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ORIGINAL ARTICLE

# Ancient white and grey marbles from Aphrodisias: multi-method characterization

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**Abstract**
The paper presents the results of the archaeometric investigation, conducted for the first time with the use of a wide range of analytical methods, on white and grey marbles exploited in the so-called City and Regional Quarries of Aphrodisias (south-western Turkey). The research, based on a multi-method approach and performed on a representative set of samples, was aimed to provide a comprehensive evaluation of the most important properties of Aphrodisian marbles. The material studied here shows a large overlap in petrographic and geochemical features among the marbles exploited in local and regional quarries, as well as with most of the widespread marbles used in Antiquity. Surprisingly, none of the methods used here, either by themselves or used in combination, is sufficient to discriminate reliably between Aphrodisian and other marble types (mainly Paros-Lakkoi and Prokonnesos), as well as between marbles extracted from the City and Regional Quarries. The only provenance indicator is the depleted $\delta^{13}C$ values below +0.5‰ for the grey variety from sectors AF3 and AF9, which constitute 15% of collected samples. The presumed international use of Aphrodisian marbles may be difficult to verify based on these indistinct outcomes. Another important element of the study are the topographical measurements used to estimate the volume of extracted material.

**KEYWORDS**
Aphrodisias, Asia Minor, Caria, geochemistry, marble quarries, petrography, provenancing

## INTRODUCTION

Aphrodisias, an important town in Caria (Fig. 1), now Geyre (province of Aydın, south-western Turkey), is a remarkably well-preserved Graeco-Roman city, famous in Antiquity for its cult sanctuary dedicated to the goddess Aphrodite and for its school of sculptors connected to the local presence of good-quality marble sources. Systematic excavations, carried out in the second half of the past century by New York University and the University of Oxford, have revealed unusually well-preserved civic buildings and a large amount of marble sculptures. The city lies at the centre of a number of debates in contemporary scholarship on marble production in the Roman period. The notion that Aphrodisias was the centre for an important 'school' of virtuoso sculptors took root in the early 20th century (Collignon, 1904; Floriani Squarciapino, 1943; Jacopi, 1939–1940). The substantial body of sculptures uncovered so far has led to the idea that Aphrodisian workshops were prominent in the Roman world (Bergmann, 1999: 26–43, 55; Hannestad, 1994: 127–143).

Recent scholarly research on Aphrodisias' marble quarries sheds valuable new light on the character of the local industry and on many outstanding questions. In addition to the well-known sources located 2 km north of the city (the so-called City Quarries), eight new quarry sites were discovered as part of the Aphrodisias Regional Survey (ARS), conducted by Leah Long (Long, 2012: 165–201; Stearns, 2012). The main goal of the ARS was to document the archaeology and geology of the newly discovered quarries and to investigate the role that marble played in the social and economic life of Aphrodisias in the Roman period. Given the prominence of Aphrodisian sculptors and the materials they used for the history of the city, it was important to understand if the local marble was used primarily for civic adornment, or also for trade. The results of this previous research showed that the city relied on a much larger network of quarries than realized, and that the exploited natural resources, while apparently adequate to support the population of the Roman period city, were not so extensive that they could be exported.

The most reliable and commonly applied characteristics and properties that allow for unequivocal identification of the ancient marbles source are mineral composition (including accessory minerals), textural features, cathodofacies, bulk elemental composition and C-O-Sr isotope composition of carbonate. Although these data have been published for Aphrodisias, they are disseminated in several publications and show that the Aphrodisian marble (AM) may be easily confused with other classical marbles from Mediterranean quarries, especially with Prokonnesos and Paros-Lakkoi (variety 2). This is a major obstacle for verifying the use of AM in Antiquity.

An interdisciplinary archaeo-geological international team carried out extensive fieldwork in the quarries of Aphrodisias in 2015 as part of the 'Marmora Asiatica' project,[1] led by the Institute (now Faculty) of Archaeology of the University of Warsaw. The new survey concerned both the City Quarries, as well as the Regional Quarries, all situated in Karacasu administrative district. It covered an area of over 500 $km^2$ divided into 12 sectors, labelled from AF1 to AF12 (Fig. 1). The City Quarries, situated around 2 km north-east of Aphrodisias, extend over an area of approximately 1.5 $km^2$. They belong to sector AF9 on Taşkesiği hill and sector AF12 on Ardıçlı and Sarnıç hills, which corresponds, respectively, to ridges 2–4 as reported by Ponti (1996).[2]

A large number of marble samples was collected from the quarries of Aphrodisias and a wide range of research methods was applied. Apart from detailed topographical

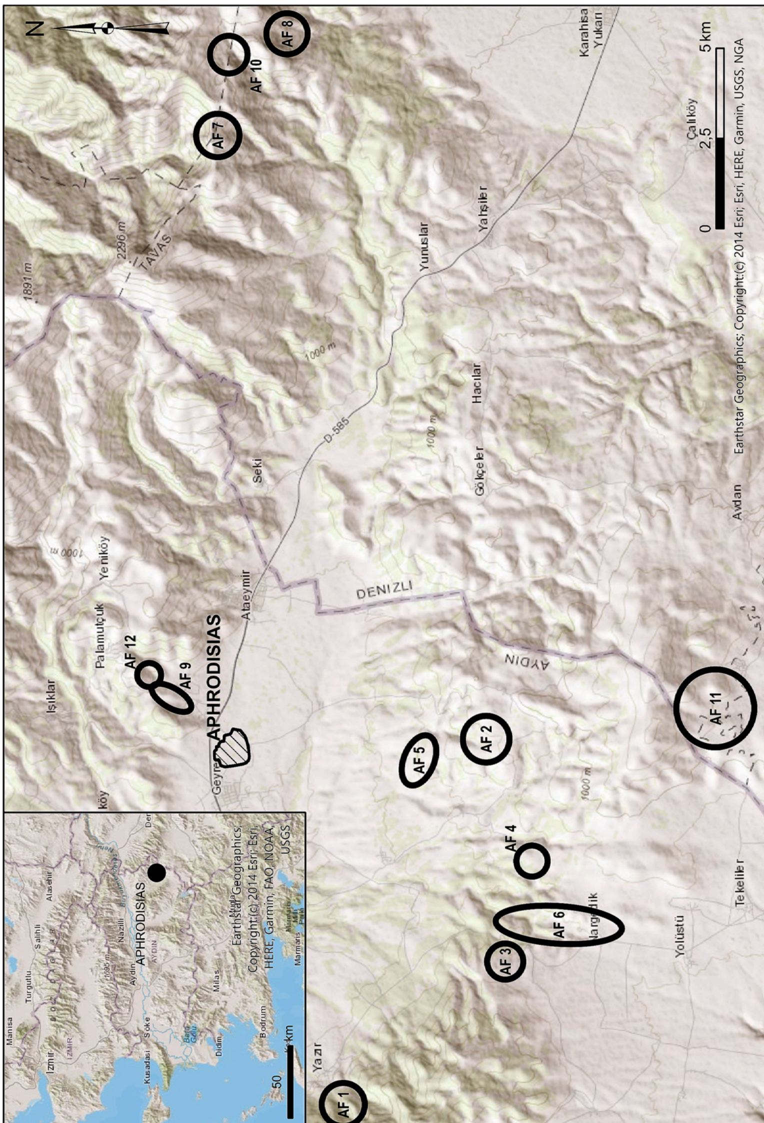


FIGURE 1 Location of the Aphrodisian quarries.

documentation, we provide a comprehensive mineralogical–petrographic and geochemical characterization of marbles based on X-ray diffractometry (XRD), thin section optical microscopy, cathodoluminoscopy (CL), scanning electron microscopy (SEM), inductively coupled plasma–optical emission spectroscopy (ICP-OES), and C, O and Sr isotope measurements. The advantage of this work is that the data are presented for a coherent and representative set of samples collected from all known ancient marble quarries. With this dataset, we attempted to address following three important issues:

- The first was to update the existing state of knowledge about archaeometric aspects of AM and to constrain the potential for discrimination between Aphrodisian and other important ancient marble sources. We intended to improve the information on the minero-petrographic features (related to the protolith and the metamorphic history of specific marble petrogenesis) that have been not considered in the previous studies on Regional Quarries, and the geochemical characteristics to allow for a more conclusive characterization of the white and grey-bluish varieties.
- The second objective regards local marble use and municipal and/or private entrepreneurial policies and strategies behind the quarrying industries at Aphrodisias. Were the individual Regional Quarries and City Quarries used for specific buildings and sculptures and/or in different time periods? To answer these questions, we evaluated possible differences between individual quarry sectors, which could allow for discrimination through scientific provenance techniques between the local AM sources. If such discrimination is possible, we would suggest a proper sampling programme for Aphrodisias' archaeological monuments and artworks to understand the city's history of marble quarrying more fully.
- The broader research question concerns the use of AM outside their place of origin. Sculptures with signatures of the local craftsmen are known both from Rome and from elsewhere in the Empire. It is of great scholarly interest to understand whether Aphrodisian sculptors relied on marble from their homeland and if AM was exported. The position of modern scholars differs somewhat on this matter. Some advocate the use of AM outside Asia Minor as a raw material for the Aphrodisian sculptors settled outside their homeland (e.g., Attanasio et al., 2012: 536–539). Others support the idea of its exclusive local use, although not totally excluding the possibility that fully carved sculptures were exported from Aphrodisias to the wider Roman market (e.g., Long, 2012; Russell, 2013). Therefore, it is also necessary to consider if the exploitation of local sources met the demand for marble within Aphrodisias and its environs. For this purpose, detailed topographical measurements were performed to estimate the volume of marble removed from all known and surveyed quarries.

## HISTORICAL SETTING AND CONTRIBUTION OF THE RESEARCH TO PREVIOUS STUDIES

Founded in the early second century BCE as a Hellenistic city, Aphrodisias took on a monumental character in the reign of Augustus and flourished under the patronage of local elites well into Late Antiquity. Aphrodisias was a typical small to medium-sized city under Roman rule until it took on some regional importance when it became the capital of the province of Caria and the seat of a bishop in 300 CE. Quarrying was tied to the urban development of the city and became important business during the most intensive phases of building in the first and second centuries CE (Ratté, 2002). The epigraphic and archaeological evidence for sculpture found at the site, the existence of a sculptor's workshop, and large number of marble sources located close to the city point to the important role the civic quarrying industry played, and provide an unparalleled picture of marble production in the ancient world.

The availability of marble resources allowed for an exceptional local carving tradition to take root in the Hellenistic period. Craftsmen used their local marbles to adhere to a traditional, Hellenistic style of statuary as well as keep abreast of current artistic trends of the Roman Empire, pioneering a successful Hellenistic–Roman style much in demand in Antiquity. Epigraphic evidence suggests that sculptors from Aphrodisias were also famous abroad and worked on special commissions throughout the Roman Empire. Nearly 40 inscribed signatures have been found on sculptures in Italy, Greece, Crete and Asia Minor, as well as at Aphrodisias itself (Erim & Roueché, 1982: 102–115; Pensabene, 2002: 217–219).

The quarries of Aphrodisias have been subject to several studies. The City Quarries have been documented archaeologically and geologically and also sampled for isotopic and petrographic analysis by many research groups (Asgarı, 1992; Attanasio et al., 2006; Joukowsky, 1988; Lazzarini et al., 2002; Long, 2012: 181–185; Monna & Pensabene, 1977; Ponti, 1996; Rockwell, 1996; Russell, 2016: 251–262; Stearns, 2012: 148–158). Eight new quarry sectors (56 quarrying sites) were discovered and documented in the region of Aphrodisias as part of the ARS (Long, 2012; Stearns, 2012). These quarries are located from 5 km to as much as 17 km (Babadağ quarries) from the ancient city. The large reserves of white and grey marbles, in close and convenient proximity to Aphrodisias, would have supplied most of the marble used in civic building and sculpture. Investigation of the regional marble quarries also included archaeometric analysis, however, were limited to stable C and O isotope analyses (Long, 2012; Stearns, 2012). A series of five sectors (AF2–AF6) located on the south side of the valley provided the white marble variety with small bluish-grey lenses, likely opened when demand peaked. Several sources of metamorphic carbonate rocks with different textures and tints are located at a considerable distance from the city. Eleven kilometres to the west, the quarry at Yazır (AF1) has a mottled blue-grey and white marble that was primarily used for wall revetment and monolithic columns in a number of buildings, beginning in the second century CE. A quarry on the mountain ridge situated south-east to the local landmark of the Babadağ mountain (AF7), located 17 km to the east of Aphrodisias, furnished a bluish and white carbonate meta-breccia; nearby, a quarry on the southern slope of the ridge, Çamova Tepe (AF8), provided a purplish-grey and white carbonate meta-breccia used as revetment and small columns within the city. Additionally, the 'Marmora Asiatica' project added a new sector AF10 situated on the eastern ridge of Babadağ (closer to the summit) that provides white and grey to violet carbonate meta-breccia. Approximately 14 km south-west from Aphrodisias, located near the village of Kırköy (sector AF11), are modern quarries with grey and black fossiliferous limestones and meta-limestones. The richness and variety of marbles provided a steady stream of materials that allowed Aphrodisian artisans to experiment with and use their marble in unique ways. For example, the fine-grained blue-grey marble, found in thick beds in the lowest unit in the City Quarries, was used for special commissions, such as the large Blue Horse in the Troilos and Achilles group (Long, 2012: 182–188). The research conducted as part of the ARS concluded that while the City Quarries supplied white marble for urban building, the smaller quarry sources in the territory of Aphrodisias were also used within its buildings.

In the past decade there has been a spate of research conducted on marble exploitation and use in the cities of Asia Minor. New data herein reported allows us to update our current understanding about whether Aphrodisias was typical—or exceptional—in the way it used its local resources. Although the question of the AM export has been raised in the past, investigations by 'Marmora Asiatica' on the geochemistry and petrography of the marbles, as well as on the volume of stone removed from the quarries, provide important new insights. In the past decades, quarry surveys in Turkey have revealed an abundance of smaller scale quarries operated by urban polities (Long, 2017). At each site, local builders were constrained by the unique geological properties of regional marble sources and adapted accordingly (Long, 2016). 'Marmora Asiatica's' findings have added to the growing corpus of marble quarrying sites in

Asia Minor. At the same time, our systematic approach, using the same methods across different sites, provides a finer resolution of marble use at the local and international levels. Our volumetric studies shed light on the scales of quarrying and broader economic questions, while rigorous archaeometric testing, with the goal of finding unique fingerprints, act as a springboard for whether or not it is feasible to undertake future research on testing archaeological artefacts.

## GEOLOGICAL SETTING OF THE QUARRIES

The marble quarries studied around Aphrodisias are located on the south-eastern flank of the Menderes Massif (e.g., Dora et al., 1991), a large crystalline complex in western Anatolia. The Massif comprises an Upper Neoproterozoic basement (core) consisting mainly of ortho- and paragneiss, various schists and amphibolites (e.g., Candan & Dora, 1998). The overlying ‘schist and marble envelope’, also known as the ‘cover series’, mainly includes metaclastic rocks and marbles with ages spanning from the Lower Palaeozoic to Palaeogene. In the close vicinity of Aphrodisias, the outcropping units represent the ‘schist and marble envelope’. With the exception of the quarries to the west-south-west of Yazır village, all studied and sampled locations including the northern City Quarries located 2 km to the north of Aphrodisias ancient city, south-eastern quarries (on the ridge between Nargedik and Avdan) and north-eastern quarries to the north of Seki Köy, southern Babadağ Mountain, are located in the same stratigraphic succession (e.g., Okay, 2001), namely within the thick Jurassic–Cretaceous metacarbonate succession of different Menderes nappes (MTA, 1994). Detailed information regarding the regional geological setting and local geology in each quarry sector investigated are given in Appendix S1 in the additional supporting information.

## MATERIAL AND METHODS

The methodological approach related to the surveying methods, volumetric measurements, mapping the analytical investigation—including standard thin section petrography, cathodoluminoscopy, SEM, XRD, stable C and O isotope measurements, Sr isotope analyses, ICP-OES for major to trace element contents—and the material examined through these methods are reported in detail in Wielgosz-Rondolino et al. (2020) and in Appendix S2 in the additional supporting information. For the analytical part of this study 123 white and grey marble samples were collected from the sectors AF2–AF6, AF9 and AF12, in the City and Regional Quarries. The sampling was representative of the extent, importance and site variability of the rocks in the quarries, and for the understanding of the genesis and relationships of different lithologies.

## RESULTS

### Volumetric estimation of quarries

Volumetric measurements of the extracted material were performed through the use of a 3D laser scanner and RTK Global Positioning System (GPS) receiver, which allowed for a high precision of the measurements with mm to cm spatial resolution (see Table S3.1 in Appendix S3 in the additional supporting information). The volume of marble extracted in the City Quarries on the Taşkesiği ridge (sector AF9) is estimated at 169,400 $m^3$, in the Hançam Quarries (sector 3) at 7500 $m^3$; and in all Regional Quarries (except Hançam), previously calculated by Leah Long (2012), adds to about 50,000 $m^3$. Thus, the total amount of material extracted from the quarries of Aphrodisias apparently did not exceed 230,000 $m^3$. This gives between 46,000 and 75,900 $m^3$ of effectively usable material if we estimate that 20–33% of the total amount of the extracted stone constituted the final product of the ancient quarries.[3] This volume was visibly too small to satisfy the needs of civic building at Aphrodisias, where 125,000 $m^3$ of marble was used only for the city walls and main buildings alone (e.g., Bouleuterion, Sebasteion, stadium, temple of Aphrodite, both agorai, etc.), not including the sculptures and sarcophagi (Long, 2012: 181).

We used the same techniques to calculate the total volume of marble extracted in other quarries of Asia Minor. Quick comparisons on the scale of exploitation suffice to mention the imperial quarries at Dokimeion, where the gross volume of marble extracted in ancient times, limited to only in Quarry I and Quarry II (Röder, 1971), amounted to 2,300,000 $m^3$. On the other hand, the well-known Göktepe white marble quarries are small-scale, amounting to only about 17,000 $m^3$ (Wielgosz-Rondolino et al., 2020; see also Attanasio et al., 2009). The numbers calculated as part of 'Marmora Asiatica' demonstrate the role of the major, long-lasting 'industrial-'scale imperial quarries in the international marble trade, which Aphrodisias clearly was not a member.

## Petro-archaeometric characteristics of Aphrodisian marbles

Archaeometric investigations were carried out on the most common AM, consisting of a white and a grey variety. Both varieties can co-occur in a single quarry and are chiefly composed of calcite. The white variety is predominantly homogeneous, but some samples exhibit indistinctive, discontinuous laminae showing a slightly darker, greyish (enriched in non-carbonate minerals) or creamy colour (enriched in dolomite). Beige or pinkish dolomitic marble intercalations (about 0.5 m thick), not studied in this work, occur rarely within the white marble sequences. The grey variety, which often exhibits a bluish tint, can be homogeneous or laminated with mica-rich layers oriented roughly parallel to the bedding. Other marble types from Aphrodisias, not studied in this work, include mostly a wide range of brecciated lithologies, for example, similar to Dokimeian *pavonazzetto* or *kaplan postu* extracted mainly in sectors AF7, AF8 and AF10, mottled blue-grey and white marble from sector AF1, and grey and black fossiliferous limestones and meta-limestones from modern quarries in sector AF11, where traces of ancient mining were not observed. These varieties were not observed co-occurring with either the white or grey marble types in any of the quarries.

### Mineralogical analysis and optical microscopy

The X-ray powder diffraction of 28 samples selected from different quarries indicated that their majority is composed of calcite only or contain traces-to-small amounts of dolomite, which rarely becomes abundant, for example, AF5A1 (Table 1). Relatively high dolomite content is also reflected in the elevated Mg concentration (see Section *Elemental composition* and Table 2). A total of 38 thin sections were prepared and examined under the polarizing microscope; the results are reported in Table 1. From this one may see that in general, the fabric of the examined white and grey AM is crystalloblastic–heteroblastic, mostly forming a mosaic of calcite crystals showing a medium-to-coarse grain size (MGS range = 1.2–4.4 mm). Moreover, grey AM are usually finer grained (median MGS = 1.8 ± 0.7 mm) than the white ones (median MGS = 2.8 ± 0.8 mm).

**TABLE 1** Results of polarizing microscopy of white and grey Aphrodisian marbles.

| *Quarry sector* | *Sample* | *Texture* | *Fabric type* | *MGS (mm)* | *Calcite crystals boundaries* |
|---|---|---|---|---|---|
| Ören Quarries AF2 | AF2A1 | HE | Mortar/mosaic with fine-grained areas and interlocked crystals | 1.7 | Embayed to sutured |
| | AF2B2 | HE | Mosaic with interlocked crystals | 2.4 | Sutured |
| | AF2F1 | HE | Mosaic with fine-grained areas | 2.4 | Embayed |
| | AF2J1 | HE/HO | Mosaic, polygonal | 2.1 | Curved to embayed |
| Hançam Quarries AF3 | AF3B1 | HE/HO | Mosaic, tending to polygonal, with rare triple points | 1.9 | Straight to curved |
| | AF3C5 | HE | Mosaic, foliated | 1.8 | Embayed |
| | AF3D1 | HE | Mosaic | 3.0 | Embayed |
| Çamarası Quarries AF4 | AF4B1 | HE | Mosaic, foliated slightly strained | 2.6 | Embayed |
| | AF4F2 | HE | Mosaic, slightly strained | 2.8 | Curved to embayed |
| Kızıl Çağıl Quarries AF5 | AF5A1 | HE | Mosaic with fine-grained areas | 1.2 | Embayed to sutured |
| | AF5C1 | HE | Mosaic with fine-grained areas | 2.5 | Embayed to sutured |
| Nargedik Quarries AF6 | AF6D2 | HE | Mosaic | 1.4 | Curved to embayed |
| City Quarries AF9 | AF9A1 | HE | Mosaic | 1.7 | Embayed |
| | AF9A3 | HE | Mosaic | 2.8 | Curved to embayed |
| | AF9A5 | HE/HO | Mosaic, slightly foliated | 1.8 | Curved |
| | AF9A8 | HE/HO | Mosaic, slightly foliated | 1.8 | Curved to embayed |
| | AF9A14 | HE | Mosaic/mortar, strained and foliated | 3.4 | Embayed to sutured |
| | AF9B1 | HE | Mosaic | 3.8 | Embayed to sutured |
| | AF9B3 | HE | Mosaic, slightly strained | 2.8 | Embayed |
| | AF9B4 | HE | Mosaic, foliated | 1.6 | Curved to embayed |
| | AF9B5 | HO | Mosaic, slightly foliated | 1.2 | Curved to embayed |
| | AF9B9 | HE | Mosaic, strained | 3.7 | Embayed |
| | AF9D1 | HE | Mosaic/mortar | 3.0 | Embayed |

(Continues)

**TABLE 1** (Continued)

| *Quarry sector* | *Sample* | *Texture* | *Fabric type* | *MGS (mm)* | *Calcite crystals boundaries* |
|---|---|---|---|---|---|
| | AF9D6 | HE | Mosaic, slightly foliated | 1.6 | Embayed to curved |
| | AF9D10B | HE | Mortar, slightly strained | 3.2 | Embayed |
| | AF9D20B | HE | Mosaic, foliated and strained | 4.4 | Sutured |
| | AF9D24B | HE | Mosaic, foliated | 2.0 | Embayed |
| | AF9F3 | HE | Mosaic/mortar | 3.4 | Embayed |
| | AF9F6 | HE | Mosaic, fine-grained | 1.7 | Embayed |
| | AF9G3 | HE | Mosaic, slightly strained | 3.0 | Curved to embayed |
| | AF9II1 | HE | Mosaic, slightly strained | 3.8 | Embayed to sutured |
| City Quarries AF12 | AF12A3 | HE | Mosaic/mortar. Mosaic, slightly strained | 3.2 | Embayed |
| | AF12B1 | HE | Mosaic/mortar | 2.2 | Embayed to sutured |
| | AF12B3 | HE | Mosaic/mortar | 3.4 | Embayed to sutured |
| | AF12B9 | HE | Mosaic, strained/mortar | 2.3 | Sutured |
| | AF12C2 | HE | Mosaic, foliated, with intergranular fine grain | 1.6 | Embayed to sutured |
| | AF12E1 | HE | Mosaic, slightly foliated and strained | 3.5 | Curved to embayed |
| | AF12F2 | HE | Mosaic, foliated, with fine-grained areas | 1.6 | Embayed to sutured |

**TABLE 1** (Continued)

| | Accessory minerals | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Quarry sector* | *Qtz* | *Mca* | *Gr* | *Ap* | *Fe-bearing minerals* | *Ep* | *Pl* | *Ttn* | *Dol** | *Colour* | *Notes* |
| Ören Quarries AF2 | | | +++ | ± | ±(Py; lm) | | | | | White | Holotype, similar to Thasos-3 |
| | | ± | +++ | | ++(Py) | | | | | White | Holotype, similar to Thasos-3 |
| | | | +++ | | ±(Py; hem) | | | | | White | Holotype |
| | | ± | +++ | ± | +(Py; hem) | | | | | Grey | |
| Hançam Quarries AF3 | | | +++ | ± | ±(Py) | | | | ± | White | |
| | ± | ++ | +++ | ± | ±(hem) | | | | | Grey | |
| | | | +++ | | ±(Py) | | | | | White | Holotype |
| Çamarası Quarries AF4 | | ± | ++ | | | | | | | White | Holotype |
| | | | ++ | ± | ±(Py; hem) | | | | | White | Holotype, similar to Paros-2 |
| Kızıl Çağıl Quarries AF5 | | | +++ | ± | | | | | +++ | White | |
| | ? | | +++ | | +(Py) | | | | | White | Holotype |
| Nargedik Quarries AF6 | | | ++ | | +(Py) | | | | | White | |
| City Quarries AF9 | + | + | +++ | + | | | | | | Grey | Holotype |
| | ± | + | +++ | ± | | | | | | Bluish | Holotype |
| | + | + | ++ | ± | +(Py: Hem) | | ± | | | Grey | Holotype, K-mica inside calcite |
| | + | ++ | +++ | + | ±(Py) | | | + | | Bluish | Holotype |
| | | | +++ | | | | | | | White | Holotype |
| | ? | ± | ++ | | +(Py) | | | | | White | Holotype |
| | | ± | ++ | ± | | | | | | White | Holotype |
| | + | ++ | +++ | ± | +(hem; lm) | | | | | Grey | K-mica trails |
| | ± | + | +++ | ± | +(Py: Hem) | | | | | Grey to bluish | Holotype, K-mica trails |

(Continues)

**TABLE 1** (Continued)

| | *Accessory minerals* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Quarry sector*** | ***Qtz*** | ***Mca*** | ***Gr*** | ***Ap*** | ***Fe-bearing minerals*** | ***Ep*** | ***Pl*** | ***Ttn*** | ***Dol**** | ***Colour*** | ***Notes*** |
| | | | ++ | ± | | | | ± | | White | Holotype, fluid inclusions? |
| | | | ++ | | ±(Py; hem) | | | | | White | Holotype, similar to Prokonnesos |
| | + | ++ | +++ | | ±(Py; hem) | ± | | ± | | Grey | |
| | | | ++ | | +(Py; hem) | | | | | White | Holotype |
| | | | +++ | ± | ± (Py) | ± | | ± | | White | Holotype |
| | ++ | +++ | +++ | ± | ++(Py; hem) | | | | | Grey | K-mica trails |
| | | ± | +++ | ± | ±(Py; hem) | | | | | White | Holotype, similar to Prokonnesos |
| | | | +++ | ± | ±(Py) | | | | | White | |
| | | ± | +++ | | ±(Py) | + | | ± | | White | Holotype |
| | ± | | +++ | ± | ++(Py; hem) | | | | | Grey | Holotype |
| City Quarries AF12 | | | ++ | ± | ±(Py) | | | | | White | Holotype |
| | | | ++ | ± | +(Py) | | | | | White | Holotype, well interlocked crystals similar to Prokonnesos |
| | | | +++ | ± | ±(Py) | | | ± | | White | Holotype, similar to Prokonnesos |
| | | | +++ | | | | | | | White | Holotype |
| | ? | | +++ | | | | | | | White | Similar to Thasos-3 |
| | | | +++ | | ±(Py) | | | ± | | White | Holotype |
| | ? | | +++ | ± | ±(Py; hem) | | | | | White | |

*Note*: Ap, apatite; Dol*, dolomite, detected by X-ray diffraction analysis; Ep, epidote; Fe-bearing minerals (Hem, haematite; Lm, limonite; Py, pyrite); Gr, graphite; HE, heteroblastic; HO, homeoblastic; Mca, mica; Qtz, quartz; titanite; MGS, Pl, plagioclase; maximum grain size; +++, very abundant; ++, abundant; +, present; ±, traces; ?, uncertain.

**TABLE 2** Geochemical proprieties of white and grey Aphrodisian marbles.

| *Quarry sector* | *Sample* | *$\delta^{18}O$ (PDB)* | *$\delta^{13}C$ (PDB)* | *$^{87}Sr/^{86}Sr$* | *Ca (%)* | *Mg (µg/g)* | *Mn (µg/g)* | *Fe (µg/g)* | *Sr (µg/g)* |
|---|---|---|---|---|---|---|---|---|---|
| Ören Quarries AF2 | AF2A1 | −2.03 | 1.96 | 0.707792 | 37.6 | 6180 | 13 | 52 | 167 |
| | AF2B2 | −2.14 | 1.99 | | 39.3 | 3410 | 12 | 44 | 169 |
| | AF2F1 | −2.81 | 1.52 | 0.707713 | 39.2 | 815 | 19 | 37 | 91 |
| | AF2J1 | −2.64 | 1.99 | 0.707822 | 39.9 | 3010 | 46 | 144 | 145 |
| | AF2J2 | −2.69 | 2.03 | | 39.2 | 2070 | 40 | 63 | 152 |
| Hançam Quarries AF3 | AF3B1 | −4.14 | 0.97 | 0.707706 | 37.8 | 5070 | 9 | 35 | 95 |
| | AF3C5 | −3.24 | −2.76 | 0.708220 | 38.3 | 2790 | 197 | 2,210 | 110 |
| | AF3D1 | −3.84 | 1.55 | | 38.4 | 988 | 18 | 83 | 124 |
| Çamarasi Quarries AF4 | AF4B1 | −3.25 | 2.07 | 0.707658 | 39.2 | 1300 | 6 | 12 | 99 |
| | AF4F2 | −3.23 | 1.46 | | 39.6 | 827 | 20 | 38 | 92 |
| Kizli Çağil Quarries AF5 | AF5A1 | −2.35 | 2.00 | 0.707671 | 31.9 | 60.800 | 12 | 22 | 122 |
| | AF5C1 | −2.66 | 1.83 | 0.707763 | 39.2 | 3430 | 5 | 11 | 176 |
| Nargedik Quarries AF6 | AF6D2 | −3.50 | 1.72 | 0.707787 | 38.1 | 9920 | 22 | 303 | 202 |
| City Quarries AF9 | AF9A1 | −2.88 | 0.32 | 0.707846 | 38.6 | 2760 | 7 | 47 | 221 |
| | AF9A3 | −3.72 | −1.21 | | 38.3 | 1740 | 19 | 259 | 101 |
| | AF9A5 | −3.77 | −2.03 | | 39.0 | 1210 | 22 | 483 | 58 |
| | AF9A8 | −2.53 | −2.29 | | 38.5 | 2500 | 57 | 583 | 154 |
| | AF9A14 | −4.14 | 1.63 | 0.707644 | 38.1 | 1240 | 31 | 282 | 81 |
| | AF9B1 | −3.16 | 2.16 | | 38.4 | 1550 | 13 | 25 | 111 |
| | AF9B3 | −3.64 | 0.64 | 0.707658 | 38.2 | 567 | 8 | 19 | 69 |
| | AF9B4 | −3.40 | −1.82 | | 37.6 | 2470 | 137 | 836 | 98 |
| | AF9B5 | −1.75 | −0.57 | | 37.1 | 3740 | 61 | 994 | 178 |

(Continues)

TABLE 2 (Continued)

| *Quarry sector* | *Sample* | *$\delta^{18}O$ (PDB)* | *$\delta^{13}C$ (PDB)* | *$^{87}Sr/^{86}Sr$* | *Ca (%)* | *Mg (µg/g)* | *Mn (µg/g)* | *Fe (µg/g)* | *Sr (µg/g)* |
|---|---|---|---|---|---|---|---|---|---|
| | AF9B9 | −3.90 | 0.91 | | 39.3 | 287 | 8 | 47 | 118 |
| | AF9D1 | −3.30 | 1.89 | 0.707673 | 38.0 | 1220 | 13 | 22 | 91 |
| | AF9D6 | −2.77 | −2.70 | 0.707892 | 37.0 | 3110 | 59 | 1760 | 91 |
| | AF9D10B | −3.08 | 1.84 | 0.707661 | 39.2 | 978 | 9 | 19 | 99 |
| | AF9D20B | −3.39 | 2.36 | | 38.8 | 446 | 7 | 59 | 132 |
| | AF9D24B | −2.88 | −1.29 | | 36.1 | 4770 | 128 | 2940 | 124 |
| | AF9F3 | −3.26 | 2.34 | 0.707829 | 38.2 | 4060 | 11 | 20 | 240 |
| | AF9F6 | −3.99 | 2.11 | 0.707907 | 33.8 | 45.700 | 31 | 100 | 135 |
| | AF9G3 | −3.99 | 2.26 | | 39.3 | 1240 | 7 | 10 | 209 |
| | AF9II1 | −2.74 | 0.78 | | 39.5 | 3220 | 13 | 95 | 222 |
| | AF9X1 | −3.69 | 2.41 | | 38.1 | 8.460 | 8 | 40 | 168 |
| City Quarries AF12 | AF12A3 | −3.25 | 2.33 | 0.707656 | 38.3 | 1970 | 6 | 8 | 134 |
| | AF12B1 | −4.37 | 2.22 | 0.707808 | 37.1 | 11.100 | 9 | 48 | 158 |
| | AF12B3 | −3.49 | 2.21 | | 37.7 | 2420 | 6 | 18 | 148 |
| | AF12B9 | −3.28 | 2.15 | | 38.4 | 10.100 | 5 | 15 | 156 |
| | AF12C2 | −3.49 | 2.11 | | 33.7 | 37.400 | 12 | 55 | 216 |
| | AF12E1 | −3.22 | 2.58 | | 37.1 | 10.200 | 6 | 10 | 109 |
| | AF12F2 | −2.68 | 2.16 | 0.707684 | 29.7 | 69.000 | 18 | 43 | 146 |

**TABLE 2** (Continued)

| *Quarry sector* | *Si (μg/g)* | *Al (μg/g)* | *Na (μg/g)* | *K (μg/g)* | *Ba (μg/g)* | *P (μg/g)* | *S (μg/g)* | *Zn (μg/g)* |
|---|---|---|---|---|---|---|---|---|
| Ören Quarries AF2 | < 30 | 6 | 26 | < 5 | 1 | 20 | 29 | < 1 |
| | < 30 | < 5 | < 10 | < 5 | 1 | 16 | 64 | < 1 |
| | < 30 | 6 | < 10 | < 5 | < 1 | 20 | < 20 | < 1 |
| | < 30 | < 5 | 11 | < 5 | < 1 | 19 | < 20 | < 1 |
| | < 30 | < 5 | < 10 | < 5 | < 1 | 22 | 22 | < 1 |
| Hançam Quarries AF3 | < 30 | 8 | < 10 | < 5 | 2 | 20 | 47 | < 1 |
| | 312 | 395 | 43 | 135 | 1 | 19 | 47 | 25 |
| | < 30 | 6 | < 10 | < 5 | 1 | 11 | 40 | < 1 |
| Çamarasi Quarries AF4 | < 30 | < 5 | < 10 | < 5 | 1 | 16 | < 20 | < 1 |
| | < 30 | < 5 | < 10 | < 5 | < 1 | 17 | < 20 | < 1 |
| Kizli Çağil Quarries AF5 | < 30 | 8 | 56 | < 5 | 1 | 19 | < 20 | 2 |
| | < 30 | < 5 | < 10 | < 5 | 1 | 13 | 26 | < 1 |
| Nargedik Quarries AF6 | < 30 | 17 | 25 | < 5 | 1 | 79 | 74 | < 1 |
| City Quarries AF9 | < 30 | 19 | < 10 | 13 | 3 | 71 | 46 | 1 |
| | 125 | 125 | < 10 | 83 | 1 | 28 | 110 | 2 |
| | 31 | 45 | < 10 | 17 | < 1 | 23 | 59 | 2 |
| | < 30 | 38 | < 10 | 23 | < 1 | 24 | 33 | 2 |
| | < 30 | < 5 | < 10 | < 5 | < 1 | 19 | 39 | 2 |
| | < 30 | 8 | < 10 | < 5 | < 1 | 32 | 39 | < 1 |
| | < 30 | < 5 | 25 | 10 | < 1 | 19 | 26 | < 1 |
| | 101 | 113 | 11 | 26 | < 1 | 20 | 144 | 6 |
| | 89 | 96 | < 10 | 68 | < 1 | 30 | 72 | 2 |

(Continues)

**TABLE 2** (Continued)

| *Quarry sector* | *Si (µglg)* | *Al (µglg)* | *Na (µglg)* | *K (µglg)* | *Ba (µglg)* | *P (µglg)* | *S (µglg)* | *Zn (µglg)* |
|---|---|---|---|---|---|---|---|---|
| | < 30 | 13 | < 10 | < 5 | < 1 | 126 | 30 | < 1 |
| | < 30 | < 5 | < 10 | < 5 | < 1 | 22 | 27 | < 1 |
| | 227 | 225 | < 10 | 75 | 1 | 15 | 396 | 4 |
| | < 30 | < 5 | < 10 | < 5 | < 1 | 17 | < 20 | < 1 |
| | < 30 | 6 | < 10 | < 5 | 2 | 32 | < 20 | < 1 |
| | 187 | 225 | < 10 | 107 | 1 | 46 | 345 | 31 |
| | < 30 | 6 | < 10 | < 5 | 1 | 14 | < 20 | < 1 |
| | < 30 | 7 | 134 | 10 | 1 | 29 | 24 | 2 |
| | < 30 | 6 | < 10 | < 5 | 1 | 15 | < 20 | < 1 |
| | < 30 | 14 | 39 | 20 | 2 | 33 | 56 | < 1 |
| | < 30 | < 5 | 113 | 8 | 1 | 24 | 48 | < 1 |
| City Quarries AF12 | < 30 | < 5 | < 10 | < 5 | 1 | 14 | < 20 | < 1 |
| | < 30 | < 5 | 66 | 6 | 1 | 19 | < 20 | < 1 |
| | < 30 | < 5 | < 10 | < 5 | 1 | 14 | < 20 | < 1 |
| | < 30 | < 5 | 85 | 5 | 1 | 17 | 27 | < 1 |
| | < 30 | < 5 | 55 | 9 | 2 | 17 | < 20 | < 1 |
| | < 30 | < 5 | 33 | < 5 | 1 | 20 | 34 | < 1 |
| | < 30 | 6 | 53 | 6 | 1 | 27 | < 20 | 2 |

Of the white marbles three main fabric types may be sorted out:

1. Holotypic, mosaic, heteroblastic, sometimes quasi-mortar fabric with MGS from 1.7 to 4.4 mm and all types of crystal boundaries except straight:
   - curved to embayed (AF4F2, AF9G3, AF12E1);
   - embayed boundaries (Fig. 2, a) (AF2F1, AF3D1, AF4B1, AF9B3, AF9B9, AF9D1, AF9D10B, AF9F3, AF12A3);
   - embayed to sutured (Fig. 2, b) (AF2A1, AF5C1, AF9A14, AF9B1, AF12B1, AF12B3);
   - sutured (AF2B2, AF9D20B, AF12B9);

   Many of the samples listed above show signs of a slight strain and foliation evidenced by bent polysynthetic twins and crystals' iso-orientation, respectively.
2. Allotypic, more regular quasi-polygonal mosaic (Fig. 2, c), sometimes foliated, showing a medium grain size (MGS range = 1.4–1.9 mm), with straight, curved, and embayed crystal boundaries (AF3B1, AF6D2).
3. Allotypic, mixed fabric, mosaic/foliated (Fig. 2, d), fine-grained (MGS < 1.7 mm), sometimes with areas/veins showing relatively larger grain size, and with embayed to sutured crystal boundaries (AF5A1, AF9F6, AF12C2, AF12F2).

Grey to bluish marbles are also characterized by three fabric types as follows:

1. Holotypic, mosaic, sometimes slightly foliated and strained fabric (Fig. 2, e) with curved, embayed and sutured calcite crystal boundaries, and MGS varying from 1.2 to 3.8 mm (AF9A1, AF9A3, AF9A5, AF9A8, AF9B5, AF9II1).
2. Allotypic, definitely foliated and slightly strained mosaic fabric (Fig. 2, f) with curved to embayed calcite crystal boundaries, MGS range = 1.6–2.0 mm (AF3C5, AF9B4, AF9D6, AF9D24B).
3. Allotypic, mosaic, quasi-homeoblastic, polygonal fabric (Fig. 2, g) with curved to embayed boundaries, MGS = 2.1 mm (AF2J1).

Ubiquitarian accessory minerals are graphite and Fe-bearing minerals (frequent pyrite and haematite, both often with rims of hydrated iron oxides); quartz and mica (mostly muscovite, sometimes in trails) are quite common, whereas titanite and epidote (clinozoisite/epidote) are rare. Detailed characterization of accessory minerals was performed by SEM analysis (see Section *Scanning electron microscopy*).

On the basis of these features, in general, most white holotypic AM may be confused with Prokonnesian and Paros-2 marbles, although the latter is more characterized by definitely curved boundaries and the MGS usually above 2 mm. One allotype is petrographically similar to Carrara marble: the little higher MGS of this Aphrodisian variety is a weak distinguishing feature. The grey to bluish variety is very similar to the white one, although strain and foliation are more frequent. As for their accessory minerals, graphite is more abundant as dispersed individual or aggregated particles, and K-mica is usually more frequent, sometimes in thin levels very well marking the foliation. A few allotypic grey AM also showed a quasi-polygonal mosaic fabric formed by crystals with curved to embayed boundaries that may be difficult to distinguish from some *bardiglio* varieties of Carrara marbles.

## Cathodoluminoscopy

It was conducted on 38 thin sections. A wide range of cathodofacies were observed for the AM (Fig. 3) and they were confronted with their bulk carbonate elemental composition. The strong variability of cathodoluminescence (CL) is clearly linked to variation of manganese

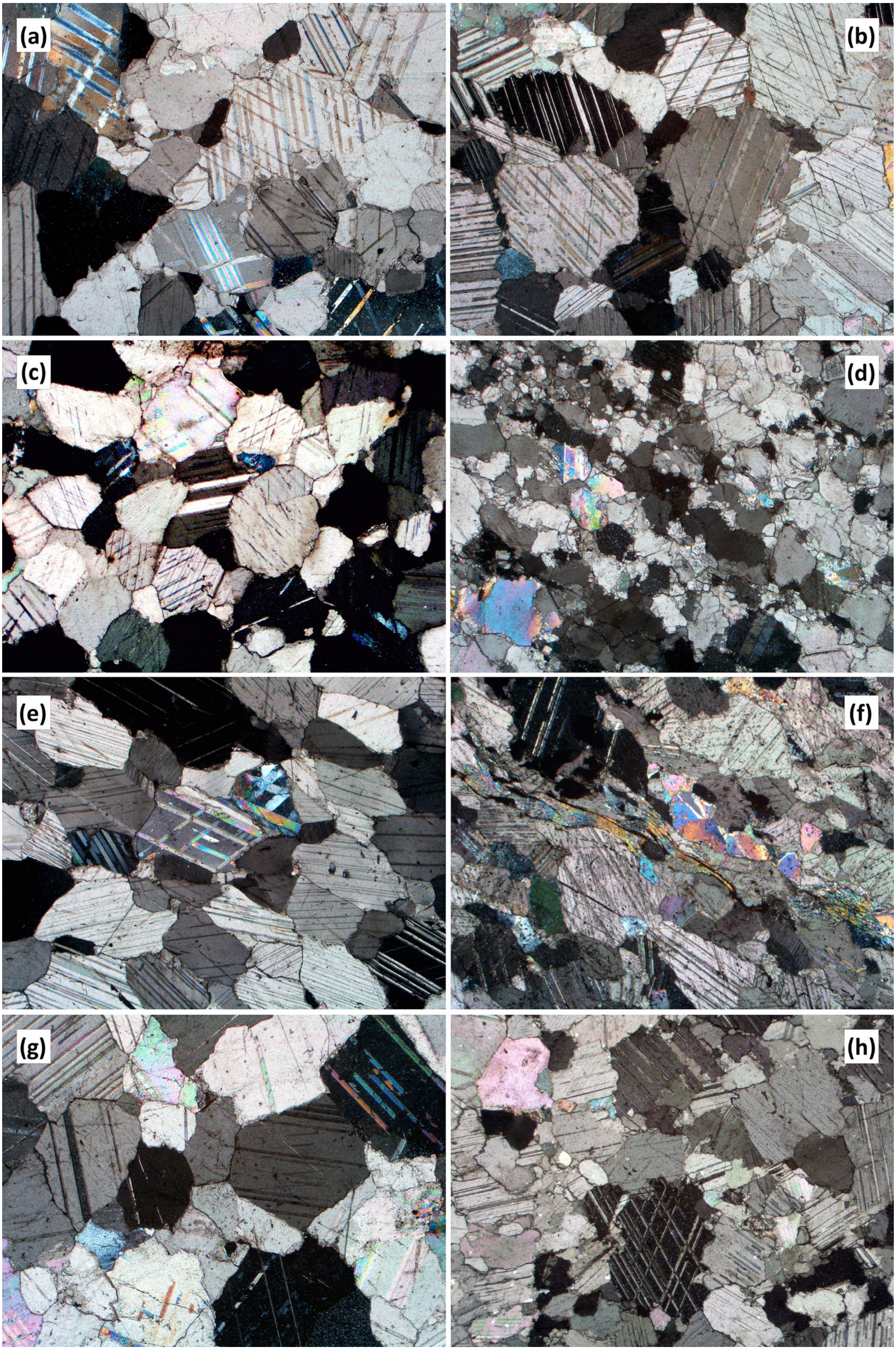


FIGURE 2 Legend on next page.

FIGURE 2 Photomicrographs showing the fabric types of the Aphrodisian marbles, taken in transmitted cross-polarized light; their long side is of 3.84 mm. (a) Heteroblastic mosaic fabric of white holotypic facies (AF3D1) with embayed calcite crystal boundaries; (b) heteroblastic quasi-mortar/mosaic fabric of white holotypic facies (AF9A14) with embayed to sutured calcite crystal boundaries; (c) white allotypic facies (AF3B1) with a homeoblastic, mosaic, quasi-polygonal fabric and curved to straight (prevailing) calcite crystal boundaries, sometimes forming triple points; (d) white allotype with foliated fabric (AF12C2) and embayed to sutured calcite crystal boundaries; (e) grey holotype (AF9A5) with a mosaic, slightly foliated fabric and curved calcite crystal boundaries; (f) grey allotype (AF9B4) with a foliated fabric and curved to embayed calcite crystal boundaries, also showing a trail of K-mica lamellae parallel to foliation; (g) grey allotype (AF2J1) with a quasi-homeoblastic, polygonal fabric and curved to embayed calcite crystal boundaries; and (h) holotypic white facies (AF2A1) with a quasi-mortar/mosaic fabric and sutured to embayed calcite crystal boundaries.

content (see Fig. S3.1 in Appendix S3 in the additional supporting information), which is known to be the main activator of extrinsic CL in carbonate minerals (e.g., Marshall, 1988). Yet, the impact of iron content, a common quencher of extrinsic CL in carbonate minerals, was observed as insignificant. Furthermore, CL patterns are related to some extent to the white/grey variety, but not to the quarry from which a given sample was extracted. The CL patterns of calcitic AM can be divided into four cathodofacies according to the colour, intensity and homogeneity of CL:

- *Cathodofacies I* (Fig. 3, a–b). Lack of luminescence in Mn-poor samples (bulk carbonate Mn < 12 ppm). In overexposed CL images, when the camera's exposition time was significantly prolonged, an intrinsic blue CL caused by defects in the crystal structure (Marshall, 1988) was observed. Such blue CL can only be visually noticed when the extrinsic CL related to Mn activation is at a very low level. Some of these samples exhibit a purple hue at a prolonged exposition time, which probably results from a very low-intensity extrinsic CL. This cathodofacies is characteristic for most of white marble samples, but it was also observed in the grey variety.
- *Cathodofacies II* (Fig. 3, c–d). Heterogeneous CL characterized by zoned calcite blasts with non-luminescent core and low- (dull) to medium-intensity orange margins, the intensity of which increases with increasing Mn content (bulk carbonate Mn from 13 to 31 ppm).
- *Cathodofacies III* (Fig. 3, e–f). Homogeneous, low-intensity (dull) orange CL observed in samples with medium Mn (bulk carbonate Mn from 18 to 46 ppm).
- *Cathodofacies IV* (Fig. 3, g–h). Homogeneous, medium-intensity orange CL in Mn-rich samples (bulk carbonate Mn from 57 to 197 ppm). This group is mainly represented by grey marble.

Irrespective of the cathodofacies, some samples contain thin streaks of secondary calcite with vivid orange CL, which occur along crystal boundaries, cleavage cracks and small fractures (Fig. 3, i–j). This calcite is probably related to metasomatic processes and is not linked to any particular cathodofacies. The presence of dolomite and, to a lesser extent, non-carbonate accessory minerals affects the general luminescence pattern. Dolomite blasts exhibit low- to medium-intensity purple to red luminescence (Fig. 3, b, l), which is generally brighter than that of coexisting calcite. Many dolomite blasts contain numerous inclusions (mostly calcite), which cause a heterogenous CL of such grains (Fig. 3, k–l). The CL intensity of calcite gradually increases in areas adjacent to the dolomite-rich laminae or domains in a few samples of cathodofacies III (Fig. 3, f). Noncarbonate accessory minerals (non-, blue and yellow luminescent) occur as tiny inclusions within carbonate blasts in all cathodofacies. The relatively larger non-carbonate accessory minerals identifiable under an optical microscope (mica, apatite, quartz, epidote, fluorite) range from non- (Fig. 3, h) to blue luminescent (Figure Fig. 3, j, l).

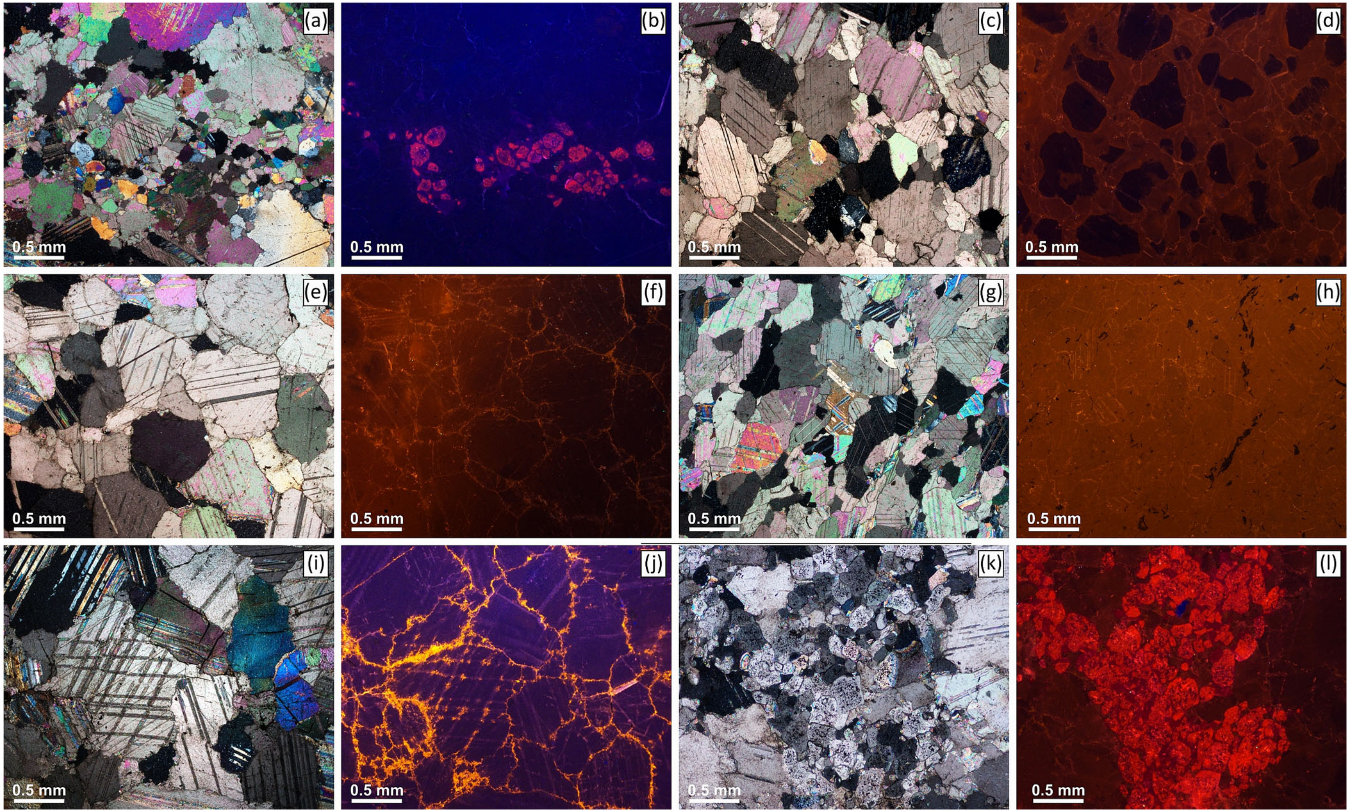


**FIGURE 3** Cathodoluminescence (CL) of Aphrodisian marbles examined. Paired, cross-polarized in (a, c, e, g, i, k) and CL images in (b, d, f, h, j, l); CL images in (b, j) are overexposed. (a, b) Cathodofacies I—non-luminescent calcite with an intrinsic blue CL and red-luminescent dolomite along a lamina (AF12B9); (c, d) cathodofacies II—heterogeneous CL characterized by zoned calcite blasts with non-luminescent core and low- (dull) to medium-intensity orange margins (AF6D2); (e, f) cathodofacies III—homogeneous, low-intensity (dull) orange CL of calcite (lower right) gradually increasing towards a dolomite-rich area, which is beyond the upper left corner of the image (AF2F1); (g, h) cathodofacies IV—homogeneous, medium-intensity orange CL of calcite with non-luminescent accessory mica flakes on the right (AF3C5); (i, j) streaks of secondary calcite with vivid orange CL along crystal boundaries, cleavage cracks and small fractures; note tiny blue-luminescent non-carbonate mineral inclusions in calcite blasts (AF9II1); and (k, l) marble with lamina especially rich in inclusion-rich dolomite and with blue-luminescent apatite (AF2A1).

The cathodofacies distinguished in this work conform to the CL patterns reported for AM by Brilli et al. (2015), except for the cathodofacies I with the intrinsic blue CL of calcite. As such modest differences in CL may result from sampling and interlaboratory biases (Wielgosz-Rondolino et al., 2020), the cathodofacies reported in this work expand only insignificantly the knowledge about possible CL patterns of AM. Consequently, the discriminating potential of CL for AM is rather low, as the cathodofacies observed are not unique among ancient marbles.

## Scanning electron microscopy (SEM)

The white and grey AM (15 thin sections studied with the use of SEM) are chiefly composed of low-magnesian calcite (Mg < 1 mol%) with subordinate dolomite. In the white variety, dolomite occurs as individual accessory grains of different sizes, which are often locally clustered in dolomite-rich laminae or domains, where it may predominate over calcite. In the grey marbles, dolomite is usually absent, but in a few samples it occurs as sparse, individual small grains. Many accessory minerals were not discernible under optical microscope due to their small sizes or non-specific optical properties. Therefore, their identification was based on a combination of optical and electron microscopy, which revealed some differences in accessory mineral assemblages between the white and grey AM (see Table S3.2 in Appendix S3 in the additional supporting information):

- White marble. In general, non-carbonate minerals are rare and dispersed randomly. The most common accessory minerals are fluorapatite occurring in all, and fluorite in almost all samples. Other ubiquitous accessories are Fe-bearing phases, such as pyrite (euhedral and framboidal) and Fe-(hydr)oxides replacing pyrite. Ti-oxide, probably rutile, is also common, but less frequent than in grey marbles. Other sparse accessories include micas (small paragonite grains), titanite, and Zn-sulphide (probably sphalerite).
- Grey marble. Noncarbonate minerals are much more common than in the white variety and they are usually clustered in the mica-rich layers. Similar to white marbles, fluorapatite, pyrite and Fe-(hydr)oxide minerals are ubiquitous and were identified in almost all samples. Micas are present in all grey samples and they reach large sizes, which makes them the most distinctive accessory minerals, especially K-mica (muscovite) that is sometimes accompanied by Na-mica (paragonite) along some laminae. Other common minerals identified in grey marbles include quartz (in all samples), zircon (within mica-rich laminae in most samples), Ti-bearing minerals such as Ti-oxide, probably rutile, and titanite. Less widespread accessory minerals include tourmaline, kaolinite, light REE-rich epidote minerals, and Zn-sulphide (probably sphalerite). Graphite, which was observed under a polarizing microscope, could not have been identified under SEM due to the fact that the thin sections were coated with carbon prior to SEM investigation.

Some of the accessory minerals identified in the grey marbles in this work, for example, apatite, quartz, muscovite, paragonite, and kaolinite, have already been reported by Capedri et al. (2004) for the AM. None of the above-mentioned minerals, except for apatite, was recognized in this study in the white variety, which suggests that marbles investigated by Capedri et al. belonged mostly to the grey variety. This conclusion is also supported by the fact that Capedri et al. did not detect fluorite and rare dolomite in the AM that they investigated. Similarly, Brilli et al. (2015) studied pure calcitic AM with quartz detected by XRD, which matches the composition of the grey variety. However, some discrepancies exist between Capedri et al. (2004) and our results irrespective of marble variety. They did not detect either Fe-sulphides or Ti-oxides in the Aphrodisian samples and they suggested that absence of these minerals may be a distinguishing feature from other important Anatolian marbles, whose C and O isotopic fields overlap with that of Aphrodisias, for example, Prokonnesos. As we show that these minerals are common in the material studied, they should no longer be considered as differentiating between Aphrodisian and other classical marbles. On the other hand, Capedri et al. and, consequently, Antonelli and Lazzarini (2015) indicated that albite is an accessory mineral characteristic for Aphrodisias, but it was not found in the course of this study neither in white nor in grey marbles. However, this might be a sample-specific issue and absence of albite in the material examined in this work might be coincidental. In summary, accessory minerals with a high discriminating potential were not found in the material examined.

## Stable C and O isotope compositions

Stable C and O isotope ratios measured for all 123 quarry samples are reported in Table S3.3 in Appendix S3 in the additional supporting information, while those corresponding to the samples thin sectioned are also reported in Table 2. The data offer only small differences with respect to those published by previous scholars (Long, 2012; Stearns, 2012; Antonelli & Lazzarini, 2015, and previous references therein). The core group of the samples clusters in a quite limited area of the upper side of the isotopic field previously defined for this marble, which is approximately contained between −4.5‰ and −2.0‰ for $\delta^{18}O$ and between +1.0‰ and +2.6‰ for $\delta^{13}C$ (Fig. 4, a). These values are close to the typical composition of marine limestones and they match those of many of the reference areas defined by other medium-to-coarse-grained white marbles quarried in classical times, in particular Paros-2, Prokonnesos-1 and, with a minor extent, Thasos-1(2) and Thasos-3.

Nevertheless, 22 samples from sector AF3 and particularly AF9 (City Quarries), tail the data distribution towards lighter isotopic values for carbon, in a region of the domain comprised between −2.8‰ and +0.5‰, (Fig. 4, a). It is important to note that all samples displaying such low $\delta^{13}C$ values belong to the grey (or white-to-greyish) lithofacies of the AM (Fig. 4, b and see Appendix S3 in the additional supporting information). Additional evidence that low $\delta^{13}C$ values are characteristic of grey marbles is sample A3C4, which is white-grey with a clear colour boundary. Independent measurements were made for the white and grey parts, which showed different carbon values: 1.69 for the white part and −1.13 for the grey part, while maintaining the same $\delta^{18}O$ value (−3.21 and −3.20, respectively). As noted by Stearns (2012), this is a unique distinctive feature with respect to the other major (medium-to-coarse-grained) Mediterranean varieties. This trend was also recorded by Brilli et al. (2015). However, all samples with such low $\delta^{13}C$ (except one) exhibit MGS < 2 mm (Fig. 4, c) and they should be in fact compared with the isotopic fields for fine-grained marbles. Still, such comparison shows only a small overlap with Paros-1, Dokimeian and Göktepe fields observed for three (out of 22) $^{13}C$-depleted samples (Fig. 4, d).

Stearns (2012) linked the low $\delta^{13}C$ values of grey and white-to-greyish marbles to the presence of organic carbon that is typically $^{13}C$-depleted. However, such isotopic effect can only be recorded if the content of organic carbon is very high (Oehlerich et al., 2013), for example, in extremely organic carbon-rich sedimentary rocks, so evidently much higher than that in the marbles examined. These low $\delta^{13}C$ values are, therefore, inherently linked to the carbonate material of these grey and white-to-greyish marbles and related to the protolith and its following alteration. Thus, these values should be taken into account for provenancing purposes the same way as the white ones. Stearns (2012) reported also on very low $\delta^{18}O$ values of marbles collected in close proximity to silicate rocks, and so did we observe that not only $\delta^{18}O$, but also $\delta^{13}C$ values drop to about −10‰ in carbonate-containing schists. Since these are not typical marbles, we excluded these samples from this work.

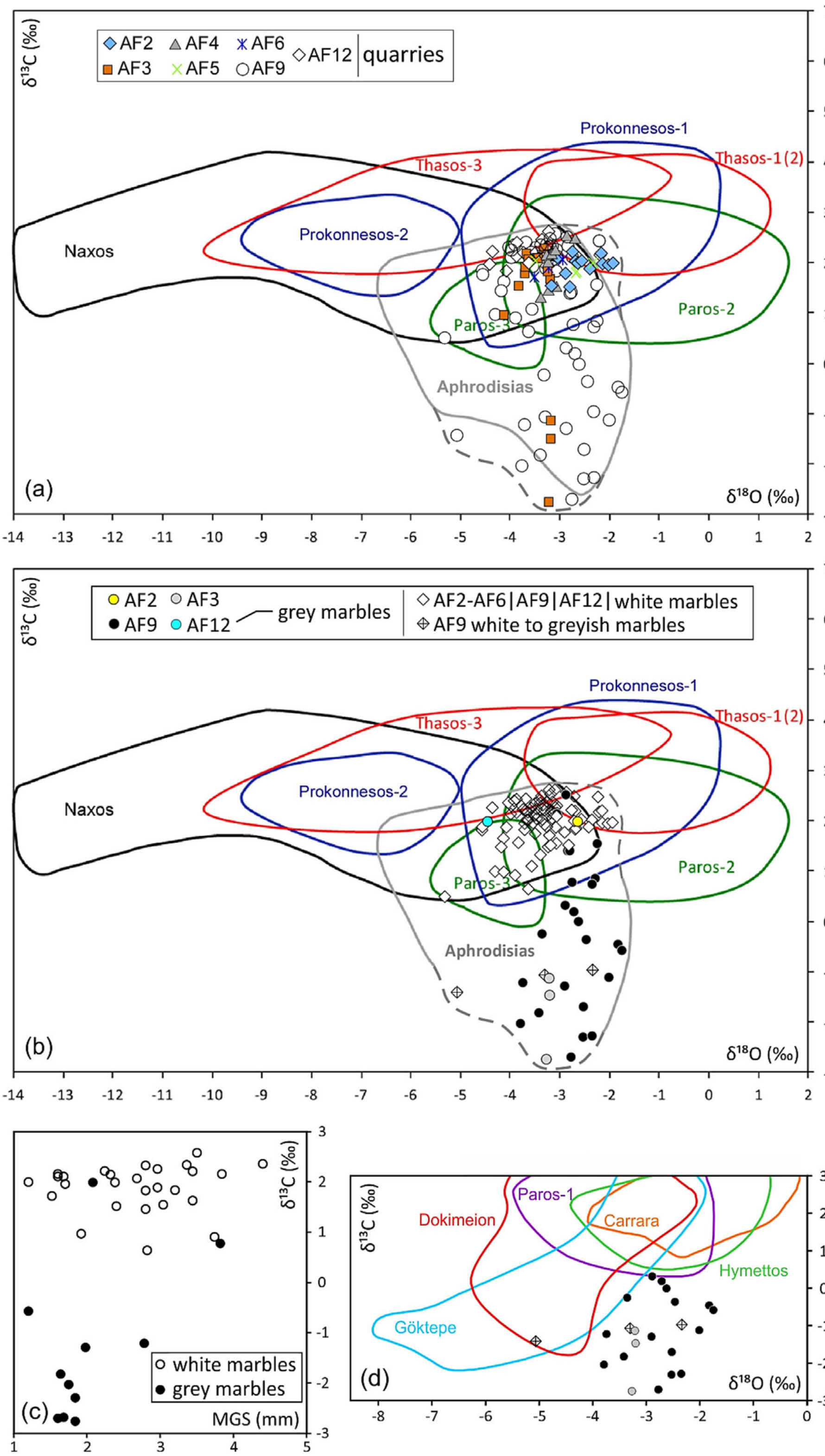


**FIGURE 4** Legend on next page.

FIGURE 4 (a) $\delta^{18}O$ versus $\delta^{13}C$ diagram presenting the new data for Aphrodisian quarries plotted against the reference isotopic database proposed by Antonelli and Lazzarini (2015) for classical quarries of white marbles with MGS > 2 mm; (b) plotting of the white marbles versus the grey and greyish varieties (beige and pink marbles are not considered); (c) $\delta^{13}C$ versus MGS diagram showing that the depleted $\delta^{13}C$ values of grey marble is associated with preferentially low MGS values; note that differences in the number of samples presented here are because only those for which MGS was measured are shown; and (d) position of samples with depleted $\delta^{13}C$ values on the isotope diagram for the fine-grained ancient marbles, isotope fields after Wielgosz-Rondolino et al. (2020) and Antonelli and Lazzarini (2015); the explanation of symbols as in (b).

Finally, even if the majority of samples falls inside the Aphrodisias isotopic domain already known, the comparison between these new data and the isotopic reference database published by Antonelli and Lazzarini (2015) suggests that a small modification of the boundaries of the field is probably necessary (Fig. 4, a–b).

## Elemental composition

The AM often show highly elevated Mg contents in the range of several weight % (wt%) indicative of the presence of dolomite. Next to Ca and Mg, the marble shows variable Mn and Fe contents (respectively between 5 and 197 and between 8 and 2940 μg/g), having implications for the cathodoluminescence, and a low to variable Sr content (between an exceptionally low 91 and 240 μg/g). The contents of P and S are usually less than 50 and 75 μg/g, respectively, but show outliers up to 126 and 396 μg/g, possibly related to the presence of apatite and sulphide accessories. Contents of Si, Al, Na, K, Ba and Zn are usually below the detection limit for the ICP-OES measurement procedure performed here, but occasionally show higher values (with a maximum content of 312 μg/g Si, 395 μg/g Al, 134 μg/g Na, 135 μg/g K, 3 μg/g Ba and 31 μg/g Zn) in the grey marbles that are relatively rich in the non-carbonate accessory minerals, for example, sample AF3C5 (Table 2).

## Sr isotope composition

The $^{87}Sr/^{86}Sr$ values (Table 2 and see Table S3.4 in Appendix S3 in the additional supporting information) of white marbles range from 0.707644 to 0.707907 ($n = 16$). For grey marbles these values range from 0.707822 to 0.707892 with one outlier from AF3 (sample AF3C5) with 0.708220 ($n = 4$). The outlier is also distinctively enriched in Si, Al, K, Mn and Fe relative to other samples (Table 2), which is evidently linked to relatively high content of non-carbonate accessory minerals identified with SEM in this sample (see Table S3.2 in Appendix S3 online), some of which may have released preferentially radiogenic Sr during sample leaching, for example, micas.

The obtained $^{87}Sr/^{86}Sr$ values in this work fit the range reported so far for AM. In particular, almost all samples match the median 50% (the interquartile range), except the only one outlier fitting the upper quartile of the $^{87}Sr/^{86}Sr$ values reported (cf. Wielgosz-Rondolino et al., 2020). Alone, the $^{87}Sr/^{86}Sr$ values of AM do not have any discriminating potential, as they overlap with those of the major classical marbles (Brilli et al., 2005; Wielgosz-Rondolino et al., 2020, *passim*). Therefore, we plotted the $^{87}Sr/^{86}Sr$ values against other proxies, such as $\delta^{18}O$, $\delta^{13}C$ and some elemental ratios (see Fig. A3.2 in Appendix S3 in the additional supporting information), but these procedures did not either provide any beneficial results. The bulk-rock concentrations of major and trace elements are also rather typical for many other major classical marbles. Thus, among the geochemical proxies applied, only the depleted $\delta^{13}C$

values exhibit the highest discriminating potential of an Aphrodisian provenance of marble artefacts. Such $^{13}C$-depleted samples represent about 15% of the material analysed in this work, which was collected from all quarries with a high resolution, so can be regarded as representative.

# DISCUSSION

Our study is the first to present archaeometric data for white and grey AM from the City and Regional Quarries obtained by comprehensive investigation on a representative set of samples collected from all currently known ancient quarries with several analytical methods (see Appendixes S1–S3 in the additional supporting information). The archaeometric investigation demonstrates the following:

- A high variation in micro-textural features of AM even within the same quarry. However, what we may consider the holotype (typical and most frequent AM) is characterized by a heteroblastic mosaic of calcite crystals with curved to embayed boundaries forming slightly strained and sometimes foliated fabrics, often containing fine-grained areas, with MGS varying in a wide range from 1.2 to 4.4 mm. Allotypes are instead showing quasi-homeoblastic grains of calcite, of finer grain size and forming foliated or polygonal fabrics: the latter may be eventually confused with Carrara marbles. On average, white marbles are coarser that the grey ones.
- $\delta^{13}C$ and $\delta^{18}O$ values (mostly white marbles) overlap with those of other ancient marbles with MGS > 2 mm, so their discriminating potential is low. Potentially discriminating $\delta^{13}C <$ +0.5‰ are specific for grey/light grey marbles from sectors AF3 and AF9, which exhibit MGS mostly < 2 mm. These $^{13}C$-depleted isotope values overlap insignificantly with the Dokimeian and Göktepe isotopic fields and can be used for quite precise identification within sectors AF3 and AF9.
- Cathodofacies are not unique among ancient marbles and so CL is not a good indicator of Aphrodisian provenance. However, presence of purple- to red-luminescent dolomite in isolated areas, oval domains or laminae, in combination with non-luminescent or intrinsic blue CL might be an additional factor excluding some sources of ancient marbles, such as Carrara, Dokimeion, Ephesos, Göktepe, Paros-2.
- Rather common and usual accessory minerals occur in the AM, mostly apatite, fluorite, pyrite, haematite, rutile, micas, and titanite. Lack of any unique accessory mineral with a high discriminating potential allows for exclusion of an Aphrodisian provenance if such minerals are observed in an artefact.
- The $^{87}Sr/^{86}Sr$ values of AM overlap with those of other major classical marbles, so they do not possess a discriminating potential.
- The elemental composition of AM as measured in this study, including low to medium Sr content and variable Fe and Mn contents, appears to have little discriminating potential, being a common but variable chemical composition for a marble.

Volume estimates of removed marble presented here provide important new data on the scale of quarrying at Aphrodisias. The total amount of marble extracted from Aphrodisian quarries was < 230,000 $m^3$, 20–33% of which was effectively used. These estimates show a much smaller amount of extracted marble, especially in comparison to other major quarry areas (e.g., Dokimeion). The newly calculated numbers confirm previous research that AM was rarely shipped outside its homeland, especially given the large quantities of marble needed to satisfy local demand. A definitive answer to the question of exporting AM to the wider international market will depend on performing more reliable marble provenancing studies on ancient artefacts, especially on those signed by Aphrodisian sculptors discovered throughout the Mediterranean basin.

# CONCLUSIONS

Our study shows that the variability of petrographic and geochemical characteristics for white and grey marbles extracted both from the City and Regional Quarries do not allow for a straightforward discrimination between the different quarrying sectors. The only indicator useful for understanding the local use of these marbles in individual monuments is $\delta^{13}$C lower than +0.5‰ indicating sectors AF3 and AF9. Additionally, the provenance of bluish-white and purple-grey-white brecciated marbles from Babadağ mountain (AF7) and Çamova Tepe (AF8), as well as mottled blue-grey and white marbles from Yazır (AF1), not discussed in this paper, can be discerned (Long, 2012). Moreover, the work demonstrates that there is no single feature that may allow for unequivocal distinction of Aphrodisian from other classical marbles, except the depleted $\delta^{13}$C values, which is the case for only about 15% of marbles collected by 'Marmora Asiatica' from all known Aphrodisian quarries. Obviously, the multi-method approach is recommended, but even with such data for a large set of samples covering all of Aphrodisias' ancient quarries, we were only able to identify properties that might help by limiting sources—rather than positively identifying them, such as through the specific cathodofacies with dolomite, petrographic characteristics of the holotype, absence or presence of specific accessory minerals. We believe that a possible way out of this quandary is to search for other unconventional proxies that may be more diagnostic and serve as precise fingerprints for an Aphrodisian provenance. These difficulties in discriminating Aphrodisian marbles from other coarse- or medium-grained marbles from the Mediterranean basin in addition to the individual quarries of the Regional and City Quarries pose a great challenge for understanding the question of marble exportation throughout the Roman Empire in addition to local use at Aphrodisias. However, international export is rather unlikely given the volumetric estimates of removed material in Aphrodisian quarries herein presented.

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## DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are all included within this article and supplementary material to this article (Annexes 1-3)

## PEER REVIEW

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/arcm.12893.

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## ENDNOTES

[1] The project was developed within a broad framework of clarifying the use of ancient marbles from Asia Minor, both in the region itself and beyond, with the aim of documenting the archaeology, geology and topography of the quarries, as well as providing a comprehensive scientific characterization of white and grey marbles. The methodology of the project relies on the application of a great variety of techniques and tools.

[2] For the detailed map of the City Quarries sector 9, see marmoraasiatica@uw.edu.pl/.

[3] According to Attanasio et al. (2009), approximately 20–33% of extracted material was efficiently used in the Roman period (see also Lambertie, 1962; Röder, 1971; Russell, 2016).

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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