to the identification of two premodern poorly preserved structures located within the quarry, dozens of partially quarried blocks and numerous architectural fragments, we also isolated several stretches of previously undocumented slipways made from marble *lapilli* (marble chips) and debris from the quarrying process. Documentation of these slipways offers insight into the process of stone extraction on Naxos, exhibiting how quarry workers shaped their local topography to develop routes to the coast, facilitating the seaborne transportation of large stone blocks.

By contrast, the landscape of Melanes displays a dense pattern of occupation and agricultural cultivation within dormant quarries, alongside the ready spoliation and modification of discarded and incomplete material, from monumental roof tiles to sculptural fragments. At Melanes, we focused on refining our fieldwalking method for vegetated landscapes with intense topography alongside the targeted documentation of 31 quarry areas. This documentation revealed a substantially wider area of intense quarrying than previously known, which, when analysed alongside the results of the lidar survey, enabled the definition of the maximal limits of stone extraction from the site. As at Apollonas, we were also able to identify a series of slipways that led from the quarry to a

nearby river, from which material was subsequently transported westward toward the coast.

Fieldwalking at Melanes highlighted one of our most surprising results: these landscapes, which present exceptionally dense, multifaceted evidence for anthropic activity, were almost entirely devoid of surface pottery. It is not immediately evident whether this dearth of surface ceramics is due to a taphonomic phenomenon that has obscured ceramics at the site (e.g. soil deposition behind terraces) or whether it represents a true lack of systematic occupation at spaces of marble extraction before the Early Modern period (c. 1800–1900).

By contrast, geobotanical investigation revealed rich and varied vegetation profiles at both Melanes and Apollonas. In areas where soil accumulation obscures geology, the presence of particular plant species, influenced by soil pH, reflects the composition of underlying bedrock and quarry debitage. For example, the western limits of quarrying at Melanes are clearly indicated by the presence of *Erica manipuliflora* (autumn heather), which commonly occurs on schist bedrock soils but is absent in calcareous marble soil (Jakobitsch *et al.* [in press](#)). Systematic study of vegetation in abandoned quarry landscapes therefore reveals how centuries of marble extraction affect soil characteristics, creating unique microhabitats with rare plant species (e.g. *Ophrys omeiifera* subsp. *israelitica*). Apart from helping identify areas of quarrying, this aspect of the study deepens our understanding of quarry zones as bio-cultural landscapes, highlighting their transformation from extractive sites to refuges of biodiversity, and offering a window into the long-term impact of premodern industry.

Conclusion

NQP's work combines modern tools with established methods for the systematic in-person documentation of stone quarrying. Although developed in response to the particular challenges and features of Naxian quarries, NQP's three-step sequence of aerial documentation, fieldwalking and specialist documentation, and analytical study is easily reconfigured for other quarries and landscapes of extraction more broadly. Similarly, employment of a recording method built on the documentation of holistic units of quarried areas allows for an integration of data from these stages and facilitates diachronic interpretation. This method highlights the benefits of studying premodern quarries through an interdisciplinary approach that encourages scholars to integrate features directly related to stone extraction into broader sociohistorical, economic and ecological themes. Although this study is ongoing, our preliminary results clearly demonstrate the numerous advantages of such a multiscalar approach to quarry documentation.

Attention to broader contexts allows the archaeology of quarries to be better situated within the spatial, functional and temporal networks of human activity. Doing so encourages an understanding of quarries not as isolated features but as important aspects of interconnected evolving landscapes. NQP's interdisciplinary workflow thereby offers a substantive documentation strategy for ancient quarries and provides an avenue for archaeologists working on sites of extraction, in the Mediterranean and beyond, to more

substantively incorporate these spaces into broader conversations on ancient landscape modification, resource extraction and premodern economies.

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