SCOTT HARRIS PIKE
Archaeological Geology and Geochemistry of Pentelic Marble, Mount Pentelikon, Attica, Greece
(Under the Direction of ERVAN GARRISON)

Mount Pentelikon was a primary source of white marble since the early fifth century BC. The fine- to medium-grain marble was heavily utilized by the ancient Greeks and Romans for statuary, architecture and epigraphic tablets. Despite the increased sophistication of recent signature studies, the archaeologically important white marble quarries on Mount Pentelikon, Attica, Greece have eluded precise characterization.

The presented research challenges the assumption of earlier scholars that Pentelic marble is homogeneous by investigating the geochemical and stable isotopic profile of the entire Pentelic quarry area. An extensive field study was undertaken to locate, map and categorize all surviving ancient and modern quarries. Field observations were also used to construct a geologic map of the quarry area. The maps reveal that the marble quarries fall within three marble units. The survey maps were used to acquire a 610 sample reference collection representing 72 of the 162 identified quarries.

Whole-rock compositional studies were carried out by NAA on sixty-one samples representing five geographically distinct quarry groups. Discriminant, cluster and principal component analyses were performed on the data to identify any significant structure within the data. No structure was evident. Since mineralogical impurities such as aluminosilicates and oxides can cause significant random compositional variation, a suggestion for future compositional studies recommends employing ICP, which has the benefit of only measuring the carbonate fraction.

Analyses using stable isotope ratios of carbon and oxygen suggest that there are regions within the greater Pentelic quarry area that can be distinguished. Correlating the $\delta^{13}C$ and $\delta^{18}O$ values with the geologic map reveals that Marble Units 1 and 2 have significantly increased $\delta^{13}C$ values. Marble Unit 3 is recognizable by having a narrow range of $\delta^{13}C$ values and significantly higher $\delta^{18}O$ values. The marble with the highest oxygen ratios are from three neighboring quarries on the upper slope of Marble Unit 3. The high values correspond to the isotope ratios of the Elgin Marbles at the British Museum in London. The success of the database in locating the quarries for the Parthenon sculptures attests to the importance of carrying out extensive fieldwork when undertaking quarry characterization studies.

INDEX WORDS: Mount Pentelikon, Pentelic marble, Marble characterization, Stable isotopes, neutron activation analysis, provenance, Elgin Marbles, Parthenon

ARCHAEOLOGICAL GEOLOGY AND GEOCHEMISTRY OF PENTELIC MARBLE, MOUNT PENTELIKON, ATTICA, GREECE

by

SCOTT HARRIS PIKE

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by

SCOTT HARRIS PIKE

Approved:

Major Professor: Ervan Garrison

Committee: Norman Herz
L. Bruce Railsback
Alberto Petino-Douce
David Wenner

Electronic Version Approved:

Gordhan L. Patel
Dean of the Graduate School
The University of Georgia
December 2000

DEDICATION

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

For over a century archaeologists and art historians have turned to earth scientists to establish quantitative criteria to distinguish between the different white marble sources exploited in the eastern Mediterranean basin. The ability to correctly identify the source regions of marble artifacts assists archeologists, art historians and museum curators with dating artifacts, piecing together ancient trade routes, giving insight into changing aesthetic values and determining modern forgeries, ancient copies and disassociated fragments (Herz 1987). The data banks that have been established, particularly those for the stable isotope ratios of carbon and oxygen, have successfully been referenced to solve many important questions concerning the provenance of archaeological marble. Yet, despite the increased sophistication of recent signature studies, the historically important marble quarries on Mount Pentelikon in Attica, Greece have eluded precise characterization.

Mount Pentelikon has been a primary source of white marble since the early fifth century BC. The fine- to medium-grain marble was heavily utilized by ancient Greeks and Romans for statuary, architectural and epigraphical monuments. It is believed that the quarries were first exploited on a large scale for the construction of the Older Parthenon atop the Athenian acropolis *circa* 489 BC (Dinsmoor 1975). The current Parthenon, built some fifty years later, and all of the other surviving ancient buildings on the acropolis are also composed of Pentelic marble. During the Roman era, both Imperial-owned and privately held Pentelic quarries provided marble for architectural and sculptural monuments throughout the empire (see Dodge and Ward-Perkins 1992, appendix 1; Abraldes 1996).

The current research represents the first systematic characterization study of the archaeologically significant Pentelikon quarry region. At present, the Pentelic quarry database is limited because researchers have focused on obtaining a single characteristic signature for the entire Pentelic quarry field. That approach assumes that the marble within the quarry region is both isotopically and geochemically homogenous. Therefore, only a relatively small number of samples chosen arbitrarily from throughout the quarry area have been used to represent the entire quarry region. Only recently have researchers recognized that the Pentelic quarries are not homogeneous. Rather, data suggests that the quarry region has geochemical and stable isotopic anomalies throughout (Matthews *et al*. 1992, Kane *et al.* 1992, 1995, Pike 1996).

The current study is an outgrowth of a wealth of research that for the past one hundred years has attempted to quantitatively discriminate between the different white marble varieties in the eastern Mediterranean. Therefore, to understand the scope and novelty of this dissertation research it is necessary to review the history of marble provenance studies. The first extensive study characterizing the major archaeological marble types in the Aegean was conducted by the German geologist G. R. Lepsius (1890). Working closely with archaeologists, Lepsius characterized the known ancient Aegean marble quarries using macroscopic and petrographic criteria such as color and grain size. Lepsius's study became so influential that the names he assigned to each of the source areas (Pentelic, Hymettian, Parian, Naxian and an anomalous coarse-grained Island variety) became descriptive labels for marbles that shared similar traits rather than true source names. Thus, Hymmetian marble was defined as a gray/blue marble despite the fact that it could have been from Mount Pentelikon or some other source. The American petrologist H. S. Washington (1898) recognized the limitations of Lepsius's study by noting that marble textures, fabrics and mineralogies can vary significantly within a quarry. Thus, Washington argued, it is not possible to assign a blanket macroscopic description to each marble type.

Unfortunately, Washington's warnings were not heeded. The subjective nature of the criteria and confusion over assigned "provenances" often led to unresolved controversies and ambiguities between scholars of ancient marble artifacts. In a 1953 paper in the *American Journal of Archaeology* Herz and Pritchett questioned the subjective nature of determining the provenance of marble artifacts by aesthetic means. Although the goal of the paper was not to improve diagnostic methods for marble provenance assignments *per se*, they do unequivocally present several tables in which various respected scholars assign conflicting provenances to published epigraphical marble tablets.

In spite of these reservations the archaeological and philological community continued, and often still continues, to refer to the Lepsius criteria when assigning a source to a marble artifact. In 1968 Renfrew and Peacey launched a sharp criticism of macroscopic provenance determination. Their petrological examination of marble samples from throughout Greece concluded that no single macroscopic characteristic or set of characteristics can adequately define a marble type. They suggested that the current state of marble provenance studies was severely limited because two essential criteria for provenance studies had not been met. The first was that an adequate reference sample collection had not been obtained from the quarries to accommodate for intra-quarry variation. The second was that no technique had been established that could effectively distinguish between the different marble varieties.

Criticism is often a hard pill to swallow and Renfrew and Peacey's negative assault on the "eighty year myth" of macroscopic marble characterization was no different. B. Ashmole (1970), the esteemed British art historian, rebuked the criticism. He retorted that until science can come up with a technique that can distinguish marbles with certainty, it was best to use the "common sense" approach outlined by Lepsius. It is ironic that Ashmole's criticism of science getting in the way of common sense is based on analyses of a geologist who, eighty years prior, was employing a scientific technique using the latest methodological advancement of his time – namely the development of the standard petrographic microscope. Had segments of the archaeological and philological community monitored the development of petrographic theory and methodology, they would have seen the scientific method revise, alter and ultimately disprove the hypothesis put forth by Lepsius.

It was not until the 1970s that new quantitative approaches to marble provenance began showing promise. The techniques being developed focused on accessory mineral concentrations, trace and rare-earth elemental concentrations, and other physicochemical techniques. To date, the most successful technique applied to marble studies was first introduced in 1972 by Valerie and Harmon Craig who demonstrated the utility of using stable isotopes of carbon and oxygen as a way to distinguish between marble varieties. Although admitting their stable isotope database was very limited, they were able to determine the provenance of five out of ten archaeological samples. Manfra, Masi and Turi (1975) extended the database by adding white marbles from five major quarry producing regions in Anatolia. They also showed that the stable isotope technique is limited to white marbles since colored marbles are isotopically variable. N. Herz continued the development of the stable isotope database and continued to publish it as more data was added through his own analyses and published reports (Herz 1985a, 1985b, 1987, 1988). In the past several years other scholars have continued to add to the database (e.g. Matthews et al. 1992, Lapuente 1995).

Stable isotope analysis of marble precisely measures stable isotope ratios of carbon ($^{13}C/^{12}C$) and oxygen ($^{18}O/^{16}O$) within the carbonate crystal structure. Stable isotopes are atoms that have the same atomic number defined as the number of protons in the nucleus, but a different number of neutrons. The atomic weight of each atom is equal to the number of protons and neutrons in the nucleus. Standard notation for isotopes is the atomic symbol of the element preceded by a superscript denoting the atomic weight (e.g. ^{87}Sr). In general, in chemical reactions isotopes behave the same. However, with atoms of low atomic number, the addition or subtraction of a neutron significantly alters the weight of the atom and will result in slightly different vibrational frequencies between the heavier and lighter isotopes (Krauskopf and Bird 1995). The higher the vibrational frequency the less strongly the atom will bond to other atoms.

Calcite ($CaCO_3$), the primary mineral in marble, is composed of carbon, oxygen and calcium. Because carbon and oxygen are light elements with multiple stable isotopes, the conditions and manner in which calcite crystallizes will effect the isotopic ratio. For example, precipitated shallow water limestones are depleted in ^{18}O and enriched with ^{13}C relative to their precipitated deep-sea counterpart. Shallow-water mollusks and foraminifera are relatively depleted in ^{18}O when compared to both shallow-water and deep-water precipitates (Veizer 1990, Milliman 1974, Wenner, Havert and Clark 1988). In most cases the stable isotope signature of marbles is thought to reflect the signature of its pre-metamorphic limestone protolith (Wenner, Havert and Clark 1988). This can graphically be expressed in the scatter-plot diagram in Figure 1 that shows the isotopic profiles of marble compared to that of limestones from different environments. The assumption of marble stable isotope analysis is that each marble region will have undergone a unique geologic history that will be reflected in a distinct set of stable isotope ratios.

However, metamorphic events can have an affect on a metacarbonate's stable isotope ratios. Rye et al. (1976) showed that isotopic fractionation occurs at the contacts between calcite grains and hydrous mineral phases. In lower grade marbles, this fractionation may only affect the outer few cm of the sample. In the thicker low-grade marble units the cores of the units remain homogeneous and unaltered. With increasing metamorphic heat, the depth of fractionation increases. In their study of water/rock interactions of marbles in Utah, Nabelek et al. (1984) concluded that marbles are relatively impermeable to metamorphic fluids. Therefore, the fractionation observed by Rye et al. (1976) must occur at the contact between the different rock units. At higher grades of metamorphism the interiors of thick units exhibit large isotopic variations and gradients. This may be caused by channelized flow of extraneous, isotopically distinct metamorphic fluids within the marble (Wenner, Havert and Clark 1988). Metamorphic fractionation between graphite or organic matter and calcite does not appear to play a major role in the isotopic fractionation of marble. Valley and O'Neil (1981) have demonstrated that the effect of metamorphic fractionation of $\delta^{13}C$ in calcite-graphite pairs is minimal at low temperatures and above 500-600°C the fractionation is relatively small (2.6-4.8‰). The effect is small and negligible when compared to the fractionation at calcite-hydrous mineral contacts.

The isotopic composition of a marble's limestone protolith is principally controlled by crystallization temperature, chemical composition and the isotopic ratios of the water (Faure 1986). Factors involved in a limestone's isotopic signature include (1) the mode of origin of the limestone i.e. does it form as a precipitate or as a hash of bioclasts, (2) the isotopic composition of the water

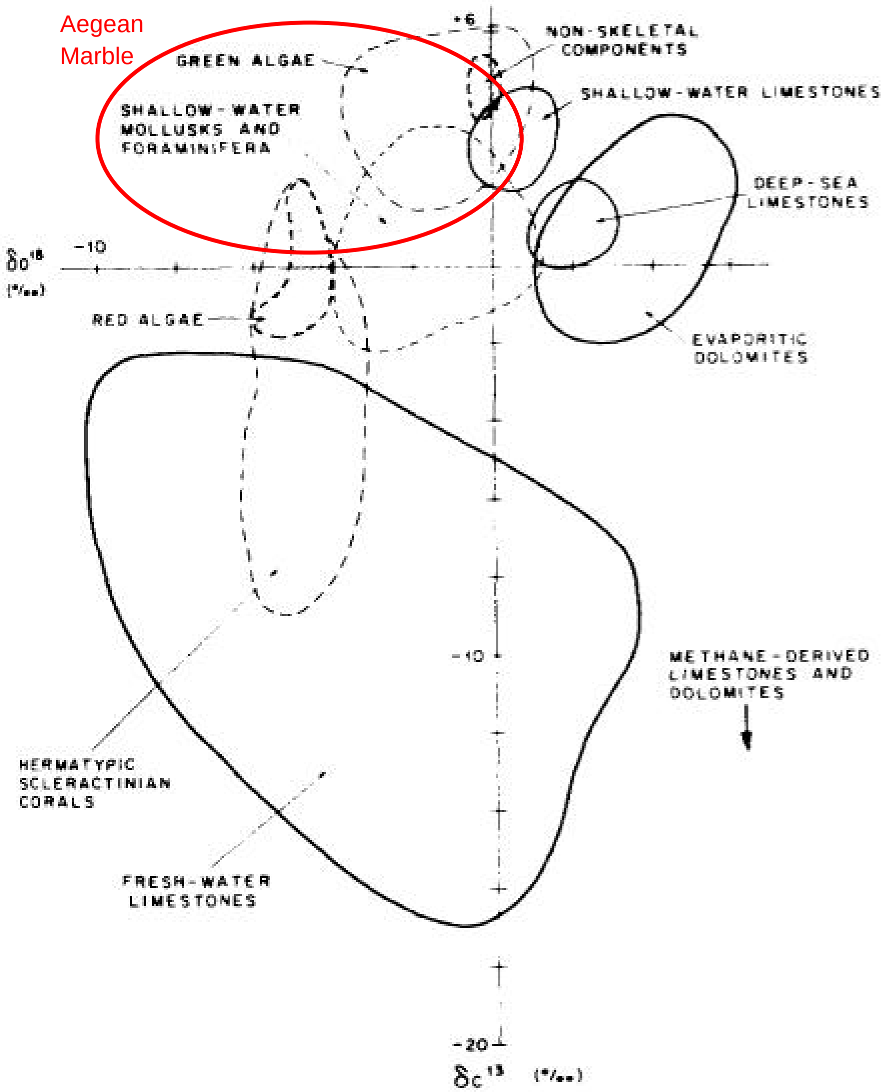

Figure 1. Typical distribution of δ^{18}O and δ^{13}C values in various types of Quaternary carbonate environments (after Milliman 1974). The red ellipse indicates the standard isotope range for Aegean marbles.

associated with the carbonate minerals during formation and later history, and (3) later weathering history (Herz 1988).

One of the underlying assumptions of stable isotope analysis as a marble provenance technique is that marble units maintain a homogenous isotopic profile. Herz (1985a) listed conditions that must be attained over a wide quarry area if a quarry is to be isotopically uniform. They are (1) that the marble must have achieved isotopic equilibrium during its formation or metamorphism, (2) that the marble unit is relatively pure and thick and (3) that the metamorphic gradient was not too steep. As Herz (1985a) pointed out, the combined effects of a steep metamorphic gradient, exchange with metamorphic pore fluids, and equilibration with other quarry rock can introduce very high variations in $\delta^{18}O$ within a short distance.

A trend in the development of the Aegean white marble stable isotope database is the expansion of the quarry fields as more and more reference samples are collected and analyzed. Leese (1988) explained this growth of the quarry fields as a statistical consequence of a more representative sample reference collection. As more samples from each of the quarries were added to the database, the quarry fields took on a profile much more representative of the true quarry field distributions. These findings are significant because they demonstrate the necessity of having a truly representative reference sample collection to ensure the adequacy of the database.

A serious consequence of the expansion of quarry signature fields as well as the addition of more white marble quarries to the Aegean marble database has been an increase in the overlap of the signature fields (figure 2). These findings limit the validity of the assumption that marble formations have distinct sets of stable isotope ratios. This increase is evident not just in the number of quarries that overlap one another, but also in the total area of overlap in $\delta^{13}C$-$\delta^{18}O$ space. Archaeological samples whose stable isotope signatures fall into one of the overlapping regions must rely on other data to distinguish between the two or more overlapping marble types.

Germann, Holzmann and Winkler (1980) in their study of marble quarries from Thessaly recognized this overlap in isotope fields and proposed that petrographical and trace-element data also be incorporated into provenance studies. This call for a multi-method approach has been the mantra of several manuscripts that have been published during the last several years (e.g. Moens et al. 1988, 1992, Jongste et al. 1995).

Petrographic analyses were the first geologic technique employed to distinguish quarries. Lepsius (1890) and Washington (1898) looked at the major marble varieties over one hundred years ago. In the 1950s, Herz (1955) and Weiss (1954) undertook petrofabric studies and showed that the grain size distribution and crystallographic orientation of calcite is sufficiently different between some quarries. Although a promising approach, the technique required a large sample for making petrographic thin-sections. For many archaeologists and curators, the size requirement is simply too large for the technique to be beneficial.

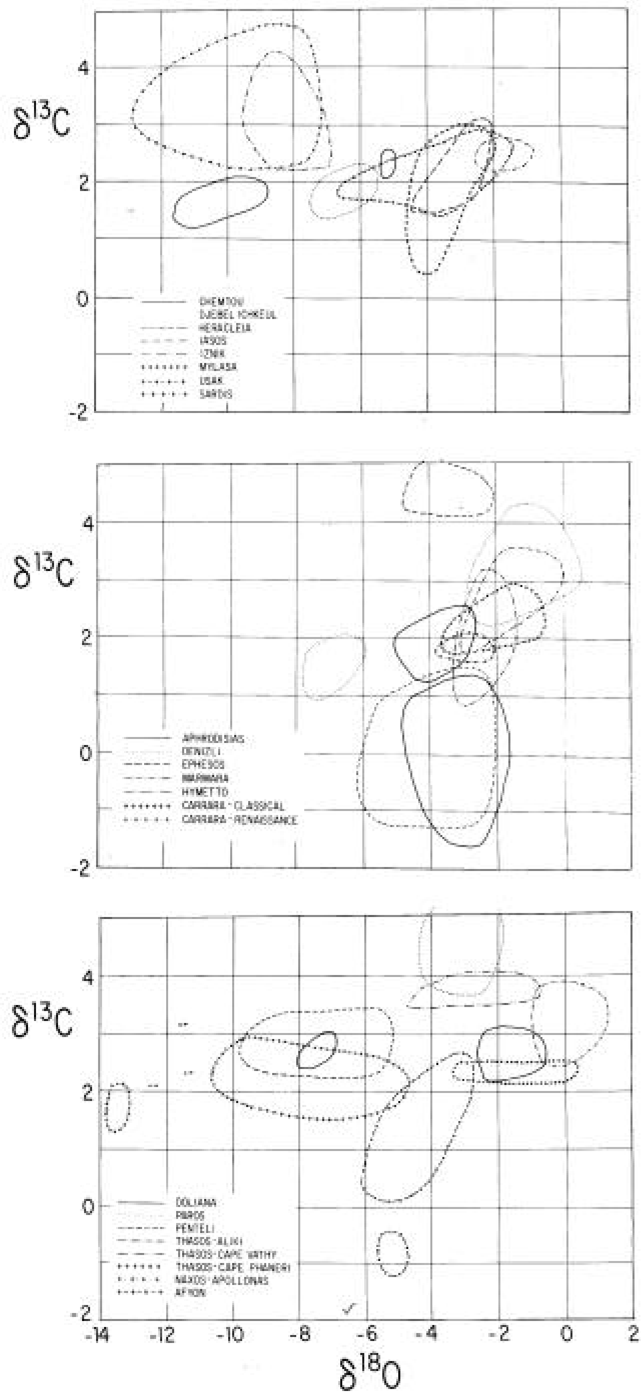

Figure 2. The stable isotope database of major marble producing ancient quarries in the eastern Mediterranean (from Herz 1987).

Since the 1960s various attempts to establish a trace- and rare-earth element database have been reported with mostly negative results. The underlying assumption of the geochemical approach is that there are trace- or rare-earth elements that are homogeneously distributed within marble units. Rybach and Nissen (1965) analyzed over 200 samples from quarries throughout the eastern Mediterranean by neutron activation analysis (NAA). Although they were able to make small distinctions between some quarry types, Herz (1985a) disqualified the technique because the variation within a single hand-sample was too large. As analytical equipment and methodologies became more sophisticated, fresh attempts to establish a trace element database for Mediterranean white marbles were made (e.g. Conforto et al. 1975, Moens et al. 1987, Grimanis and Grimani 1988, Meloni et al. 1988, Mello et al. 1988, Matthews et al. 1995). Mandi et al. (1995) evaluated the contribution of trace element analysis to the determination of marble provenance. Their conclusion was that trace element concentrations are too varied within quarries to be suitable for provenance investigations when more than two quarry sources are in consideration.

Electron spin resonance (ESR also referred to as electron paramagnetic resonance [EPR]) is another analytical technique receiving much attention lately. First used in marble provenance studies by Cordischi *et al.* (1983) and Lloyd *et al.* (1985) the mechanics and applications of ESR have been further developed by Dr. Yannis Maniatis, Director of the Archaeometry Laboratory at Demokritos, Athens, Greece. ESR is an active technique such that a small amount of ground marble sample is placed into a quartz tube and put inside a cavity in the center of an electromagnet. As the magnetic field is varied, microwaves of known wavelength are sent through the sample. A spectrum is obtained of the resonant absorption of the microwaves as the magnetic field varies (Maniatis *et al.* 1988). The absorption is caused by the presence of unpaired electron species, either transition-metal ions or free-radicals in the sample (Lloyd *et al.* 1988). The technique provides several different parameters that are currently being investigated for their effectiveness as provenance discriminators. The parameters are mostly related to Mn^{2+} impurities within the calcite matrix.

Despite these advances in geochemical methodology and techniques, when they are applied to archeological quarries there is still a great deal of variance among the parameters being used. Vezier (1990) succinctly summed up the reason why geochemical analyses will not work to establish distinctive signatures for each of the quarry regions:

> The chemical and isotopic composition of carbonate sediments and rocks is…not simply the sum of the chemistries of the constituent carbonate minerals. Noncarbonate constituents, such as aluminosilicates – which account for up to 50% of the sample – usually harbor considerably higher trace element concentrations than do carbonate minerals…Consequently…the bulk of rock chemistries of sedimentary carbonates are controlled primarily by the quantity and the characteristics of the noncarbonate constituents. This essentially random feature, which is largely determined by provenance, can be quantified only with difficulty…

In reviewing the vast array of physico-chemical techniques developed over the past thirty years it becomes clear that there are two primary factors that limit their usefulness. The first is that methodological constraints play a key roll in limiting the extent of some techniques. For example, electron spin resonance analysis, although proving to be a promising technique to differentiate between some regional quarries, is limited by not being able to use powdered samples (Maniatis et al. 1998, Mandi et al. 1992). The requirement of ESR to use a chip is a practical limitation since most museum curators and archaeologists do not grant permission for this type of destructive sampling. Cathodoluminescence of marble artifacts has had success with distinguishing between some different quarries by monitoring the wavelengths of visible light emitted as electrons trapped in Mn^{2+} lattice-traps are released to a lower energy level after being subjected to cathode-generated electron beams of known energy (Ramseyer et al. 1989, Barbin et al. 1992, Luete 1987). However, the technique is difficult to quantify and is limited by not being reproducible in other labs (Blanc 1995, Elali, 1993). Also, sample size requirements are still large and the technique faces similar sampling size restrictions imposed by curators and archaeologists as for ESR.

The second limitation of many of the provenance studies is the inadequacy of the reference sample collections used to characterize quarry districts. With few exceptions, all characterization studies have focused on either the advancement and increased sophistication of analytical techniques or the application of techniques to archaeological material. Little attention has been given to the acquisition of or degree to which a reference sample collection adequately represents a marble source area. As outlined above, the underlying assumption of earlier marble provenance studies was that geologic marble units are geochemically and isotopically homogeneous. Therefore, these studies attempted to characterize entire quarry regions as single units with measurable and limited stable isotopic and geochemical compositions. The sampling strategies for acquiring reference sample collections on which these studies are based were modeled under this same assumption. That is, the reference sample collections comprised a few arbitrarily chosen samples from throughout the quarry region. These sample populations were then considered sufficient to represent the entire area geochemically and isotopically. Little consideration was given to the geologic history of the quarry region, the stratigraphic placement of the quarries or the proximity of the quarries to the nearest schist intercalation.

The current study of the Mount Pentelikon marble quarries investigates these earlier assumptions. To successfully profile the geochemical and isotopic signature of the Penteli region it is of primary importance that a reference sample population is obtained that adequately represents the marble varieties exhumed from the ancient quarries. It is also important to insure that the reference collection accounts for the geologic variations within the region. Therefore, as the foundation of this study, a truly archaeologically and geologically representative reference sample population was acquired. To achieve this goal an extensive topographic and geologic survey was carried out to identify every ancient and modern quarry and to make observations and take measurements of the local geology. The data from the survey were used to construct a topographic map showing the locations of every individual quarry within the ancient quarry region and a geologic map to illustrate the marble units spatial relationship. With reference to these maps a sampling program was initiated to collect samples from all possible quarries. The samples were then subjected to a battery of analyses to see if any geochemical or isotopic patterns emerged.

The current study not only refines the database for the Pentelic quarry region as a whole, but also provides signatures for distinct groups of quarries. The ability to discriminate between quarries within the same quarry region expands the scope of marble provenance studies and allows for more specific archaeological questions to be addressed. An example of one such archaeological problem that can be addressed with this high resolution characterization study concerns the source quarries for the Penteic marble monument know as the Parthenon. M. Korres (1995), the former architect of the multimillion-dollar Parthenon reconstruction project, argued that the classical Greeks began quarrying on the lower south slope of Mount Pentelikon in the famous *Spilia Divali* quarry. Based on his topographic survey of the ancient quarry area and the chronology of large-scale Pentelic building programs, Korres speculated that *Spilia Divali* provided the material for the Parthenon’s construction. However, the stable isotope results from Matthews et al.’s (1992) study of the Parthenon sculptures housed at the British Museum in London strongly suggested that the Parthenon is constructed from marble extracted from the uppermost quarries on the south slope in the area called *Aspra Marmara* (Lepsius 1893). It is anticipated that a high-resolution Pentelic marble database will provide statistically viable information relevant to this current debate. It is also possible that the database may reveal that the Parthenon's architectural blocks were extracted from a different and perhaps relatively distant quarry than the quarry that produced the marble for the monument's sculptural program.

Furthermore, the database can also be used to relatively date periods of quarry operation. For example, if a match can be made between the Parthenon samples and an individual quarry or group of quarries, then it will be possible to date periods of operation for the identified quarries. If an undated marble artifact is found to be from a dated quarry, then the artifact itself can relatively be dated. Therefore, by increasing the resolution of the Pentelic database, scholars will not only be able to distinguish Pentelic marble from other types, but may also be able to collect data on exploitation practices and economics of the Penteli marble quarries.

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CHAPTER 2

AN EXTENSIVE TOPOGRAPHIC AND GEOLOGIC SURVEY OF MOUNT PENTELIKON AND THE SYSTEMATIC ACQUISITION OF A REFERENCE SAMPLE COLLECTION[1]

[1] Pike, S. H. To be submitted to *Geoarchaeology*

Abstract

An extensive topographic and geologic survey was undertaken as an integral part of the first systematic characterization study of the important ancient marble quarries on Mount Pentelikon, Attica, Greece. The aim of the survey was twofold. First, the topographic survey was to locate and catalog every ancient and modern quarry within the ancient Pentelic marble quarry region. The second aim was to observe, record and interpret the local geology. Results of the survey were used to design and implement a sample acquisition program to obtain a sample reference collection that accurately and inclusively reflects the ancient quarrying district and the underlying local geology. The results of the survey and sampling program are reported here. Two important outcomes are immediately apparent. The first is that there are many more distinguishable and traceable quarries than had previously been recognized and second, that the quarries fall into three distinct mappable marble units. These results reveal the importance of extensive fieldwork when undertaking lithic provenance studies. Concluding remarks encourage physical scientists involved in archaeological characterization studies, whether in marble or other lithic resources, to adequately carryout field surveys prior to sampling to ensure that a truly archaeological and geological representative reference sample collection is obtained. An appendix describes each individual quarry and quarry maps locate each sample spot and other important features.

Introduction

Mount Pentelikon, northern Attica, Greece has been a primary source of white marble since the late sixth century BC (Dinsmoor 1975). The low- to medium-grade, fine- to medium-grain size marble was heavily utilized by the ancient Greeks and later exported throughout the Roman Empire (Fant 1988, 1995, Abraldes 1996). The demand for Pentelic marble is evidenced by its widespread distribution throughout the central and eastern Mediterranean. Perhaps the most well known architectural use of Pentelic marble is the Parthenon atop the Athenian acropolis. The archaeological importance of Pentelic marble has prompted scholars to seek quantitative methods to differentiate Pentelic marble from all other white marble varieties exploited in antiquity. The ability to correctly identify source regions for marbles assists archaeologists and art historians with dating, tracing ancient avenues of commerce, giving insight into changing aesthetic values, and determining modern forgeries, ancient copies and disassociated fragments (Herz 1987). Despite its archaeological significance, researchers have had difficulty determining a set of criteria that effectively distinguish Pentelic marble from all other marble varieties in the eastern Mediterranean.

The current research represents the first systematic characterization study of the ancient marble quarries on Mount Pentelikon (figure 1). Previous efforts by earth scientists to obtain a provenance signature for the extensive Pentelic quarries focussed on establishing a characteristic fingerprint that identifies the entire Pentelic quarry area (e.g. Craig and Craig 1972, Herz 1985, Roos et al.

1988, Meloni et al. 1988, Cordischi et al. 1983). These studies assumed that the Pentelic marble quarry region is geochemically and isotopically homogenous. Therefore, these studies attempted to characterize the entire quarry region as a single unit with a measurable and limited stable isotope and geochemical composition. The use of statistical ellipsoids drawn around dataplots in two-dimensional space further assumes a centroidal value for each of the measured variables (Leese 1988, Pentia et al. 1995). However, recent reports suggest that the large Pentelic stable isotope field may contain geographically distinguishable sub-regions with marked differences in isotopic and geochemical compositions (Matthews et al. 1992, Kane et al. 1992,1995, Pike 1996). These findings lead one to question the assumption of isotopic and geochemical homogeneity within quarry regions that has stood at the core of the earlier provenance studies.

In an effort to understand the true nature of chemical variability within the Mount Pentelikon quarry region a systematic characterization study of the entire ancient Pentelic marble region has been undertaken. An integral part of this investigation is the establishment of a sample reference collection that is truly representative of the quarry area. Since previous studies assumed a homogenous geochemical and isotopic profile for the Pentelic quarry region these earlier characterization studies relied on reference sample collections of relatively few arbitrarily chosen samples from within the quarry region. Only the characterization studies published by Waelkens and his Belgian colleagues (see Roos et al. 1988) showed any indication of where individual sample spots are located. However, their base map, published over 100 years ago (Lepsius

1890), was drawn to such a large scale that the symbols used to locate each sample spot cover over 100 meters. Furthermore, modern extraction activities in the quarry area have significantly altered the topographic profile of the quarry region making one suspect of the accuracy of the locations of each the sample spots.

To effectively monitor chemical trends and variations it is therefore necessary to obtain a reference sample collection where each sample location and geologic setting is recorded. In order to obtain such a collection an extensive topographic and geologic field survey was conducted throughout the entire ancient quarry area of Mount Pentelikon.

The field survey had two primary objectives. The first was to identify and record every ancient and modern quarry within the ancient quarry region. Many of the quarries found in the study had not previously been reported and do not appear on earlier maps of the quarry region or in Greek military aerial photographs. The second goal of the survey was to observe, measure and record the local geology. An extensive geologic survey of the quarry region allows for assessing petrologic, stable isotopic and geochemical data within its geologic context. Following the survey a detailed and extensive sampling program was designed and carried out to acquire a truly representative reference sample collection. This paper reports on the findings from the survey and the description of the sample reference collection of Pentelic marble that resulted from it.

The Geologic Setting

The geologic evolution of Mount Pentelikon is not well understood. To date, the Institute of Geology and Mineral Exploration (IGME), the Greek State's geologic survey, has yet to publish a geologic map of the northern Attic region. Despite the lack of consensus over Mount Pentelikon's origin, there are aspects of the mountain's history that are in agreement by most scholars. Mount Pentelikon lies in the northern section of the Attic-Cycladic geotectonic zone (Figure 1). This zone marks the southernmost of three massifs forming the Pelogonian Zone of the Hellenides mountain system (Katsikatsos et al. 1986, Dürr 1986). The belt of metamorphic rocks continues south to the Cycladic islands and to the east where it merges with the Menderes massif near the Anatolian coast. The Menderes massif is geologically similar to the Attic-Cycladic metamorphic belt, but also shows some affinities with metamorphic rocks from Africa (Higgins and Higgins 1996). It is still not clear whether the Menderes massif is a remnant of African crust or if it is simply a lateral extension of the Attic-Cycladic belt. Schliestedt et al. (1988) suggest that the metamorphic rocks comprising the Attic-Cycladic massif were rapidly subducted roughly 50 km during the Eocene compression of the Alpine orogeny. Soon after the downthrusting the subduction ceased. Thus the shallow-sea rocks that are thought to have been similar to the Bahamian-style Pelogonain massif to the north underwent typical blueschist facies metamorphism of high pressure and low temperature. Most of the major marble producing quarries within Greece and Anatolia are located within the Attic-Cycladic / Menderes metamorphic belt.

The German geologist Lepsius (1893) described the western section of Mount Pentelikon as being composed of three autochthonous formations he labeled the Lower Marble Formation, the Intermediate Schist Formation and the Upper Marble Formation. Lepsius dated the rock formations to the Precambrian. Since then several authors have isolated unmetamorphosed fossils indicating the autochthonous formations date to the Triassic through Upper Cretaceous (Steinmann 1890, Negris 1912, 1915, Kober 1929, Marinos and Petrascheck 1956, Leleu and Neuman 1969, Papdeas 1970, Katsikatsos 1976, 1977, 1986). Avdis (1991) lists the relative thicknesses of the marble units. The Upper Marble is 100 m thick and the lower marble is estimated to have a minimum thickness of at least 500 m. Research suggests that the current Attic topography is the result of a series of tectonic nappes related to the Eohellenic orogeny of the Eocene (Katsikatsos 1977). This orogenic event resulted in the uplift of Mount Pentelikon by a northeastward thrusted, northeast plunging anitclinorium (Markoulis pers. comm.). Avdis (1991) argues that the topography of Mount Pentelikon is the result of uplift of the autochthonous crystalline basement rocks by a long series of many high-angle dip-slip faults. This interpretation, although compelling, fails to take into consideration the structural major and minor folds throughout the formation. The ancient Greek and Roman white marble Pentelic quarries are situated in the exposed upper section of the Lower Marble Formation on the southwest limb of the primary fold.

Methodology

The initial base map acquired for the survey was a 1:5000 topographic map issued by the Greek Military. Due to a military installation at the summit of Mount Pentelikon, the Greek military literally blacked out the elevation data at and near the summit. Since many of the quarries fell within the blacked-out area, the first contour maps were of little use. With the assistance of IGME an uncensored set of contour maps was obtained. The second set of contour maps were also drawn to a scale of 1:5000. Unfortunately, as field work progressed it became apparent that the maps were incomplete and inaccurate. In the areas of extensive quarry extraction, topographic lines were omitted. Contour lines that did appear on the maps were not accurate. Benchmarks were not located where indicated on the map and altimeter measurements indicated that contour lines did not adequately reflect the topography, perhaps due to modern reworking of the quarries, road building and military construction projects (e.g. underground garrisons and retaining walls).

In 1995, M. Korres published a map that recorded and labeled ancient and modern quarries that fell within a band of quarries that traditionally have been interpreted as comprising all of the ancient Pentelic quarries on Mount Pentelikon (Figure 2). Comparing his map with features on the Greek Military contour map, it is apparent that he used the latter as his base map. Despite the shortcomings of the contour map, Korres estimated the location and elevations of many of the quarries and added contour lines where there were none. Korres labeled all of the quarries drawn on the map using a notation system that distinguished between individual quarries and identified them as either ancient or modern. In an effort to avoid confusion and multiple numbering schemes, the established protocol at the onset of the current field survey was to continue the labeling scheme established by Korres for any additional quarries that were identified outside the boundaries of his narrow field area.

Using the incomplete contour map and the Korres map as guides, a survey was initiated to observe and record the location, coordinates and dimensions of each quarry. Ancient quarries were identified by surviving tool marks left by ancient workers on quarry walls (Waelkens 1988 and others), abandoned partially carved architectural elements, *gourna* – carved marble basins used for repair of metal tools (Kezelj 1988) – and paved quarry roads leading directly to quarry mouths. Also identified and recorded were the locations of quarry roads and quarry debris piles. It is important to recognize that it is likely that many ancient quarries have been reworked by later extraction activities limiting the amount of physical evidence of ancient extraction. It is also likely that modern extraction practices have partially destroyed and in some circumstance, completely obliterated any physical evidence of ancient quarrying. Therefore, there is an unavoidable bias in following this protocol when distinguishing between the ancient and modern quarries.

The geologic component of the field survey recorded structural and mineralogical observations in the marble and noted the presence of interbedded and intercalated schist horizons. Also, structural data were recorded to correlate the quarries with the local geology. The strike and dip of foliation bands within and adjacent to schist intercalations and micaceous bands in the marble were recorded to determine the orientation of the rock units. Grain size, color and texture were also measured in an attempt to locate any possible trends throughout the geographic extent of the study area. Observations from the topographical and geologic survey were recorded in a field book as well as marked on field maps. The field maps were then digitized using the vector-graphic program CorelDraw version 8.

Results

Topographic Survey

The field survey identified 172 discrete quarries. A location map shows the spatial distribution and traces of the quarries (Figure 3). The map is color coded to distinguish the known ancient quarries (red lines) from the modern quarries (blue lines). Tool marks, quarry trenches and unfinished worked blocks indicate that at least thirty quarries were worked during antiquity. Also included on the map are vehicle accessible roads, vehicle inaccessible roads, and surviving traces of ancient roads.

Note that the quarry location map does not follow the quarry labeling system established by Korres (1995). The Korres map employs two different numbering sequences. One numbering sequence identifies ancient quarries with an uppercase lambda followed by an identification number. The modern quarries are identified with a lowercase lambda and are also labeled sequentially. However, careful observations of all the quarries revealed that several quarries that were identified as modern on the Korres map do, in fact, show physical evidence of being worked in antiquity. For example, careful observation revealed traces of the ancient pick etched into the quarry walls identified by Korres as modern quarry λ37 (figure 4). To reclassify a quarry using the Korres scheme would require the renumbering of the quarry and a break in the quarry numbering sequence. Therefore, for the sake of clarity, a new cataloguing system was established. The system adopted for this study is to number each quarry sequentially. Distinctions between ancient and modern quarries are made by color-coding the quarry traces: Red-traces indicate ancient quarries and blue-traces are modern. Also, ancient quarry labels are underlined. All quarry identifications are preceded by an uppercase Greek *pi* (Π).

Another significant distinction between the Korres map and the one presented here is that the traces of many quarry walls are noticeably different. This is because many of the traces in the Korres map are speculative. That is, they do not represent surviving remnants of quarry walls. Rather, these speculative lines enhance the quarry distribution model purposed by Korres, particularly in the areas with a high density of ancient quarries. The map presented here is an attempt to accurately depict the location of all quarry walls. However, it must be noted that determining the boundaries of adjacent quarries is sometimes an arbitrary exercise. For example, there is no clear-cut distinction between the boundaries of quarries Π75, Π76, Π77 and Π78. Other areas with somewhat arbitrary quarry distinctions include the boundaries in the deep pit quarries at the southern end of the survey area: quarries Π32, Π33, Π34, and Π42 as well as quarries Π46, Π47, and Π53.

Other quarries on the Korres map appear to be traces directly copied from quarries outlined in the military 1:5000 contour maps. This is especially true for quarries away from the *Spilia* and *Aspra Marmara* areas. As previously mentioned, the topography of Mount Pentelikon has been altered significantly since the contour maps were issued. These surface changes are the result of later quarrying activity and road building which significantly altered several of the quarry boundaries. Therefore, only direct observation can accurately identify and record a quarry.

Geologic Survey

The white regions on the geologic map (Figure 5) denote marble while the gray denote intercalations of green phyllitic schist. The marbles are predominately white with an accessory mineral assemblage of white mica and pyrite visible in hand specimen. Petrographic examination reveals small amounts of quartz and graphite. The distribution of quarries within each marble unit may assist with the interpretation of analytical data by providing a geochemical boundary between the three mapped marble units. The abundant microfolds with more-or-less parallel axes trending towards the NE suggest that the quarries sit on the southeast limb of a northeastward plunging anticlinorium.

The marble outcrops have a high concentration of faults and joints with three joint sets commonly being recognized (Mariolakos and Papanikolaou

1973). On many of the quarry faces, joints and faults are less than two meters apart. Korres (1990) agues that the spatial distribution of these fractures was a primary concern for ancient Greek architects because the joints limit the maximum possible length for construction stone. He further asserts that the natural spacing of fractures would have played an important parameter in ancient quarrying technology and methodology.

Acquisition of Reference Sample Collection

The aim of the sampling program was to obtain an archaeologically significant representative reference sample collection of the Pentelic quarries that also adequately reflects variations in the local geochemical and isotopic profile. To this end, the sample location and geologic maps were referenced to design a sampling program to collect unweathered and unaltered marble samples from every mapped ancient and modern quarry. In order to monitor geochemical and isotopic trends throughout the quarry region, samples were also collected from exposed bedrock in areas of low quarry concentration. With the use of standard geologic steel picks and rock hammers, reference samples roughly 20 cm X 20 cm X 20 cm were collected from accessible quarry walls. No samples were collected from quarry spoils since there is no control on the provenance of these loose materials. Where possible, multiple samples were obtained at roughly ten meter vertical and horizontal intervals to investigate for intra- and interquarry geochemical and isotopic variations. Limitations on the access to some quarries and the lack of a permit to climb quarry walls prevented a complete sampling.

Each sample elevation was measured with a calibrated altimeter to ensure that geochemical data can be interpreted in three-dimensional space. As a control over the possible isotope fractionation and geochemical alteration associated with schist interbeds and intercalations in carbonate metamorphic environments (Rye et al. 1976, Wenner, Havert and Clark 1988), the distances between each sample spot and the nearest schist intercalations were measured and recorded. There are 610 samples in the reference sample collection representing 83 quarries. Appendix 1 offers a description of each of the quarries.

Conclusions

A fundamental aspect of all lithic provenance studies is that the more representative a reference sample collection is the more accurate the resultant physicochemical database will be. Thus, prior to obtaining a reference sample collection it is imperative that researchers know the topographic and geologic profile of the resource area. The current study has shown that systematic observations of the field area reveal important information concerning the placement of extraction pits as well as structural differences in the rock units. Prior to this study, previous researchers inadvertently ignored several ancient quarries that were not located in what was thought to be the only area of significant ancient quarrying activity (i.e. in Marble Unit 3). Also, believing that the Pentelic quarries are isotopically and geochemically homogenous, researchers paid little attention to the geologic location of each reference sample. It is hoped that this report will encourage future characterization studies to undertake systematic and detailed topographic and geologic surveys of the field area prior to developing and implementing a reference sample acquisition program.

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Appendix 1

A Description of the Quarries

The following are concise descriptions for each of the 163 quarries identified. For those quarries from which fresh samples were collected there are also adjoining diagrams outlining the general shape of the quarry. Underlined quarry labels and red traces indicate ancient quarries whereas blue traces indicate modern quarries. In the quarry diagram each sample location is marked with an 'X' along with the sample number and the calibrated sample spot elevation when known. Also recorded is the Marble Unit location for each of the quarries.

Quarry Π1

Marble Unit 3, south end

Description: This quarry is marked by a surviving northwest wall. The remainder of the quarry has been destroyed by later quarrying activity and back fill. There is no physical evidence of ancient extraction.

Quarry Π2

Marble Unit 2, south end

Description: This is a small shallow quarry with a maximum depth of 3 meters. Surviving walls include the NE, NW and SE walls. There is no physical evidence of ancient extraction.

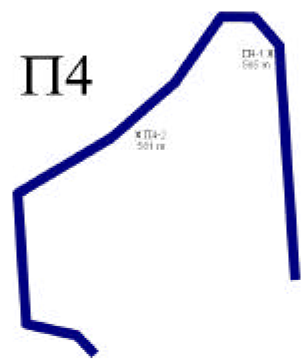
Quarry Π3

Marble Unit 2, south end

Description: This is a small, shallow quarry with a maximum depth of 3 meters. Surviving walls include the NW, NE and SE walls. There is no physical evidence of ancient extraction.

Quarry Π4

Marble Unit 2, south end



Description: This is a large quarry with a surface area of ~200 m^2. Most of this quarry is filled in with quarry debris and modern refuse. There is no evidence of ancient extraction.

Quarry Π5

Marble Unit 2, south end

Description: This is a medium size quarry with a surface area of ~60 m^2. Most of this quarry is filled with later quarrying debitage. A foliation band of green micaceous schist about 10 cm thick cuts across the west wall of the quarry. There is no evidence of ancient extraction.

Quarry Π6

Marble Unit 2, south end

Description: This is a medium size quarry. Tool marks on the west wall indicate antiquity of quarry. A 10 cm thick band of white mica schist cuts through this quarry and can be correlated to a similar intercalation in quarry Π5. Marble from this quarry is banded with thin (<2 cm) foliation bands of white mica. In center of quarry is an *in situ* block with excavation trenches etched around it. The presence of a metal wedge beneath the block indicates that the quarry was also active in modern times.

Quarry Π7

Marble Unit 2, south end

Description: This quarry is represented by a 40 m long quarry wall trending NW-SE. The marble from this quarry contains many thin (<2 cm) intercalations of schist and orange and green-blue color banding. On the western end of the quarry the wall cuts through a ~70 cm thick band of green mica schist. On the east end of the wall there is an exposure of a ~30 cm thick white mica schist. There is no physical evidence of ancient extraction.

Quarry Π8

Marble Unit 2, south end

Description: This quarry is represented by a ~25m long wall trending NE-SW. The quarry wall is poorly preserved. In the eastern corner of the quarry there is a terrace that may be a remnant from a removed block. There is no physical evidence of ancient extraction.

Quarry Π9

Marble Unit 2, south end

Description: This is a small quarry with a surface area of ~20 m^2. The quarry walls are poorly preserved. The marble is extensively banded with schist intercalations. A green mica schist, similar in appearance to that seen in quarries Π5 and Π6, penetrates through the quarry with an orientation S55W, 25W. There is no physical evidence of ancient extraction.

Quarry Π10

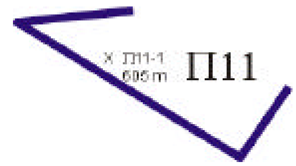
Marble Unit 2, south end

Description: This quarry has a surface area of ~100 m^2. The quarry is transected by a dark green chlorite epidote schist with a thickness ranging from 100-120 cm. The schist cuts through the center of the quarry and trends N40E. The marble in the quarry has abundant thin (<2 cm) foliation bands trending between N31E -N35E and with a dip between 30-45 degrees to the west. The SE extension of the quarry reveals markings that may be ancient.

Quarry Π11

Marble Unit 2, south end

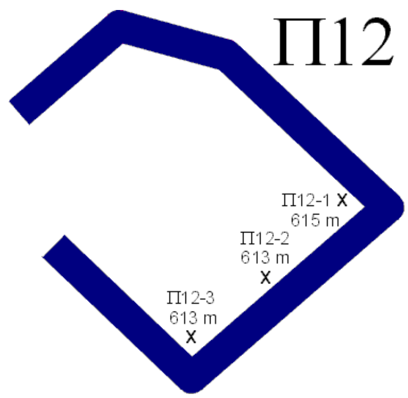
Description: This is a small quarry located at the intersection of two large quarry roads. The quarry is 10 m long and is filled in with large discarded boulders. The marble from this quarry has reddish/orange foliation bands up to 1 cm thick. The colored bands are probably a result of weathering of the mica foliation layers. There is no physical evidence of ancient quarry extraction.



Quarry Π12

Marble Unit 2, south end

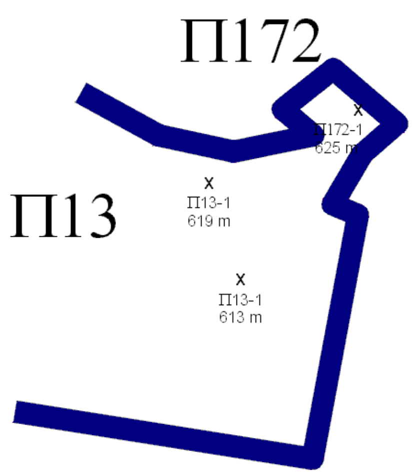
Description: This is a small square quarry with a surface area of ~30 m^2. The marble is white with intermittent ~1cm thick pink/red foliation bands. There is no physical evidence of ancient quarry extraction.



Quarry Π13 and PΠ107

Marble Unit 2, south end

Description: This is a medium size quarry. The quarry is ~7m deep with walls along its NE and S sides. There is a thick bed of mica schist on the W side of the quarry. The schist includes quartz

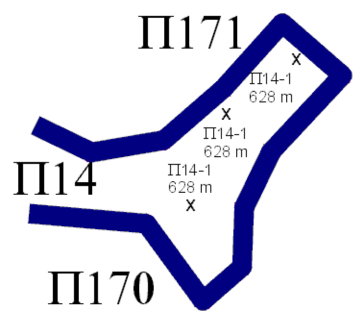


veins up to 10 cm thick. There is a chlorite-epidote schist interbed with a thickness of 50 cm exposed on the N wall and another chlorite-epidote schist bed 10 cm thick on the E wall. There is no physical evidence of ancient quarry extraction.

Quarry Π107 to the north is a small quarry with similar marble.

Quarry Π14, Π170 and Π171

Marble Unit 2

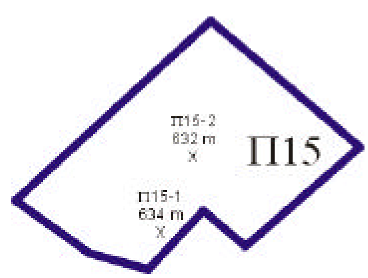


Description: This is a series of small to medium sized quarries with a total surface area of ~45 m^2. The quarry entrance is on the west side and all walls have survived. The quarry is 2-5 m deep on the north end and 15 m deep on the south end. The marble is marked with foliation discoloration bands with an orientation averaging N33E, 42W. There is no physical evidence of ancient quarry extraction.

The small quarries Π170 to the south and Π171 to the north contain similar marble.

Quarry Π15

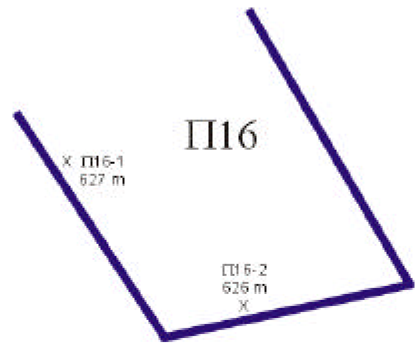
Marble Unit 2



Description: This is a small quarry with a surface area of about 15 m^2. The marble from this quarry is white with reddish/pink discoloration bands no more than 1 cm thick. There is no physical evidence of ancient quarry extraction.

<u>Quarry Π16</u>

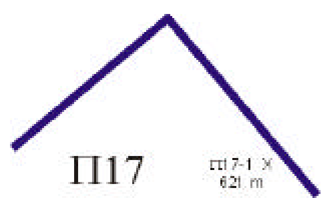
Marble Unit 2



Description: This small quarry is located in the center of a high concentration of shallow quarries in Marble Unit 2. The marble from this quarry has varied textures. Along the west wall the marble is white with reddish/orange discolored foliation bands. Whereas on the southeast wall the white marble has white mica foliation bands and is of high quality. There is no physical evidence of ancient extraction.

<u>Quarry Π17</u>

Marble Unit 2



Description: This is a small quarry. The quarry is shallow with abundant post-quarry debris filling it in. The quarry may show tool marks. Even if verified, the tool marks are too corroded to determine antiquity. There is no physical evidence of ancient quarry extraction.

Quarry Π18

Marble Unit 2

Description: This is a shallow quarry with a surface area of ~28 m^2. There is fill in the middle of the quarry. An *in situ* 3 m long block with a chiseled trench around its circumference lies in the NW corner. The trench surface is too weathered to determine if tool marks are ancient or modern. There is no physical evidence of ancient extraction.

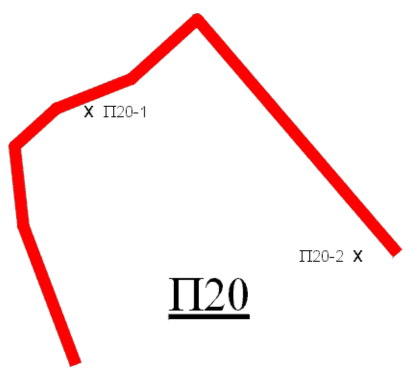
Quarry Π19

Marble Unit 2

Description: This is a medium sized quarry with a surface area of ~45 m^2. The quarry is partially refilled with debris from later quarrying activities. The walls are extensively weathered and the marble contains intercalations of mica schist up to several cm thick. There is no physical evidence of ancient quarry extraction.

Quarry Π20

Marble Unit 2

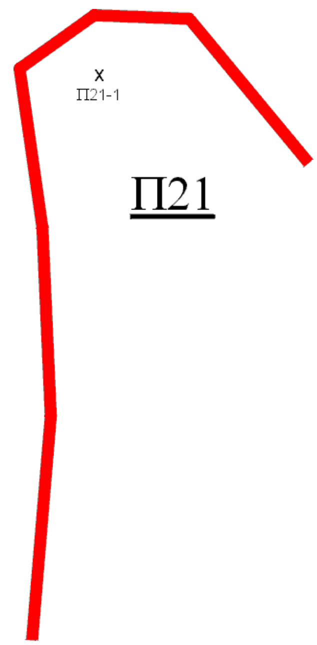


Description: This is a medium sized quarry with a surface area of ~45 m^2. The quarry is partially refilled with quarry debris presumably from later quarrying activities. There are two distinctive floor levels. Two sets of ancient tool marks along the NW wall of the northern, higher section suggest that modern reworking of the quarry lowered the quarry floor to its present elevation.

Quarry Π21

Marble Unit 2

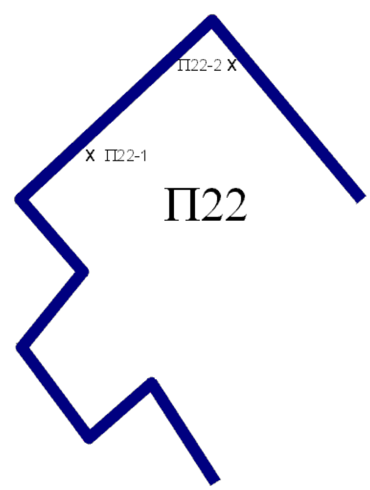
Description: This quarry has a surface area of ~55 m^2. The maximum depth of the quarry is 6 m. A 15 cm thick green mica schist cuts through the quarry and is exposed at the NW corner of the quarry. Wedge marks in the quarry are modern. Graffito in the quarry dates back to 1957. The orientation of the schist intercalation is N29E, 37W. Tool marks indicate the antiquity of this quarry.



Quarry Π22

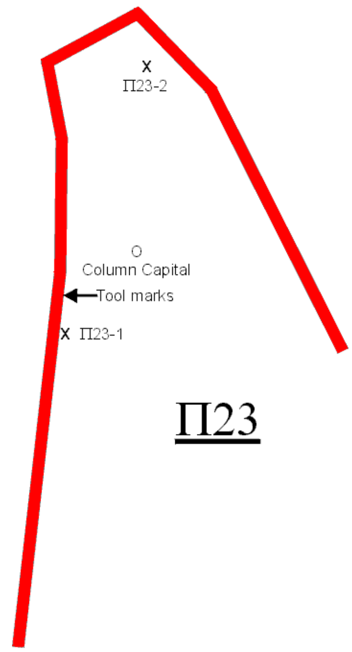
Marble Unit 2

Description: This quarry has a surface area of ~35 m^2. The quarry entrance is from the SE. It is a shallow quarry. All of the walls are extensively weathered. The marble is white with banded layers of reddish discolored marble. Some exposures of the marble show large areas of red/pink splotches that are up to 70 cm long. In the center of the quarry lies an unfinished carved block with a worked rectangular top and unworked marble protruding from its base. There is no physical evidence of ancient quarry extraction.



Quarry Π23

Marble Unit 2

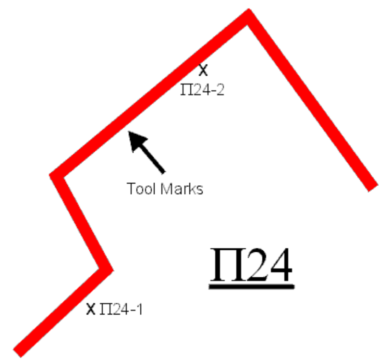


Description: The quarry entrance is from the SE with a maximum depth of about 8 m on the northern end. The quarry is composed of white marble with intercalations and bands of schist and reddish discoloration. The front of the quarry levels out with the natural slope. The bottom of the quarry is filled with quarry debris from later extraction activity. It is possible that some of the debris is synchronous with extraction from this quarry. In the center of the quarry lies a nearly complete carved Doric column capital (Figure 6). One side of the capital reveals a green chlorite schist exposed on its surface. It is assumed that the schist imperfection led to the eventual abandonment of the capital. Other evidence supporting the antiquity of the quarry includes tool marks on the west wall of the quarry.

Quarry Π24

Marble Unit 2

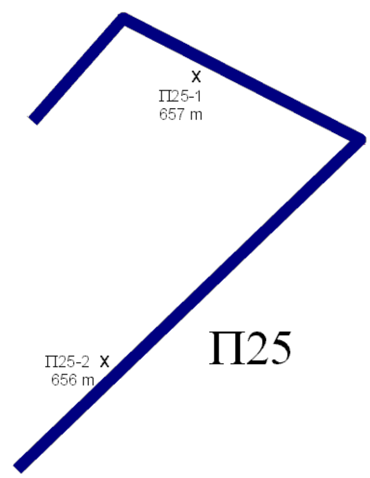
Description: This is a small quarry with a surface area of ~20 m. The marble entrance is from the southeast. The marble has many colored foliation bands of red and blue/gray. The bands are spaced from 1-10 cm apart. The maximum thickness of the bands is 2 cm, but most are less than 1 cm. The foliation orientation averages N35E, 38W. Tool marks on the central section of the NW wall reveal the antiquity of this quarry.



Quarry Π25

Marble Unit 2

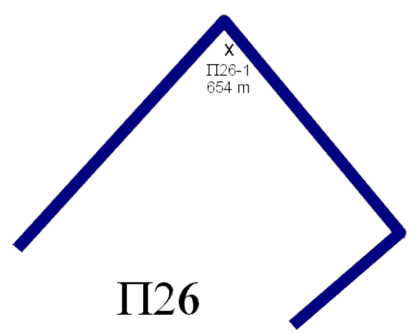
Description: This is a small quarry. The quarry entrance is from the SW. The marble in this quarry is of poor quality. The marble is friable and discolored throughout. There is no physical evidence of ancient quarry extraction.



Quarry Π26

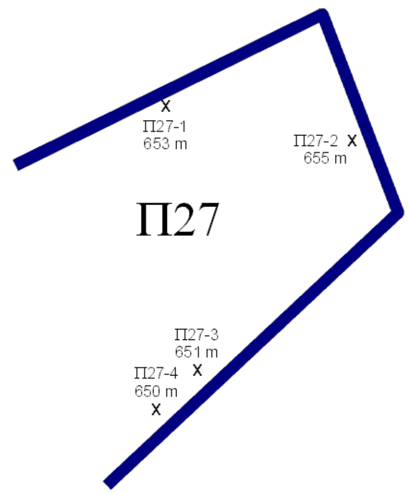
Marble Unit 2

Description: This is a small quarry. The quarry walls are extensively weathered. This quarry did not produce high quality marble. There is no physical evidence of ancient quarry extraction.



<u>Quarry Π27</u>

Marble Unit 2



Description: This is a small quarry. The quarry entrance is from the SW. The quarry is placed on the hinge of a fold as indicated by the trace of a schist intercalation on the NE wall. White mica foliation layers penetrate through the collected samples with some discoloration near the exposed marble surface. On the exposed surfaces there are also small patches of discoloration, probably a result of mica weathering. There is no physical evidence of ancient quarry extraction.

<u>Quarry Π28</u>

Marble Unit 2

Description: This is a medium sized quarry with a surface area of ~280 m^2. The quarry is situated on the west side of a gully separating Marble Units 2 and 3. The marble from quarry Π28 is white with schist intercalations and parallel red color banding. The foliation orientation averages N25E, 51W. There is no physical evidence of ancient quarry extraction.

Quarry Π29

Marble Unit 2

This is a small quarry. The quarry is represented by a single wall trending NE-SW and facing the SE. The quarry is very shallow and is located on the west side of a modern quarry road. There is a modern wedge hole in the quarry wall. There is no physical evidence of ancient quarry extraction.

Quarry Π30

Marble Unit 2

Description: This is a very small quarry with a surface area of 5 m^2. The quarry is V-shaped with a NE-SW trending wall facing the SE and a SE-NW trending wall facing the SW. The quarry is very shallow with the walls not reaching more than 2 m in height. There is no physical evidence of ancient quarry extraction.

Quarry Π31

Marble Unit 2

Description: This is a very small quarry with a surface area of 4 m^2. It is located immediately west of a large modern quarry road. The NE-SW trending wall contains the contact between the marble unit comprising Marble Unit 2 and the large schist unit separating Marble Units 2 and 3. There is no physical evidence of ancient quarry extraction.

Quarry Π32

Marble Unit 3

Description: This quarry is located on the west wall of the large quarry pit at the southern end of Marble Unit 3, and is represented by a single NE-SW trending wall that is a product of modern quarry extraction. The quarry was excavated along the western slope of a gully between Marble Units 2 and 3. The gully itself has been excavated away. There is no physical evidence of ancient quarry extraction.

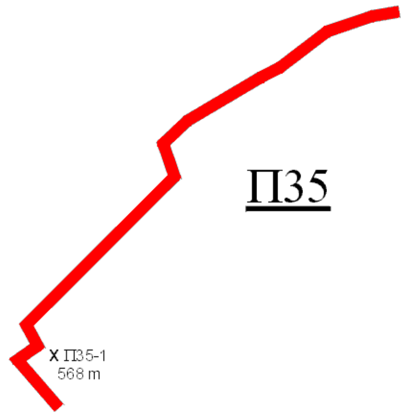
Quarries Π33 & Π34

Marble Unit 3

Description: These two large quarries are marked by a long NE-SW trending wall on the east side of the incised schist gully separating Marble Units 2 and 3. The quarry wall faces towards the west. The maximum height of the wall is ~40 m on the east side. The unquarried section of the slope where quarries Π40 and Π41 are located suggests that the eastern slope of the gully extended 55 m towards the west from the quarry wall. Ancient tool marks appear on the upper 10 m of the quarry wall suggesting that these quarries were once relatively shallow ancient quarries. Modern quarry extraction reworked the ancient quarries by extending the quarry to the NW and lowering the quarry floor some 30 m. There is no physical evidence of ancient quarry extraction in either quarry.

Quarry Π35

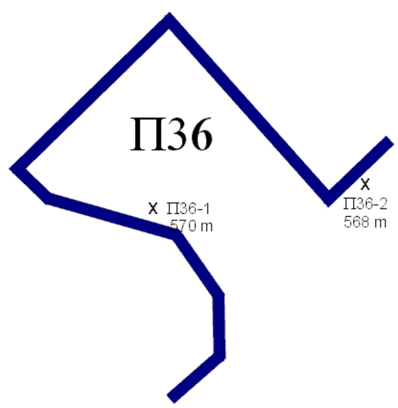
Marble Unit 3



Description: This quarry is situated near the hinge of a NE-SW trending fold. The tallest portion of the quarry wall is 5 m. An ancient quarry road leads directly to the front of the quarry. The road's antiquity is established by the chiseled-out groove marks in the road surface in front of quarry Π38 (Figure 7). The marble from this quarry is white with orange discoloration bands on weathered surfaces. A schist layer of unknown thickness overlies the marble. On the floor of the quarry is a chlorite schist intercalation.

Quarry Π36

Marble Unit 3



Description: The quarry is situated near the hinge of a NE-SW trending fold on the SE-dipping slope. The tallest portion of the quarry wall is 7 m. An ancient quarry road leads directly to the front of the quarry. The road's antiquity is established by the chiseled-out groove marks in the road surface in front of quarry Π38. The marble from this quarry is white with orange discoloration bands on weathered surfaces. A schist layer of unknown thickness overlies the marble. On the floor of the quarry is a chlorite schist intercalation. There is no physical evidence of ancient extraction in this quarry.

Quarry Π37

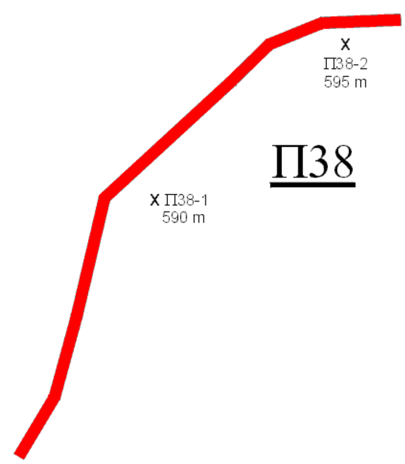
Marble Unit 3

Description: This quarry has a surface area of about 20 m^2. The quarry is situated near the hinge of a NE-SW trending fold along the SE-dipping slope. The tallest portion of the NE-SW trending quarry wall is 4 m. An ancient quarry road leads directly to the front of the quarry. The road's antiquity is established by the chiseled-out groove marks in the road surface in front of quarry Π38. There is no physical evidence of ancient extraction in this quarry.

Quarry Π38

Marble Unit 3

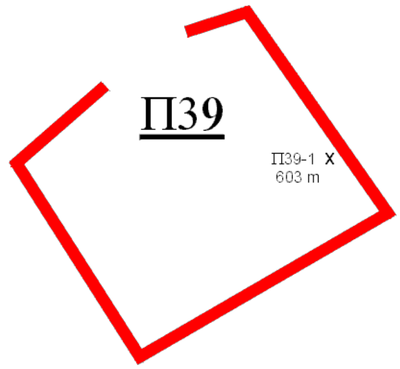
Description: The quarry is situated near the hinge of a NE-SW trending fold along the SE-dipping slope. The tallest portion of the NE-SW trending quarry wall is 7 m. An ancient quarry road leads directly to the front of the quarry. The road's antiquity is established by the chiseled-out groove marks in the road surface in front of the quarry.



Quarry Π39

Marble Unit 3

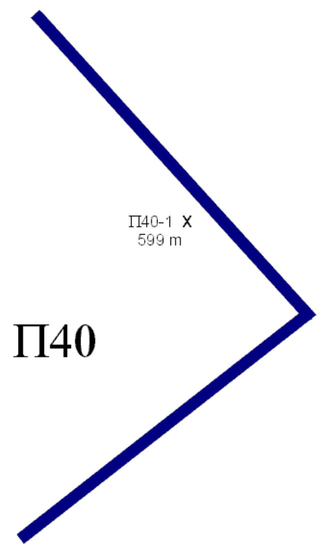
Description: This small quarry is located on the eastern limb of the NE-SW trending hinge of a fold. The hinge of the fold is ~5 m to west of the quarry. The foliation planes in the quarry are oriented N71E, 31E. This quarry is shallow with a maximum depth of 6 m. The quarry entrance is from the NW.



Quarry Π40

Marble Unit 3

Description: This small quarry has a total surface area of 5 m^2. It has a maximum depth of 8 m. The quarry is situated on the westward dipping slope of the gully between Marble Units 2 and 3. The marble from the quarry is white with thin (<2 cm) reddish discoloration bands throughout. There is no physical evidence of ancient extraction.



Quarry Π41

Marble Unit 2/3

Description: The maximum depth of the quarry is 8 m. The marble in the quarry includes intercalations of mica schist with a maximum thickness of 10 cm and reddish discoloration foliation bands on the exposed surfaces. The averaged orientation of the foliation bands is N41E, 42E. There is no physical evidence of ancient extraction.

Quarry Π42

Marble Unit 2

Description: The quarry is survived only by the NE-SW trending wall that faces the SE. The floor of the quarry contains debris from later quarry activity so it is difficult to calculate the total depth of the quarry. The current depth of the quarry is ~10 m. The marble exposed on the wall is extensively weathered and discolored. There is no physical evidence of ancient extraction.

Quarry Π43/Π44

Marble Unit 2/3

Description: This small quarry only has 23 m of its east wall preserved. The quarry is filled with debris from later quarrying activity. The marble is heavily intercalated with mica schist. The foliation is oriented N35E, 57W. There is no physical evidence of ancient extraction. See quarry Π46 for a quarry diagram.

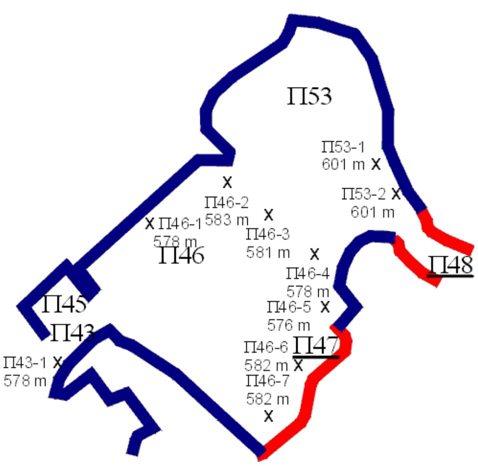
Quarry Π45

Marble Unit 2

Description: This small quarry has been enlarged on its NE side by later quarrying activities. Much of the quarry has been filled in with debris. The quarry walls indicate that the white marble was heavily penetrated by thin (<1 cm) red discoloration bands rich in white mica. There is an increase in mica schist thickness and frequency near the top of the quarry. There is no physical evidence of ancient extraction. See quarry Π46 for a quarry diagram.

Quarry Π46

Marble Unit 2/3



Description: This is a large modern quarry within the extensive pit at the southern end of the Pentelic quarry region. The west wall of the quarry is over 25 m tall. The full eastward extension of the quarry is difficult to determine. The marble is white with thin (<2 cm) mica schist intercalations penetrating throughout the sample. Measurements of the foliation planes give an average orientation of N37E, 31E. The quarry displays three prominent joint systems: one parallel to the foliation plane, the other two have orientations of N45E, 85N and N58W, 80S. There is no physical evidence of ancient extraction.

Quarry Π47

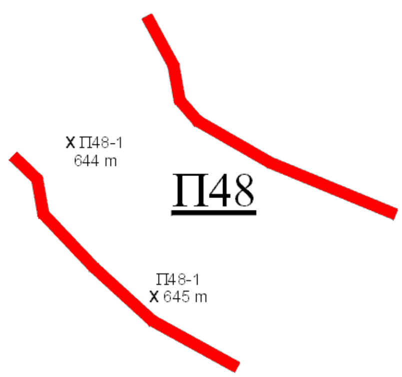
Marble Unit 3

Description: This is a large quarry. The quarry is marked by a NE-SW trending wall that faces towards the west. Ancient tool marks are visible on the top 10 m of the wall. Below this level the NE-SW trending wall and the NW-SE trending walls are products of modern expansion of the quarry. It is difficult to determine the full extent of the ancient quarry. However, the surface area of the ancient quarry can be calculating by assuming that the depth of the ancient floor did not exceed 10 m and that the surface slope of the hill the quarry was dug into was consistent with the profile of the undisturbed slope immediately to the west. If these assumptions hold true then the surface area of the ancient quarry may have been 300 m^2. No samples were collected due to the lack of access to the vertical quarry walls. See quarry Π46 for a quarry diagram.

Quarry Π48

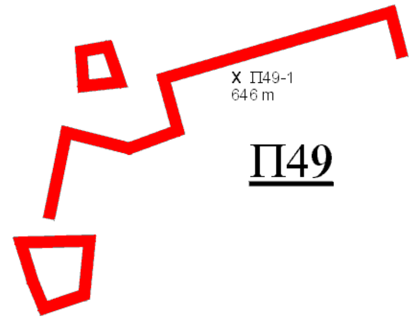
Marble Unit 3

Description: This is an ancient quarry with a surviving surface area of ~95 m^2. A modern quarry has encroached on the western portion of the quarry. Ancient tool marks are visible on the SW wall.



Quarry Π49

Marble Unit 3



Description: This shallow quarry extends ~40 m in a NE-SW line. The northern end of the quarry has a 4 m face with ancient horizontal tool marks. Extensively weathered excavation trenches mark the southern end of the quarry. The depth of the southern end of the quarry does not exceed 2 m.

Quarries Π50, Π51, Π52

Marble Unit 3

Description: These three quarries are situated on an eastward dipping slope. They are small quarries with no evidence of ancient workings. There is an old quarry road that leads directly to their entrance on their east side. As the quarry road continues its course upslope it is cut off by the large modern quarry Π61.

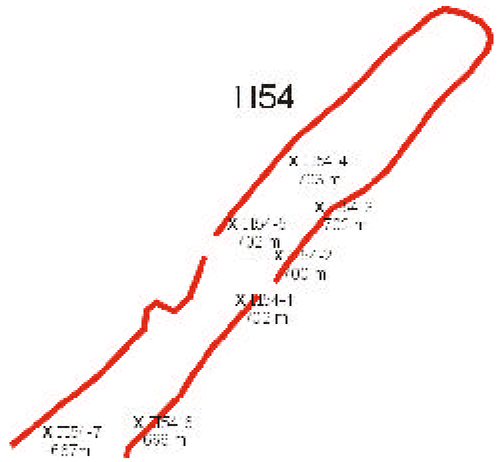
Quarry Π53

Marble Unit 2/3

Description: The surface area of this large quarry is ~560 m^2. It is a modern quarry that was cut into the eastern dipping slope of the gully between Marble Units 2 and 3. The west wall is over 35 m in height. The marble from the quarry is white with some schist intercalations and discoloration bands on exposed weathered surfaces. There is no physical evidence of ancient extraction. See quarry Π46 for a quarry diagram.

Quarry Π54

Marble Unit 2

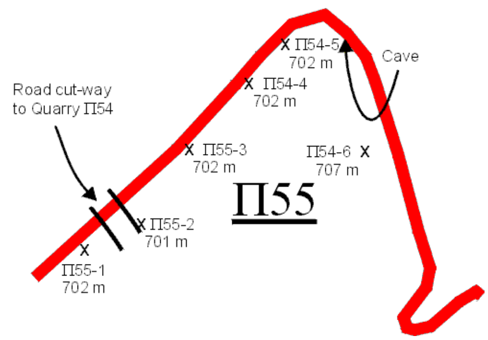


Description: This is a very long quarry that parallels the trend of the major fold axis that divides Marble Units 2 and 3. It's length measures ~200 m and it has a total surface area of ~600 m^2. A debris pile that supports a modern quarry road dissects the quarry. The quarry walls are up to 50 m deep. Ancient tool marks and excavation trenches are found in the northern section of the quarry. Paralleling the east side of the quarry is a 3 m thick green schist intercalation that separates Marble Units 2 and 3. The bulk of ancient quarries appear to follow this layer of schist up the slope of Mount Pentelikon. The marble in the quarry is bright white with mica schist intercalations, mostly less than 2 cm thick, penetrating the marble throughout.

Quarry Π55

Marble Unit 3

Description: The "Spilia" quarry. This is the most well known quarry on Mount Pentelikon. A large cavern opens up at the quarry's northern end. The cavern is a natural karst feature that was exposed during quarry extraction. A Byzantine

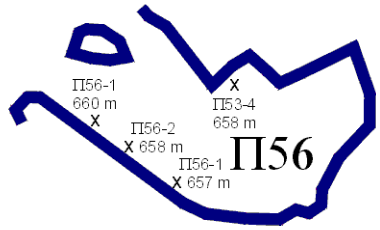


chapel was constructed in the mouth of the cavern during the 6th century AD (Korres 1995). The floor of this quarry has been altered by modern quarrying and military construction projects. The height of the quarry is ~45 m from the present floor. However, a window in the floor by the western quarry wall near the modern road that leads to the quarry indicates the quarry was as much as 10 m deeper. The tall walls are marked with garland-type tool marks from top to bottom. Korres (1993, 1995) speculates that this is the earliest large-scale quarry on Mount Pentelikon and that it supplied marble for the Parthenon. However, Waelkens (1988) suggests that the garland tool marks date the quarry to the Roman era of operation. The west wall has widely spaced joints. The west wall of the quarry abuts the 13 m thick schist intercalation that trends the length of the active quarry and separates Marble Units 2 and 3.

The ancient quarry was larger than it appears now. Backfilling of the south end of the quarry has completely buried that portion of the quarry. An extensively weathered wall near the ancient paved road shows the full extent of the quarry. The calculated surface area of the quarry is ~730 m^2. The white marble from the quarry is of high quality with thin (< 1 cm) mica foliation layers penetrating the sample.

<u>Quarry Π56</u>

Marble Unit 3



Description: This large modern quarry has a surface area of ~420 m^2. The quarry entrance is from the west side. The marble in the quarry is white with intercalations of mica schist and thin mica layers parallel to foliation. It is possible that this is an ancient quarry and that modern excavation has obliterated any evidence of ancient extraction. However, no physical evidence exists to support its antiquity.

<u>Quarry Π57</u>

Marble Unit 2

Description: This small quarry was excavated for a military munitions storage facility in the early 1970s. The quarry is in a thick schist intercalation. The NE wall of the quarry has a trace of a tight recumbent fold whose axis parallels the general trend of the large schist intercalation the divides Marble Units 2 and 3. There is no physical evidence of ancient extraction.

<u>Quarry Π58</u>

Marble Unit 2

Description: This small quarry has a surface area of 15 m^2. The marble is heavily banded with white mica schist intercalations. The NE wall gives a profile of a fold limb steepening towards the west. It is possible that this quarry was connected with quarry Π59. See description for quarry Π59. There is no physical evidence of ancient extraction.

Quarry Π59

Marble Unit 2

Description: A single wall on the western side of a gully represents this quarry. The length of the wall is 50 m. It is possible that quarries Π59 and Π58 were connected by a NW trending wall that was later covered by modern quarry debris dumped from the slope above. There is no physical evidence of ancient extraction.

Quarry Π60

Marble Unit 2

Description: This quarry has a surface area of 320 m^2. The maximum height of the quarry at the NW corner is 35 m. This is a modern quarry excavated into the eastward dipping slope of a gully. There is no physical evidence of ancient extraction.

Quarry Π61

Marble Unit 3

Description: This is a very large modern quarry with surface exposure over 1100 m^2. The quarry walls are over 50 m tall. The marble quality varies from pure white calcitic marble to banded marble with mica schist intercalations. The entrance of the quarry was from the east along a natural ravine. The quarry has destroyed the ancient road network that once lay across its upper reaches. There is no physical evidence of ancient extraction.

Quarry Π62

Marble Unit 3

Description: This quarry is situated on the eastward dipping slope of Marble Unit 3. It once had a surface area of ~150 m^2. With the construction of a modern quarry road across the northern third of the quarry pit, the quarry was divided into two sections. There is no physical evidence of ancient extraction.

Quarry Π63

Marble Unit 3

Description: This quarry is a remnant of a larger quarry that was partially destroyed by the construction of a large quarry road cutting across its upper portion. The quarry is preserved by a 20 m long west wall and a 20 m long northeast wall. There is no physical evidence of ancient extraction.

Quarry Π64

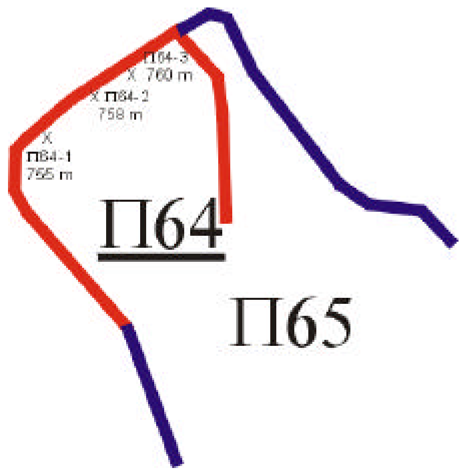
Marble Unit 3

This ancient quarry has a surface exposure of ~55 m^2. The marble from the quarry is white with thin (<2 cm) mica schist intercalations penetrating throughout the quarry. The textural density of mica schist bands is up to 50% of the total rock volume. Ancient tool marks are visible on *in situ* blocks remaining in the quarry. See quarry Π65 for a quarry diagram.

Quarry Π65

Marble Unit 3

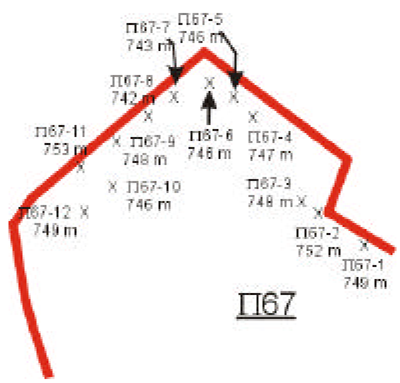
Description: This quarry is a shallow modern extension of quarry Π64. The physical remains of quarry Π65 are few due to extensive weathering of the walls and the dumping of later quarrying debris in the NW section of quarry. There is no physical evidence of ancient extraction.



Quarry Π66 and Π67

Marble Unit 3

Description: During the modern era the large ancient quarry Π67 was later reworked and extended to form quarry Π66. High quality white marble with thin white mica foliation bands comprises the remaining quarry walls. It is not possible to see the full extent of the ancient quarry due to the modern quarry workings. The same thick schist band that marks the west wall of quarry Π55



also marks the west wall of these two quarries. Ancient tool marks are visible along the top of the NW wall.

Quarry Π68

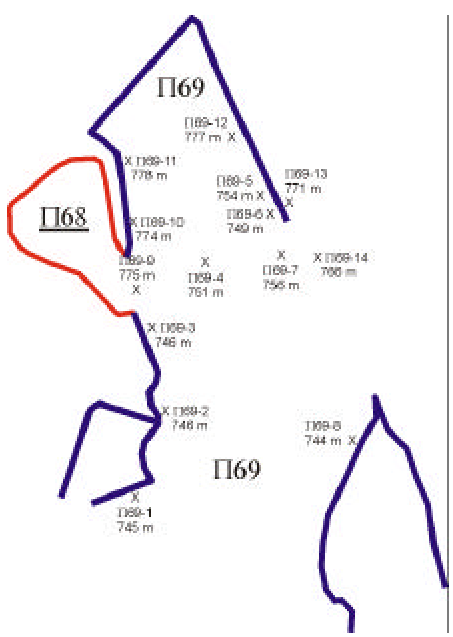
Marble Unit 3

Description: This is an ancient quarry with some modern quarry extraction. The entrance to Π68 faces east towards quarry Π69. The floor of the neighboring quarry has been lowered by as much as 20 m below the floor of Π68 making Π68 inaccessible from its front. The marble from this quarry is white with thin white mica foliation bands. No samples were collected from this quarry due to the inability to access it from Π69. Ancient tool marks are preserved along the top of the NW wall.

Quarry Π69

Marble Unit 3

Description: This is a very large quarry with both ancient and modern quarry workings. The evidence of ancient extraction is centered along the top portion of the NW facing quarry wall. Modern extraction has lowered the quarry by ~ 60 m along the NW wall. The quarry extends downslope toward the SE. A cinderblock structure and metal

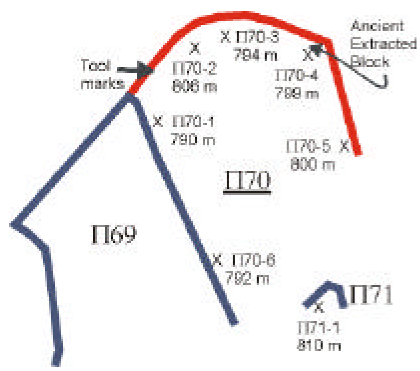


and rubber debris suggest that at the south end of quarry Π69 was a modern quarry operations center.

Quarry Π70

Marble Unit 3

Description: This is a large ancient quarry with later modern extraction. Ancient tool marks are seen from the top of the NW wall extending down ~30 m to the current floor level. The marble is white with mica foliation layers. There are also several thin schist intercalations. Immediately SE of this quarry are the remains of the Cave of the Nymphs (Wickens 1986). In 1952 the overlying rocks were removed. The only physical remains of the cave are a poorly preserved 10 m^2 pit with stairs leading down about 7 m.



Quarry Π71

Marble Unit 3

Description: This is a small modern quarry. It is a modern extension of quarry Π70. Quarry debris fills the space between this quarry and Π70. The excavated Cave of the Nymphs is to the west of the quarry. There is no physical evidence of ancient extraction.

Quarry Π72

Marble Unit 3

Description: Quarry debris from later quarrying activity and road construction has filled in much of this quarry. What remains of this quarry is a single wall trending NNW with exposure on the west side. The maximum height of the wall is 4 m. The exposed marble includes intercalations of green mica schist. There is no physical evidence of ancient extraction.

Quarry Π73

Marble Unit 3

Description: This modern quarry opens towards the south. The floor of the quarry is filled in with large quarry debris blocks. No samples were collected from this quarry due to the inability to safely access the quarry. There is no physical evidence of ancient extraction.

Quarry Π74

Marble Unit 3

Description: This modern quarry was not sampled due to its steep walls. The south side of the quarry near the modern road is piled up high with quarry debris from a nearby quarry. The marble from this quarry is white with no evidence of mica schist intercalations in the quarry walls. There is no physical evidence of ancient extraction.

Quarry Π75

Marble Unit 3

Description: This quarry shows no indications that it operated in antiquity. A road that traverses the quarry bifurcates with the northern branch leading to quarry Π70 and the southern branch leading towards the NW wall of Π69. However, the southern branch of the road is cut off at the boundary between Π75 and Π69 by the east wall of quarry Π69. Therefore, it is not possible to ascertain if the roads are ancient.

It was not possible to collect samples from this quarry. The NW wall was inaccessible due to a large talus pile fronting it. Along the east wall the marble is intercalated with a green epidote chlorite schist.

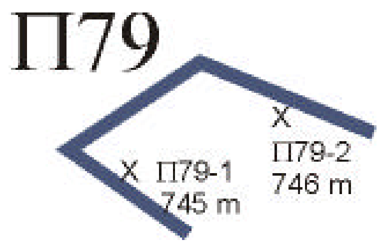
Quarries Π76, Π77, Π78

Marble Unit 3

Description: These three quarries are mostly filled with later quarrying debris. The height of the debris piles increase towards the NE. Due to the steep slope the debris piles it was not possible to obtain fresh marble samples from any of these quarries. Due to the NE exposure of a wall in quarry Π77 it is not possible that the quarry extended up to Π74. There is no physical evidence of ancient extraction.

<u>Quarry Π79</u>

Marble Unit 3



Description: This is a small quarry situated in front of quarries Π65, Π66 and Π67. There are no physical indicators to suggest that this quarry is ancient. The maximum height of the quarry walls is 5 meters. Note that the floor is covered by quarry debris and that the true quarry floor may be lower. The marble from this quarry is of good quality. Weathered surfaces show a slight greenish discoloration. Thin mica foliation bands are seen throughout the samples.

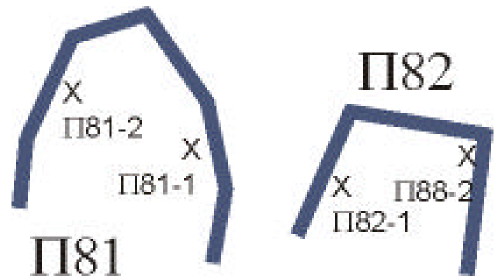
<u>Quarry Π80</u>

Marble Unit 3

Description: Two small exposed walls comprise this quarry. The wall on the east side trends SW-NE and faces the SE. The western wall trends NW-SE and faces the SW. Both walls are short, not exceeding a height of 2 m. From the physical evidence the quarry would not have produced much material, however, there are no joints across the faces of either wall so it is possible that a few large-dimensional blocks were extracted. The marble from this quarry is too poorly weathered to collect fresh samples. Discoloration bands in the marble suggest thin mica foliation layers. There is no physical evidence of ancient extraction.

Quarries Π81 and Π82

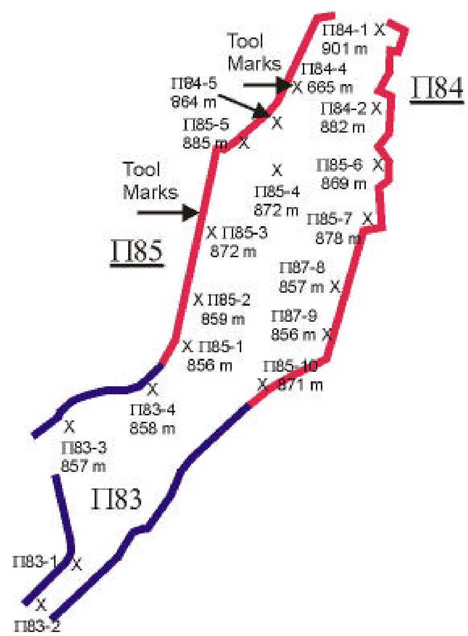
Marble Unit 3



Description: These two small quarries contain white marble with white mica schist foliation bands. The foliation planes are nearly horizontal. The northern end of the quarries is truncated by the intersection of two prominent joints. It is possible that these small pits were quarried for large blocks between joints (see Korres 1992). There is no physical evidence of ancient extraction.

Quarry Π83

Marble Unit 3



Description: This large modern quarry is a southern extension of ancient quarry Π85. The quarry pit is almost entirely filled with large debris from later quarrying activity. The depth of the quarry is estimated to be about 15 m. Marble exposures on the east and west walls indicate that this marble is intensely foliated with thin reddish and gray/green bands of weathered mica layers paralleling thin mice schist intercalations. The foliation bands measure 1 to 5 cm apart. At the southern end of the quarry the joint exposures are closely spaced. There is no physical evidence of ancient extraction.

Quarry Π84

Marble Unit 3

Description: This is a large ancient quarry that may have been connected to quarry Π87 to its north. Later quarrying activity increased the size of the quarry pit. A modern quarry road with a foundation of marble debris separates the two quarries. To the south of quarry Π84 is ancient quarry Π85. A large drop of ~15 m separates the lower quarry floor of Π84 with the upper floor of quarry Π85.

The marble from the east wall of this quarry displays white mica foliation bands. The thickness of the foliation bands range from about 0.5 cm to thicker mica schist at 10 cm. On the west wall near the top the marble is pure white. At the bottom of the wall 1 m thick schist intercalations are present. See the diagram for quarry Π83. Garland style tool marks are visible along the west wall the quarry.

Quarry Π85

Marble Unit 3

Description: This is a large ancient quarry. It is immediately south of quarry Π84. Separating the two quarries is a 15 m ledge between the quarry floors. The marble is foliated with thin layers of white mica. On the east wall there are inclusions of thick green epidote schist. The epidote schist appears near the mouth of the quarry at the southern end of the quarry. Within the quarry there are small bands of gray marble. The bands are parallel to the mica foliations. See the diagram for quarry Π83. Garland-type tool marks are present on the west wall of the quarry.

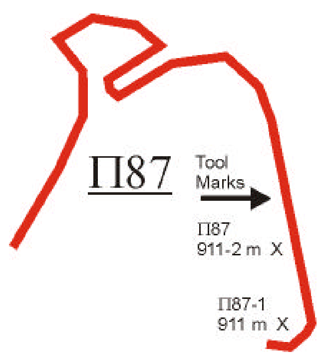
Quarry Π86

Marble Unit 3

Description: This medium sized pit quarry shows no physical evidence indicating an ancient origin. The quarry pit is about 6 m deep and the topography around the perimeter of the quarry is relatively flat with a downward gradient towards the SW. At the small passageway at the entrance to the quarry the ground surface does not drop off. Due to the steep walls and a stone wall presumably built by a shepherd at the entrance to the quarry, it was not possible to enter the quarry and investigate or collect marble samples.

Quarry Π87

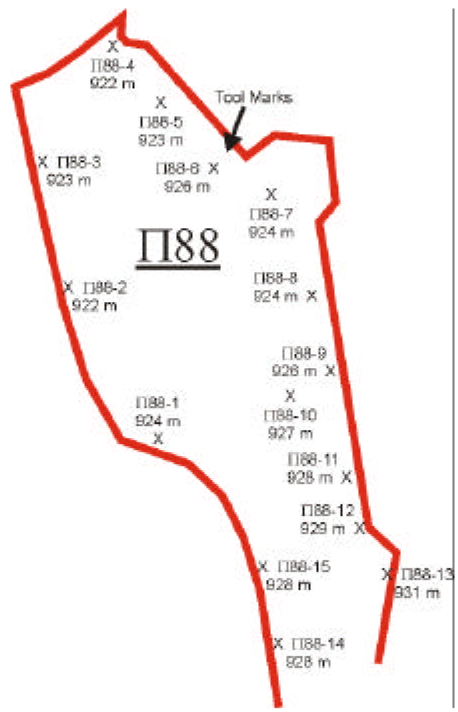
Marble Unit 3



Description: This quarry is an ancient extension of quarry Π84. The quarry contains white marble with some white mica and thin mica schist foliation layers. The schist foliation bands are not as thick as they are in quarry Π84. Exposures indicate a more pure white marble as this series of long quarries advances towards the northeast. The quarry pit has a maximum depth of about 15 m. Ancient tool marks are visible 4 m below the top of the east wall.

Quarry Π88

Marble Unit 3



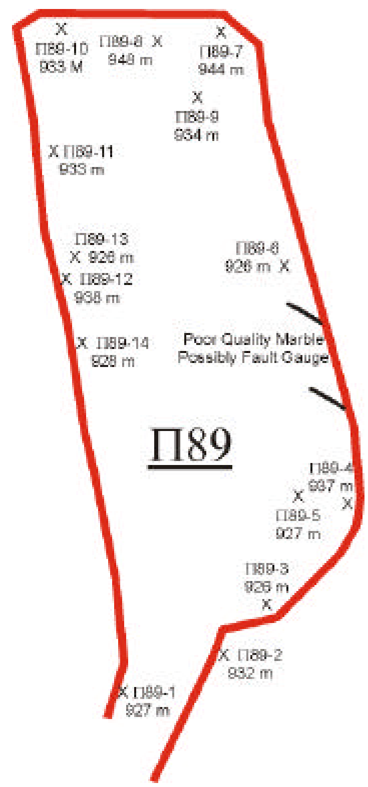
Description: This is a large ancient quarry that was reworked in the modern era. It is a long, narrow quarry that extends into the natural southeastward dipping slope. This is the northern most quarry in the *Aspra Marmara* region of Mt. Pentelikon (Lepsius 1893). The elevation of the quarry floor is higher at the southern entrance. It is 933 m and dips sharply to the north to an elevation of 924 m about midway in the quarry. The quarry floor is covered with quarry debitage. Therefore, the true quarry bottom may be below current elevations. At the northern end the quarry walls are from 35-40 m high. Towards the middle of the quarry the walls are 15 m high and the natural slope dips down to the entrance at the southern end of the quarry.

The marble from this quarry is white with thin white mica foliation layers penetrating the marble. In some areas the foliation bands reach a thickness of 2 cm. Many of the collected samples have chlorite weathering on their exposed surfaces. Most likely the chlorite is a product of mica weathering. Towards the entrance of the quarry at its southern end the marble is of an inferior quality, with areas of large pink and orange discoloration penetrating through the marble. Ancient tool marks are visible on the northern section of the east wall.

<u>Quarry Π89</u>

Marble Unit 3

Description: This is a large narrow quarry between quarries Π88 and Π90 in the area called *Aspra Marmara*. It is an ancient quarry that was later expanded by modern extraction. Along the northern end of the quarry a modern quarry building has been undercut by extraction activities and has partially collapsed into the quarry. The entrance is at the southern end and proceeds into the southeastward-dipping slope. The quarry floor is fairly flat and has an elevation of roughly 924 m. The quarry pit is 35 m in depth at the north and 10 m where the quarry entrance bifurcates from the entrance to quarry Π90.



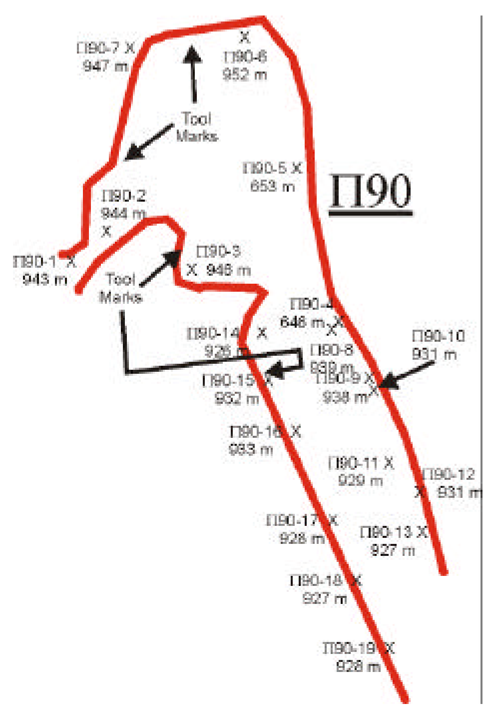
The marble from this quarry is pure white with thin white mica foliation layers penetrating through it. There are some mica schist intercalations up to several cm thick. The intercalations are more concentrated at the southern end of the quarry. Several of the collected samples had chlorite weathering on their exposed surfaces, presumably a weathering product of the white mica. The chlorite is limited to the surfaces and does not penetrate into the samples. Along the east wall is a 10 m section of fractured marbles, possibly fault gauge.

Evidence of ancient extraction are ancient tool marks on west wall. On the lower section of wall separating this quarry from Π88 is a quarry debris pile with small fragments. The small fragments and developed soil may indicate that this is an ancient debris pile (Korres 1995). Also, within the debris pile are unfinished or broken carved fragments, another indication that this is an ancient quarry debris pile.

<u>Quarry Π90</u>

Marble Unit 3

Description: This long, narrow ancient quarry lies in the area of *Aspra Marmara*. The entrance of the quarry is at its southern end and extends into the slope paralleling quarries Π88 and Π89. At the south end of the quarry the surface slopes down to the floor. At the northern end of the quarry there is a raised relatively flat floor of quarry debris. The elevation of this floor is 955 m. It is not possible to determine the total depth of the



quarry. About 15 m from the north wall the debris pile slopes downward to an elevation of 926 m. At the top of the northwest section is a cut away that leads to quarry Π91. The width of the cutaway is 10 m and has a depth of 943 m. Due to the raised floor at the northern end of the quarry, the pit is only several meters high. Once the floor has sloped down in the center of the quarry, the pit has a depth of 20 m.

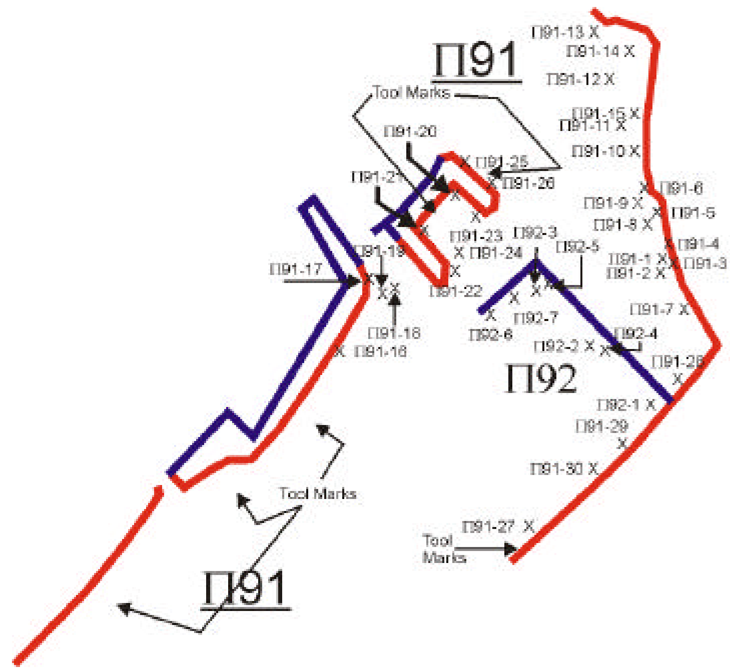
The marble from the quarry is foliated with thin white mica layers with some areas having red and green bands. Most likely, these bands are the results of weathering alteration of the mica foliation layers. Samples collected with this banding are Π90-1, Π90-2, Π90-5, Π90-6, Π90-7, Π90-9, Π90-11, Π90-13, Π90-14, Π90-16, Π90-18 and Π90-19. Samples Π90-12 and Π90-17 were collected less than 1 m from a thick intercalation of mica schist. Samples with apparently no weathering alteration have a fine grain sugary texture. Chlorite weathering is common on most surfaces of the collected samples and is probably an alteration product from the weathering of mica. The chlorite does not penetrate into the samples.

Evidence of ancient extraction includes tool marks seen throughout the northern section of the quarry. The tool marks are of the horizontal-type indicating that this quarry was one of the first large scale quarries on Mount Pentelikon (see Waelkens 1988 for a discussion on the chronology of quarry marks).

<u>Quarries Π91and Π92</u>

Marble Unit 3

Description: This is a very large ancient quarry that has been extensively reworked during modern times. The northeast wall of the quarry is 71 m long. The majority of the tool marks are along the northwest wall that trends NE-SW for 125 m. The marble from this quarry is white with thin white mica foliation layers. Mica schist intercalations are prevalent throughout the quarry, however, they are more abundant towards the eastern section. The schist intercalations are no more than 6 cm thick. The northwest wall follows the near-vertical outcrop of the 6 m thick mica schist interlayer that separates Marble Unit 2 from Marble Unit 3. A 30 cm thick interlayer of deep green chlorite epidote schist with no mica outcrops along the quarry's southeast wall. This schist also cuts through the eastern sections of quarries Π88, Π89 and Π90. Quarry Π92 is a small modern extension in the center of the quarry floor.

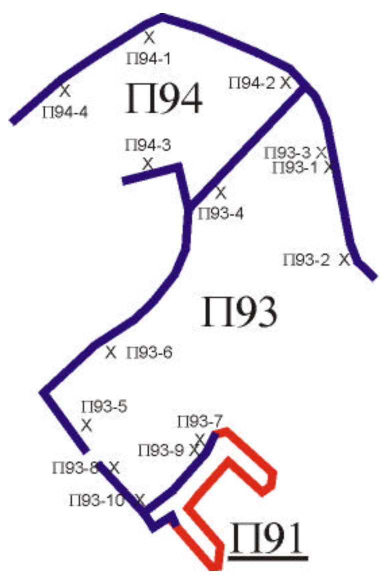


It is difficult to determine the original orientation of the ancient quarries. Along the northwest wall are several unquarried projections that may have served as quarry walls separating ancient quarry pits that opened towards the SE. These walls would have been roughly parallel with the two walls separating quarries Π88, Π89 and Π90. Korres (1992, 1995) argues that these walls would have been used to support the near-vertical mica schist interlayer and prevented it from collapsing into the quarry. Most of the tool marks found in the quarry are on or near these projections. Other tool marks are also found on the south corner of the east wall. Note that elevation measurements were not made at any of the sample locations.

<u>Quarry Π93</u>

Marble Unit 2

Description: This is a large modern quarry. The quarry adjoins quarry Π91 at a modern excavation cut through the 9 m thick northwest trending mica schist intercalation that abuts many of the ancient quarries. The east side of the quarry is bounded by the mica schist interlayer. The north wall is a continuation of the north wall in quarry Π91. The western limit of the quarry appears to be marked by the transition from a white mica foliated marble to a poor quality banded mica schist foliated marble. Within the mica schist are intercalations of quartz. Along the west side of the quarry the joint planes are closely spaced. Modern quarry Π94 lies immediately to the northwest of the quarry. The samples collected from



this quarry are limited to the lower elevations due to a lack of access to the upper quarry walls. The marble samples include white mica foliation layers and were collected from areas where the mica schist intercalations are no thicker than 30 cm. There is no physical evidence of ancient extraction.

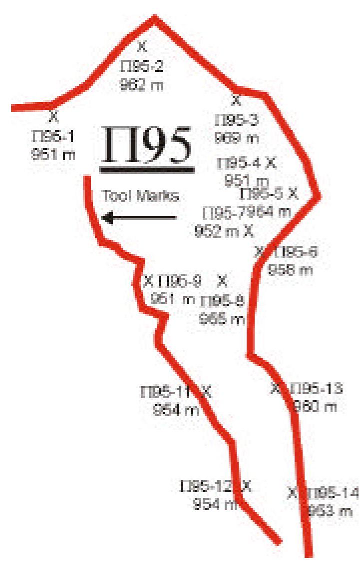
Quarry Π94

Marble Unit 2

Description: This is a modern quarry that extends off of quarry Π93 to the east. The frames of modern quarrying buildings and sheds also indicate a modern history. Several series of debris piles have been dumped in the quarry as is evident by the coverage of quarry roads. The marble from this quarry is jointed and has intercalations of green mica schist. Refer to the description of quarry Π93 to see sampling map of quarry. There is no physical evidence of ancient extraction.

Quarry Π95

Marble Unit 2

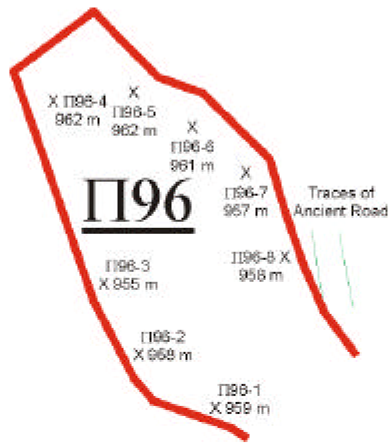


Description: This is an ancient quarry with tool marks on the west wall immediately south of the north entrance. The surviving marble in this quarry is of poor quality. It is a white marble with white mica foliation layers as well as brownish layers up to 1 cm thick penetrating through most of the quarry region. The brown discolorations appear to be a byproduct of the weathering of mica. Modern extraction has extended the quarry southward and indications are that the northern section of the quarry was reworked as well.

Quarry Π96

Marble Unit 2

Description: This is an ancient quarry that was reworked in the modern era. The quarry is about 20 m deep. The marble from this quarry is white with mica foliation bands penetrating through the sample. Along the northeast wall many of the foliation bands have weathered to a light brown.

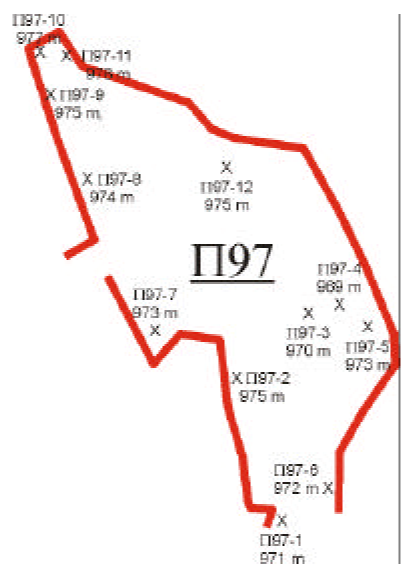


Above the quarry atop the east wall are poorly preserved remains of an ancient paved road. The paved road extends about 15 m on the east wall of the quarry.

Quarry Π97

Marble Unit 2

Description: This is an ancient quarry with tool marks around its periphery. The quarry of the marble in this quarry is variable. Nearly all exposures of the marble are foliated with white mica layers. The marble in the southern section of

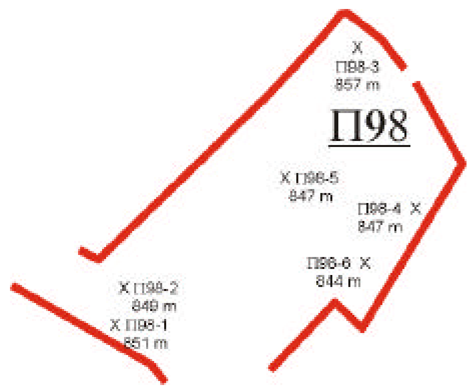


the quarry is foliated with up to 1 cm thick brown foliation layers. Through the northernmost section of the quarry and through the southern section are exposures of chlorite-epidote schist intercalations. The intercalations parallel the mica foliation layers. Joints are widely spaced which would have allowed for large blocks to be extracted.

Quarry Π98

Marble Unit 2

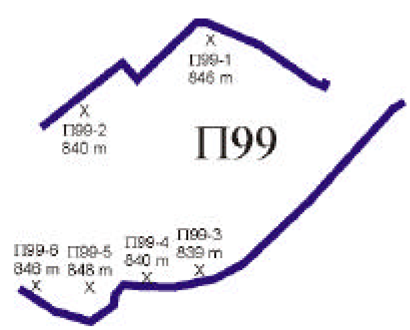
Description: This quarry is located on the west side of the mica schist ridge separating Marble Units 2 and 3. It is a deep quarry with wall heights exceeding 30 m. The east wall of the quarry abuts the mica schist spine and the marble is highly foliated with many thin mica schist intercalations. Along the top of the east wall are quarry marks and excavation trenches. A secondary mica schist intercalation delineates the west wall of the quarry.



Quarry Π99

Marble Unit 2

Description: This is a large modern quarry that may have extended into a former ancient quarry. The east wall of the quarry is composed heavily of

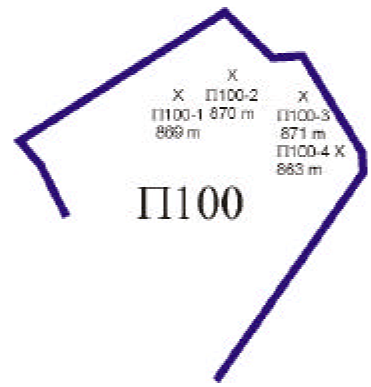


intercalated white mica schist. The west wall is also delineated by white mica schist. The marble from the center of the quarry appears to be of high quality with no discoloring foliation layers. There is no physical evidence of ancient extraction.

Quarry Π100

Marble Unit 2

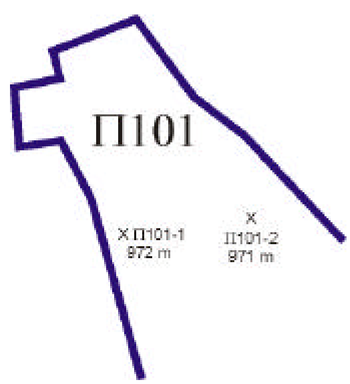
Description: This quarry is characterized by having a very high quality white marble layer running through it. The thickness of the high quality marble is at least 5 m. The marble is visible in the northwest wall of the quarry. Samples Π100-1 and Π100-2 were collected from this bed. Sample Π100-3 is a white marble sample collected adjacent to a chlorite-epidote schist intercalation. There is also a 5 m thick mica schist that penetrates the quarry and cuts through the north corner. The mica schist is heavily weathered. Lineation measurements from the schist indicate it is trending roughly N10W. There is no physical evidence of ancient extraction.



Quarry Π101

Marble Unit 2

Description: This is a small to medium sized quarry. The surface exposures and samples show that the quarry contains white marble with white mica and

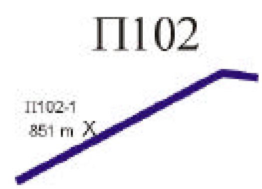


schist foliation layers and prominent banding on weathered surfaces. The average orientation of the foliation layers is N85W, 31S indicating that this marble is part of a southwestward dipping limb of a secondary fold. There is no physical evidence of ancient extraction.

<u>Quarry Π102</u>

Marble Unit 2

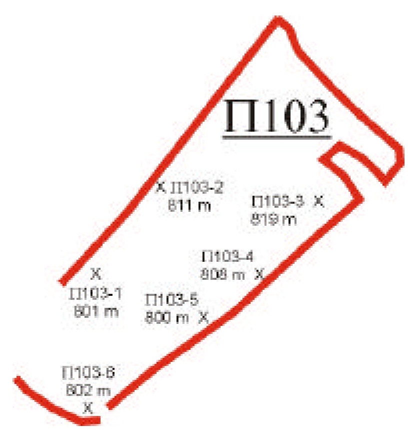
Description: This is a small quarry that is only represented by a single wall facing towards the northwest. It is located in front of the entrances and south of quarries Π100 and Π101. The marble from the quarry is white with 1 cm brown mica-rich foliation layers. There is no physical evidence of ancient extraction.



<u>Quarry Π103</u>

Marble Unit 2

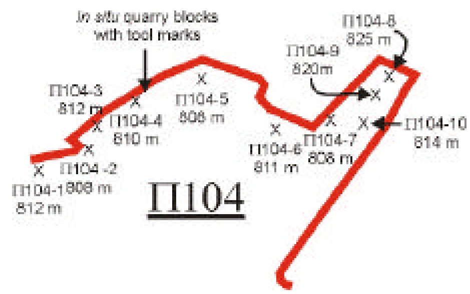
Description: This is a large quarry with a depth of ~50 m. Along the top of the east wall are traces of the ancient quarry pick. The bottom of the quarry does not show any signs of ancient extraction. The marble is white with white mica foliations. The bottom of the quarry shows blue/gray banding. The banding is more prominent on the east side than the west. The strike of the foliation planes is oriented toward the NE. The northwest wall of the quarry is



delineated by a nearly vertical green schist intercalation. This wall is highly weathered and has some exposures of schist and mica foliated marble. The SE wall is similar in texture Therefore, not many samples were collected along these two walls.

Quarry Π104

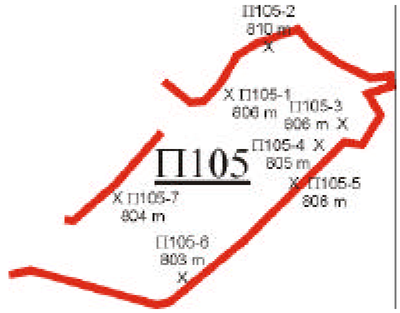
Marble Unit 2



Description: This large ancient quarry was reworked in modern times. The width of the quarry is about 83 m from the northwest wall to the southeast. The depth of the quarry pit is no more than 25 m. This quarry has good quality white marble with few discoloration foliation bands. There are thin foliations of white mica. At the northwest wall are two large blocks left *in situ* by ancient quarry workers. The blocks were shaped by ancient picks as the tool marks on their edges indicate. The white band is about 3 m thick. The blocks are of a pure white marble. It is possible that the quarry workers were following this particular band of white marble. There is a green mica schist intercalation 3 meters above the white marble band.

Quarry Π105

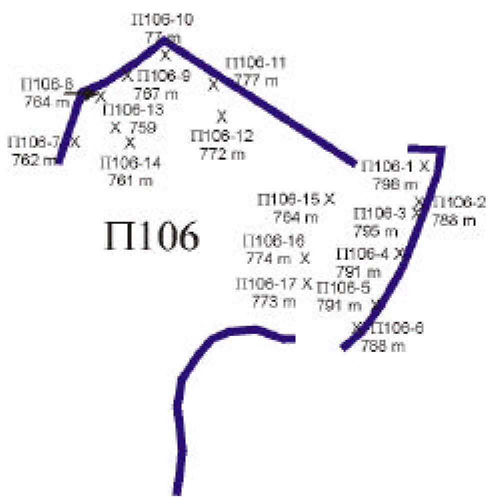
Marble Unit 2



Description: This large ancient quarry has a similar marble distribution as quarry Π103. The northwest wall is comprised of white marble with many schist intercalations penetrating throughout. The southeast wall is comprised of a near-vertical thick green mica schist interbed. All marbles collected from this quarry are within a meter of a schist intercalation. Ancient tool marks are located on the upper section of the southeast wall.

Quarry Π106

Marble Unit 2



Description: This is a large modern quarry pit with a maximum depth of 30 m. The quarry is split into two sections: the main pit and a small accessible section of on the upper east wall which was cut back for a quarry road. Most of the marble in this quarry has green mica schist intercalations penetrating it. The intercalations are up to 3 cm thick. There are also several 30 cm thick schist interbeds. Some marble along the east wall also has gray banding. There is no physical evidence of ancient extraction.

Quarry Π107

Marble Unit 2

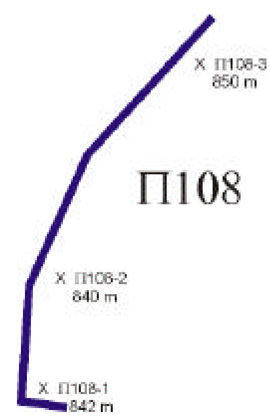
Description: This is a large, long ancient quarry. The vertical green mica schist layer that divides Marble Units 1 and 2 runs along the east wall of the quarry. Most of the exposed marble in this quarry is along the west wall. The outcrops show that the marble has foliations of white mica. Along the southern section of the west wall is a

several cm thick chlorite-epidote schist interbreed. Throughout the rest of the quarry there are thin green mica schist intercalations. Several samples were collected that are of high-quality pure white marble. Garland-style ancient toolmarks are located on the upper east wall and lower west wall.

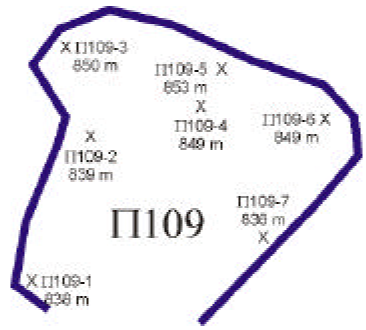
Quarry Π108

Marble Unit 1

Description: This is a small modern quarry. The white marble is foliated with mica layers and 1 cm thick brown layers. There is no physical evidence of ancient extraction.



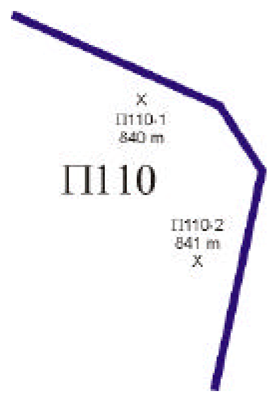
<u>Quarry Π109</u>



Marble Unit 1

Description: This is a medium-size modern quarry. This quarry exhibits a white marble with a series of 1 cm thick mica schist intercalations spaced infrequently apart every 0.5 to 1 m. There is no physical evidence of ancient extraction.

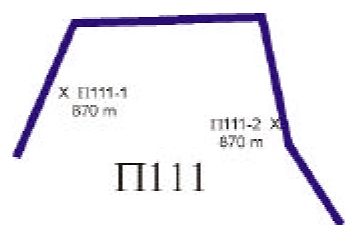
<u>Quarry Π110</u>



Marble Unit 1

Description: This is a small quarry immediately to the west of quarry Π109. The quarry has good quality marble interspersed with thin chlorite-epidote schist intercalations. There is no physical evidence of ancient extraction.

<u>Quarry Π111</u>



Marble Unit 1

Description: This is a small, shallow quarry. The marble from this quarry is white. The exposed surfaces on the west wall show 2 cm thick foliation bands of green, brown and maroon. There is no physical evidence of ancient extraction.

Quarry Π112

Marble Unit 1

Description: This is a small, shallow modern quarry. The marble is of poor quality with many thin white mica and green schist foliation layers. The surviving quarry wall is heavily fractured. It is unlikely that any large blocks were extracted from this quarry. There is no physical evidence of ancient extraction.

Quarry Π113 and Π114

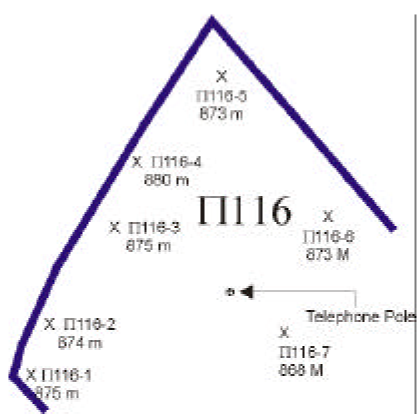
Marble Unit 1

Description: A 2-4 wide wall separates these two large modern quarries. The marble in this quarry is highly fractured with schist and mica foliation layers. No samples were collected from these quarries due to the inability to locate fresh, intact marble. There is no physical evidence of ancient extraction in either quarry.

Quarry Π115 – There is no quarry Π115.

Quarry Π116

Marble Unit 1

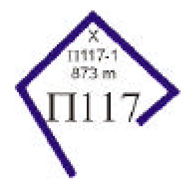


Description: This quarry is medium-sized with white mica foliated white marble. Along the upper portion of the 10 meter high walls is a 30 cm thick schist intercalation. It appears that this layer had blanketed the quarry and was removed to extract the material beneath it. There is no physical evidence that suggests that this quarry was in operation during antiquity. A modern telephone pole with a lone wire leading up slope to the military installation sits atop a small island of unquarried material in the center of the quarry. The fact that the island is there suggests that the quarry was excavated after the placement of the telephone pole.

Quarry Π117

Marble Unit 1

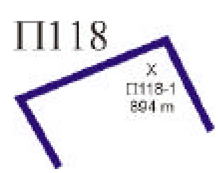
Description: This is a very small quarry with a maximum depth of 4 meters. A single sample collected from this quarry indicates that the marble is white with white mica foliation layers. The marble also exhibits brown and green foliation layers which most likely indicate diagenetic alteration of the mica grains by pore fluids. There is no physical evidence of ancient extraction.



Quarry Π118

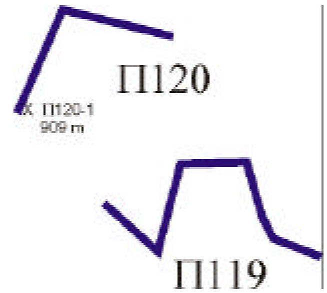
Marble Unit 1

Description: This is a very small modern quarry with very shallow walls. A single sample indicates that the marble from this quarry was white with thin brownish foliation layers that include white mica. There is no physical evidence of ancient extraction.



<u>Quarries Π119 and Π120</u>

Marble Unit 1



Description: These two quarries are situated side-by-side. Both quarries are no more than 7 m deep. The exposed walls are heavily weathered or buried by quarry debris. It was not possible to collect a sample from quarry Π119. The single sample from quarry Π120 indicates that the quarry marble is white with thin chlorite schist foliation bands. There is no physical evidence of ancient extraction.

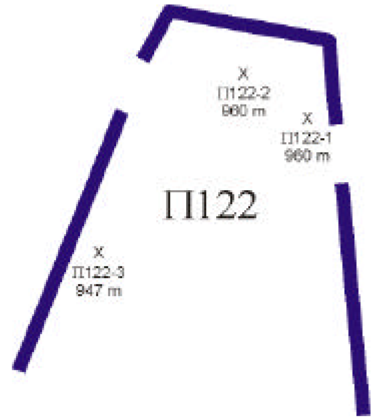
<u>Quarry Π121</u>

Marble Unit 1

Description: This is a modern quarry located at the apex of a hairpin curve of the paved road that leads to the military installation atop the mountain. The quarry is about 15 m deep. Large quarry debris blocks prevented the collection of fresh samples from the quarry walls. However, from a distance several large green schist interbeds can be seen penetrating through the quarry. There is no physical evidence of ancient extraction.

<u>Quarry 122</u>

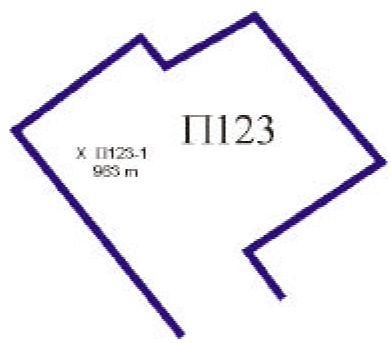
Marble Unit 1



Description: This quarry is dissected into two parts by the modern quarry road that provides access to the quarry operations on the north slope of Mount Pentelikon. The surviving upper section of the quarry is significantly smaller than the southern section. Samples collected in the northern upper section indicate that the quarry contained white marble with thin brown foliation layers rich in white mica. Only a single sample was collected from the lower section due to very poor quality marble caused by intense weathering and/or abundant impurities. There is no physical evidence of ancient extraction.

Quarry Π123

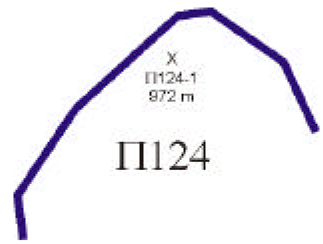
Marble Unit 1



Description: This quarry lies along the modern quarry road that provides access to the quarry operations on the north slope of Mount Pentelikon. The maximum depth of the quarry is about 8 meters. The quality of the marble preserved in the quarry is very poor. The marble is very dense with thin mica-rich foliation bands. The foliation bands include large (~0.5 mm) opaque minerals. A single sample was collected from the quarry. There is no physical evidence of ancient extraction.

Quarry Π124

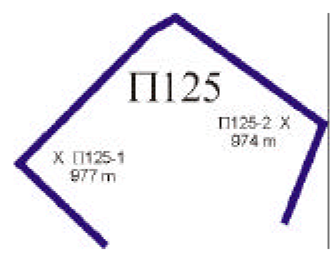
Marble Unit 1



Description: This quarry lies along the modern quarry road that provides access to the quarry operations on the north slope of Mount Pentelikon. The maximum quarry depth is about 6 meters. The quarry marble is penetrated with mica-rich foliation bands up to 1 cm thick. A single sample was collected from this quarry. There is no physical evidence of ancient extraction.

Quarry Π125

Marble Unit 1



Description: This quarry lies along the modern quarry road that provides access to the quarry operations on the north slope of Mount Pentelikon. The walls in this quarry are no more than 6 meter tall. The marble is white with mica foliation layers. In one sample chlorite grains penetrate about 2 cm into the marble along the foliation planes. There is no physical evidence of ancient extraction.

Quarry Π126

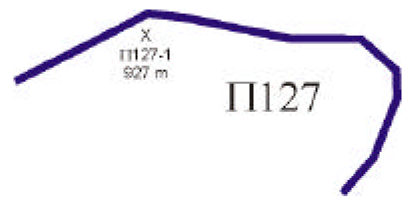
Marble Unit 1

Description: This is a very small surface quarry. The walls are no more than 2 m deep. The quarry exposures are heavily weathered with lichen growth and gray discoloration. Because of the high degree of alteration on the surface no fresh samples were collected. There is no physical evidence of ancient extraction.

<u>Quarry Π127</u>

Marble Unit 1

Description: The marble from this medium sized quarry is white with brownish white mica-rich foliation layers. Only a single sample was collected from this quarry due to the highly altered nature of exposed walls and difficulty with obtaining fresh marble samples of adequate size. There is no physical evidence of ancient extraction.



<u>Quarry Π128</u>

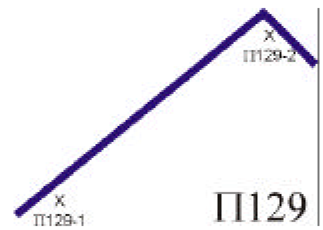
Marble Unit 2

Description; This medium sized quarry is about 15 m deep. A single sample from this quarry reveals that the marble was of poor quality with dense (up to 1.5 cm thick) brownish white-mica foliation layers. The color of the marble is beige/cream. There is no physical evidence of ancient extraction.

<u>Quarry Π129</u>

Marble Unit 2

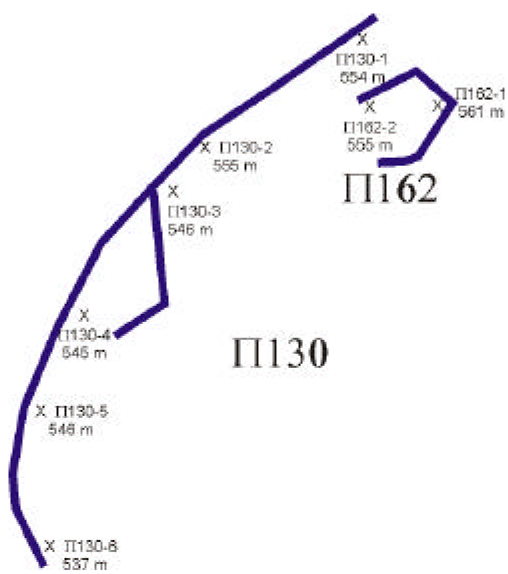
Description: This is a small to medium size quarry on the eastward-dipping slope of the anticline of Marble Unit 2. There is no evidence of ancient extraction. The marble from the quarry is white with many thin foliation layers of white mica. Many of the foliation layers are reddish and grayish/blue indicating the likely alteration of mica by diagenetic fluids.



<u>Quarry Π130</u>

Marble Unit 3

Description: This large modern quarry is mostly filled in with quarrying debris material and municipal garbage. The marble from this quarry is of poor quality. It is white with persistent foliation bands of white mica. Many of the bands are red due to diagenetic alteration of the mica. Throughout the exposed wall there are epidote schist and chlorite schist intercalations. The schist thicknesses range from 20-40 cm. All samples collected were within one meter of a schist intercalation or immediately next to an altered white mica foliation layer.

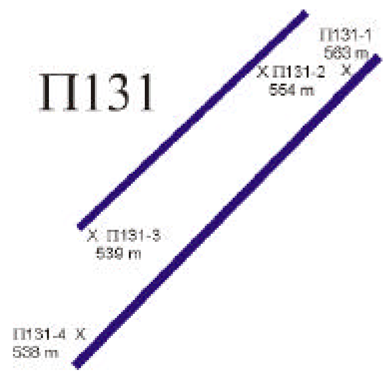


Boreholes identify this quarry as modern. There is no physical evidence of ancient extraction.

Quarry Π131

Marble Unit 1

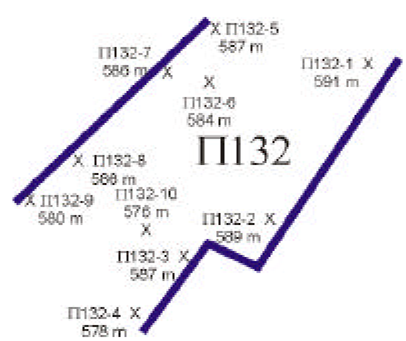
Description: This quarry was once a large quarry, but debris dumped in front of quarry Π132 has filled in much of it leaving just the front of the east and west walls exposed. The east and west walls are lined with schist interbeds. Many thin white mica foliation layers penetrate the white marble. Some of the mica foliation layers have been altered to a reddish color most likely as a result of weathering due to percolating waters. Boreholes help identify this quarry as modern. There is no physical evidence of ancient extraction.



Quarry Π132

Marble unit 1

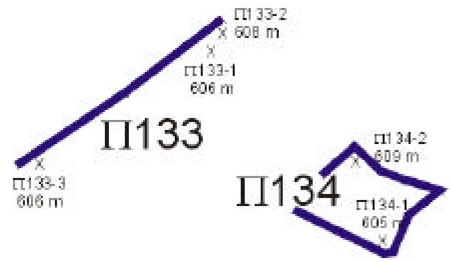
Description: This large quarry is comprised of white marble with white mica foliation layers. Many of the foliation layers have a reddish color, most likely as a result of diagenetic fluid alteration. Within the marble are green schist intercalations. The intercalations are up to 20 cm thick. There is no physical evidence of ancient extraction.



<u>Quarry Π133</u>

Marble Unit 1

Description: This is a small quarry represented by a single wall near the gully at the base of an eastward dipping slope. The quarry face appears fresh suggesting a modern extraction history. The marble is heavily banded with red and blue/green schist intercalations up to 10 cm thick. The three samples from this quarry all include thin (approximately 0.5 cm thick) schist intercalations. There is no physical evidence of ancient extraction.



<u>Quarry Π134</u>

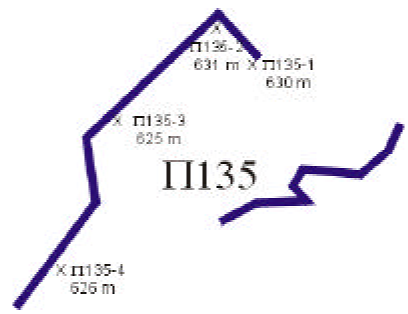
Marble Unit 1

Description: This is a small quarry with a maximum depth of 4 m. There is color banding within the white marble. Two samples were collected from the quarry. For diagram of quarry see the description for quarry Π133. There is no physical evidence of ancient extraction.

<u>Quarry Π135</u>

Marble Unit 1

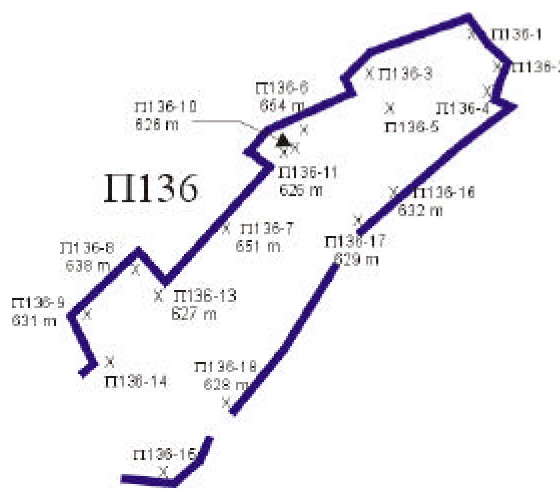
Description: This medium sized quarry extends to the south from quarry Π136. Modern extraction evidence includes bore and drill holes. The quarry contains white marble with many schist intercalations. White mica foliation layers up to 5 mm thick penetrate most of the quarry. Much of the foliation has been discolored to red, brown and green and mostly likely is the result of diagenetic alteration from percolating water. The quarry has been partially filled in with quarry debris and municipal garbage. The quarry walls are jointed suggesting only small blocks were removed. There is no physical evidence of ancient extraction.



Quarry Π136

Marble Unit 1

Description: This is a large quarry with evidence that its extraction record is polyphased. On the 1:5000 military base map two quarries are identified. The current outline is that of a single quarry suggesting modern extraction connected the two quarries. The wall dividing this quarry from Π135 to the south was also removed by modern quarry workings. The dumping of debris into the quarry has artificially raised the quarry floor. Therefore, it is not possible to determine the true depth of the floor. The length of the quarry follows a small topographic ridge that trends towards the NE. The marble from this quarry is white with many colored bands and mica foliation layers. The west wall appears to follow a schist intercalation. The banding is

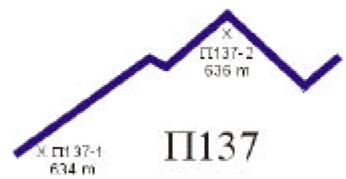


rich in mica and discolored red, greenish blue and gray. There is no physical evidence of ancient extraction.

<u>Quarry Π137</u>

Marble Unit 1

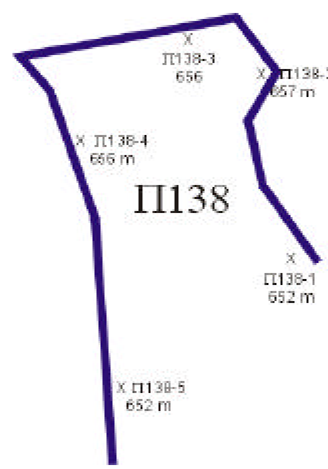
Description: This quarry lies immediately to the east of the large quarry Π136. The marble from this quarry is white with green mica schist intercalations and interbeds throughout. There is no physical evidence of ancient extraction.



<u>Quarry Π138</u>

Marble Unit 1

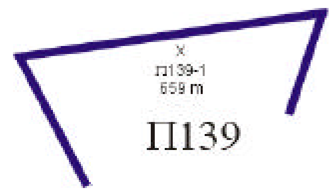
Description: The walls of this medium sized quarry are cut parallel to joint surfaces. Much of the quarry is filled in with debris material. The debris pile extends from the quarry's southern end by 10 m. The maximum depth of the quarry is 7 m at the NW corner. The marble from the quarry is white with mica foliation layers. There are no large schist intercalations visible in the exposed walls. There is no physical evidence of ancient extraction.



Quarry Π139

Marble Unit 1

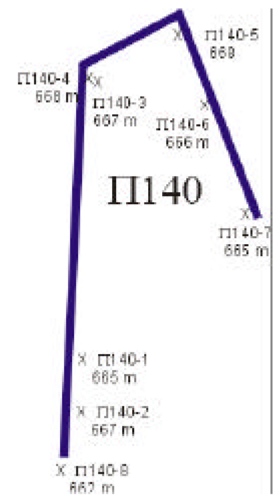
Description: This is a small quarry immediately to the north of quarry Π138. The marble from this quarry is white with schist intercalations oriented parallel to the NE wall and seen penetrating the same wall. The schist is about 6 cm thick. There is no physical evidence of ancient extraction.



Quarry Π140

Marble Unit 2

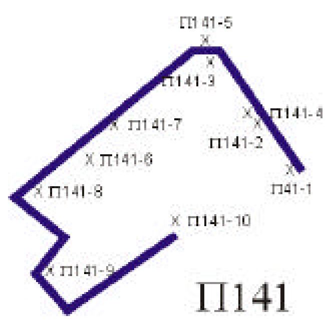
Description: This medium size quarry has a maximum depth of 8 m. The marble is white with thin white mica foliation bands. Many of the bands have been altered to green or red. No large schist intercalations are visible in the quarry walls. The center of the quarry is filled with debris. There is no physical evidence of ancient extraction.



Quarry Π141

Marble Unit 1

Description: This quarry has a maximum depth of 8 m. The weathered walls clearly show schist intercalactions. Banding is also prevalent in many

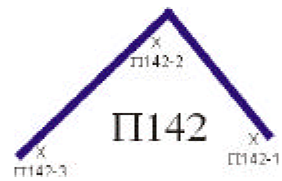


areas of the quarry. Thin bands of white mica schist penetrates the quarry. There is no physical evidence of ancient extraction.

Quarry Π142

Marble Unit 1

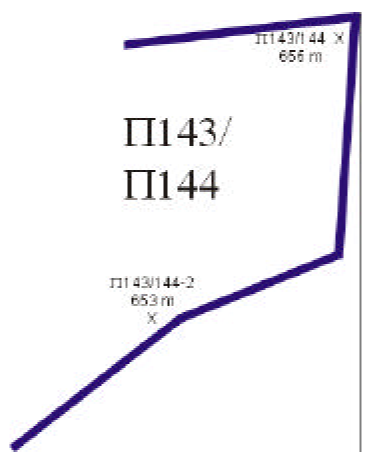
Description: This is a small quarry. It represents the upper most quarry on the ridge defining Marble Unit 1. There is no physical evidence of ancient extraction. A modern quarry wedge hole is visible in a large detached block in the center of the quarry. The marble in the quarry is white with mica foliation layers. Schist intercalations can be seen penetrating the NE wall.



Quarry Π143/Π144

Marble Unit 1

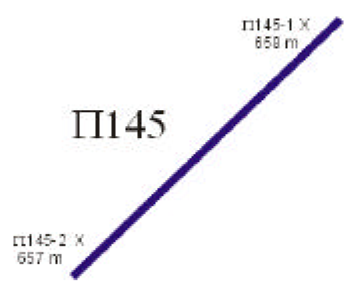
Description: This small to medium quarry is filled with large boulders. The marble is white with thin discolored foliation bands of reddish pink. There is no physical evidence of ancient extraction.



Quarry Π145

Marble Unit 1

Description: This is a small quarry represented by a single wall. The quarry faces towards the west. The



maximum depth of the quarry is 3 m. The marble in the quarry is of poor quality. It is speckled with oxide impurities. The weathered face is more friable when compared to the marble from other quarries. There is no physical evidence of ancient extraction.

Quarries Π146, Π147, Π148 and Π149

Marble Unit 1

Description: These medium sized quarries are about half way up the south slope of Mount Pentelikon. The marble from the three quarries is similar. It is extensively fractured and the exposed marble is banded. Many of the bands are discolored presumably due to alteration of mica foliation layers. The foliation layers are crenulated. None of the quarries shows any physical signs of activity during antiquity. In quarry Π147 there are unfinished carved blocks. The large boreholes suggest a modern origin. No samples were collected from these quarries.

Quarries Π150 and Π152

Marble Unit 1

Description: These two small quarries are situated half way up the south slope of Mount Pentelikon. The marble exposures from both quarries are gray and it is difficult to discern any structural features from them. There are no tool marks indicating ancient activity at these quarries. Due to the severe weathering of the exposed surfaces no samples were collected.

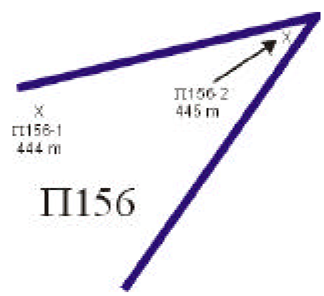
<u>Quarries Π154 and Π155</u>

Marble Unit 1

Description: These two adjacent quarries lies on the westward dipping slope of the ridge in Marble Unit 1. The two quarries contain quarry debris. Both quarries have white marble with schist intercalations. In quarry Π154 a 70 cm thick schist interbed lies at the base of the east wall. The marble in both quarries is foliated with white mica layers. Many of the foliation layers have a reddish tinge suggesting alteration with pore waters within the foliation planes. The red foliation layers are up to 2 cm thick. There is no physical evidence of ancient extraction.

<u>Quarry Π156</u>

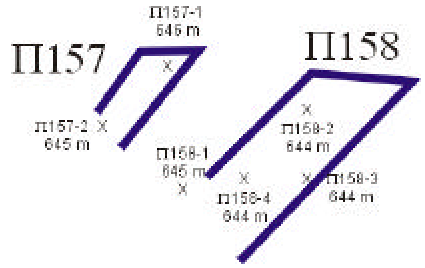
Marble Unit 1



Description: This is a small to medium quarry with banded white marble. In the center of the quarry is a large debris pile from later quarrying activities. The quarry is shallow with a maximum depth of 5 m. There is no physical evidence of ancient extraction.

Quarries Π157 and Π158

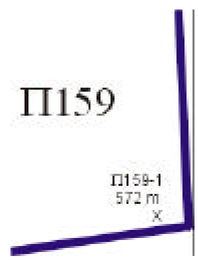
Marble Unit 1



Description: This is a small quarry with white mica foliated marble. The mica has undergone some alteration so that the broken surface of the marble appears to have reddish speckles. There are also thin schist intercalations penetrating through the quarry wall. There is no physical evidence of ancient quarry extraction.

Quarry Π159

Marble Unit 1



Description: This small quarry is located near the eastern contact of Marble Unit 1. The marble in the quarry is white with striped gray-green foliation bands with a thickness ranging from 0.5 cm to 4 cm. The quarry appears to be located in the former bend of a now-dry stream bed. The maximum height of the quarry walls is 3 m. There is no physical evidence of ancient extraction.

Quarry Π160

Marble Unit 1

Description: This is a small triangular shaped quarry in a creek bed between Marble Units 1 and 2. The surface of the walls have a thick weathering rind and it is difficult to ascertain the characteristics of the marble. No samples were collected from this quarry. There is no physical evidence of ancient extraction.

Quarry Π161

Marble Unit 3

Description: This quarry is situated on the eastward dipping slope of Marble Unit 3 to the west of the *Spilia* quarry. Two opposing walls are the only surviving traces of the quarry. Later, large scale quarrying activities dumped literally tons of debris into the quarry from above, effectively covering most of the quarry walls. I was unable to ascertain the macro-characteristic of the marble from either wall. No samples were collected from this quarry due to its inaccessibility. There is no physical evidence of ancient extraction.

Quarry Π162

Marble Unit 1

Description: This is a small quarry to the west of the upper part of quarry Π130. The quarry must have been mined prior to the 1950s since it appears on the Military Army's 1950s topographic maps. The marble from this quarry includes schist intercalations up to 2 cm thick. Two samples were collected from this quarry. See description for Quarry Π130 for a diagram of the quarry. There is no physical evidence of ancient extraction.

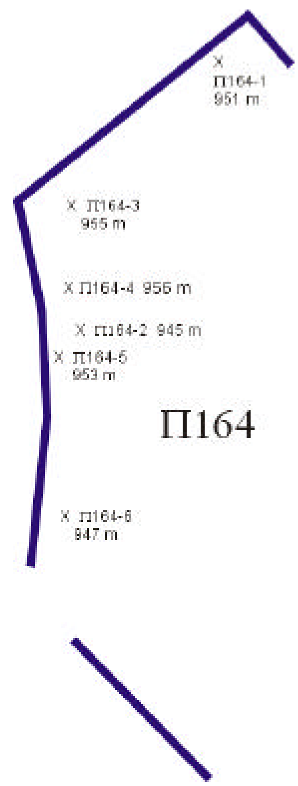
Quarry Π163

Marble Unit 3

Description: This quarry is to the west of the large quarry Π85 in the *Aspra Marmara* region. The quarry is very small with little of its wall visible. However, it was probably a larger quarry that has since been buried by the large quarry debris piles to the northwest. A single sample from the quarry indicates that it produced a good quality white marble. There is no physical evidence of ancient extraction.

Quarry Π164

Marble Unit 3

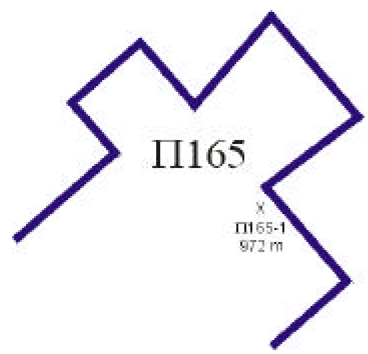


Description: This is a large modern quarry. It is divided into an upper and lower section. The upper section is defined by having an elevated relatively flat surface of fill. The west wall of the lower section is visible sticking through a large quarry debris pile that has been dumped from the upper section. The upper section is the larger of the two. The marble in the upper section is not pure white. It is marked by thin foliation layers of red and green. The foliation layers are often compactly spaced. Green schist intercalations are also a common feature in the marble. The schist thickness varies up to several meters in width. Note that this quarry is near a gradational contact with a thick mica schist unit to the west that is outside the quarry district. I was not able to collect a fresh marble sample at the northern end of the quarry where the marble is highly fractured and foliated with mica and mica schist. I also was unable to access the lower quarry due to the steep and slippery debris pile that leads down to it. There is no physical evidence of ancient extraction.

<u>Quarry Π165</u>

Marble Unit 3

Description: This is a small quarry near the top of the south slope. The quarry is immediately south of the only surviving benchmark in the ancient quarry area. The maximum width of the quarry is 10 m. The marble from this quarry is foliated with up to 1 cm thick white mica foliation layers. There is a gray tint to the marble. There is no physical evidence of ancient extraction.



<u>Quarry Π166</u>

Marble Unit 3

Description: This modern quarry lies immediately to the east of ancient quarry Π91. The quarry trace is along the same wall excavated for Π91. Evidence suggests that the current floor is quarry debris material and that the true quarry floor is meters below. Marble exposures in the quarry are limited due to an abundance of green schist exposures. No samples were collected from this quarry. There is no physical evidence of ancient extraction.

Quarry Π167

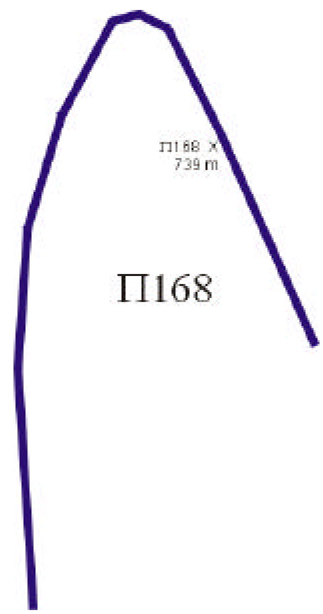
Marble Unit 2

Description: A single quarry wall delineates this small modern quarry. The quarry penetrates into a steep southward plunging slope. The marble is of poor quality and no samples were collected due to the inability to collect a fresh sample. There is no physical evidence of ancient extraction.

Quarry Π168

Marble Unit 3

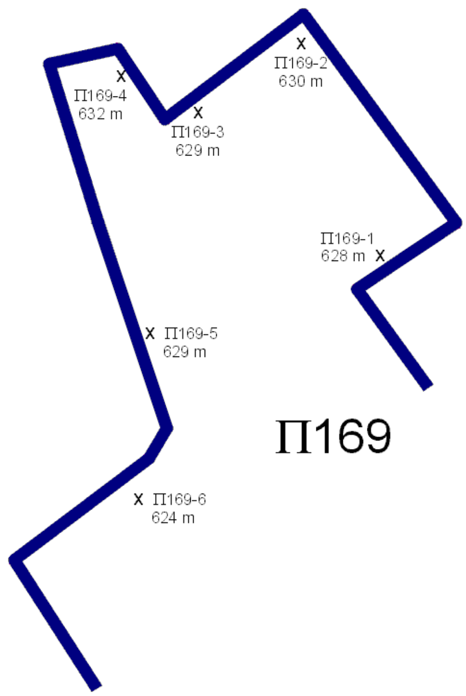
Description: This is a small quarry that is most likely a modern extension of quarry Π69. The marble from this quarry is pure white with thin white mica foliation layers. There is no physical evidence of ancient extraction.



<u>Quarry 169</u>

Marble Unit 2

Description: This small to medium sized quarry is in the highly concentrated quarry zone in Marble Unit 2. Six samples were collected from this quarry. The quarry contains white marble. Along the northeast wall the marble is of high quality with few mica intercalations. Other areas of the quarry show marble with white and greenish-white mica foliation layers. There is no physical evidence of ancient extraction.



<u>Quarries Π170 and Π171</u>

Marble Unit 2

Refer to the description of quarry Π14.

<u>Quarry Π172</u>

Marble Unit 2

Refer to the description of quarry Π13.

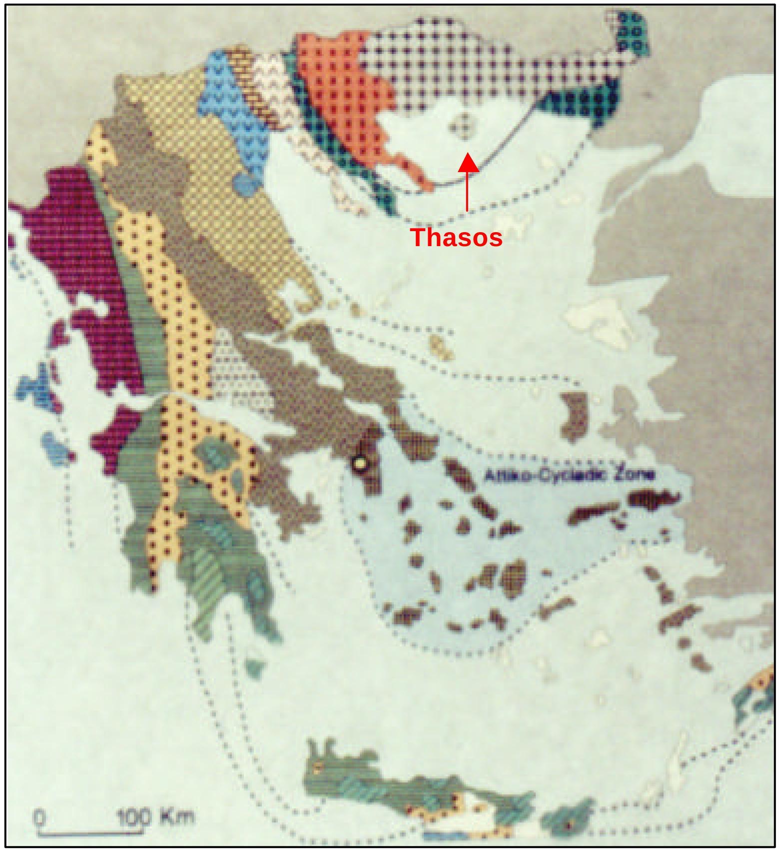
Quarry Π173

Marble Unit 3

Description: This is a shallow (<2 m) highly weathered pit quarry to the south of quarry Π39 and adjacent to the ancient quarry road. The marble in the quarry is heavily weathered and covered with lichen. Therefore, no samples were collected and no assessment could be made on the characteristics of the marble. There is no physical evidence of ancient extraction.

Figures

a



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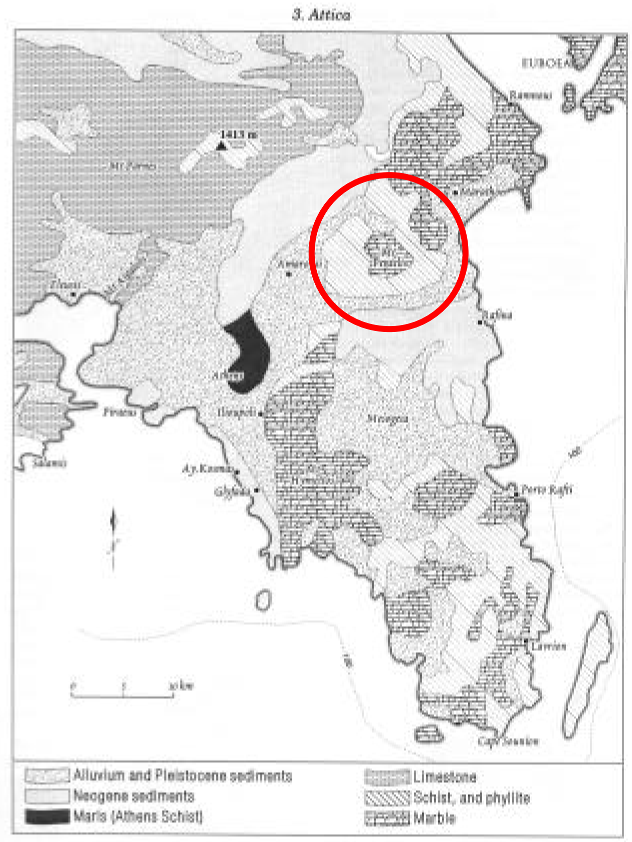

Figure 1. (a) Geotectonic map of Greece. Most of the important ancient marble sources in Greece lie within the Attic-Cycladic Zone. The island of Thasos in the north Aegean is the exception. Mount Pentelikon lies in the NW corner of the Attic-Cycladic metamorphic complex. (b) Generalized geologic map of Attic Peninsula. Mount Pentelikon, identified by the circle, is located in the northern region of Attica (from Higgins and Higgins 1996).

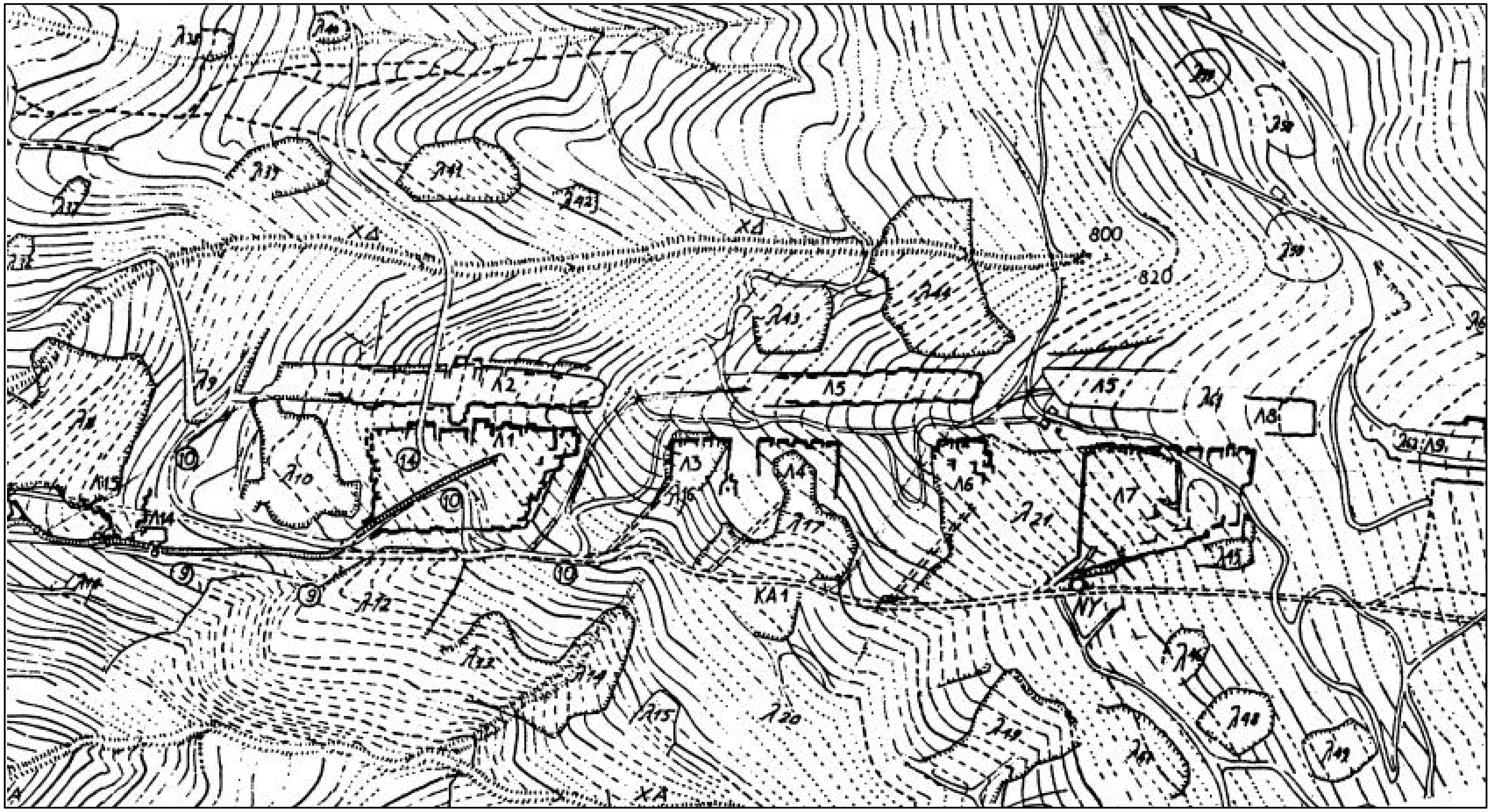

Figure 2. The Korres map (1995) of the archaeological quarries on Mount Pentelikon. Many of the quarry boundary lines drawn are either directly traced from the 1:5000 contour map published by the Greek military or are speculated by Korres.

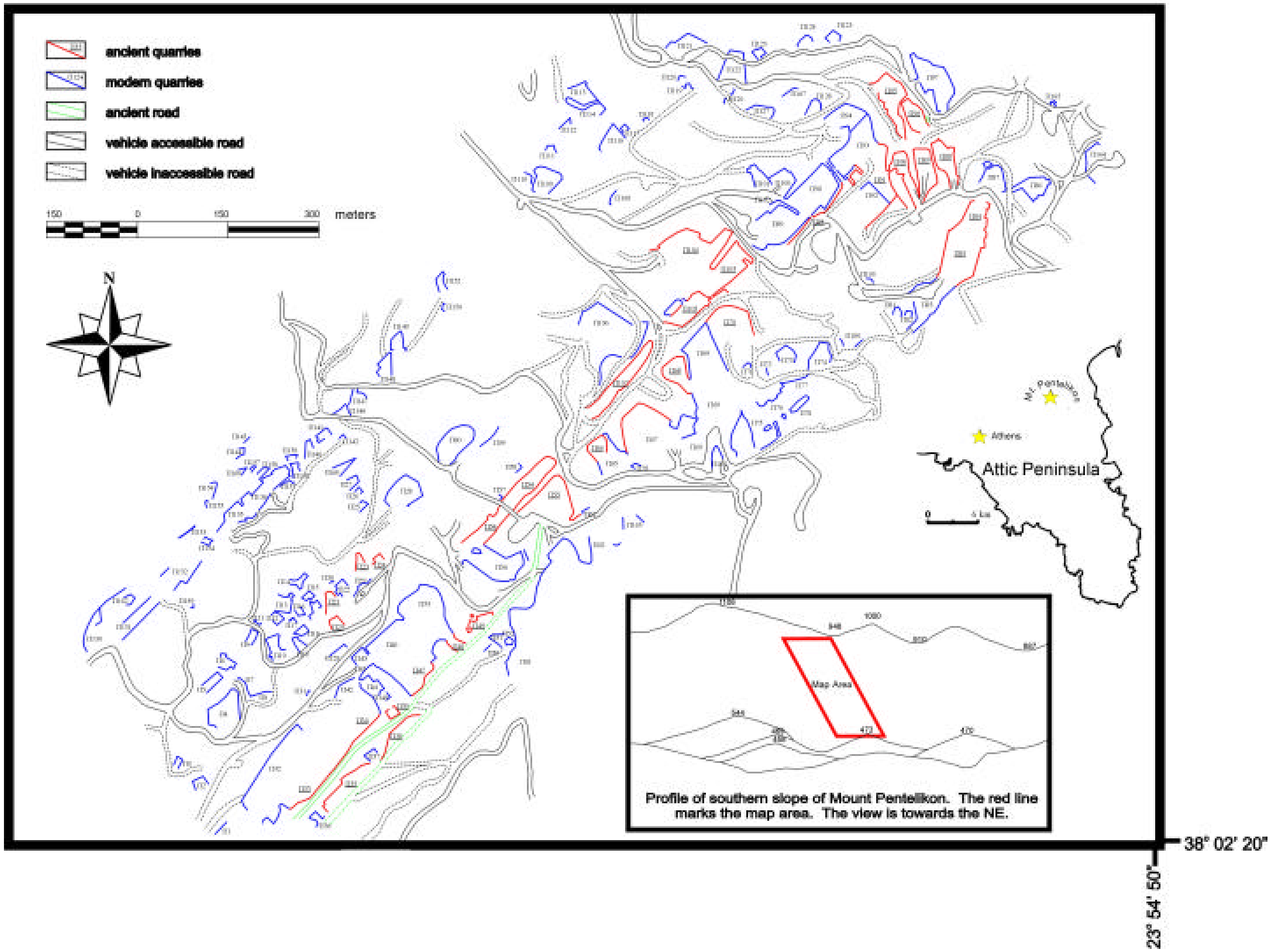

Figure 3. Quarry location map for the south slope of Mount Pentelikon.

Figure 4. Tool marks in quarry Π23. The garland-type marks are on the large block in the center of the photograph. This quarry was previously labeled as modern quarry λ37 by Korres (1993).

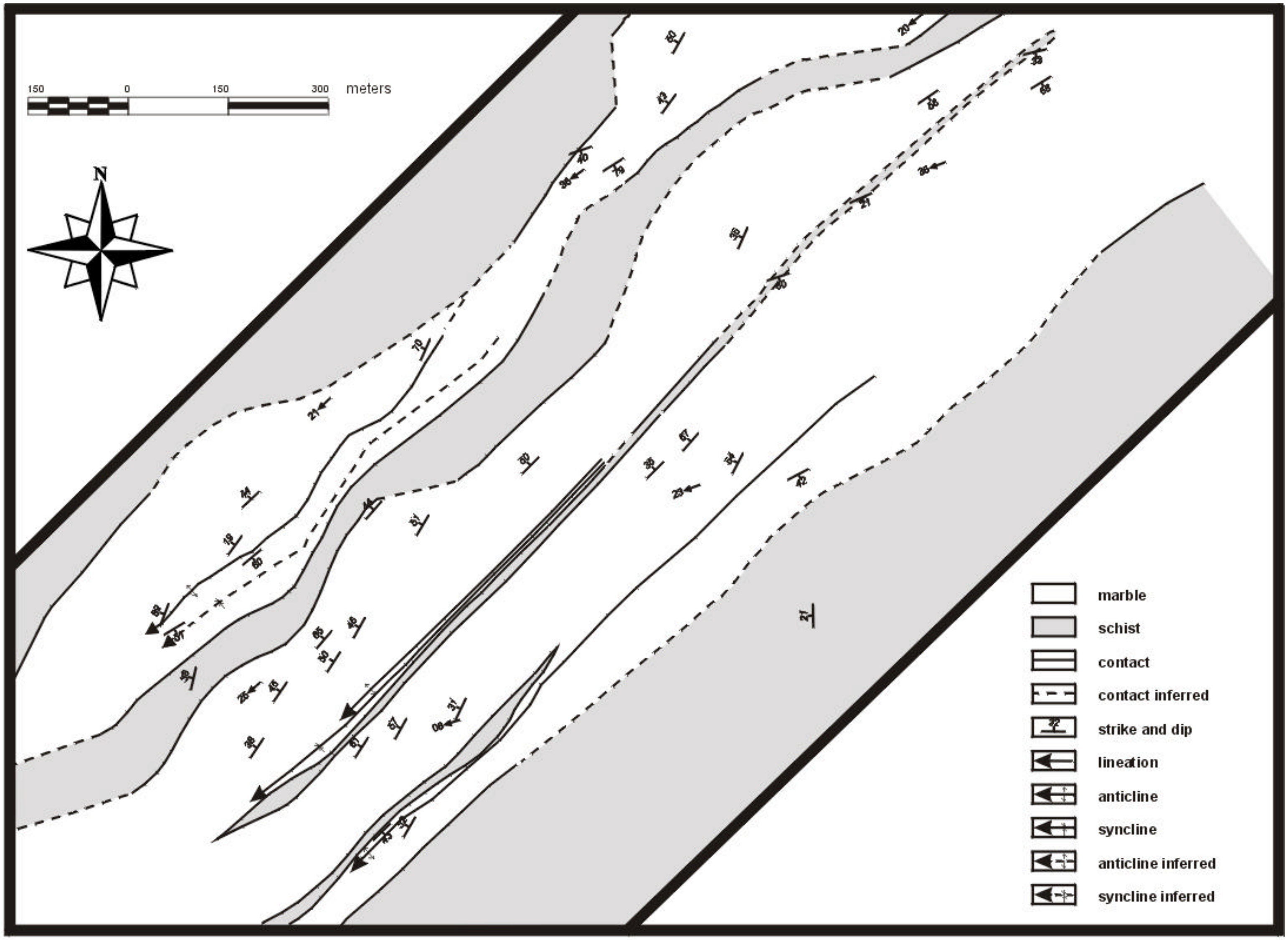

Figure 5. Geologic map of quarry region on the south slope of Mount Pentelikon.

Figure 6. Unfinished column capital found in quarry Π23.

Figure 7. Ancient quarry road to east of quarry Π38. Note the chiseled grooves that used to help keep marble-laden vehicles on the road.

CHAPTER 3

AN EXAMINATION OF THE USE OF WHOLE-ROCK NAA DATA FOR INTRA-QUARRY DISCRIMINATION OF ANCIENT MARBLE FIELDS WITHIN THE PENTELIC QUARRY REGION[1]

[1] Pike, S. H. To be submitted to *Archaeometry*

Abstract

Multivariate statistical treatment of compositional neutron activation analysis data from 63 samples representing five geographically distinct quarry groups from the archaeologically important quarry region of Mt. Pentelikon, Attica reveal that whole-rock compositional data is unable to discriminate between the selected quarries. The analyses show that there is no apparent geochemical structure within the greater Pentelic quarry region. This study suggests that whole-rock geochemical inter- and intra- quarry characterization studies of white marble be abandoned. Discussions of possible improvements for future compositional characterization studies include ICP analysis where only the carbonate fraction of the marble is measured.

Introduction

As part of the first systematic characterization study of the important ancient marble quarries on Mount Pentelikon, Attica, Greece, a trace- and rare-earth element compositional study was carried out to investigate the distribution and structure of elements throughout the entire ancient Pentelic quarry region. Recent reports suggest that there are sub-regions within the greater quarry area with marked differences in isotopic and geochemical compositions (Matthews et al. 1992, Kane et al. 1992, 1995, Pike 1996). These studies suggest that rather than treating the quarry region as a whole unit with one characteristic signature as earlier studies have done, it may be possible to use whole-rock geochemical signatures to discern sub-regions within the quarry area. The ability to distinguish between individual quarries or groups of quarries will assist archaeologists, art historians and museum curators with dating artifacts, piecing together ancient trade routes, giving insight into changing aesthetic values and determining modern forgeries, ancient copies and disassociated fragments (Herz 1987). This paper reports on the feasibility of using whole-rock geochemical data to discriminate between individual quarries or groups of quarries within the ancient marble quarry region of Mount Pentelikon.

Only through an extensive survey of the quarry area could a truly representative reference sample collection be obtained for this study. To this end, an extensive field study was conducted to geologically and geographically map and sample the ancient quarry area. For a detailed discussion of the field survey including the techniques, theory and sampling protocol refer to Pike 2000. The quarry location map in figure 1 plots the location and identifying number for every exposed quarry in the ancient quarry region of Mount Pentelikon. The map also indicates those quarries with *in situ* evidence of being operational during antiquity (e.g. surviving ancient tool marks on quarry walls). A sample reference collection was established from multiple samples of fresh marble collected from almost all of the identified ancient quarries and most of the modern quarries. The geologic map in figure 2 displays the geologic exposure of the quarry area. Note that there are three separate marble units identified as Marble Units 1,2, and 3. The ancient quarries lie in Marble Units 2 and 3.

Earlier whole-rock marble characterization studies of Pentelikon and other marble regions assume that entire quarry areas are geochemically homogenous.

However, a literature review does not conclusively support this general assumption. Although isotope studies indicate that there are some high-grade marble regions that do have relatively homogenous chemistries (Peters and Wickham 1995, Bickle et al. 1995), research on fluid-rock interactions during metamorphism illustrate that metamorphic mechanisms do not successfully homogenize marbles at low and medium grades. Studies demonstrate that the character of fluid-rock interaction changes as metamorphic grade intensifies (Rye and Bradbury 1988, van Haren et al. 1996). In low-grade metamorphic environments fluid flow occurs along grain boundaries and fractures. Chemical exchange can occur at the contact between the crystals and fluids (Lewis et al. 1998). As metamorphic grade intensifies, fluid flow becomes channelized. Van Haren et al. (1996) describe low-grade, grain-boundary fluid flow as pervasive. However, their data is collected from schist units. Marble, on the other hand, is significantly more massive and thus is relatively impermeable to fluids during metamorphism (Nabelek et al. 1984). As Valley et al. (1990) point out, massive marbles generally preserve their sedimentary signatures. Therefore, to understand the geochemical profiles of low- and medium-grade marbles it is necessary to examine the mechanisms responsible for the chemical profile of the limestone protolith.

The elemental composition of a limestone protolith depends on the primary and secondary geologic history of the rock. Such factors include effects due to the age, the depositional setting and the diagenetic history of the limestone. Periods of tectonic activity, such as the Neohellenic orogeny in the eastern Mediterranean, produce periods of extensive uplift which consequently results in massive amounts of surface erosion. Limestones formed during periods of intense erosion are subjected to increased amounts of trace elements derived from the mass weathering of the elevated rock. During periods of quieter tectonic activity, analogous to the modern Bahamas of today, the oceans would receive less terrigenous material and thus would encourage the formation of more chemically pure marbles.

The chemical profile of limestone also is dependent on its depositional environment. Temperature, salinity, acidity and the distance from the terrigenous source play a role in determining a limestone's chemical concentration. Studies of depositional environments in modern seas illustrate this point. In general, low Mg-calcite in limestones form in meteoric and deep-sea waters whereas in warmer latitudes the major constituents of modern marine limestones are high Mg-calcite and aragonite. Hard-parts from some modern shallow-sea organisms contain from 2 up to 29 mol% $MgCO_3$ (Table 1, Mackenzie et al. 1990). Thus, Mg concentrations increase in warmer waters. Limestones located near sources of terrigenous sediment may entrap some of that sediment. Sediment held in suspension by river waters may be deposited onto a carbonate shelf as the water slows and loses it carrying capacity upon entering the sea. The deposited material will add trace elements to the limestone. Furthermore, periods of increased dolomite and aragonite deposition have varied throughout geologic history (Tucker 1990a). Tucker (1990b) discuses several models that explain the crystallization of dolomite in natural environments.

A final important aspect of trace element compositions of marble is that the diagenetic history of the rock may alter the chemical profile. Pore waters can have a great impact on the chemical composition of the limestone protolith as well as the metamorphosed marble. Pore waters generally contain abundant amounts of dissolved ions that can substitute into the calcite crystal lattice. These impurities include the alkali earth metals as well as many other trace elements such as Mn and U. Mg^{2+} and Sr^{2+} commonly replace the equally charged divalent Ca^{2+} ion. Pore water alteration can influence the chemical composition both early in the diagenetic history of the limestone or much later after the limestone has been buried or metamorphosed into a marble. Diagenetic events such as compaction due to overbearing stress may cause the evacuation of pore fluids and the possible loss of saturated ions.

Despite the obvious roll that geologic conditions have on the chemical profile of a quarry region, earlier trace- and rare-earth element characterization studies virtually ignore this fact. The assumption adopted by these studies is that within a quarry region there is a homogenous and discrete range of elemental concentrations. Therefore, the studies analyzed an arbitrarily selected reference sample collection, measured the concentration of trace- and rare-earth elements and assumed that the compositional ranges reflected the geochemical profile of the entire quarry region. Preliminary results of these studies looked promising, but as statistical methods became more sophisticated and more samples were added to the database, it became apparent that the range of values was simply too large to successfully discriminate between each of the major quarries.

The extensive reference sample collection for Mt. Pentelikon provides an opportunity to investigate the geochemical structure of the Pentelic quarry region while at the same time challenge the assumptions of geochemical homogeneity adopted by earlier studies. The marble from Mount Pentelikon is ideal for this study. It is fine- to medium grained (maximum grain size is 1 mm), low- to medium grade implying that its geochemical composition was little affected by metamorphic processes. Therefore, the geochemical profile of the marble should reflect that of its limestone protolith. However, there is little evidence to suggest just what the protolith may have been. Stable isotope ratios strongly suggest a shallow-marine origin for the limestone (Wenner et al. 1988, Pike 2000). This environment is further supported by unpublished reports of coral structures visible in metalimestones on Mount Pentelikon (Katsikatsos, pers. comm.). Petrographic analysis of the marbles reveals an accessory mineral assemblage of white mica, chlorite, pyrite, iron oxide and dolomite up to 10% (Roos et al. 1988, Pike, unpublished data). There is no pattern or structure within the quarry that indicates regional differences in the concentration of the accessory minerals.

Sample Preparation and Analysis

A total of 63 samples representing the three Marble Units and five geographically distinct Pentelic quarry areas were prepared for INAA using procedures developed at the University of Missouri Research Reactor (MURR). Samples were prepared and analyzed following the established MURR protocol (Neff 1992). The sampled quarries are Π85, Π90, Π107, Π136 and the combined samples from quarries Π91 and Π92 (Π92 is a small modern quarry within the larger ancient quarry Π91). The samples were ground in a dedicated agate mortar and pestle, stored in glass vials and transported to MURR. The dedicated agate mortar and pestle is used only for carbonate samples to curtail possible contamination from other mineral phases. The samples were then oven-dried at 100º C for 24 hours. Aliquots weighing approximately 200 mg each were placed into high-density polyethylene vials for short irradiation exposures. Samples undergoing long irradiation were weighed out in about 250 mg aliquots and placed into high-purity quartz vials. Internal standards were also included in the analyses.

Short-irradiation sample analysis was carried out through a pneumatic tube irradiation system, as described by Glascock (1992). A neutron flux of 8 X 10^3 $n{\cdot}cm^{-2}{\cdot}s^{-1}$ sequentially irradiated the polyvials, two at a time, for five seconds. After a 25 minute decay samples were counted for 720 seconds using a high-resolution, high-purity germanium (HPGe) detector to collect spectra containing peaks for the short-lived isotopes of Al, Ba, Ca, Dy, K, Mn, Na, Ti and V (Table 1). The long irradiation samples in the quartz vials were bombarded by a neutron flux of 5 X 10^{13} $n{\cdot}cm^{-2}{\cdot}s^{-1}$ for 24 hours. After a delay of 7 to 8 days the samples were counted for 2,000 seconds with the HPGe detector coupled with an automatic sample changer. This second count measures the concentration for As, La, Lu, Nd, Sm, U and Yb (Table 2). The long half-life isotopes of Ce, Co, Cr, Cs, Eu, Fe, Hf, Ni, Rb, Sb, Sc, Sr, Ta, Tb, Th, Zn and Zr were counted for 10,000 seconds after a further decay of three to four weeks (Table 2). Elemental concentrations were determined electronically by comparing the gamma-ray peaks of each sample to well-known concentrations of the included standard reference material. Table 3 lists the raw data.

Quantitative Analysis

Table 4 provides descriptive statistics on the total number of samples with detectable concentrations (n), mean values, standard deviations and the range of values for each of the elements. A simple review of the data does not show any apparent structure that can effectively delineate the five quarries. Exploratory statistical techniques were employed to assess if there is any significant multidimensional structure in the data that distinguishes between the five Pentelic quarries.

Due to large amounts of missing data, elements As, Nd, U, Cs, Hf, Ni, Rb, Sb, Ta, Zr, Al, Ba, Dy, K, Ti and V were omitted from further consideration. The extremely high concentrations for sample Π92-2 are outliers and suggest that the sample is contaminated. The contamination may be from laboratory preparation or, perhaps from an alluminosilicate mineral such as muscovite or chlorite which are common impurities in Pentelic marble. Sample Π92-2 therefore was eliminated from further exploratory analysis. When analyzing chemical compositional data expressed in a range from parts per million to parts per hundred the difference in magnitudes may negatively influence multivariate statistical functions (Baxter 1994). Therefore, the data were transformed to log base-10. Transforming the data to log base-10 also has the advantage of expressing the data normally.

The statistical package SPSS version 10 was used to perform multivariate analysis. As a first step, discriminant analysis (DA) was performed to determine if any geochemical structure exists within the data. DA presumes that a set of variables, in this case the elemental data, can best distinguish between a set of known groups (the quarries). DA also can be used to improve distinctions between the quarry groups by statistically removing variables that have little or negative discriminating information. Because quadratic discrimination performs poorly for small sample sizes (<25) the limited sample sizes for each of the quarry groups (from 5 to 15 cases) specified that linear discrimination be undertaken (Baxter 1994). For DA to be successful and theoretically sound several assumptions must be met. First, DA assumes that the variable groups have multivariate normality and equal covariance matrices. Normal plots for each of the remaining variables suggest normality for all variables except Na and Sm. These two variables have some skewness towards their tails. However, Seber (1984) suggests that this departure from normality may have little effect on the linear discriminant function if the skewness is mild or if the distributions have long tails. The Box's M test was also undertaken to provide a statistic that looks at the difference in the covariance of each group, although this test is better suited for larger samples sizes (Baxter 1994).

Several permutations of DA were run with a cross-validation test to assess the suitability of the analysis. The significance level of the Box M scores ranges from 0.000 to 0.005, indicating that the null hypothesis of equal covariance matrices was false. Furthermore, in all permutations of the analyses, the cross-validation test that removes each case from the analysis and then plugs it into the linear equation as an unknown successfully classified only 5-15% of the cases (Table 5). Plotting the original data back into the linear equation successfully classified only 40-60% of the cases. This low success rate clearly indicates that no chemical structure exists that can be determined through DA analysis. Of interest, however, are the tolerance calculations for inclusion into the step-wise analysis. Tolerance is a measure of the proportion of a variable's variance not accounted for by other independent variables in the analysis. In order of inclusion, Na, Ca, Zn, Mn, Sc, Tb and La were the only elements with suitably large tolerances.

Cluster analysis was also performed on the data set. The procedure attempts to identify relatively homogenous groups of cases based on selected characteristics, using an algorithm that starts with each case in a separate cluster and combines clusters until only one is left. (SPSS Base 10.0 User's Guide 1999, p. 339). Cluster analysis differs from DA in that no known grouping of cases are assumed at the outset. The few missing values were replaced with predicted values from a regression of existing values from the series on an index variable scale from 1 to n. As the dendrogram in figure 3 indicates the samples are scattered with no consistent pattern observed. This apparent random distribution of samples may indicate that many elements with large uncertainties were included in the distance matrix. Despite these uncertainties, the cluster analysis is evidence that the inter- and intra-source geochemical differences between the individual Pentelic quarries are comparable. Other attempts at cluster analysis were made with other clustering methods as well as with using fewer variables, such as using only those with high tolerance in the discriminant analysis, with no significant improvement in the grouping of the cases.

As a final exploratory tool, principal component analysis (PCA) was performed on the data set. In PCA, linear operations transform the data set to maximize variance such that a new basis for describing the data matrix is established. PCA identifies correlated variables and chemical groupings within the data set. It also can establish which variables provide the greatest separation between groups. Approximately 90% of the variance is typically explained by the first four or five principal components (Shennan 1997). Additionally, the technique allows complex multivariate data sets to be graphically represented by plotting the top ranking principle components against one another in two- or three-dimensional space.

Figures 4 and 5 are bivariate plots of the first principal component against the second and third, respectively. Table 6 indicates that the first two components explain nearly 60% of the variance, 47.6% for the first component and 12.0% for the second. The third component only explains 7.9%. The ability of PCA to observe useful chemical structure within the Pendeli quarries can be assessed by viewing the distribution of the 61 Pentelic samples in PCA space. Figure 6 is a bivariate plot of the first and second principle components showing the distribution of each of the samples in PC space. It is clear that PCA does not reveal any significant chemical structure. PCA was also performed on the standardized log transformed data with nearly identical results.

Discussion and Conclusion

Discriminant analysis, cluster analysis and principle component analysis of compositional data from five discrete marble quarries within the ancient Pentelic quarry region do not reveal any significant chemical structure that can be used to distinguish between intra-quarry regions. That this conclusion reflects those of compositional studies where chemical signatures were sought to segregate whole quarry regions (e.g. Glascock 1996, Mandi et al. 1995, Grimanis and Vassilaki-Grimani 1988) suggests that there may be a fundamental flaw in the theoretical basis of the technique. The flaw is not in the analytical procedure for NAA. Compositional data has successfully distinguished between different obsidian sources and flows (e.g. Williams-Thorpe et al. 1984) as well as ceramics, (e.g. Pollard 1986, Vitali and Franklin 1986a,b) glass (e.g. Baxter 1991, Glascock et al. 1988) and other materials. Therefore, there must be a crucial distinction between utilizing NAA data to characterize marble from other archaeological materials.

The inherent difficulty with using compositional data from NAA is that marble is not mineralogically or geochemically homogenous. As Veizer (1990) writes

> The chemical and isotopic composition of carbonate sediments and rocks is, however, not simply the sum

> of chemistries of the constituent carbonate minerals. Noncarbonate constituents, such as aluminosilicates – which account for up to 50% of the sample – usually harbor considerably higher trace element concentrations than do carbonate minerals…Consequently…the bulk of rock chemistries of sedimentary carbonates are controlled primarily by the quantity and the characteristics of the noncarbonate constituents. This essentially random feature, which is largely determined by provenance, can be quantified only with difficulty.

Because low- and medium-grade marbles retain their sedimentary signatures the non-carbonate constituents contribute significantly to compositional studies. These non-carbonate accessory minerals are neither homogeneous in concentration or composition.

Marble provenance studies have to some degree recognized this inherent quality and have analyzed small aliquots collected from larger "homogenized" whole-rock samples. Despite these attempts to include and evenly distribute chemical concentrations, the presence of any amount of non-carbonate accessory minerals in the analyzed aliquot may have a significant impact on the analysis. Furthermore, if large samples must be collected and homogenized in order to ascertain a representative signature composition, it would be most unlikely that an archaeologist or museum curator would permit the collection of an adequately large sample from an archaeological marble artifact. This latter point is important because no matter what technique scientists use to characterize archaeological marble, it must involve a minimal amount of archaeological material.

Future studies employing chemical analyses would benefit from using a technique that would only analyze the elements associated with the carbonate phases of the sample. To this end, inductively coupled plasma spectroscopy (ICP) has the potential to become a useful tool in marble characterization studies. This technique has the advantage of allowing analysis of only the carbonate fraction of the carbonate sample. Prior to analysis, the marble sample is placed in an acid bath. The carbonate is attacked by the acid and released as CO_2 gas leaving trace elements in solution. Analysis of the solution through injection into the ICP furnace provides compositional data of only the elemental impurities in the carbonate fraction. The technique also has the advantage of being much less expensive than NAA and thus, more accessible. ICP is a developing technique in marble provenance studies with only a few studies published (Jongste et al. 1995, Moens et al. 1994). However, until a sample preparation and analysis protocol is established for ICP, elemental data should be treated with some reservation.

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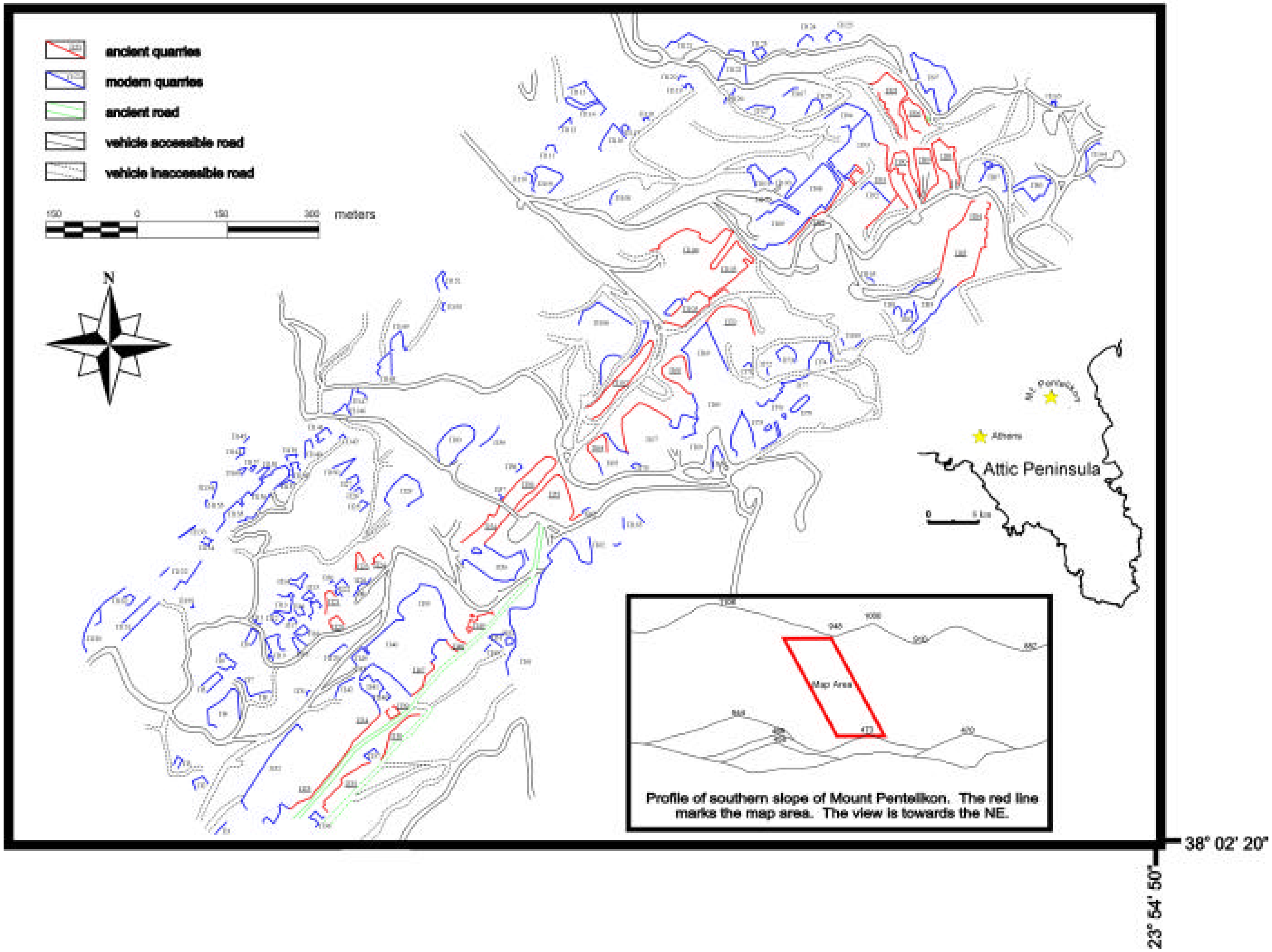

Figure 1. Quarry location map plotting the location of every exposed quarry in the ancient quarry region on the south slope of Mount Pentelikon, Attica, Greece. Ancient quarries can be distinguished by red outlines and underlined quarry labels.

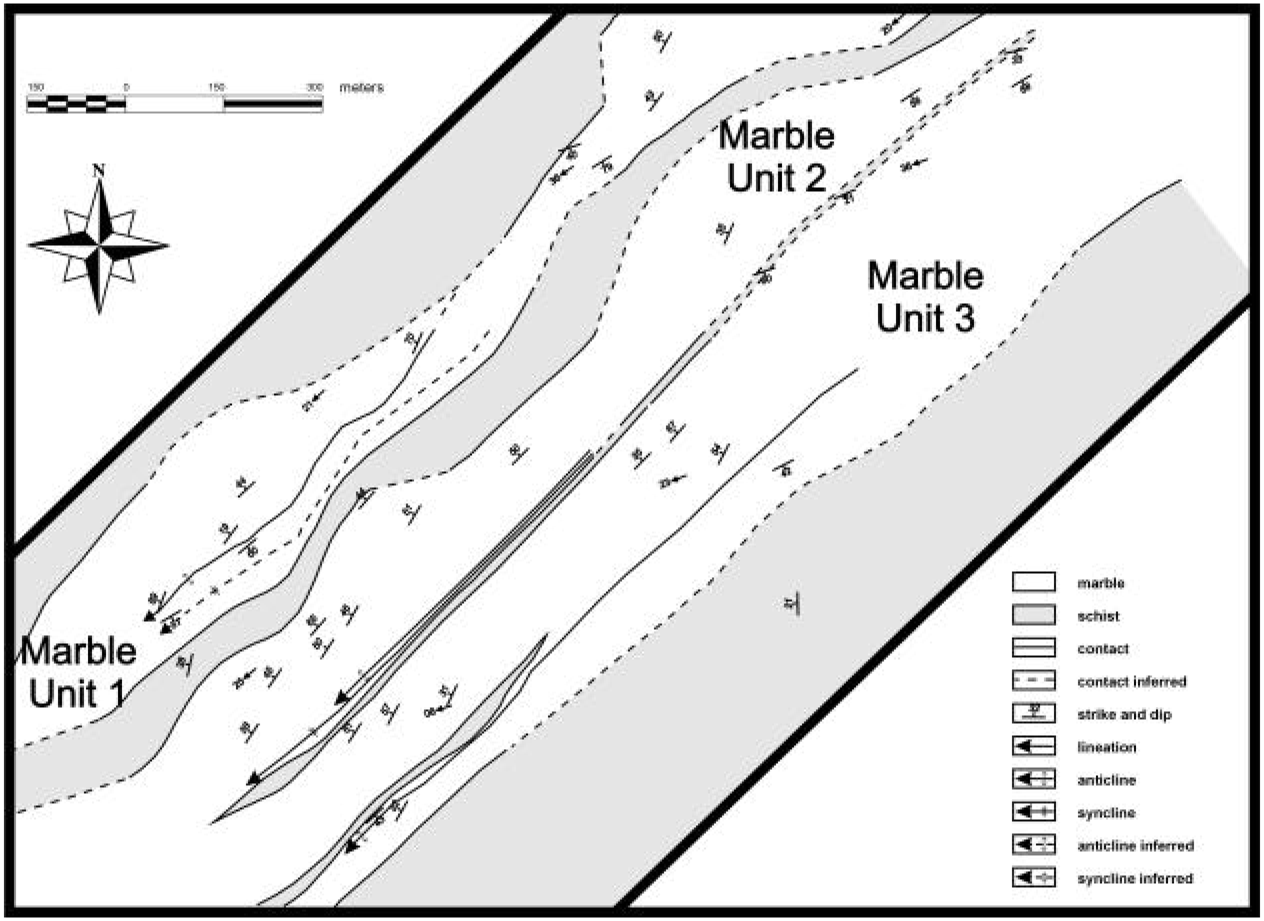

Figure 2. Geologic map of the ancient quarry region on the south slope of Mount Pentelikon, Attica, Greece. Note the three marble units. The ancient quarries are located in Marble Units 2 and 3.

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* * * * * * H I E R A R C H I C A L   C L U S T E R   A N A L Y S I S * * * * * *

 Dendrogram using Average Linkage (Between Groups)

                        Rescaled Distance Cluster Combine

    C A S E      0         5        10        15        20        25
  Label     Num  +---------+---------+---------+---------+---------+

  107-4      41   ⇩⬂
  107-9      46   ⇩▫
  136-1      47   ⇩⇧⇩⬂
  90-2       20   ⇩▫ ⇔
  136-15     52   ⇩⬃  ⇔
  107-12     36   ⇩×⇩⬂
  107-6      43   ⇩⬃ ▭⇩⬂
  90-19      19   ⇩⬂ ⇔ ⇔
  107-14     38   ⇩▫ ⇔ ⇔
  90-8       25   ⇩▫ ⇔ ⇔
  107-13     37   ⇩▫ ⇔ ⇔
  136-9-1    60   ⇩▫ ⇔ ⇔
  90-14      15   ⇩▫ ⇔ ⇔
  90-4       22   ⇩▫ ⇔ ⇔
  90-17      18   ⇩▫ ⇔ ⇔
  91-7       30   ⇩▫ ⇔ ⇔
  90-12      14   ⇩⇧⇩⬃ ⇔
  90-9       26   ⇩▫   ⇔
  90-16      17   ⇩▫   ⇔
  90-15      16   ⇩⬃   ⇔
  91-2       28   ⇩×⇩⬂ ⇔
  91-25-1    29   ⇩⬃ ▭⇩⬃
  92-3       32   ⇩⇩⇩⬃ ⇔
  107-11     35   ⇩⇩⇩⇩⇩✓⇩⬂
  136-5      57   ⇩⇩⇩⇩⇩⬃ ▭⇩⇩⇩⬂
  139-16     61   ⇩⇩⇩⇩⇩⬃ ⇔   ⇔
  85-1        1   ⇩×⇩⇩⇩⇩⇩⬃   ⇔
  85-2        3   ⇩⬃         ⇔
  91-10      27   ⇩⬂         ⇔
  136-18     53   ⇩⇧⇩⬂        ⇔
  136-11     49   ⇩▫ ⇔        ⇔
  136-13     50   ⇩⬃ ▭⇩⬂      ⇔
  136-8      59   ⇩⇩⇩⬃ ⇔      ⇔
  107-10     34   ⇩⇩⇩⬃ ⇔      ⇔
  85-5        6   ⇩⬂   ⇔      ⇔
  90-1       12   ⇩⇧⇩⬂ ⇔      ▭⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⬂
  85-7-1      8   ⇩▫ ⇔ ⇔      ⇔                  ⇔
  85-7-2      9   ⇩▫ ⇔ ⇔      ⇔                  ⇔
  107-1      33   ⇩▫ ⇔ ⇔      ⇔                  ⇔
  107-7      44   ⇩▫ ⇔ ⇔      ⇔                  ⇔
  136-2      54   ⇩⬃ ⇔ ⇔       ⇔                  ⇔
  90-10      13   ⇩⬂ ⇔ ⇔       ⇔                  ⇔
_

    C A S E      0         5        10        15        20        25

  Label     Num  +---------+---------+---------+---------+---------+

  107-3      40   ⇩▫ ⇔ ⇔      ⇔                  ⇔
  136-14     51   ⇩▫ ⇔ ⇔      ⇔                  ⇔
  107-5      42   ⇩▫ ▭⇩⬃     ⇔                  ⇔
  136-10     48   ⇩▫ ⇔ ⇔      ⇔                  ⇔
  136-3      55   ⇩▫ ⇔ ⇔      ⇔                  ▭⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⬂
  85-10       2   ⇩▫ ⇔ ▭⇩⇩⇩⇩⇩⬃                  ⇔                ⇔
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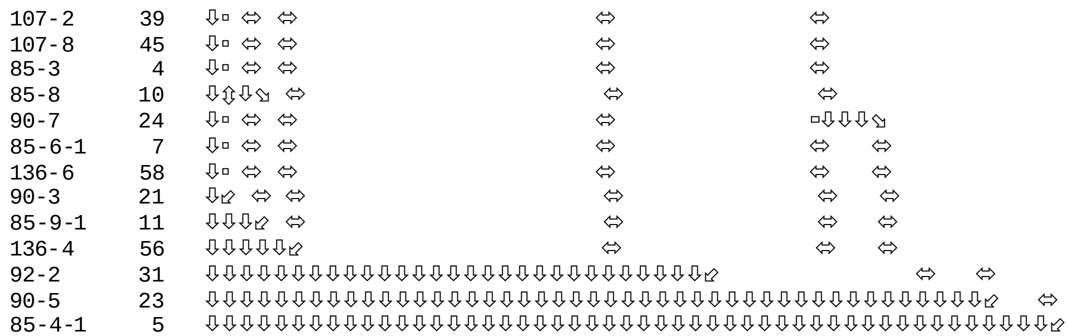

Figure 3. Dendrogram of log transformed data set using averaged linkage clustering – squared Euclidean distance method of cluster analysis. The data are scattered throughout the clusters with no apparent chemical structure.

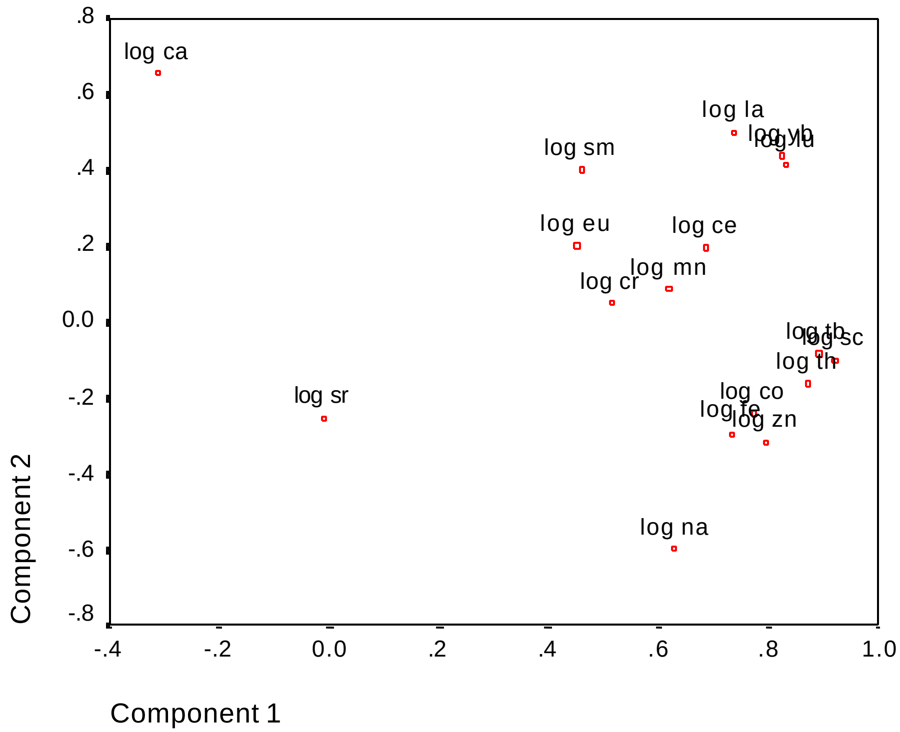

Figure 4. Bivariate plot of the first and second principle component of the correlation matrix using log transformed data. The plot represents roughly 60% of the variance in PC space. The plot is nearly identical when the log transformed data is standardized. Distance from the origin to each of the chemical symbols illustrates the degree to which that element contributes to explaining the multivariate space. Elements closely spaced have strong correlations. Elements opposite from one another are negatively correlated.

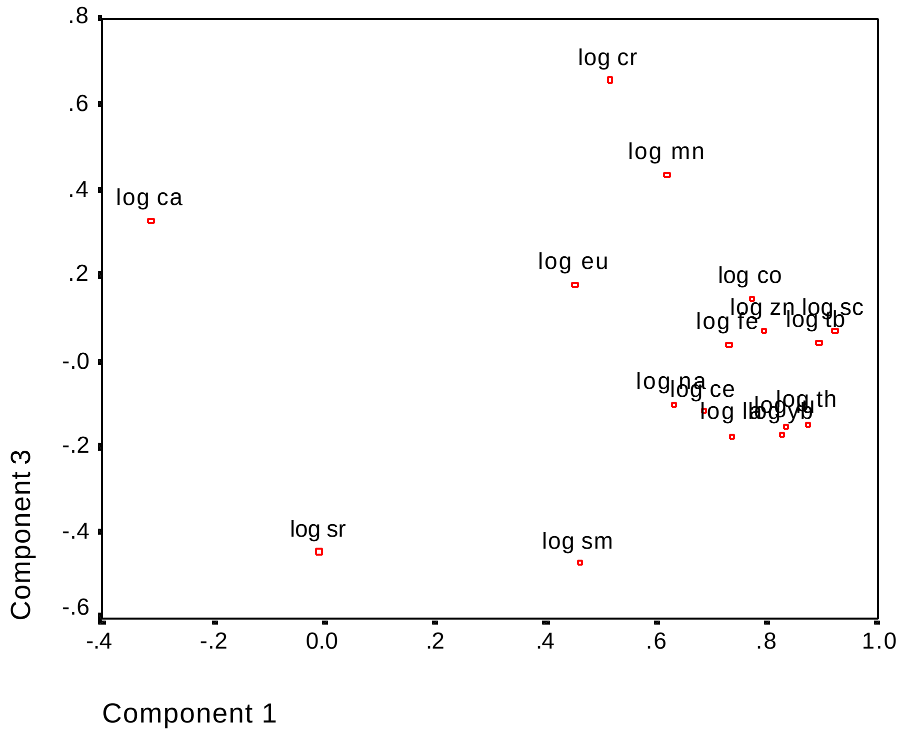

Figure 5. Bivariate plot of the first and second principle component of the correlation matrix using log transformed data. The plot is nearly identical when the log transformed data is standardized. Almost 7% of the variance in PC space is represented in this plot.

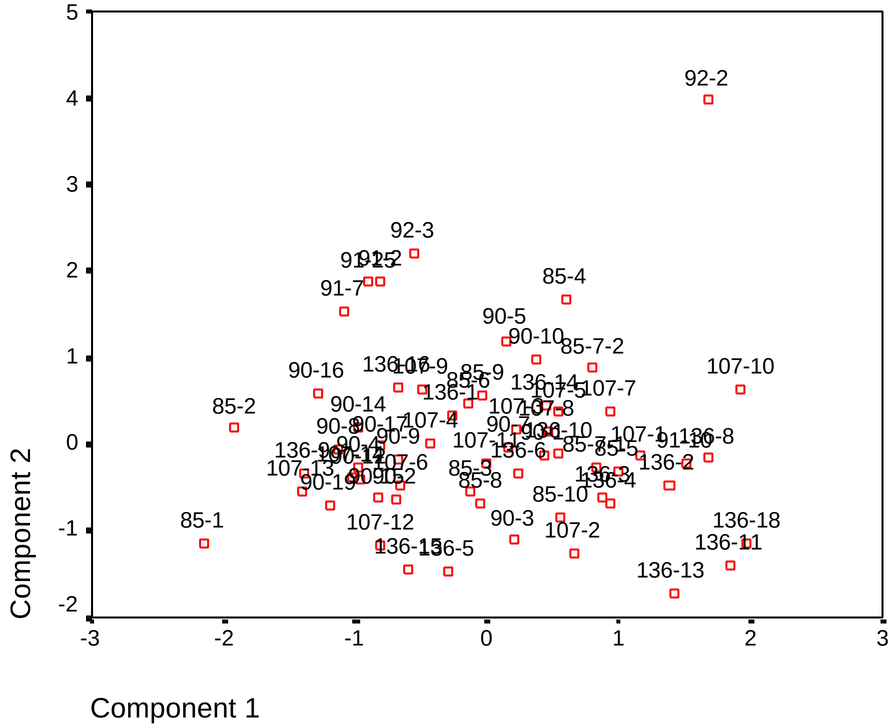

Figure 6. Scatter-plot diagram of each sample plotted in principal component 1 – principal component 2 space. Note that sample Π92-2 was not used in calculating the principal components. The distribution of the data plots indicates that PCA fails to identify any significant chemical structure within the data set. Three samples from quarry Π136 group away from the central cluster of samples toward the right side of the plot, however other samples from the quarry are distributed throughout the plotted data.

Table 1. Isotopes, halflives, gamma rays, and concentrations for short-lived isotopes (after Glascock 1996).

Element	Isotope	Halflife	Gamma ray (keV)	Concentration and Ref. Material
Al	^{28}Al	2.24 m	1779.0	14.1%; SRM-163a
Ba	^{139}Ba	84.63 m	165.8	1320 ppm; SRM-1633a
Ca	^{49}Ca	8.72	3084.5	8.79%; SRM-688
Dy	^{165}Dy	2.33 h	94.7	14.6 ppm; SRM-1633a
K	^{42}K	12.36 h	1524.7	1.89%; SRM-1633a
Mn	^{56}Mn	2.58 h	846.8	190 ppm; SRM-1633a
Na	^{24}Na	14.96 h	1368.6	1650 ppm; SRM-1633a
Ti	^{51}Ti	5.76 m	320.1	8230 ppm; SRM-1633a
V	V-52	3.75 m	1434.1	300 ppm; SRM-1633a

Table 2. Isotopes, halflives, gamma rays, and concentrations for medium- and long-lived isotopes (after Glascock 1996).

Element	Isotope	Halflife	Gamma ray (keV)	Concentration and Ref. Material
As	^{76}As	26.32 h	5559.1	145 ppm; SRM-1633a
La	^{140}La	40.27 h	1596.2	79.1 ppm; SRM-1633a
Lu	^{177}Lu	6.71 d	208.4	1.075 ppm; SRM-1633a
Nd	^{147}Nd	10.98 d	91.1	75.7 ppm; SRM-1633a
Sm	^{153}Sm	46.27 h	103.2	16.83 ppm; SRM-1633a
U	^{239}Np	2.36 d	228.2	10.3 ppm; SRM-1633a
Yb	^{175}Yb	4.19 d	396.3	7.50 ppm; SRM-1633a
Ce	^{141}Ce	32.5 d	145.4	168.3 ppm; SRM-1633a
Co	^{60}Co	5.27 y	1332.5	44.1 ppm; SRM-1633a
Cr	^{51}Cr	27.7 d	320.1	193 ppm; SRM-1633a
Cs	^{134}Cs	2.06 y	795.8	10.42 ppm; SRM-1633a
Eu	^{152}Eu	13.33 y	1408.0	3.58 ppm; SRM-1633a
Fe	^{59}Fe	44.5 d	1099.2	9.38 %; SRM-1633a
Hf	^{181}Hf	42.4 d	482.2	7.29 ppm; SRM-1633a
Ni	^{58}Co	70.8 d	810.8	130 ppm; SRM-1633a
Rb	^{86}Rb	18.7 d	1076.6	134 ppm; SRM-1633a
Sb	^{124}Sb	60.2 d	1691.0	6.15 ppm; SRM-1633a
Sc	^{46}Sc	83.8 d	889.3	38.6 ppm; SRM-1633a
Sr	^{85}Sr	64.8 d	514.0	835 ppm; SRM-1633a
Ta	^{182}Ta	114.5 d	1221.4	1.93 ppm; SRM-1633a
Tb	^{160}Tb	72.3 d	879,4	2.53 ppm; SRM-1633a
Th	^{233}Pa	27.0	312.0	24.0 ppm; SRM-1633a
Zn	^{65}Zn	243.9 d	1115.5	220 ppm; SRM-1633a
Zr	^{95}Zr	64.0 d	756.8	240 ppm; SRM-1633a

Table 3. Raw NAA data of 61 samples from 5 geographically distinct quarry units on the south slope of Mt. Pentelikon.

Quarry	Sample ID	As	La	Lu	Nd	Sm	U	Yb	Ce	Co
85	85-1	0.25	0.36	0.003	0.00	0.052	0.061	0.020	0.375	0.061
85	85-2	0.00	0.63	0.005	0.00	0.071	0.000	0.037	0.812	0.037
85	85-3	0.32	1.05	0.017	0.70	0.167	0.032	0.129	1.432	0.115
85	85-4-1	0.00	2.09	0.024	2.71	0.442	0.000	0.203	1.890	0.114
85	85-5	0.18	1.92	0.039	1.45	0.344	0.046	0.299	2.997	0.162
85	85-6	0.00	1.30	0.019	2.16	0.228	0.126	0.134	1.090	0.211
85	85-7	0.79	2.15	0.036	1.75	0.411	0.061	0.253	1.276	0.151
85	85-7-2	2.75	2.30	0.048	2.40	0.519	0.000	0.339	1.164	0.275
85	85-8	0.00	1.05	0.015	1.08	0.186	0.000	0.119	1.136	0.123
85	85-9	0.00	1.41	0.020	1.58	0.267	0.111	0.150	1.356	0.207
85	85-10	0.21	1.54	0.024	1.05	0.347	0.092	0.167	1.352	0.174
90	90-1	0.00	1.79	0.027	1.46	0.296	0.045	0.210	2.780	0.115
90	90-2	0.40	0.93	0.012	0.79	0.133	0.080	0.088	1.677	0.070
90	90-3	0.22	1.30	0.016	1.22	0.274	0.041	0.121	1.955	0.096
90	90-4	0.00	0.99	0.010	0.65	0.167	0.000	0.089	1.056	0.035
90	90-5	0.20	1.19	0.022	0.68	0.193	0.000	0.159	1.997	0.085
90	90-7	0.37	1.82	0.020	0.95	0.194	0.000	0.144	1.706	0.102
90	90-8	0.24	0.78	0.011	0.72	0.128	0.000	0.085	0.857	0.052
90	90-9	0.00	0.89	0.010	0.65	0.140	0.041	0.084	1.275	0.078
90	90-10	0.22	1.98	0.031	1.67	0.321	0.000	0.229	2.519	0.073
90	90-12	0.14	1.13	0.008	1.00	0.164	0.038	0.064	1.596	0.081
90	90-14	0.00	0.94	0.012	0.72	0.155	0.035	0.090	1.278	0.058
90	90-15	0.00	0.93	0.007	0.57	0.142	0.037	0.055	1.128	0.179
90	90-16	0.18	0.77	0.013	0.49	0.135	0.040	0.090	0.874	0.042
90	90-17	0.17	1.15	0.011	0.81	0.169	0.000	0.080	1.529	0.058
90	90-19	0.00	0.66	0.008	0.67	0.097	0.000	0.057	0.787	0.068
91	91-10	3.05	1.58	0.035	1.99	0.459	0.000	0.244	2.292	0.266
91	91-2	0.00	1.32	0.013	2.26	0.308	0.000	0.112	2.659	0.046

Quarry	Sample ID	As	La	Lu	Nd	Sm	U	Yb	Ce	Co
91	91-25	0.00	1.90	0.009	1.50	0.233	0.000	0.090	2.957	0.153
91	91-7	0.00	1.14	0.011	0.00	0.212	0.000	0.097	1.385	0.042
92	92-2	495.85	44.97	0.512	50.64	10.276	4.931	3.717	1.734	0.154
92	92-3	0.00	2.13	0.038	2.13	0.480	0.000	0.307	1.643	0.063
107	107-1	0.00	2.76	0.032	2.08	0.455	0.000	0.244	2.825	0.178
107	107-10	0.00	3.49	0.062	3.18	0.810	0.099	0.460	3.852	0.177
107	107-11	0.00	3.75	0.013	2.25	0.137	0.060	0.088	6.772	0.139
107	107-12	1.44	0.52	0.011	0.64	0.145	0.087	0.081	0.413	0.127
107	107-13	0.52	0.52	0.008	0.47	0.075	0.000	0.058	0.473	0.074
107	107-14	0.00	0.83	0.009	0.52	0.115	0.058	0.080	0.791	0.060
107	107-2	0.00	1.32	0.024	0.93	0.260	0.122	0.179	1.240	0.175
107	107-3	0.00	1.71	0.019	1.46	0.378	0.056	0.145	2.315	0.060
107	107-4	0.00	1.24	0.016	0.83	0.181	0.036	0.111	1.425	0.035
107	107-5	0.21	2.08	0.027	1.45	0.373	0.064	0.204	2.061	0.125
107	107-6	0.14	0.75	0.013	0.56	0.117	0.063	0.092	0.524	0.137
107	107-7	0.00	1.97	0.032	1.71	0.394	0.000	0.254	2.050	0.118
107	107-8	0.00	1.60	0.028	1.88	0.362	0.094	0.203	1.586	0.093
107	107-9	0.00	1.29	0.016	1.23	0.194	0.061	0.122	1.437	0.041
136	136-1	0.00	1.37	0.025	1.20	0.220	0.000	0.184	1.142	0.075
136	136-10	0.16	1.83	0.025	1.22	0.295	0.073	0.168	1.750	0.163
136	136-11	0.12	3.44	0.035	3.28	0.633	0.092	0.251	3.204	0.390
136	136-13	0.30	1.77	0.026	1.50	0.370	0.070	0.185	1.988	0.319
136	136-14	0.00	1.91	0.029	1.65	0.426	0.000	0.222	1.772	0.102
136	136-15	0.00	1.09	0.011	0.70	0.172	0.000	0.100	1.184	0.062
136	136-16	0.00	2.49	0.021	0.00	0.317	0.280	0.143	0.802	0.085
136	136-18	0.23	2.35	0.036	2.46	0.583	0.078	0.286	2.574	0.575
136	136-2	0.00	3.04	0.040	2.49	0.540	0.000	0.301	3.039	0.204
136	136-3	0.00	1.85	0.030	1.49	0.289	0.079	0.220	2.104	0.174
136	136-4	0.00	1.49	0.019	0.00	0.222	0.000	0.124	1.863	0.231

Quarry	Sample ID	As	La	Lu	Nd	Sm	U	Yb	Ce	Co
136	136-5	2.69	0.84	0.015	0.00	0.132	0.000	0.130	1.119	0.144
136	136-6	0.00	1.45	0.023	0.98	0.216	0.064	0.176	1.301	0.153
136	136-8	0.00	3.55	0.040	2.86	0.709	0.000	0.318	4.969	0.249
136	136-9	0.00	0.68	0.009	0.41	0.074	0.000	0.070	0.787	0.067

Quarry	Sample ID	Cr	Cs	Eu	Fe	Hf	Ni	Rb	Sb	Sc
85	85-1	0.571	0.005	0.012	198.2	0.003	0.0	0.00	0.016	0.017
85	85-2	0.668	0.000	0.018	205.2	0.000	0.0	0.00	0.000	0.018
85	85-3	0.525	0.028	0.037	323.3	0.051	0.0	1.10	0.030	0.147
85	85-4-1	0.666	0.017	546.400	0.0	0.027	0.0	0.00	0.000	0.173
85	85-5	0.557	0.084	0.057	486.7	0.137	0.0	3.53	0.027	0.352
85	85-6	0.461	0.018	0.046	493.4	0.018	0.0	0.00	0.000	0.097
85	85-7	0.623	0.000	0.087	271.3	0.022	0.0	0.00	0.078	0.258
85	85-7-2	0.734	0.049	0.102	294.2	0.053	0.0	1.15	0.016	0.331
85	85-8	0.800	0.018	0.040	354.1	0.034	0.0	0.85	0.014	0.154
85	85-9	0.509	0.000	0.055	438.6	0.022	0.0	0.00	0.000	0.130
85	85-10	0.830	0.028	0.059	502.1	0.045	0.0	1.31	0.019	0.216
90	90-1	0.465	0.040	0.048	377.0	0.060	0.0	2.24	0.016	0.229
90	90-2	0.308	0.023	0.026	197.5	0.033	0.0	0.58	0.045	0.077
90	90-3	0.221	0.023	0.055	889.8	0.011	0.0	0.00	0.011	0.140
90	90-4	0.473	0.000	0.038	262.7	0.006	0.0	0.00	0.009	0.044
90	90-5	0.229	0.028	0.039	272.0	0.029	0.0	0.80	0.039	0.136
90	90-7	0.744	0.022	0.048	390.3	0.029	0.0	0.77	0.032	0.150
90	90-8	0.349	0.098	0.028	201.1	0.016	0.0	0.00	0.093	0.051
90	90-9	0.337	0.007	0.031	532.5	0.007	0.0	0.00	0.000	0.065
90	90-10	0.655	0.028	0.065	307.2	0.026	0.0	0.84	0.021	0.170
90	90-12	0.376	0.008	0.037	233.9	0.009	0.0	0.00	0.008	0.033
90	90-14	0.557	0.005	0.036	281.5	0.008	0.0	0.00	0.011	0.036
90	90-15	0.569	0.008	0.032	340.4	0.009	0.0	0.00	0.024	0.028
90	90-16	0.314	0.000	0.028	184.3	0.006	0.0	0.00	0.012	0.045
90	90-17	0.453	0.013	0.038	239.1	0.013	0.0	0.27	0.015	0.068
90	90-19	0.565	0.011	0.022	212.9	0.006	0.0	0.00	0.037	0.041
91	91-10	1.490	0.145	0.084	623.9	0.142	0.0	7.88	0.056	0.839
91	91-2	0.463	0.000	0.051	258.1	0.000	0.0	0.00	0.000	0.102

Quarry	Sample ID	Cr	Cs	Eu	Fe	Hf	Ni	Rb	Sb	Sc
91	91-25	0.488	0.000	0.044	175.6	0.000	0.0	0.00	0.045	0.043
91	91-7	0.517	0.000	0.042	261.2	0.013	0.0	0.00	0.000	0.051
92	92-2	0.745	0.025	0.055	…	0.033	0.0	0.98	0.031	0.114
92	92-3	0.453	0.000	0.032	…	0.010	0.0	0.00	0.000	0.026
107	107-1	0.818	0.072	0.102	559.4	0.078	0.0	1.73	0.019	0.297
107	107-10	1.374	0.088	0.150	450.7	0.178	0.0	4.25	0.010	0.741
107	107-11	0.231	0.011	0.032	322.4	0.008	0.0	0.00	0.017	0.079
107	107-12	0.366	0.009	0.021	315.6	0.010	0.0	0.00	0.013	0.069
107	107-13	0.463	0.007	0.019	185.9	0.008	0.0	0.00	0.035	0.039
107	107-14	0.577	0.008	0.026	178.1	0.009	0.0	0.00	0.000	0.062
107	107-2	0.534	0.030	0.049	437.4	0.039	0.0	1.03	0.029	0.201
107	107-3	0.610	0.017	0.074	270.5	0.021	0.0	1.01	0.013	0.158
107	107-4	0.525	0.012	0.045	176.9	0.162	0.0	0.36	0.012	0.093
107	107-5	0.597	0.018	0.076	356.4	0.033	0.0	1.30	0.123	0.209
107	107-6	0.528	0.013	0.027	274.6	0.012	0.0	0.00	0.033	0.072
107	107-7	0.915	0.046	0.085	324.7	0.085	0.0	2.20	0.017	0.360
107	107-8	0.774	0.021	0.071	223.9	0.063	0.0	1.50	0.009	0.253
107	107-9	0.448	0.012	0.051	161.6	0.026	0.0	0.46	0.026	0.103
136	136-1	0.297	0.033	0.049	217.1	0.025	0.0	0.70	0.020	0.163
136	136-10	0.629	0.049	0.055	526.7	0.035	0.0	1.17	0.012	0.179
136	136-11	0.998	0.089	0.118	898.4	0.119	0.0	2.14	0.013	0.433
136	136-13	0.636	0.041	0.067	1080.7	0.065	4.0	0.72	0.037	0.269
136	136-14	0.329	0.015	0.076	421.9	0.011	0.0	0.29	0.010	0.185
136	136-15	0.192	0.024	0.040	346.8	0.008	0.0	0.00	0.010	0.053
136	136-16	0.271	0.024	0.020	235.3	0.000	0.0	0.00	0.022	0.051
136	136-18	1.299	0.151	0.108	616.9	0.127	0.0	3.47	0.026	0.511
136	136-2	0.730	0.108	0.100	398.7	0.058	0.0	1.78	0.013	0.312
136	136-3	0.538	0.070	0.055	548.6	0.050	0.0	1.63	0.020	0.213
136	136-4	0.778	0.085	0.698	466.1	0.091	0.0	2.03	0.009	0.358

Quarry	Sample ID	Cr	Cs	Eu	Fe	Hf	Ni	Rb	Sb	Sc
136	136-5	0.300	0.036	0.045	307.6	0.000	0.0	0.00	0.000	0.121
136	136-6	0.326	0.015	0.049	461.2	0.016	0.0	0.00	0.005	0.134
136	136-8	0.321	0.093	0.144	1056.8	0.044	0.0	2.48	0.014	0.367
136	136-9	0.213	0.019	0.015	154.2	0.012	0.0	0.00	0.016	0.051

Quarry	Sample ID	Sr	Ta	Tb	Th	Zn	Zr	Al	Ba	Ca
85	85-1	189.4	0.000	0.009	0.008	1.58	0.00	1190.9	0.0	389239.0
85	85-2	169.5	0.000	0.010	0.010	2.00	0.00	0.0	0.0	401669.1
85	85-3	217.0	0.007	0.028	0.152	2.60	1.52	0.0	0.0	383713.0
85	85-4-1	270.2	0.000	0.049	0.120	5.03	0.00	0.0	0.0	402235.3
85	85-5	199.8	0.023	0.060	0.586	6.56	2.63	2643.7	0.0	380702.0
85	85-6	227.9	0.000	0.028	0.058	4.35	0.00	0.0	0.0	403024.4
85	85-7	233.2	0.003	0.078	0.385	9.77	2.35	0.0	0.0	376590.0
85	85-7-2	210.1	0.011	0.066	0.179	8.07	0.00	0.0	0.0	407393.7
85	85-8	228.8	0.005	0.036	0.090	4.33	2.32	499.3	0.0	385337.0
85	85-9	198.5	0.000	0.034	0.018	4.36	0.00	0.0	0.0	405353.4
85	85-10	224.0	0.008	0.050	0.087	6.12	0.00	1127.1	0.0	375436.0
90	90-1	254.9	0.015	0.052	0.268	3.69	0.00	2497.0	0.0	381137.0
90	90-2	231.7	0.003	0.023	0.098	3.56	0.90	0.0	0.0	375550.0
90	90-3	234.4	0.000	0.046	0.152	4.05	0.00	0.0	0.0	372950.0
90	90-4	249.8	0.000	0.030	0.023	1.55	0.00	0.0	0.0	372950.0
90	90-5	253.4	0.006	0.038	0.109	2.65	0.00	2544.8	0.0	384137.0
90	90-7	200.6	0.004	0.033	0.074	4.96	0.00	0.0	0.0	382592.0
90	90-8	192.1	0.000	0.025	0.024	2.74	0.00	0.0	0.0	394531.0
90	90-9	249.0	0.000	0.030	0.016	2.29	0.00	0.0	0.0	398128.0
90	90-10	200.6	0.000	0.055	0.088	3.63	0.00	0.0	0.0	398953.0
90	90-12	310.2	0.000	0.026	0.016	2.50	0.00	0.0	0.0	389798.0
90	90-14	199.5	0.000	0.030	0.012	1.79	1.74	0.0	0.0	384601.0
90	90-15	192.8	0.000	0.022	0.020	2.68	0.00	0.0	74.2	386672.0
90	90-16	213.6	0.000	0.024	0.007	2.48	1.41	0.0	0.0	399554.0
90	90-17	228.5	0.000	0.030	0.019	2.89	1.50	1139.7	0.0	388066.0
90	90-19	200.3	0.000	0.019	0.017	2.68	1.84	0.0	0.0	384753.0
91	91-10	184.8	0.025	0.126	0.227	7.54	0.00	4988.2	0.0	395646.8
91	91-2	162.7	0.000	0.028	0.010	1.22	0.00	0.0	0.0	417066.5

Quarry	Sample ID	Sr	Ta	Tb	Th	Zn	Zr	Al	Ba	Ca
91	91-25	213.3	0.000	0.022	0.007	1.59	0.00	0.0	0.0	420709.5
91	91-7	178.5	0.000	0.022	0.022	2.27	0.00	0.0	0.0	417992.9
92	92-2	161.2	0.012	0.029	0.121	3.73	0.00	0.0	0.0	393083.6
92	92-3	182.4	0.000	0.015	0.016	2.35	0.00	0.0	0.0	407823.4
107	107-1	206.5	0.014	0.082	0.284	4.63	3.03	3239.1	0.0	379756.0
107	107-10	172.1	0.041	0.151	0.647	10.06	7.53	3844.2	0.0	388882.0
107	107-11	227.1	0.000	0.027	0.028	3.49	0.00	0.0	0.0	375452.0
107	107-12	203.5	0.000	0.017	0.017	8.40	0.00	0.0	0.0	389072.0
107	107-13	153.8	0.000	0.015	0.011	2.37	0.00	0.0	0.0	389970.0
107	107-14	187.5	0.000	0.019	0.020	3.08	0.00	0.0	0.0	385198.0
107	107-2	252.4	0.014	0.046	0.171	6.40	0.00	0.0	0.0	383892.0
107	107-3	156.7	0.005	0.051	0.082	4.51	0.00	0.0	0.0	375866.0
107	107-4	160.5	0.003	0.038	0.042	3.36	0.00	0.0	0.0	377431.0
107	107-5	235.6	0.007	0.057	0.111	5.79	0.00	0.0	0.0	397939.0
107	107-6	182.1	0.000	0.024	0.021	3.69	1.02	1069.2	0.0	389790.0
107	107-7	180.5	0.017	0.078	0.287	6.16	3.22	1867.1	0.0	396164.0
107	107-8	190.6	0.011	0.064	0.177	5.23	0.00	1296.0	42.7	389184.0
107	107-9	174.1	0.000	0.036	0.048	3.35	0.00	2131.6	0.0	395792.0
136	136-1	216.1	0.000	0.049	0.074	4.28	1.50	1168.8	0.0	396254.0
136	136-10	202.4	0.009	0.053	0.133	4.56	0.00	0.0	0.0	393386.0
136	136-11	204.0	0.023	0.091	0.394	5.98	0.00	2995.1	0.0	367354.0
136	136-13	182.0	0.018	0.058	0.299	8.31	4.82	0.0	0.0	377757.0
136	136-14	218.2	0.000	0.067	0.064	4.83	0.00	3723.7	0.0	399038.0
136	136-15	196.9	0.000	0.033	0.047	4.01	2.45	2746.7	0.0	363862.0
136	136-16	165.3	0.000	0.016	0.200	3.84	0.00	0.0	0.0	396572.1
136	136-18	191.8	0.029	0.090	0.394	14.66	5.29	0.0	0.0	365292.0
136	136-2	190.6	0.013	0.086	0.215	12.21	4.82	2689.9	0.0	379051.0
136	136-3	244.2	0.010	0.051	0.159	8.02	2.24	1539.8	0.0	380952.0
136	136-4	174.3	0.018	0.046	0.337	13.36	0.00	0.0	0.0	393243.1

Quarry	Sample ID	Sr	Ta	Tb	Th	Zn	Zr	Al	Ba	Ca
136	136-5	1664.0	0.000	0.028	0.066	6.92	0.00	0.0	0.0	391556.6
136	136-6	221.8	0.004	0.038	0.083	4.11	0.00	0.0	0.0	386947.0
136	136-8	198.9	0.009	0.123	0.185	5.83	2.21	0.0	0.0	381866.0
136	136-9	168.8	0.000	0.019	0.038	2.20	0.00	1003.3	0.0	393805.0

Quarry	Dy	K	Mn	Na	Ti	V
85	0.000	0.0	84.9	122.3	0.0	0.00
85	0.000	0.0	47.9	83.2	0.0	0.00
85	0.000	0.0	82.9	182.8	0.0	0.00
85	0.322	0.0	101.8	77.3	…	…
85	0.293	0.0	65.4	188.0	0.0	0.00
85	0.223	0.0	148.5	69.5	0.0	0.00
85	0.000	0.0	102.7	143.3	0.0	0.00
85	0.558	0.0	84.6	123.7	0.0	0.00
85	0.000	0.0	70.2	163.4	152.6	0.00
85	0.214	0.0	152.6	101.8	0.0	0.00
85	0.000	0.0	89.8	193.6	0.0	0.00
90	0.000	0.0	60.8	147.3	0.0	0.00
90	0.000	0.0	55.0	124.9	0.0	0.00
90	0.000	0.0	86.7	166.5	0.0	0.00
90	0.000	0.0	86.8	112.9	0.0	0.00
90	0.121	0.0	66.3	147.6	0.0	0.00
90	0.000	0.0	124.8	119.2	0.0	0.00
90	0.000	0.0	48.7	132.2	0.0	0.00
90	0.000	0.0	158.0	124.1	0.0	0.00
90	0.000	0.0	198.9	132.7	0.0	0.00
90	0.000	0.0	55.7	155.1	0.0	0.00
90	0.000	0.0	68.1	95.0	0.0	0.00
90	0.000	0.0	92.0	122.9	0.0	0.00
90	0.000	0.0	102.4	90.2	0.0	0.00
90	0.243	0.0	57.6	116.8	217.9	0.00
90	0.000	0.0	62.5	143.4	0.0	0.00
91	0.415	2049.6	221.9	219.2	0.0	0.00
91	0.161	0.0	127.6	83.7	0.0	0.00

Quarry	Dy	K	Mn	Na	Ti	V
91	0.136	0.0	150.8	67.7	0.0	0.00
91	1.084	0.0	66.4	61.8	0.0	0.00
92	0.207	0.0	167.1	136.9	162.9	0.00
92	0.000	0.0	138.9	69.9	0.0	0.00
107	0.312	0.0	163.6	201.7	0.0	0.00
107	0.905	0.0	215.2	181.0	0.0	0.00
107	0.000	0.0	141.8	171.7	0.0	0.00
107	0.000	0.0	88.4	149.3	0.0	0.00
107	0.000	0.0	96.7	146.7	0.0	0.00
107	0.000	0.0	71.9	140.6	0.0	0.00
107	0.000	0.0	162.1	411.0	0.0	0.00
107	0.000	0.0	176.7	131.1	0.0	0.00
107	0.000	0.0	136.1	156.2	0.0	0.00
107	0.170	0.0	136.1	158.7	0.0	0.00
107	0.000	0.0	142.6	133.4	0.0	0.00
107	0.000	0.0	190.0	191.2	0.0	0.00
107	0.000	0.0	104.6	187.5	345.0	0.00
107	0.000	0.0	126.7	130.9	0.0	0.00
136	0.000	0.0	41.3	134.1	0.0	0.00
136	0.000	0.0	137.0	183.0	301.1	0.00
136	0.000	0.0	146.7	561.1	302.8	0.00
136	0.000	0.0	235.2	563.5	0.0	0.00
136	0.000	0.0	185.9	173.8	0.0	0.00
136	0.000	640.3	36.5	231.2	0.0	0.00
136	0.088	0.0	28.9	104.5	0.0	0.00
136	0.000	0.0	407.0	242.7	0.0	0.00
136	0.000	0.0	103.4	324.1	0.0	0.00
136	0.000	0.0	198.9	208.6	0.0	0.00

Quarry	Dy	K	Mn	Na	Ti	V
136	0.365	0.0	112.5	218.0	0.0	0.00
136	0.190	0.0	67.2	144.1	0.0	0.00
136	0.541	0.0	212.2	179.6	0.0	0.00
136	0.521	0.0	335.5	261.5	0.0	0.00
136	0.000	0.0	43.6	142.2	0.0	0.00

Table 4. Descriptive statistics of the raw data

	N	Range	Minimum	Maximum	Mean	Std. Deviation
AS	61	495.8473	.0000	495.8473	8.382839	63.456824
LA	61	44.6082	.3627	44.9709	2.279446	5.612066
LU	61	.5086	.0029	.5115	2.91E-02	6.38989E-02
ND	61	50.6360	.0000	50.6360	2.063405	6.375265
SM	61	1932.9479	.0521	1933.0000	32.126315	247.441665
U	61	4.9308	.0000	4.9308	.120510	.628083
YB	61	3.6967	.0203	3.7170	.217348	.463841
CE	61	6.3971	.3751	6.7722	1.769279	1.082058
CO	61	.5398	.0349	.5747	.132431	9.41552E-02
CR	61	1.2978	.1922	1.4900	.562774	.265163
CS	61	.1511	.0000	.1511	3.19E-02	3.54692E-02
EU	61	546.3879	.0121	546.4000	9.020608	69.951175
FE	59	1080.7167	.0000	1080.7167	369.2088	211.978777
HF	61	.1780	.0000	.1780	3.72E-02	4.22049E-02
NI	61	4.0191	.0000	4.0191	6.59E-02	.514593
RB	61	7.8814	.0000	7.8814	.861687	1.354087
SB	61	.1229	.0000	.1229	2.11E-02	2.21278E-02
SC	61	.8220	.0172	.8392	.172375	.162122
SR	61	1510.1565	153.8435	1664.0000	229.2643	189.301597
TA	61	.0407	.0000	.0407	5.97E-03	8.77116E-03
TB	61	.1420	.0091	.1511	4.46E-02	2.90203E-02
TH	61	.6401	.0065	.6466	.125707	.140433
ZN	61	13.4412	1.2200	14.6612	4.774211	2.879262
ZR	61	7.5283	.0000	7.5283	.890489	1.597138
AL	61	4988.2	.0	4988.2	753.200	1242.951
BA	61	74.2	.0	74.2	1.916	10.882
CA	61	56847.5	363862.0	420709.5	389159.2	12182.924
DY	61	1.0840	.0000	1.0840	.115880	.222569
K	61	2049.6	.0	2049.6	44.097	273.625
MN	61	378.08	28.94	407.02	122.4987	70.0224
NA	61	501.69	61.80	563.49	166.9077	94.6940
TI	60	345.0	.0	345.0	24.705	78.336
V	60	.0	.0	.0	.000	.000

Table 5. Measuring the degree of success of Discriminant Analysis at classifying samples to their correct sources. Taking the original data and plugging it into the linear model produces a 60% correct identification. Cross-validation suggests that only 15% of samples are correctly identified

			Predicted Group Membership					
		QUARRY	85	90	91	107	136	Total
Original	Count	85	8	1	1	1	0	11
		90	3	11	1	0	0	15
		91	0	0	4	1	0	5
		107	2	2	0	7	3	14
		136	2	2	0	5	6	15
		Ungrouped cases	0	0	1	0	0	1
	%	85	72.7	9.1	9.1	9.1	.0	100.0
		90	20.0	73.3	6.7	.0	.0	100.0
		91	.0	.0	80.0	20.0	.0	100.0
		107	14.3	14.3	.0	50.0	21.4	100.0
		136	13.3	13.3	.0	33.3	40.0	100.0
		Ungrouped cases	.0	.0	100.0	.0	.0	100.0
Cross-validated[a]	Count	85	0	7	0	0	4	11
		90	0	4	0	0	11	15
		91	0	0	1	0	4	5
		107	0	7	0	0	7	14
		136	0	11	0	0	4	15
	%	85	.0	63.6	.0	.0	36.4	100.0
		90	.0	26.7	.0	.0	73.3	100.0
		91	.0	.0	20.0	.0	80.0	100.0
		107	.0	50.0	.0	.0	50.0	100.0
		136	.0	73.3	.0	.0	26.7	100.0

a. Cross validation is done only for those cases in the analysis. In cross validation, each case is classified by the functions derived from all cases other than that case.

b. 60.0% of original grouped cases correctly classified.

c. 15.0% of cross-validated grouped cases correctly classified.

Table 6. Chart showing the total variance explained by each of the principal components and the cumulative percentage up to the fourth iteration. Note that the cumulative variance of 74.208% after the fourth iteration is a low value suggesting disorder in the data matrix.

	Initial Eigenvalues			Extraction Sums of Squared Loadings		
Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	8.097	47.627	47.627	8.097	47.627	47.627
2	2.004	11.790	59.417	2.004	11.790	59.417
3	1.344	7.904	67.321	1.344	7.904	67.321
4	1.171	6.887	74.208	1.171	6.887	74.208
5	.916	5.388	79.596			
6	.787	4.628	84.224			
7	.568	3.343	87.567			
8	.499	2.937	90.504			
9	.458	2.696	93.200			
10	.357	2.098	95.298			
11	.257	1.514	96.812			
12	.229	1.346	98.158			
13	.117	.690	98.848			
14	.114	.672	99.520			
15	4.630E-02	.272	99.792			
16	3.146E-02	.185	99.977			
17	3.876E-03	2.280E-02	100.000			

CHAPTER 4

A $\delta^{13}C$ AND $\delta^{18}O$ DATABASE FOR THE ANCIENT WHITE MARBLE QUARRIES ON MOUNT PENTELIKON, ATTICA, GREECE: A TOOL FOR INTRA-QUARRY CHARACTERIZATION[1]

[1] Pike, S. H. To be submitted to Geochimica et Cosmochimica Acta

Abstract

A systematic stable isotope characterization study of the archaeologically important ancient marble quarries on Mt. Pentelikon, Attica, Greece suggests that $\delta^{13}C$ and $\delta^{18}O$ ratios can be used to differentiate between several of the ancient quarry pits within the greater quarry area. The results challenge the fundamental assumptions utilized in previous Pentelic marble isotope characterization studies that assume a homogeneous isotopic signature throughout the entire quarry region. The study analyzed 379 samples representing 83 quarries including all identified ancient quarries. Results indicate that upslope quarries in Marble Unit 3 are distinguishable from all other Pentelic quarries. Marble Units 1 and 2 are distinguished from Marble Unit 3 by having a larger range of $\delta^{13}C$ values up to 5.1‰. The database can be applied to solve important problems in archaeology. For example, the database identifies a group of three quarries from which the marble exploited for the Parthenon's sculptural program was extracted.

Introduction

Variations in the range of $\delta^{13}C$ and $\delta^{18}O$ values in discrete marble formations in the eastern Mediterranean have been used with limited success to distinguish between many different ancient white marble quarries (e.g. Herz 1985a, b, 1988; Ven der Merwe et al. 1995 and others). The ability to quantitatively distinguish between the different quarries utilized in antiquity provides a tool for archaeologists, art historians and museum curators to assign provenance to ancient Greek and Roman marble artifacts. The correct assignment of provenance assists scholars in their investigations of dating an execution of a sculpture, tracing ancient avenues of commerce, giving insight into evolving aesthetic values, and in determining modern forgeries, ancient copies and dissociated fragments (Herz 1987).

The quarries on Mount Pentelikon, Attica, Greece have been a primary source of white marble since the beginning of the fifth century BC (Whycherely 1978). The quarries were first exploited on a large scale for the construction of various monuments on the Athenian acropolis, including the Parthenon. During the Roman era, the immensely popular Pentelic marble was widely exported throughout the Aegean for both architectural and sculptural uses (Abraldes 1996, Fant 1995). The Romans were so fond of the material that *Pausanius* (i.19) writes that Heroditus Atticus exhausted the quarries for his various building programs.

Recent research suggests that the reference sample collection used to develop the stable isotope signature field for the Pentelic quarries inadequately represents the entire quarry region. Matthews et al. (1992) show that marble samples of sculptural and architectural elements from the Parthenon and other monuments currently housed at the British Museum, which are historically documented as being Pentelic (see Dinsmoor 1975), have a higher oxygen isotope ratio than those in the established database. Samples collected by the authors near the top of the south slope of the Pentelic quarries have similar high oxygen values as the British Museum samples. Thus, the addition of the high $\delta^{18}O$ results further broadens the already wide $\delta^{13}C$ – $\delta^{18}O$ isotopic field for Pentelic marble as represented by the statistical ellipses in figure 1. Furthermore, the Matthews et al. study suggests that there may be some measurable stable isotope variation or trend within the Pentelic quarry field.

This idea is further supported by Kane et al.'s (1995) analyses of Pentelic sculptures from the *Nymphaeum* of *Herodes Atticus* at Olympia, Greece. Ancient records of the economics of the monument's construction attest to the marble's Pentelic origin (Kane et al. 1995, Walker 1987). Stable isotope and geochemical analyses of marbles from several statues, their disassociated bases and material from different phases of the building construction suggest the possibility that marbles were not from the same block or quarry, but from isotopically distinct blocks or possibly distinct quarries within the Pentelic quarry region. However, the current marble database is insufficient to address these propositions. The database has limited information on the sample spot locations of its reference samples and thus the reference samples can not be correlated with an accurate map of the quarry region.

To investigate the isotopic as well as geochemical character of Mount Pentelikon, an extensive systematic characterization study of the ancient Pentelic quarry region was undertaken. The study includes a survey phase, a sampling phase and an analyses phase. Results from the extensive field survey and sampling program are reported elsewhere as are the geochemical analyses (Pike 2000). This report presents results of the isotopic analyses.

Methodology

To successfully model the isotopic and geochemical profile of the ancient quarries on Mount Pentelikon, it was critical that a representative marble reference collection be obtained. Only this way can the reference sample collection be assured that every quarry is represented and that, if present, spatial isotopic and geochemical trends can be mapped. To this end, an extensive topographic and geologic field survey was conducted. A detailed description of the survey and sampling program, the methodology employed and findings are reported in Pike (2000). A summary of the results of the survey and sampling are reported here.

A quarry location map identifies 172 discrete quarries (figure 2). Tool marks and unfinished worked blocks indicate that at least thirty quarries were worked in ancient times (figure 3, Kozelj 1988, Waelkens, de Paepe and Moens 1990). The ancient quarries are identified by red traces representing the surviving quarry walls and the underlining of the quarry identification label. Quarries traced in blue do not show any physical evidence of ancient quarry extraction and are interpreted as being modern quarry pits. "Modern" is defined as the time following Greece's independence from the Ottoman Empire in 1846. Because many modern quarries expanded their operations into abandoned ancient quarries, it is likely that physical evidence of several ancient quarries has been completely obliterated (Korres 1995). Therefore, there may be several quarries identified as modern when, in fact, marble was extracted from them during antiquity.

The survey also recorded observations related to the geologic structure of the quarries. The Greek State has not yet published a geologic map of Mount Pentelikon and little information on its structure is published. Geologists who have studied northern Attica and Mount Pentelikon suggest that the mountain is an autochthonous, low- to medium-grade metamorphic complex that has been folded and uplifted into a large northeastward-plunging anticlinorium (Katsikatsos, pers. comm., Markoulis, pers. comm.). The mountain is comprised of two marble formations – the Upper and the Lower marbles – with an intermediate schist formation between them (Lepsius 1893, Katsikatsos et al. 1986). The schist is often called the Kaisariani Schist and is assumed to extend to Mount Hymettus in the east (Markoulis, pers. comm.) Within the Kaisariani Schist is a large marble lens often referred to as the Middle or Intermediate Marble (Markoulis, pers. comm., Lepsius 1893). The quarries are situated on the eastern limb of the plunging anticlinorium (figure 4). A central ridge through the quarry area on the south slope of Mount Pentelikon trends NE-SW. The ridge contains the axis of a large anticlinal fold with adjacent parallel axes of minor anticlines and synclines. All the surviving ancient quarries and most of the modern quarries flank the limbs of the central ridge.

The geologic map (figure 4) shows the surface exposures of three distinct NE-SW trending marble units. These marble units comprise the uppermost section of the Lower Marble with the younger rocks toward the west. Markoulis et al. (1975) warns that although the surface exposure suggests three different geologic units, they can be interpreted as one and the same and their surface exposure is the result of recumbent folding and preferential weathering. Despite this possibility, the small regional scale of the current project is interested in localized discrepancies within the quarry area and not within a larger regional model. Therefore, the three marble units are identified as Marble Unit 1, Marble Unit 2 and Marble Unit 3 as indicated on the geologic map (figure 4). The majority of ancient quarries fall within Marble Unit 3, with several also in Marble Unit 2. There is no physical evidence suggesting ancient quarrying activity in Marble Unit 1, although there are many modern quarry pits located at the lower elevations.

With the aid of the quarry location map (figure 2) and the geologic map (figure 4) a sample reference collection of 610 samples was collected. For a detailed description of the field survey and acquisition of the Pentelic marble reference collection refer to Pike (2000). A synopsis of the reference collection is presented below.

The samples were collected from a total of 83 of 172 quarries. Of the 83 sampled quarries, over 30 are known to be ancient. All samples were collected directly from exposed quarry walls. To guarantee that each sample accurately represents its sampling spot, no samples were collected from loose debris on the quarry floor or from any quarry debris piles. The location and elevation of each sample is marked on a quarry map (see Pike 2000, Chapter 2 for descriptions and maps of the quarries and sampling locations). Where possible, multiple samples were collected from quarries to investigate for any textural, geochemical or isotopic lateral or vertical intra-quarry variation. Several quarries are not represented in the database because they could not be safely accessed or because there were no fresh marble surfaces to sample. Samples were collected using standard geologic steel chisels, hammers and picks. Care was taken not to damage or mar any surviving ancient worked surfaces.

Stable isotope analysis was conducted at the Stable Isotope Laboratory, Department of Geology, University of Georgia using a Finnigan MAT-delta E gas-source mass spectrometer. Ten-twenty mg aliquots of white marble powder were reacted with anhydrous phosphoric acid in a vacuumed reaction tube at 50°C following the protocol outlined by Swart, Burns and Leder (1991). The resultant CO_2 gas was then purified in a glass extraction line and analyzed with the mass spectrometer. The obtained isotope ratios $^{13}C/^{12}C$ and $^{18}O/^{16}O$ were then compared to the PDB standard of the University of Chicago (*Belemnitella americana*, PeeDee formation, Cretaceous, South Carolina) and transformed to the standard delta notation by using the following equations (Faure 1986):

$$\partial^{13}C = \left[\frac{\left(\frac{^{13}C}{^{12}C}\right)_{\text{sample}} - \left(\frac{^{13}C}{^{12}C}\right)_{\text{standard}}}{\left(\frac{^{13}C}{^{12}C}\right)_{\text{standard}}} \right] \times 1000‰$$

$$\partial^{18}O = \left[\frac{\left(\frac{^{18}O}{^{16}O}\right)_{\text{sample}} - \left(\frac{^{18}O}{^{16}O}\right)_{\text{standard}}}{\left(\frac{^{18}O}{^{16}O}\right)_{\text{standard}}} \right] \times 1000‰$$

During the analyses, the mass spectrometer is programmed to measure the mass of the sample gas eight times. The multiple readings allow for the assessment of the homogeneity of the CO_2 gas and provide an important check on the precision of the analysis.

Two methods were used to collect the sample aliquots prior to reaction. The first employed a variable speed dental drill with a carbide drill-bit. Because fractionation may occur between the ambient room moisture and fine marble powder at frictional temperatures achieved with high speed drilling (Wenner, Havert and Clark, 1988) the lowest possible speed was used when collecting samples. Marble material drilled from the outer 2 mm of each sample was discarded to prevent possible contamination from weathered and isotopically altered marble.

Drilling is the preferred method of sample collection for marble stable isotope analysis since it most reflects the conditions in which archaeological samples are collected and also allows for sample collection at precise surfaces on artifacts so that minimal damage is achieved. It is important to note, however, that drilling is not suitable for all physio-chemical characterization techniques. For example, in electron spin resonance, drilling causes a large "drilling peak" which is associated with electrons that partially fill defects generated by drilling at any speed (Mandi et al. 1992).

The second method of sample preparation involved the use of an agate mortar and pestle to crush several of the samples. Small sample fragments were separated from hand samples using a two-pound crack hammer. Samples crushed in the mortar and pestle only came from the unweathered fragments of the broken cores of the handsamples. The mortar and pestle had been purchased and allocated for use only with carbonate materials to prevent possible contamination from other types of samples.

Of the 610 samples in the reference collection, stable isotope analyses were performed on 379 samples. Nearly all of the samples of which no data are presented show evidence of diagenetic alteration. Evidence of alteration includes chloritic mica veins penetrating throughout the sample as well as pink and orange discoloration plumes penetrating deep into the sample. Stable isotope analyses were not performed on these samples since there is the likelihood that some fractionation occurred between metamorphic fluids and calcite grains along the calcite – hydrorous mineral interface (Rye et al. 1976). Inclusion of these altered samples into the Pentelic marble database would lessen the integrity and accuracy of the database. Several samples were analyzed twice on separate runs to monitor analytical precision over time. In all instances, the two sets of values fell within a single standard deviation.

Results

Table 1 lists the results of the stable isotope analyses. The averaged data from multiple sample runs are reported and are identified with asterisks. The data are displayed graphically in the scatter-plot diagram in figure 1.

As can be seen from the scatter-plot diagram in figure 1 the sample distribution encompasses all of the 90% probability ellipsoid of Matthews et al.

(1992) while also extending the $\delta^{13}C$ range in the positive direction. A significant pattern appears when the quarries are segregated by their respective Marble Units. Figure 1 reveals that Marble Units 1 and 2 contain higher $\delta^{13}C$ values than the quarries in Marble Unit 3. An independent sample t-test confirms with over 95% confidence that the mean $\delta^{13}C$ value of the combined group of Marble Units 1 and 2 is different than the mean of Marble Unit 3 (Table 2). Although there is significant overlap of the three Marble Units between $\delta^{13}C$ values of 2-3.5‰, the elevated $\delta^{13}C$ values of Marble Units 1 and 2 clearly separate from the narrow range of $\delta^{13}C$ values of Marble Unit 3. Since Marble Unit 1 does not have any archaeological quarries any associated archaeological Pentelic sample with a relatively high $\delta^{13}C$ must have been extracted from Marble Unit 2. Only samples from Marble Unit 3 have relatively high $\delta^{18}O$ values (>-5.5‰) and relatively low $\delta^{13}C$ values (<3.5‰).

The scatter-plot diagrams in figures 5-7 display the sample distributions of all the quarries identified as ancient during the initial field survey as well as quarry Π69. Quarry Π69 is included in this subgroup because of its very large size, its location in the apparent center of ancient quarrying activities and because it most likely is an ancient quarry with no physical evidence preserved.

The scatter-plot diagram figure 5 represents all of the upslope quarries in Marble Unit 3. Quarries Π88, Π89 and Π90, all neighboring quarry pits in the northern section of the quarry, in the area called *Aspra Marmara* (Lepsius 1890), have the highest $\delta^{18}O$ values in the database. The quarries are identified by open-symbols. The $\delta^{18}O$ values distinguish these quarries from all others in the quarry region. Quarry Π85 does have one sample with a high $\delta^{18}O$ value (-4.3‰), but that single value is a statistical outlier for it falls outside the 95% confidence interval for quarry Π85. Several samples from Π88 and one from Π89 trend towards the lower $\delta^{18}O$ values associated with other Pentelic quarries. The lower values of the samples from Π88 are from the southern end of the quarry where the marble is of inferior quality and shows extensive weathering alteration and discoloration. Therefore, it is likely that these more negative values reflect fractionation with meteoric fluids.

The $\delta^{18}O$ signatures of the other Marble Unit 3 upper slope quarries do not reflect the same high $\delta^{18}O$ values or distribution as quarries Π88, Π89 or Π90. These quarries are Π84, Π85, Π87 and Π91 and are represented by the solid symbols in figure 5. The $\delta^{18}O$ values range from –9.4‰ to –5.5‰ with one statistical outlier from quarry Π85 of –4.3‰. The maximum value is still more positive than most reference samples from the database. The extensive quarry Π91 has the same range as the quarry grouping of Π84, Π85 and Π87. The $\delta^{13}C$ values of quarry grouping Π84, Π85 and Π87 have less variance and range from 2.7‰ to 3.2‰ with a single outlying sample having a $\delta^{13}C$ value of 4.2‰. For quarry Π91, $\delta^{13}C$ values range from 2.41‰ to 3.18‰ with a single sample measuring 1.7‰ that falls well outside the 95% confidence interval for the quarry. For both outliers there is no distinguishable feature to single them out in quarry space.

The scatter-plot diagram in figure 6 represents the remaining ancient quarries in Marble Unit 3. The closed symbols indicate the quarries in the mid-slope region, the crossed symbols represent the three ancient quarries on the lower slope of the quarry and the open symbol reflects quarry Π55. Comparing the isotope profiles of the large, mid-slope quarries reveals that they share a similar profile with one another. The $\delta^{13}C$ ratios representing quarry Π70 fill a narrow range between 2.7‰ and 3.1‰ and are roughly 0.2‰ below the average $\delta^{13}C$ value for quarry Π69. The $\delta^{18}O$ values range between –8.7‰ and –4.1‰. Further downslope ancient quarries Π64 and Π67 have very similar distribution of $\delta^{13}C$ and $\delta^{18}O$ ratios.

Quarry Π55 (figure 6, open symbols), the famous *Spilia Divali* quarry, has a narrow field of five measurements and one extraneous sample with a relatively higher $\delta^{18}O$ value. The box-plot in figure 7 displays the degree to which the high value is an outlier. The main group of samples falls within the range of 2.7‰ to 3.1‰ for $\delta^{13}C$ and –9.1‰ to –8.4‰ for $\delta^{18}O$. Two comparable analyses of the single outlier gave an averaged stable isotope signature of 2.9‰ for $\delta^{13}C$ and –4.8 for $\delta^{18}O$. After reconciling the sample locations with the stable isotope data (see Pike 2000), it is apparent that the sample with the lone data plot was the only sample collected from the northeast wall of the quarry. This end of the quarry shows no evidence of ancient extraction and was possibly exposed in 1846 to supply construction material for the new royal palace in Athens (Korres 1995, Dworakowska 1973). The grouped samples were all collected on the quarry's west wall within the area of extensive ancient tool marks.

A review of figure 6 reveals that the small ancient quarries Π39, Π48 and Π49, situated on the lower flanks of Mount Pentelikon's south slope in Marble

Unit 3, have a more negative $\delta^{18}O$ value and a $\delta^{13}C$ value at or near 3.0‰. Quarries Π35 and Π38, the lowest sampled ancient quarries in the study area, do not follow the same relatively low-valued $\delta^{13}C$ trend as the other Marble Unit 3 quarries. Rather, they maintain a high $\delta^{13}C$ value between 4.4‰ and 4.7‰ and $\delta^{18}O$ values between –6.6‰ and –5.7‰.

Figure 8 displays the $\delta^{13}C$-$\delta^{18}O$ scatter-plot diagram for all the ancient quarries in Marble Unit 2. Ancient quarries Π95 and Π96 are located at the top of the south slope of Mount Pentelikon and are represented by open-symbols in figure 8. These two quarries have a significantly higher $\delta^{13}C$ range than the upslope quarries of Marble Unit 3 (see figure 5). Also, quarries Π95 and Π96 have lower maximum $\delta^{18}O$ values of -6.8‰ and –6.4‰, respectively, when compared to neighboring Marble Unit 3 quarries. To the west and north of quarry Π70 on the opposite side of the thick mica schist layer that separates Marble Unit 2 from Marble Unit 3 lie quarries Π103 and Π105. The profiles of these quarries show a narrow range of $\delta^{13}C$ values and a relatively small range for $\delta^{18}O$. Both the carbon and oxygen isotope ratios are on the lower end of the Pentelic marble spectrum with the $\delta^{13}C$ values ranging from 2.6‰ to 3.1‰ and the $\delta^{18}O$ values from –9.9‰ to –7.3‰. Further downslope along the schist interlayer in Marble Unit 2 lies quarry Π107. With a similar oxygen ratio range as Π103 and Π105, this quarry displays a larger range for the carbon ratio values, ranging from 2.2‰ to 3.9‰. However, this maximum falls outside the 95% confidence interval of the quarry. The $\delta^{18}O$ values of Quarry Π107 range from –8.9‰ to –7.7‰ with a single outlier of -6.7‰.

The seven samples from quarry Π54 all have low $\delta^{18}O$ values between –8.9‰ and –7.0‰ (figure 8). The $\delta^{13}C$ values plot into two groups, one with $\delta^{13}C$ values below 3.0‰ and the other with values above 4.0‰. After reconciling these two groups with the location of the sample spots from the quarry (see Pike 2000), it becomes clear that the low $\delta^{13}C$ values are associated with the east wall of the quarry adjacent to the schist interlayer. The three samples with high $\delta^{13}C$ values were collected along the opposite wall on the west side of the quarry. Thus, within the narrow 15-20 m width of the quarry, the $\delta^{13}C$ value significantly increases from east to west by more than 1.0‰. This trend is also apparent in quarry Π107 where sample Π107-1 has a high $\delta^{13}C$ value of 3.9‰. Sample Π107-1 was obtained from the quarry's west wall and is the furthest sample collected from the schist interlayer in quarry Π107.

The stable isotope data from the small ancient quarries on the lower slope of Marble Unit 2 are distinguished by crossed symbols in figure 7. The two samples from quarry Π20 show a wide $\delta^{18}O$ discrepancy of nearly 2‰. Despite this, this small set of samples shows that quarries Π20 and Π21 maintain an isotopic signature with relatively low $\delta^{18}O$ and high $\delta^{13}C$ values. The single sample from quarry Π23 maintains a $\delta^{13}C$ value similar to the lower quarries in Marble Unit 3. The fact that these three quarries lie in close proximity to one another and that they maintain a large stable isotope range suggests that the upper portion of Marble Unit 2 may not be as isotopically distinct as that of

Marble Unit 3. The data from all of the ancient quarries can be summarized on the isotopic field map displayed in Figure 9.

Discussion

There is a current debate concerning the location of the quarries that supplied marble for the construction of the Parthenon. The Greek architect M. Korres, formally of the multimillion dollar Parthenon reconstruction project, has proposed that the marble for the construction of the Parthenon was extracted from the famous *Spilia* quarry, quarry Π55 (Korres 1995). He argues that the ancient Greeks methodically started quarring from the lower slopes of Pendeli and worked their way upslope as the lower quarries became exhausted. Quarry Π55 is the lowest surviving large ancient quarry with very wide spaced joints to foster extraction of large dimensional blocks (Korres 1988). Korres argues that since the Parthenon was the first large-scale construction project made with Pentelic marble, it must have been constructed from marble from this lowest quarry.

This hypothesis counters that put forth by Matthews et al. (1992) which suggests that the Parthenon, or at least the marble for the sculptural program of the Parthenon, was extracted from the upper quarries in *Aspra Marmara*. This debate can partially be resolved with the use of the refined stable isotope database. Unfortunately, no data is available for the large architectural blocks from the Parthenon. However, the Matthews et al. study (1992) supplies data for the marble statuary currently housed at the British Museum. Comparing the stable isotope ratios of the sculptural monuments to those of the database reveals that the high $\delta^{18}O$ values obtained for the Parthenon sculptures correlate with the high values obtained for quarries Π88, Π89 and Π90 (figure 10). The ancient portion of the *Spilia* quarry reflects a significantly lower $\delta^{18}O$ range. Therefore, the marble for the Parthenon sculptures was extracted from at least one of these three quarries near the top of the south slope.

Characterization of the surviving ancient tool marks in quarries Π88, Π89 and Π90 further supports the isotope findings and may even suggest the actual quarry from which the sculptural blocks were extracted. Waelkens, de Paepe and Moens (1988) outline a chronology of tools and their associated tool marks used in Mediterranean quarrying from the Archaic through the period of Roman domination. This chronology suggests that during the Archaic and Early Classical Periods the quarryman used short-handled picks that left a series of horizontal groove marks (figure 3B). During the Hellenistic period a longer handle was attached to the pick allowing the quarrymen to stand at a single spot for several swings of the pick. This latter technique results in a series of garland-shaped trace patterns (figure 3A). Of the three quarries identified as likely sources of the Parthenon sculptural marbles, quarry Π90 is the only one with evidence of ancient horizontal toolmarks. Therefore, quarry Π90 is the most likely source for the Parthenon marbles.

Conclusion

Prior to this extensive study of the Pentelic quarry region, the heterogeneous nature of the Pentelic stable isotope field was perceived to be a limiting factor on the resolution of the Pentelic quarry database. The wide ranges for $\delta^{13}C$ and $\delta^{18}O$ were seen as problematic since the large signature field increased the likelihood that the Pentelic quarry field would overlap signature fields of other quarry districts. Overlapping signature fields make provenance assignments more difficult for those artifacts that fall within the overlap. However, this research has illustrated that the wide range of isotope values can be an asset rather than a hindrance.

With detailed surveying and systematic and extensive sampling the presented database improves the discriminatory ability of stable isotopic analysis for marble provenance studies. Rather than treating the entire Pentelic quarry region as a homogenous whole, the presented database distinguishes between three mappable and exploited marble units. By correlating individual samples within the Marble Units to their quarry sample spots it is possible to recognize stable isotopic sub-regions within the quarry area. In some special cases individual quarries or groups of quarries can be identified. The utility of the database is illustrated by determining the probable quarry or group of quarries from which the famous Parthenon sculptures were extracted. The extensive field survey and sampling of the quarry region provided the information necessary to investigate and identify intra-quarry isotopic variation. Future characterization projects of other ancient quarry districts should undertake similar extensive sampling protocols.

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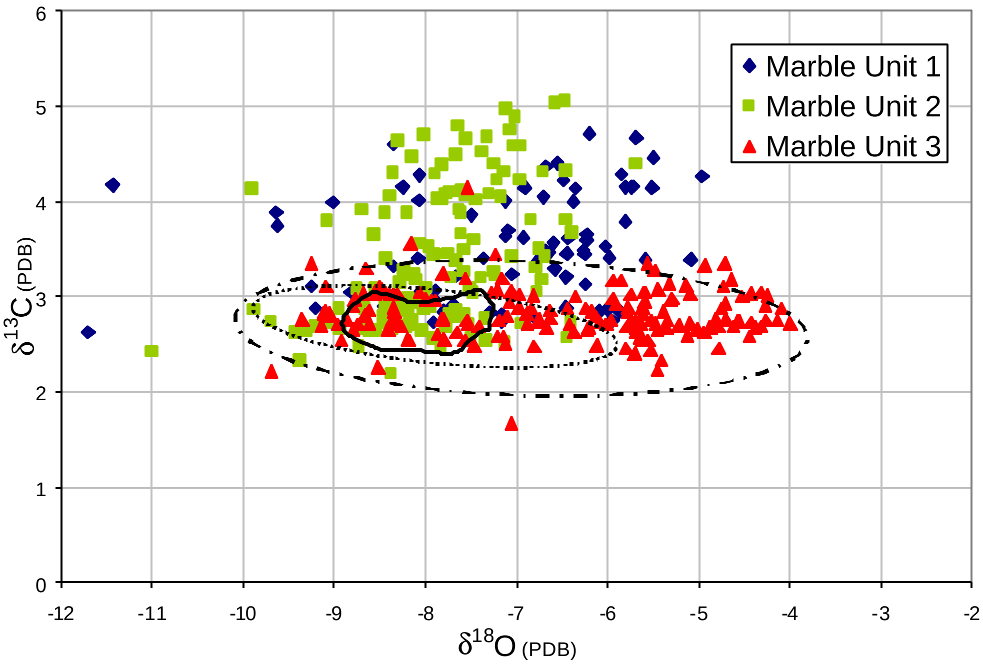


Figure 1. The development of the $\delta^{13}C$ and $\delta^{18}O$ stable isotope field for Pentelic marble. The inner polygon (solid line) represents the data first published in 1972 by Craig and Craig. The middle ellipse (stippled line) represents the 90% probability ellipsoid of the 1987 Pentelic database of Herz. The outer ellipse (dashed line) represents the 90% ellipsoid of the combination of the earlier published data and Matthews et al. 1992. Analyzed samples in the current study verify the $\delta^{18}O$ range of the Matthews ellipsoid. The $\delta^{13}C$ range is significantly expanded in the positive direction. Samples from each of the marble units are distinguished by distinctive symbols. Note the relatively high $\delta^{18}O$ values for Marble Unit 3 and the relatively high $\delta^{13}C$ values for Marble Units 1 and 2.

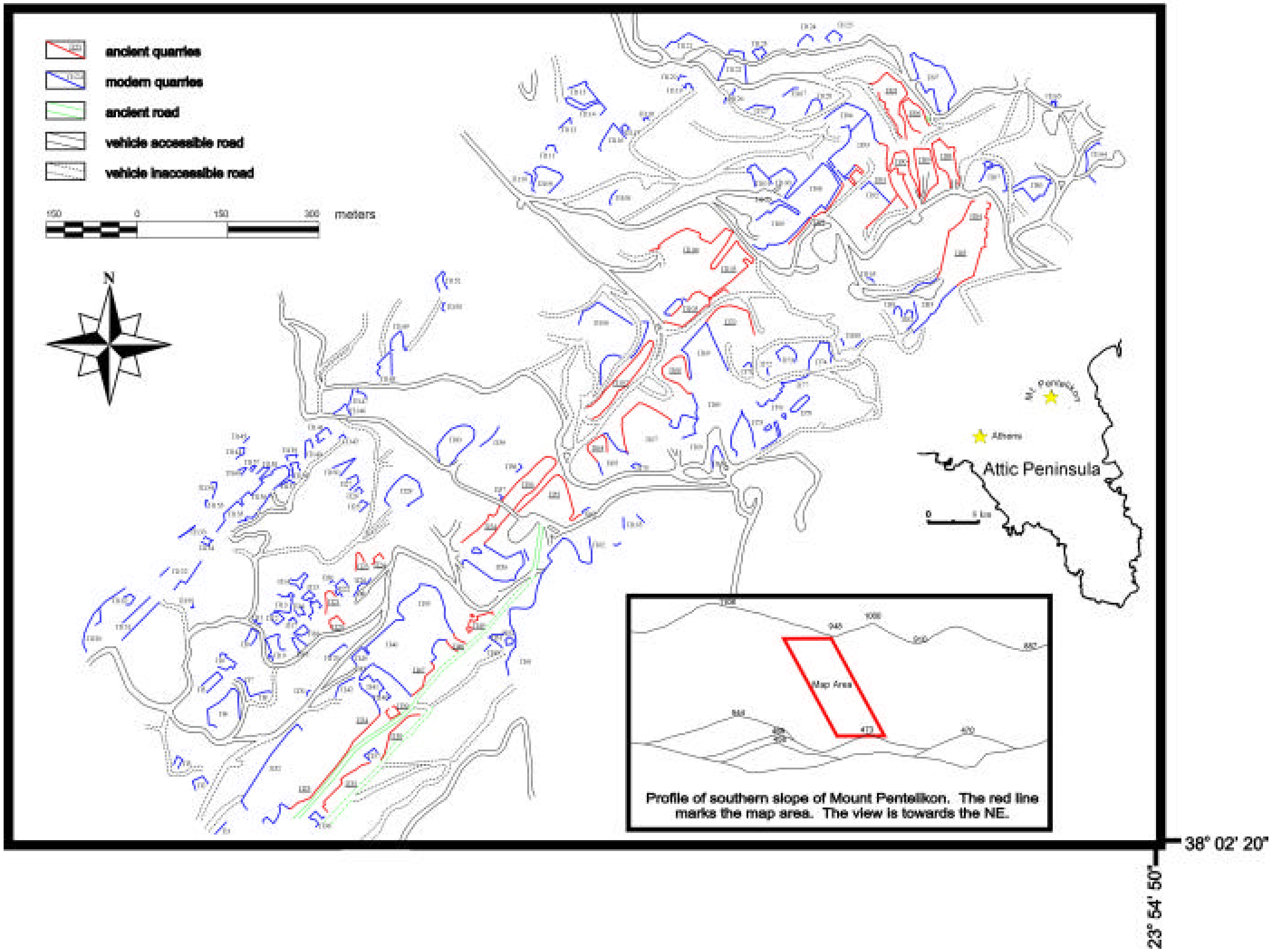
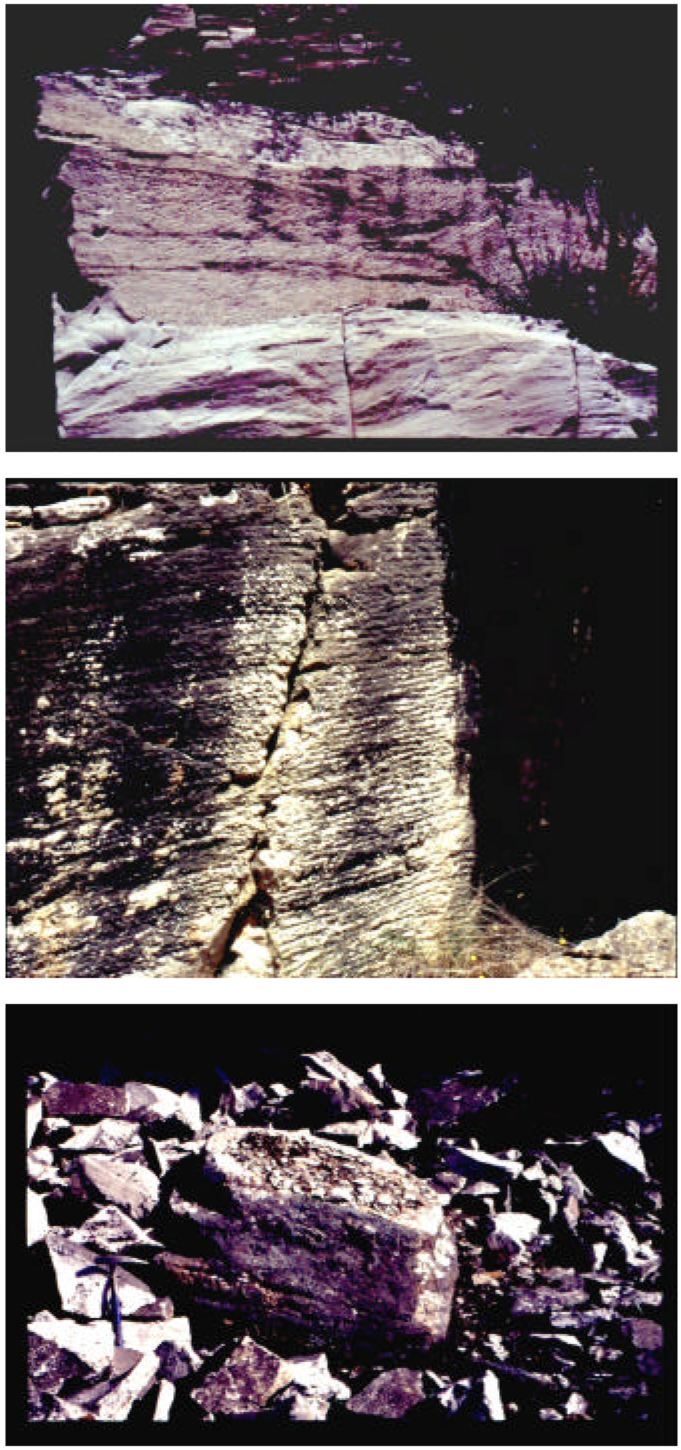


Figure 2. Location map indicating spatial distribution of surviving ancient and modern quarries on Mount Pentelikon's south slope.



A

B

C

Figure 3. Tool marks and unfinished worked blocks abandoned in quarries used to identify antiquity of quarry operations. (A) garland-type tool marks associated with the long-handle pick (quarry Π54); (B) horizontal tool marks associated with the Archaic and early Classical short-handled pick (quarry Π44); (C) unfinished column capital from the floor of quarry Π23.

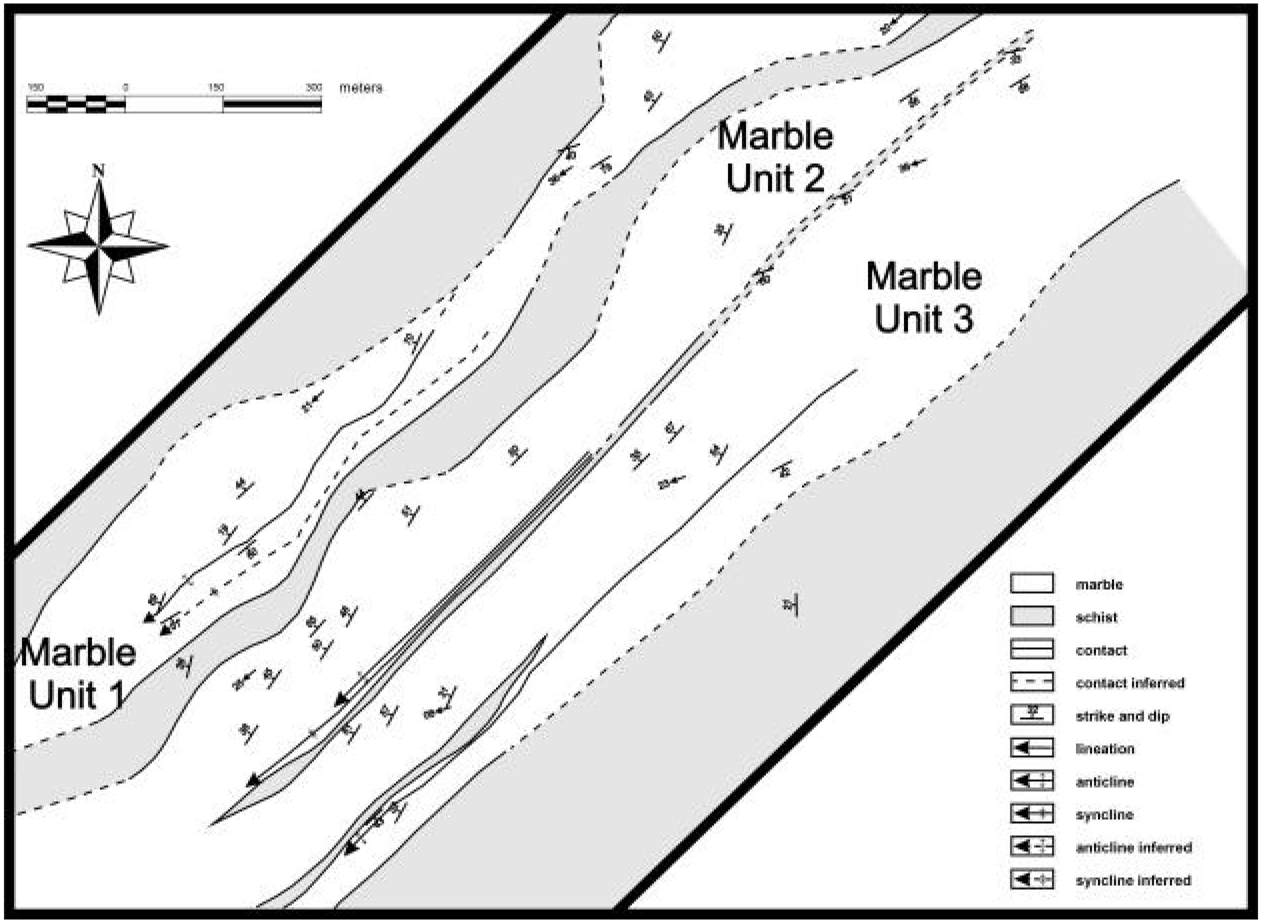


Figure 4. A geologic map showing the lateral distribution of marble and schist interbeds in the upper portion of the Lower Marble formation. The younger units are towards the NW. Note the geologic distinction between marble groups 1,2 and 3.

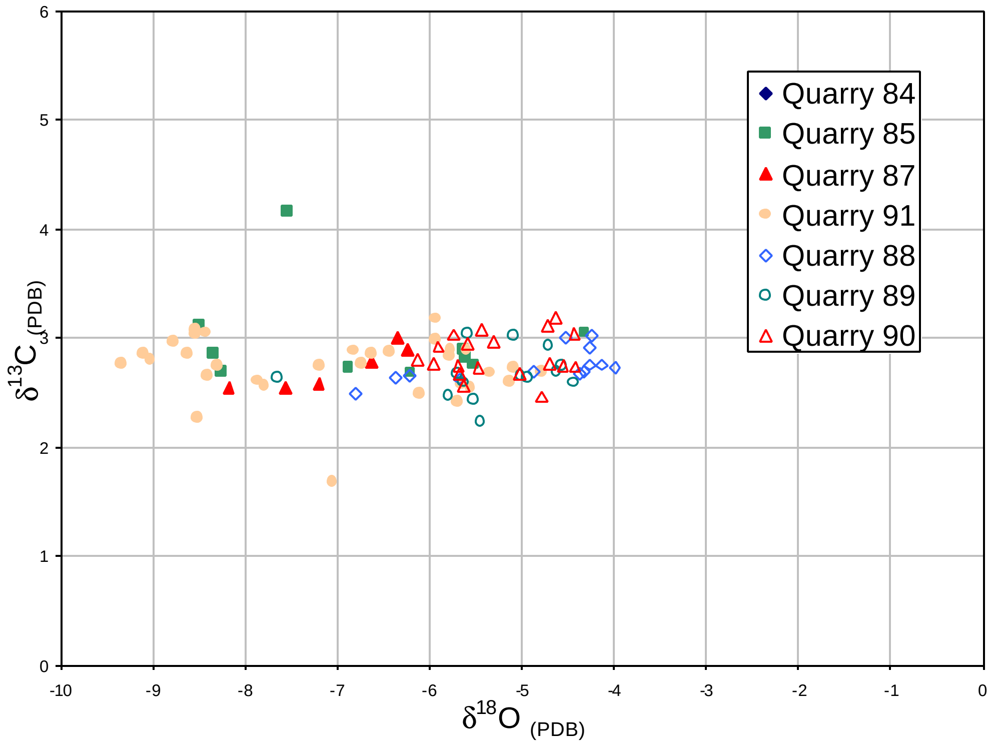


Figure 5. $\delta^{13}C$ and $\delta^{18}O$ scatter-plot diagram of all analyzed samples from the ancient quarries located on the upper slope of Marble Unit 3. The open-symbols represent the *Aspra Marmara* samples from which the Parthenon sculptures most likely were extracted.

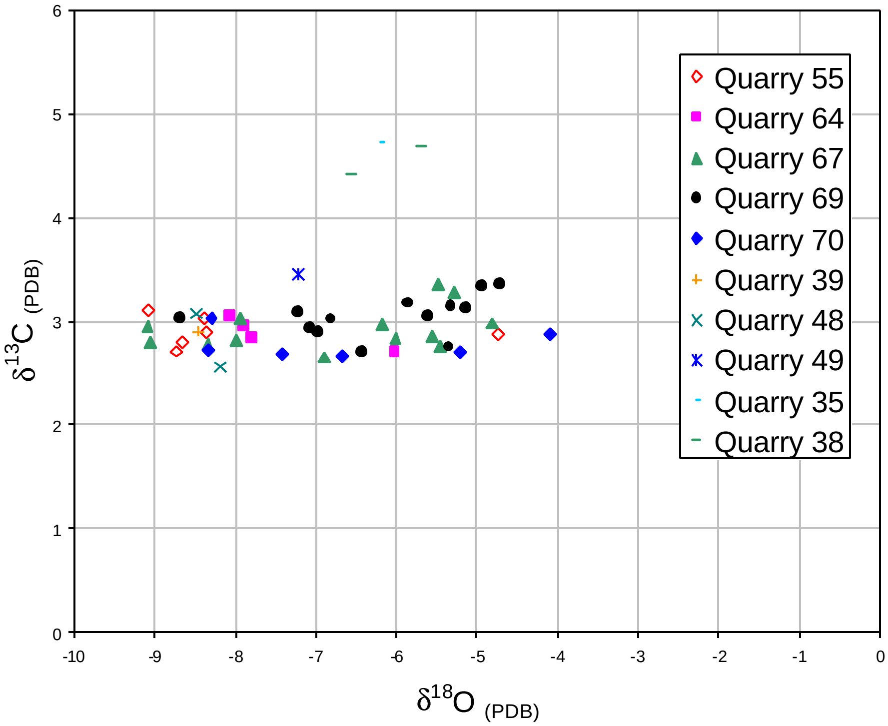


Figure 6. $\delta^{13}C$ and $\delta^{18}O$ scatter-plot diagram of all analyzed samples from all archaeological quarries and Quarry Π69 on the mid- and lower-slope of Marble Unit 3. The open-symbol represents quarry Π55, the famous *Spilia Divali* quarry discussed on page 177. The solid symbols represent the other mid-slope quarries. The crossed and dashed symbols represent those quarries on the lower slope. Note the narrow range of $\delta^{13}C$ values and the relatively positive values of quarries Π35 and Π38.

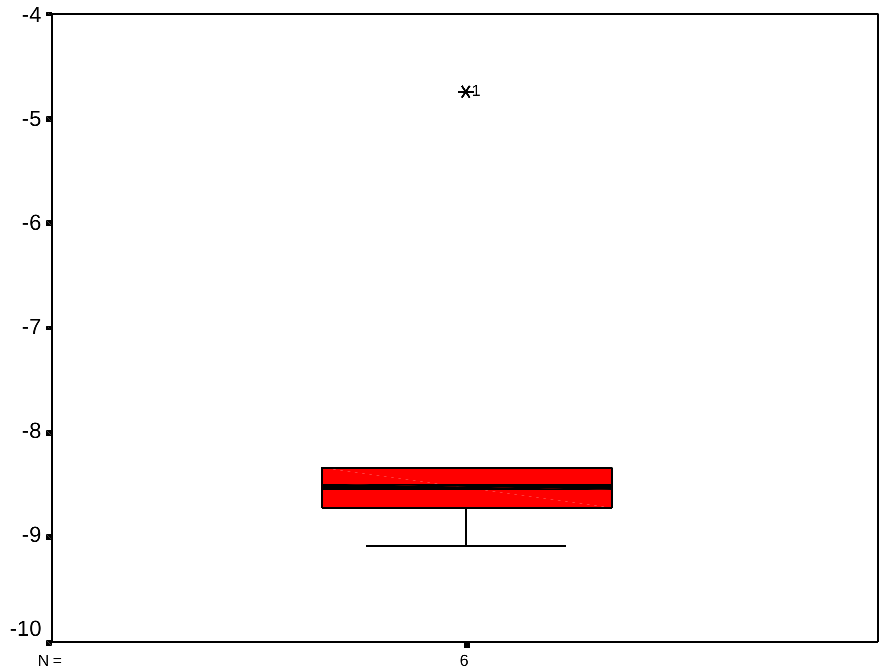


Figure 7. Box-plot of $\delta^{18}O$ values from the six samples collected at *Spilia Divali*, quarry Π55. The box represents the 95% interval. The outlying sample at the top of the diagram is the lone sample collected from the northeast wall of the quarry. This northeast wall was most likely exposed in the modern era, possibly during the construction of the new Royal Palace in Athens in 1846 (Korres 1995, Dworakowska 1973). The remaining five samples were all sampled from the steep, archaeologically exposed west wall of the quarry.

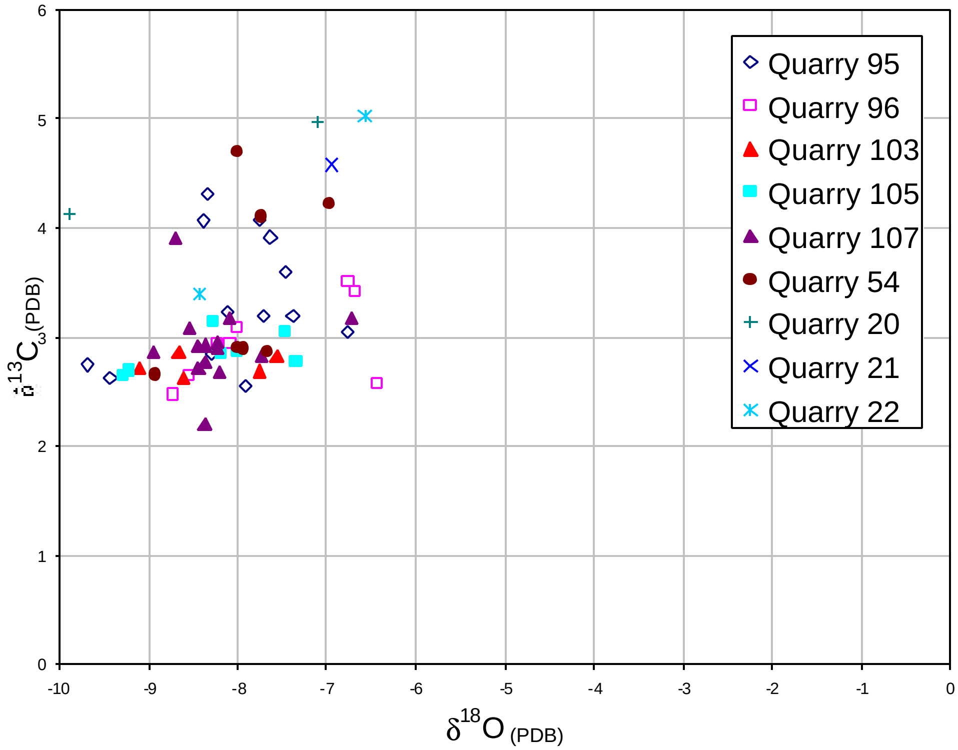


Figure 8. $\delta^{13}C$ and $\delta^{18}O$ scatter-plot diagram of the archaeological quarries in Marble Unit 2. Note the relatively narrow range of $\delta^{18}O$ when compared to Marble Unit 3 (see figures 4 and 5). The relatively high $\delta^{13}C$ values can also distinguish Marble Unit 2 from Marble Unit 3.

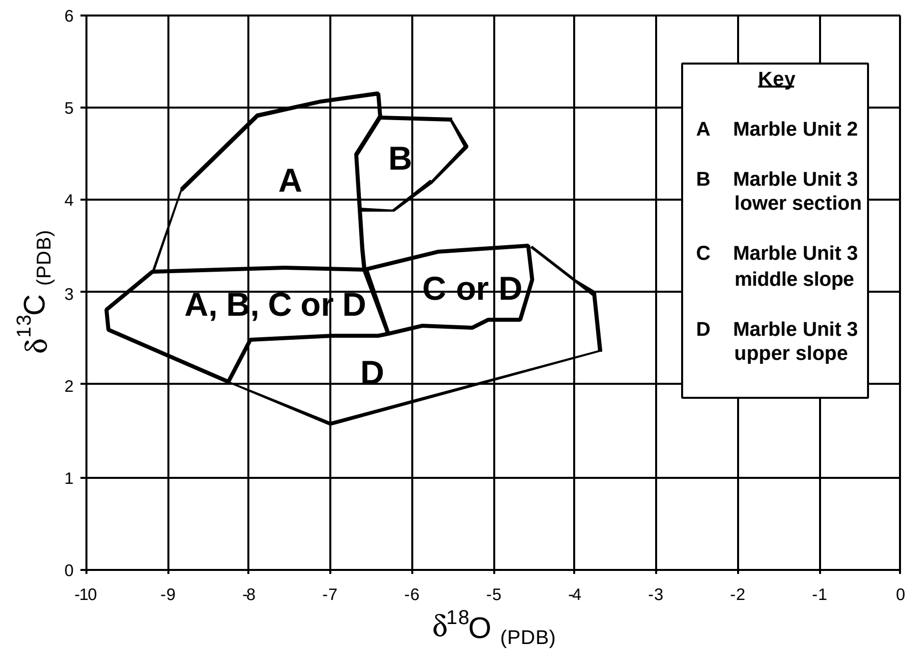


Figure 9. Scatter-plot diagram distinguishing isotope fields within the Pentelic quarry region.

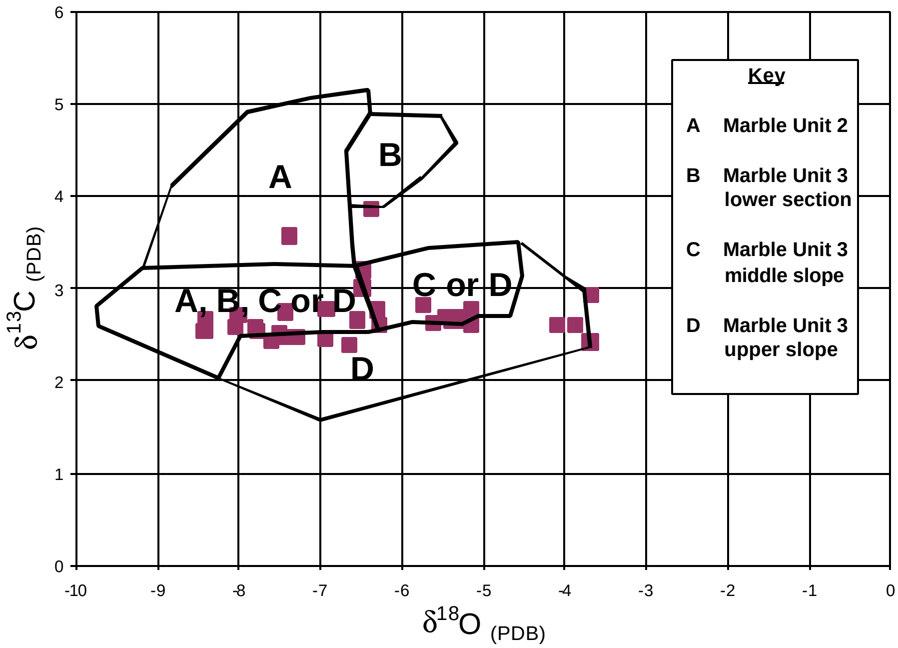


Figure 10. Scatter-plot diagram locating the Parthenon sculptural marbles within the Pentelic marble database. The four samples with relatively high $\delta^{18}O$ ratios were likely extracted from quarries Π88, Π89 or Π90. At least half of the marbles are from Marble Unit 3. Parthenon sculptural marble data from Matthews et al. 1992.

Table 1. Stable isotope data of δ^{13}C and δ^{18}O for all analyzed samples from the Pentelic marble sample reference collection.

Quarry	Sample ID	d^{13}C	d^{18}O
4	4-1	4.2	-7.2
4	4-2	3.8	-6.5
11	11-1	4.0	-7.8
12	12-1	4.3	-7.1
12	12-2	2.7	-8.2
12	12-3	3.8	-9.1
13	13-1	3.9	-7.6
13	13-2	3.6	-8.6
14	14-1	4.1	-7.6
15	15-1	4.6	-7.0
15	15-2	4.5	-7.4
16	16-1	4.7	-7.6
16	16-2	4.8	-7.1
17	17-1	4.8	-7.6
20	20-1	5.0	-7.1
20	20-2	4.1	-9.9
21	21-1	4.6	-6.9
22	22-1	5.0	-6.6
22	22-3	3.4	-8.4
23	23-1	2.8	-8.4
25	25-1	3.3	-8.2
25	25-2	3.2	-8.2
26	26-1	2.7	-8.3
27	27-1	4.0	-7.4
27	27-2	4.3	-6.7
27	27-3	3.3	-7.6
27	27-4	3.2	-7.2
35	35-1	4.7	-6.2
36	36-1	4.2	-8.3
36	36-2	4.0	-6.4
38	38-1	4.7	-5.7
38	38-2	4.4	-6.5
39	39-1	2.9	-8.5
40	40-1	2.8	-7.8
43	43-1	2.6	-8.0
46	46-1	2.7	-8.8
46	46-2	2.7	-8.6
46	46-3	3.0	-7.3
46	46-5	2.8	-5.4
46	46-6	2.7	-5.8
46	46-7	2.8	-6.8

Quarry	Sample ID	d^{13}C	d^{18}O
48	48-1	2.6	-8.2
48	48-2	3.1	-8.5
49	49-1	3.5	-7.2
53	53-2	2.5	-7.1
54	54-1	2.9	-7.7
54	54-2	2.9	-8.0
54	54-3	2.9	-7.9
54	54-4	4.1	-7.7
54	54-5	4.2	-7.0
54	54-6	2.7	-8.9
54	54-7	4.7	-8.0
55	55-1	2.9	-8.4
55	55-2	3.0	-8.4
55	55-3	3.1	-9.1
55	55-4	2.8	-8.7
55	55-5	2.7	-8.7
55	55-6	2.9	-4.7
56	56-2	3.0	-7.0
56	56-3	3.2	-7.2
56	56-4	3.1	-7.1
64	64-1	2.8	-7.8
64	64-1	2.8	-7.8
64	64-2	3.0	-8.1
64	64-2	3.0	-8.1
64	64-3	3.0	-7.9
64	64-3	3.0	-7.9
64	64-4	2.7	-6.0
67	67-1	2.8	-6.9
67	67-2	2.7	-5.5
67	67-3	2.8	-4.8
67	67-4	3.0	-5.3
67	67-5	3.3	-5.5
67	67-5	3.4	-5.6
67	67-6	2.9	-6.2
67	67-7	3.0	-8.0
67	67-8	2.8	-9.0
67	67-9	2.8	-9.1
67	67-10	3.0	-7.9
67	67-11	3.0	-8.3
67	67-12	2.8	-7.8
69	69-1	3.1	-5.6
69	69-2	3.3	-4.9
69	69-3	3.1	-5.1
69	69-4	2.8	-5.3

Quarry	Sample ID	d ^{13}C	d ^{18}O
69	69-5	3.1	-5.3
69	69-6	3.4	-4.7
69	69-7	3.0	-6.8
69	69-8	3.0	-8.7
69	69-10	2.9	-7.0
69	69-11	2.7	-6.4
69	69-12	2.9	-7.1
69	69-13	3.2	-5.9
69	69-14	3.1	-7.2
70	70-1	2.7	-5.2
70	70-2	3.0	-8.3
70	70-3	2.7	-8.3
70	70-4	2.7	-6.7
70	70-5	2.7	-7.4
70	70-6	2.9	-4.1
71	71-1	2.5	-7.1
72	72-1	2.5	-7.5
79	79-1	2.7	-7.5
79	79-2	2.8	-7.5
81	81-1	2.7	-9.1
81	81-2	2.9	-8.8
82	82-1	2.8	-8.4
82	82-2	3.6	-8.2
83	83-1	2.2	-9.7
83	83-2	3.3	-8.6
83	83-3	2.5	-8.9
83	83-4	2.7	-9.0
84	84-1	2.6	-7.1
84	84-2	2.8	-9.1
84	84-3	3.0	-7.0
84	84-4	2.8	-7.1
84	84-5	3.2	-7.6
85	85-1	2.9	-8.3
85	85-2	2.9	-5.6
85	85-3	2.7	-6.9
85	85-4	2.8	-5.6
85	85-5	2.7	-6.2
85	85-6	2.8	-5.5
85	85-7	3.1	-8.5
85	85-8	3.0	-4.3
85	85-9	2.7	-8.3
85	85-10	4.2	-7.5
87	87-1	2.9	-6.2
87	87-2	2.8	-6.6

Quarry	Sample ID	d^{13}C	d^{18}O
87	87-3	2.5	-8.2
87	87-4	2.6	-7.2
87	87-5	2.5	-7.6
87	87-6	3.0	-6.4
88	88-1	2.7	-4.3
88	88-2	2.7	-4.9
88	88-3	2.7	-4.0
88	88-4	2.8	-4.1
88	88-5	3.0	-4.5
88	88-6	3.0	-4.3
88	88-7	2.8	-4.3
88	88-8	2.9	-4.3
88	88-9	2.7	-4.4
88	88-11	2.7	-6.2
88	88-12	2.6	-6.4
88	88-14	2.5	-6.8
88	88-15	2.6	-5.9
89	89-1	2.6	-7.7
89	89-2	2.7	-5.7
89	89-3	2.6	-5.6
89	89-4	2.5	-5.8
89	89-5	2.4	-5.5
89	89-6	2.7	-4.6
89	89-7	2.9	-4.7
89	89-8	3.0	-5.6
89	89-9	2.2	-5.5
89	89-10	2.7	-5.0
89	89-11	3.0	-5.1
89	89-12	2.7	-4.6
89	89-13	2.6	-4.4
89	89-14	2.6	-4.9
90	90-1	3.0	-5.7
90	90-2	3.1	-5.4
90	90-3	3.2	-4.6
90	90-4	2.7	-4.4
90	90-5	3.0	-5.3
90	90-6	2.8	-6.1
90	90-7	2.9	-5.9
90	90-8	3.0	-4.4
90	90-9	3.1	-4.7
90	90-10	2.5	-4.8
90	90-11	2.7	-4.6
90	90-12	2.6	-5.6
90	90-13	2.7	-5.7

Quarry	Sample ID	d^{13}C	d^{18}O
90	90-14	2.7	-5.7
90	90-15	2.8	-4.7
90	90-16	3.0	-5.6
90	90-17	2.7	-5.0
90	90-18	2.8	-6.0
90	90-19	2.7	-5.5
91	91-1	2.7	-5.4
91	91-10	2.8	-5.8
91	91-11	3.0	-8.8
91	91-12	2.8	-9.0
91	91-13	2.7	-8.3
91	91-14	2.8	-9.4
91	91-15	2.8	-7.2
91	91-16	3.0	-8.4
91	91-11a	1.7	-7.1
91	91-13a	3.0	-8.5
91	91-15a	2.9	-6.8
91	91-17	3.1	-8.5
91	91-18	2.9	-8.6
91	91-19	2.7	-8.4
91	91-2	2.5	-5.6
91	91-20	2.6	-7.8
91	91-22	2.3	-8.5
91	91-23	2.9	-6.4
91	91-24	2.9	-6.6
91	91-25	2.9	-9.1
91	91-26	2.6	-7.9
91	91-27	2.7	-4.8
91	91-28	2.7	-5.1
91	91-29	3.0	-5.9
91	91-3	2.5	-6.1
91	91-30	3.2	-5.9
91	91-4	2.4	-5.7
91	91-5	2.9	-5.8
91	91-6	2.8	-6.7
91	91-7	2.6	-5.7
91	91-8	2.6	-5.1
91	91-9	2.9	-5.6
92	92-2	2.3	-5.4
92	92-3	2.7	-5.6
93	93-1	2.8	-8.4
93	93-10	3.4	-7.0
93	93-11	3.1	-8.7
93	93-12	2.7	-6.4

Quarry	Sample ID	d^{13}C	d^{18}O
93	93-13	2.7	-8.4
93	93-3	2.7	-7.5
93	93-4	3.3	-6.8
93	93-5	2.8	-8.1
93	93-6	3.0	-8.0
93	93-7	2.8	-7.6
93	93-8	3.0	-8.2
95	95-1	3.2	-7.7
95	95-10	2.8	-8.3
95	95-11	2.6	-9.4
95	95-12	2.4	-11.0
95	95-13	2.7	-9.7
95	95-14	2.6	-7.9
95	95-2	3.2	-8.1
95	95-3	4.3	-8.3
95	95-4	3.0	-6.8
95	95-5	3.9	-7.6
95	95-6	4.1	-8.4
95	95-7	3.2	-7.4
95	95-8	4.1	-7.8
95	95-9	3.6	-7.5
96	96-1	2.5	-8.7
96	96-2	3.1	-8.0
96	96-3	2.9	-8.1
96	96-4	3.5	-6.7
96	96-5	3.4	-6.7
96	96-6	2.6	-6.4
96	96-7	2.9	-8.2
96	96-8	2.6	-8.5
97	97-10	3.5	-7.6
97	97-11	3.4	-7.7
97	97-12	4.3	-6.5
97	97-13	4.3	-7.9
97	97-2	3.5	-8.1
97	97-3	3.7	-7.6
97	97-4	4.1	-7.6
97	97-5	3.4	-7.9
97	97-6	3.4	-7.7
97	97-7	3.9	-8.2
97	97-8	4.0	-7.2
97	97-9	3.3	-7.2
98	98-1	2.7	-6.9
98	98-2	2.5	-7.3
98	98-3	2.6	-7.5

Quarry	Sample ID	$\delta^{13}C$	$\delta^{18}O$
98	98-4	2.7	-8.7
98	98-5	2.5	-7.8
98	98-6	2.3	-9.4
103	103-1	2.9	-8.7
103	103-2	2.8	-7.6
103	103-3	2.7	-7.8
103	103-4	2.7	-9.1
103	103-5	2.6	-8.6
104	104-2	4.5	-8.1
104	104-3	3.7	-6.4
104	104-4	3.8	-6.8
105	105-1	2.9	-8.0
105	105-2	2.8	-7.3
105	105-3	2.8	-8.2
105	105-4	3.1	-8.3
105	105-5	2.7	-9.2
105	105-6	2.6	-9.3
105	105-7	3.0	-7.5
106	106-12	2.9	-9.9
106	106-14	4.0	-7.9
107	107-1	3.9	-8.7
107	107-10	2.8	-8.4
107	107-11	3.1	-8.5
107	107-12	2.7	-8.2
107	107-13	2.9	-8.9
107	107-14	2.7	-8.4
107	107-2	3.2	-6.7
107	107-3	2.9	-8.4
107	107-4	2.9	-8.2
107	107-5	3.2	-8.1
107	107-6	2.9	-8.2
107	107-7	2.9	-8.4
107	107-8	2.8	-7.7
107	107-9	2.2	-8.4
109	109-1	4.3	-8.1
109	109-2	3.6	-6.9
109	109-3	3.4	-6.7
109	109-4	3.5	-6.7
109	109-5	4.4	-6.7
109	109-6	3.5	-6.5
109	109-7	4.2	-6.5
122	122-1	3.1	-7.9
122	122-2	2.9	-8.0
124	124-1	2.8	-7.3

Quarry	Sample ID	d^{13}C	d^{18}O
125	125-1	3.3	-6.6
125	125-2	2.7	-7.2
127	127-1	3.1	-7.5
129	129-1	4.6	-8.3
129	129-2	4.4	-7.8
130	130-1	2.9	-9.2
130	130-2	2.8	-6.1
130	130-3	3.2	-8.1
130	130-4	3.1	-9.2
130	130-5	2.6	-11.7
130	130-6	4.0	-9.0
130	130-6	3.3	-8.4
131	131-1	2.8	-7.2
131	131-2	4.0	-7.1
131	131-3	3.7	-7.1
132	132-1	2.7	-7.9
132	132-10	4.3	-5.8
132	132-2	2.9	-7.7
132	132-4	3.2	-7.7
132	132-5	4.1	-6.9
132	132-6	4.0	-6.7
132	132-8	3.7	-6.2
132	132-9	3.5	-6.0
133	133-1	3.6	-6.2
133	133-2	2.8	-6.8
134	134-1	2.9	-5.9
134	134-2	2.9	-6.5
135	135-1	3.8	-5.8
135	135-2	3.1	-8.8
135	135-3	3.6	-6.4
135	135-4	2.7	-6.0
136	136-1	4.3	-5.0
136	136-10	4.1	-6.4
136	136-11	4.5	-5.5
136	136-13	3.6	-6.6
136	136-14	3.5	-6.6
136	136-15	4.2	-5.7
136	136-16	3.4	-6.0
136	136-18	3.4	-5.6
136	136-2	3.4	-5.1
136	136-3	4.2	-5.8
136	136-4	3.5	-6.3
136	136-5	4.1	-5.5
136	136-6	3.9	-7.5

Quarry	Sample ID	d^{13}C	d^{18}O
136	136-8	3.4	-6.3
136	136-9	4.2	-5.7
137	137-1	4.2	-11.4
137	137-2	4.0	-8.1
142	142-1	3.7	-9.6
142	142-4	3.9	-9.6
154	154-1	3.2	-6.5
154	154-2	3.6	-7.1
155	155-2	3.0	-8.3
156	156-1	3.1	-6.2
156	156-2	3.2	-7.0
157	157-1	3.4	-6.8
158	158-2	2.9	-7.7
158	158-3	3.4	-7.4
158	158-4	2.9	-6.0
159	159-1	4.6	-8.3
162	162-1	3.4	-6.7
162	162-2	3.4	-8.0
164	164-1	3.4	-9.3
164	164-2	2.8	-5.4
164	164-3	2.6	-6.4
164	164-4	2.7	-6.1
164	164-6	2.8	-8.9
164	164-7	2.7	-5.8
165	165-1	2.6	-5.0
168	168-1	3.3	-7.8
169	169-1	4.5	-7.7
169	169-2	4.7	-7.3
169	169-3	4.4	-5.7
169	169-4	4.4	-7.2
169	169-5	4.9	-7.0
169	169-6	5.1	-6.5
171	171-1	4.1	-7.3
171	171-2	3.9	-8.4
172	172-1	3.5	-8.0

Table 2. Score from Independent Sample t-Test comparing mean of Marble Unit 3 to the mean of the conjoined group of Marble Units 1 and 2. The low significance value of the Levene's test for equality of variance rejects the null hypothesis of equal variance within the two groups. Inference must be made assuming unequal variance. The 95% confidence interval do not include a zero. Therefore, the null hypothesis of equality of means is rejected.

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
d13C	Equal variances assumed	166.970	.000	-11.649	379	.000	-.63155	5.4214E-02	-.73815	-.52495
	Equal variances not assumed			-12.363	276.715	.000	-.63155	5.1083E-02	-.73211	-.53099

CHAPTER 5

CONCLUSION

The research presented significantly contributes to the study of the ancient Pentelic marble quarry region and to marble provenance studies in general. Although the desire to characterize ancient marble quarries is an archaeological inquiry, this study has shown that the problem of marble characterization (or that of any lithic material), by its very nature, must be addressed using geologic techniques and methodology. It is essential that a geologic approach be undertaken in all phases of research – from project design to fieldwork to analyses to interpretation.

At the start of this study the assumption of stable isotope and geochemical homogeneity in marble quarries was addressed. A review of the sample reference collection used to characterize Mt. Pentelikon in earlier studies was found to be insufficient to test this critical assumption. Furthermore, the published maps insufficiently represented the quarry area in terms of the local geologic environment and the distribution and location of ancient quarries. These findings lead to what is perhaps the most significant contribution of the current research. That is, the undertaking of an extensive and systematic field survey and sampling program of the Pentelic quarry region. The resultant digital maps of the quarry area and detailed catalog of the extensive sample reference collection allow for geographical distributional analyses of quantitative data. Without the systematic approach to fieldwork, mapping and sample collection, it would not be possible to identify intra-quarry distinctions within the Pentelic quarry region.

The geologic map, the large reference sample collection and $\delta^{13}C$ and $\delta^{18}O$ data show statistically viable compositional trends within the quarry region. The map reveals that the quarries fall into three distinctive marble units. The regional stable isotope pattern highlights this separation. Marble Units 1 and 2 have a much broader range of $\delta^{13}C$ ratios than Marble Unit 3. Likewise, the upslope section of Marble Unit 3 has significantly more positive $\delta^{18}O$ ratios than all of the other Pentelic quarries.

Discrimination between Pentelic quarries can not be established with whole-rock compositional data. NAA data of 62 samples from five distinct quarry groups representing the three Marble Units show no homogeneity within each quarry group. Thus, no chemical structure can be established that discriminates between Pentelic quarries. Furthermore, a geologic interpretation of the NAA data provides grounds to question assumptions of the applicability of the analytical technique. NAA measures trace- and rare- earth element concentrations in the entire sample. Accessory minerals that are common in Pentelic marble, including silicates and oxides, contribute significantly to the total elemental composition. Since the percentage of accessory minerals varies greatly between Pentelic samples and elemental concentrations vary greatly within accessory minerals, the NAA data of Pentelic marble samples are determined to be of little consequence. Future trace- and rare-earth compositional studies should focus on developing a protocol for ICP compositional analyses in which only the carbonate fraction of the marble sample is analyzed. By limiting the analysis to the carbonate fraction random elemental spikes associated with noncarbonate impurities can be avoided providing a more effective database.

A systematic approach to characterizing marble sources should be adopted for all quarry characterizing studies. Extensive fieldwork must be undertaken and sufficiently representative sample reference collections obtained and analyzed in order to develop a stable isotope and compositional database that adequately reflects the true geologic nature of the study area. The studies by Matthews et al. (1992) and Kane et al. (1992, 1995) suggested stable isotopic structure within the Pentelic quarries. Subsequent investigations of the database used by these researchers revealed that it insufficiently represented the quarry area. Reviews of other important ancient quarry regions must be undertaken and systematic fieldwork and analyses carried out where needed, in order to improve the representative nature of the Aegean marble databases. The improved database may increase the discriminating powers between and possibly within other marble quarries. A high-resolution database of significant marble sources throughout the Mediterranean basin will allow scholars of antique marble artifacts to expand the limits of their research and permit them to broaden the scope of their research questions.

A high-resolution database also will further promote the use of quantifying techniques in marble studies. There is still a school of scholars that resist quantitative techniques of marble provenance. Rather than submit a negligible portion of a marble artifact for geochemical analysis, the inherently subjective technique of visual characterization is still preferred. For example, Abraldes (1996) in her meticulous dissertation investigating the history of exportation and use of Pentelic marble in architecture and epigraphy throughout antiquity identifies many monuments as Pentelic based on a short list of macroscopic criteria. Her study does not employ a single quantitative technique because "none of the geochemical methods have proved conclusive" due to a limited number of samples in the database (Abraldes 1996: 6). Although it is true that the reference sample database is inadequate in many instances, the macroscopic criteria used to identify Pentelic marble is based on a much more limited and biased set of assumptions. Statistically, no database will ever be 100% conclusive. Yet, an objective, quantifiable protocol for marble characterization provides physical evidence to support assigned provenances. Add to that the ability to identify regions within a quarry, the analytical approach to marble identification adds new dimensions to the growing field of marble studies.

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