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Digital approaches to ancient metrology: new insights into methods and tools for measuring and designing marble in late antiquity

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***Abstract* – The paper deals with a particular category of production indicators, namely circular holes on Late Antique architectural sculpture. The Mediterranean-wide distribution of these graphic signs suggests that they had a defined meaning and function during the production process. A sample of marble objects from Late Antique Ravenna has been 3D digitally survey and analysed here as a case study. A comparative assessment of these marks suggests their identification as calliper holes. The evaluation of their positioning on the marble objects provides precise clues to their function for metrological and design purposes. Moreover, it points to a specific production technique used during manufacture, namely the three-compass method. The chronological distribution of archaeological evidence between the 5th and 6th centuries AD makes it possible to link the phenomenon to the floruit of the quarries of Proconnesus and the introduction of new techniques to speed up marble working.**

I. INTRODUCTION*

In Antiquity, stone industry was one of the most thriving market sectors. Architecture was indeed a privileged means to show off patrons' social standing and the use of stone materialised the intention of ensuring impressiveness and durability to monuments. Stone workshops engaged in carving architectural members (columns, column bases, capitals etc.) multiplied on different regions of the Mediterranean. Over time, each craft unit developed its own technical and artistic identity, which relied on specific working methods. They were consolidated and at times modified according to the demands of the patrons and the needs of the market in general. Working techniques mainly drew on the knowledge of descriptive geometry, the science of accurately defining the shape of two- and three-dimensional objects using graphic methods [1]. The transmission of ideas and proportions had to be entrusted not only to the flat geometry of drawings, but to direct reproduction from three-dimensional prototypes. This seems to be confirmed by the discovery in the quarries of Proconnesus of a life-size capital in Auresina limestone from Aquileia, likely used as a prototype provided by the patron to the marble workshop for the manufacturing of a marble set [2]. Therefore, in many cases, it was a matter of reproducing artefacts from a reference model. The modelling had to be precise respecting the original proportions, but in accordance with the measurements provided by the patrons. Such a procedure required uniformity in the unit of measure used and a careful and pre-arranged organisation right from quarrying operations. The production of architectural elements on a large scale thus entailed the coordination of numerous workers and the adoption of uniform procedures for the duplication of several objects of the same type. Many scholars have extensively investigated the phenomenon in relation to Greek and Roman architecture [3], while less attention has been paid to the metrological and design aspects of late antique sculptural production.

As for Late Antiquity, dozens of quarries with different ranges of exported products have been mapped. Among the most active were the Proconnesus quarries that came to be exploited on an unprecedented scale to decorate both Constantinople and the provinces. Their prosperity stemmed from both their location on the sea and the proximity to the Capital. It is usually stated that from the first half of the 5th century onwards Proconnesus quarries were marked by mass production for several categories of artefacts, due to the increasing demand for marble furnishing. It shall be deemed that workshops developed a highly efficient operational chain, featuring a progressive rationalization of production technology as well as a speeding-up of the carving process. To this conclusion points firstly the simplification of the manufacturing phases for the most sophisticated marble products, like Corinthian capitals, as has been assumed on the analysis of rough-out artefacts lying in Saraylar district [4]. Secondly, it is now well established that a high percentage of artefacts was exported in semi-finished form and completed on the final spot according to local stylistic features [5]. Nevertheless, practical and technical measures adopted by stone-carvers in the various stages of production to fulfil serial production and hasten crafting accordingly remain largely yet to be scrutinized. These procedures mostly rely on metrological principles applied in the very first stages of workmanship and sometimes leave material traces on rough-out marble products.

Graphic guidelines, measurement points and small calliper holes recur with high frequency on several artefact categories, such as Ionic and Ionic impost capitals, imposts, and column bases mainly in Proconnesian marble, both in Constantinople and other Mediterranean regions. These graphic markers have been often overlooked in the analysis of marble items so far. Nevertheless, on the one hand they may provide novel insights into the tools used by stonemasons to design, measure, and shape artefacts, and on the other hand they can also provide tangible evidence of how the major technological changes in the stone industry of late antiquity were achieved.

This paper mainly focuses on incised calliper holes to determine their role in the manufacturing of architectural members (Fig. 1). By this, it aims to verify if they can be effectively related to measuring procedures carried out during the design and production process. Through the study of iconographic and archaeological sources, it also seeks to relate these graphic signs to the use of ancient measuring tools and to the application of specific mathematical procedures. In this regard, an attempt will be made to understand whether and how these production proxies reflect technical solutions adopted to duplicate an existing object used as a model. Finally, the archaeological evidence will be contextualised within the technological development of the Late Antique marble industry.

II. METHODOLOGY

II.1. A Mediterranean-wide survey provides evidence of measuring and design signs consisting in small, incised holes on marble artefacts from Constantinople, mainland and insular Greece, Asia Minor, North Africa, and the Italian peninsula, thus pointing to the broad dimension of the phenomenon. Calliper holes are regularly placed on the plinth of column bases, and on the abacus of Ionic and Corinthian capitals and imposts as well. In some instances, these marks seem also meant to define the axial positioning of decorative elements, such as crosses and vegetal motifs. The observation of these incisions on full sets of furniture (as in the case of pedestals from Mitropolis baptistery, Gortyn, Crete), assumes that they were marked by incision, paint or lapis on all elements of a stock. The final smoothing and polishing of marble surface may presumably have caused the limited preservation of such graphic markers.

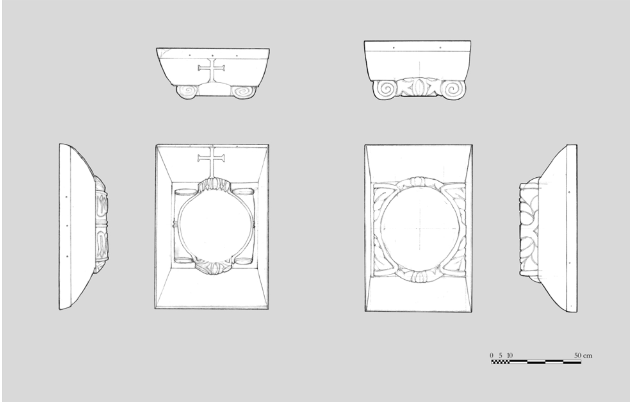

Fig. 1. Kos, Kephalos, St. Stephen Basilica, Ionic impost capital with calliper holes on main and lateral sides (after I. Baldini, S. Cosentino (eds.), Archeologia protobizantina a Kos, III. Il complesso di S. Stefano e l'insediamento della baia di Kephalos, Bologna 2021, Fig. III.2.1.3 p. 148).

The city of Ravenna will be here used as a case study both for the abundance of archaeological remains and for the possibility of carrying out direct surveys of architectural elements. A sample of 20 materials has been digitally surveyed to verify the morphology and the distribution logic of measuring signs, and to evaluate them in comparative terms as well. Most of artefacts pertain to still-standing ecclesiastical monuments, while a small group is stored in the National Archaeological Museum. The majority is carved in Proconnesian marble. Only a small sample is worked in Aurisina limestone and was included in the study as it provides interesting clues about the application of the same technique for modelling items in different kind of stones.

II.2. In addition to direct measurements, digital surface models were used to verify the metric and volumetric features of objects. 3D scanning is now the most widely used technology for the digital reconstruction of archaeological artefacts and is increasingly being used for diagnostic and restoration purposes. Notably, the ability to capture overly complex geometries with remarkable accuracy allows in-depth inquiry of manufacturing techniques. It grants the evaluation of geometric details on distinct stages of the design and crafting processes, otherwise difficult to detect. For the sake of this research, we opt for a portable scanner for dynamic surveying using a professional LiDAR-type sensor. The key features are ease of use, reliability, efficiency, relatively low running costs, reduced post-processing and accuracy. Metric information can be extracted from the complete millimetric-resolution model provided by LiDAR sensor for medium-scale artefacts [6]. Most of the artefacts could not be scanned in the same recording environment,

Fig. 2. Early-Christian monuments of Ravenna mentioned in the text: 1. St. Vitale Basilica; 2. Ss. Apostles Basilica; 3. St. Apollinare Nuovo Basilica; 4. St. Agatha Basilica; 5. St. Apollinare in Classe Basilica; 6. St. Pietro in Vincoli church (C. Lamanna).

as they are currently on display in museums or in their original context of use. However, some measures were taken to reduce the margin of interference caused by different lighting conditions, such as the use of LED spotlights with designated positions.

III. DISCUSSION

III.1. The materials under scrutiny include bases and imposts from Ss. Apostles Basilica, column bases from St. Agatha Basilica, imposts from St. Apollinare Nuovo and St. Apollinare in Classe basilicas, stepped-profile column bases and imposts from St. Vitale Basilica. All these monuments were built between the end of the 5th (St. Apostles, St. Agatha, St. Apollinare Nuovo basilicas) and the first half of the 6th century (St. Vitale and St. Apollinare in Classe basilicas, Fig. 2) for the initiative of prominent patrons. They were mainly members of the episcopal body of the city, except for the *Theodericianum* (St. Apollinare Nuovo basilica), commissioned by the Gothic king, Theoderic, as his palatine church [7]. In all cases, architectural elements in Proconnesian marble were commissioned to the quarries with the intent of adhering to aesthetic and ideological models of the capital on the Bosphorus. The materials were purposely manufactured for the building where they are currently preserved, except for St. Agatha Basilica. In the latter, most marble items of the architectural order were indeed reused from previous buildings so that it is presumable that also the column bases bearing calliper holes were originally in place elsewhere.

To the architectural members still *in situ*, four elements (two imposts and two Ionic impost capitals) stored in the National Museum of Ravenna must be added. Two imposts in Proconnesian marble are of unknown origin, while the other two, carved in Aurisina limestone, originally belonged to St. Pietro in Vincoli church [8]. Given the medieval foundation of the monument, also in this case it shall be assumed that the architectural members were originally in use in another monument.

Fig. 3. St. Agatha Basilica, column base with calliper holes on torus and plinth; St. Vitale Basilica, impost with calliper holes on abacus (G. Marsili).

On column bases, calliper holes are generally carved on the horizontal axis of the plinth or on the curved surface of the torus. On imposts and Ionic impost capitals, calliper holes are horizontally placed on the abacus (Fig. 3). Both on column bases and capitals, two signs usually appear on the major side (secondary side, according to the position toward the aisle), and sometimes they are reduplicated on the smaller ones (main side, according to the position toward the nave). Firstly, a comparative assessment of the spatial distribution of the holes allows verification that they are located at metrically relevant points for modelling the object. Namely, they divided the surface into three, with a variable-length centre and two uniform side segments. The reference measure was the central segment, which always turns out to be the reference metric unit (the foot in use), or a multiple/sub-multiple thereof. When also occurring on the side face(s), calliper holes would follow the one and same logic, proportionally defining the central segment on a smaller scale according to the corresponding unit of measurement. This is the instance with the impost capital stored in the National Museum (inv. No. 719), carved in Proconnesian marble and decorated with acanthus leaves on a lateral side and water-leaves on main ones (Fig. 4). Calliper holes on the abacus are placed as follows: on the secondary side (major by length), they define a central segment of 0,31

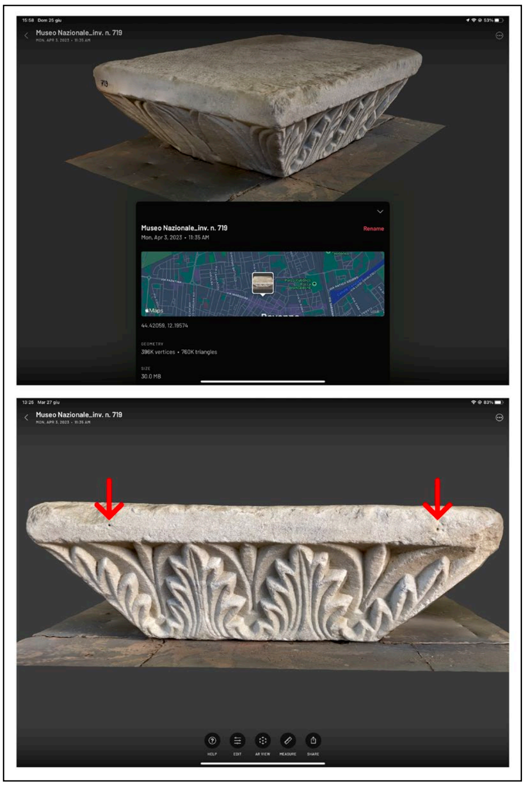

Fig.4. 3D scan of an Impost capital stored in the National Museum (inv. no. 719), carried out with a LiDAR-type sensor (C. Lamanna).

m, corresponding to 1 foot, with two quite equal lateral segments (0,75-0,85 m); on the main side (smaller in length), they scan a central segment of 0,21 cm, corresponding to ¾ foot, with two equal lateral segment (0,85 m). Relevant is also the case of impost capitals from St. Apollinare in Classe Basilica. Here circular holes appear on the secondary side of abacus, and they frame a central segment of 0,64 cm and two lateral segments of 0,10 m. The figure of the central partition gives the exact measurement of two feet, as it has recently been shown that the unit of measurement used in the building corresponds to one foot of 0,316 m [9].

Given the high variability of foot size in late antiquity [10], this evidence underlines a long-distance coordination between workforce, namely among quarry workshops and construction manager, being marble items purposely crafted according to the metric unit in use on the building site to fit the destination column order. Moreover, the recurrence of these measurement marks on the abacus hints at the importance of this partition in the design process, implicitly confirming Wilson Jones' "cross-section rule" [11]. It is also relevant that the same ratio is ascertained on capitals in Aurisina limestone stored in the National Museum, belonging to St. Pietro in Vincoli church, where they were likely reused in the Middle Ages (nn. inv. 711, 712). Calliper holes on the lateral side frame a central segment of 22 cm,

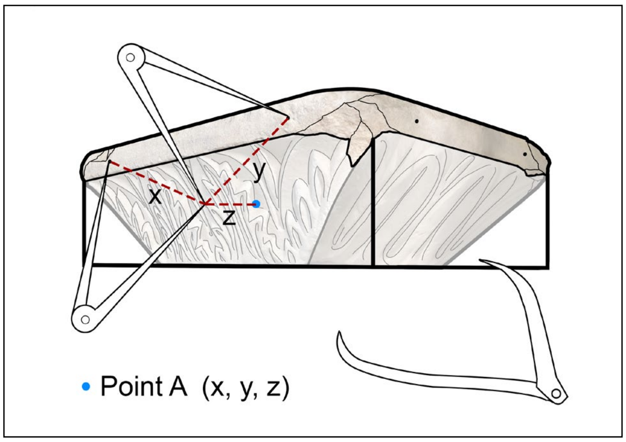

Fig. 5. Graphic reconstruction of three-compasses methods (C. Lamanna).

corresponding to a ¾ Roman foot (0,295 m), i.e. the one in used in local quarries.

III.2. We shall also propose that calliper holes were linked to the geometric process that underpinned the definition of general volumes and the design of decorative elements of marble elements. More precisely, it might be referred to the "three-compass method". This technique relies on the trilateration of points, that is the process of determining absolute or relative locations of points by measurement of distances, using the geometry of circles, triangles, or spheres respectively for two-dimensional or three-dimensional geometry. In marble manufacture, the principle applies in locating any point on the volume to be reproduced by means of three coordinates (x, y, z) determined with a calliper (Fig. 5). Since three compasses are sufficient to transfer the coordinates of the model to the block to be carved, this method does not require sophisticated equipment. Only two types of callipers were needed: two straights (or curved) for linear distances (x, y) and one necessarily curved for height/distance from the working plane (z). The straight compass (*circinus* or *circinus rectus*) consisted of two equal parts joined by an axis held by a small key for fixing points [12]. Available in different sizes, its rather rigid structure allowed the same measurement to be kept and repeated many times. The *circinus curvus*, whose head was pierced by an axis held by two buttons, was used as a calliper. The two types callipers were often depicted together (Fig. 6), mainly in funerary reliefs [13]. Rare archaeological findings come from Pompeii and other Vesuvian cities [14].

In several cases, marble elements of the same set with slightly different dimensions are marked with circular incisions. In these cases, it shall be assumed that aligned holes may reveal the geometric process used to reproduce elements of different size according to a same proportional ratio. In this case, a possible explanation

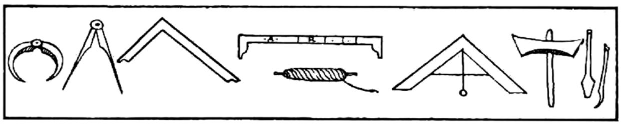

Fig. 6. Rome, St. Callistus catacombs, funerary relief depicting plain and round callipers, detail (after W. Déonna, see footnote n. 11).

would be to identify these traces as pivots for a pantograph support. The existence and function of this device is known from Heron of Alexandria's "Mechanics" [15]. In Book I, Chapters 15-18, Heron deals with the subject of reproducing two or three-dimensional shapes from a given model in accordance with a specific proportion [13]. To this end, he describes the pantograph, an impressive tool consisting of a flat base with two interconnected toothed wheels and two parallel toothed rulers running inside two grooved rods. The gears could rotate around a single axis passing through their common centre, while the parallel rulers were attached transversely to an arm that rotated around the centre of the gears. Two rods welded perpendicularly to the ends of the two rulers had a point and a lapis at their ends, aligned with the centre of the gearwheels. When the operator used the point to trace the shape of the object to be reproduced, the lapis automatically made a replica according to the proportional ratio given by the gearwheels. Although no archaeological remains have survived, the morphology and operation of the device can be easily understood by observing the same tool in use in a 20th century sculpture workshop (Fig. 7).

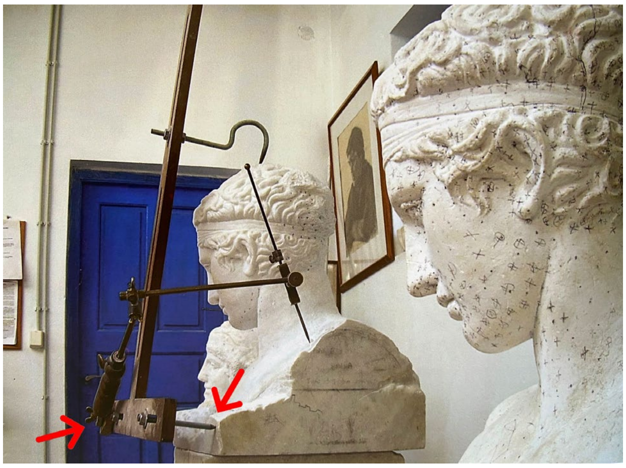

Fig. 7. A pantograph in use in a 20th century workshop (after A.E. Florakis, I Tiniaki Marmarotechnia. Istoria kai Techniki, Politistiko Idryma Omilou Peiraioos, Athens, 2008).

IV. CONCLUSIONS

The paper focus on a category of graphic signs in the shape of small circular engravings on marble items usually overlooked in archaeological research, namely calliper holes. They frequently occur on late antique architectural members, mainly in Proconnesian marble but also in other kind of stone. Being regularly carved in specific parts of marble items, such as the abacus for capitals and the plinth for column bases, these marks can be taken as measurement and control points, often associated with carving guidelines. Since they were engraved in the preliminary phases of workmanship, they are still visible on artefacts laying in total or partially roughed-out form, whereas finishing and polishing operations usually wiped them off the surface. In terms of functionality, measuring instruments and callipers were used to guide the initial design and shaping of marble items, with the breakdown of volumes for the generation of planar and curved surfaces. Furthermore, they were functional to scale volumes and reproduce morphologies from a model to other objects. The wide distribution of such finds outlines the spread of this procedure, meant to rationalize production, and save processing times. Archaeological documentation enables us to contextualize the phenomenon in a specific chronological span, corresponding to the peak of early Byzantine architectural enterprises between the mid-5th century and the second half of the 6th century. The city of Ravenna, raised to Western capital at the beginning of the 5th century, attracted a large amount of marble architectural material from all over the Mediterranean to decorate civil and ecclesiastical public buildings. The large amount of material still preserved, together with the possibility of applying modern 3D digital surveying techniques, makes Ravenna an exceptional case study for the phenomenon under scrutiny. The presence of measurement marks on artefacts made of Proconnesian marble and Auresine limestone also opens up further research scenarios, both in terms of the transmission of techniques between different craftsmen and the on-site processing of artefacts by allogenous stonecutters. These aspects can be further explored in future research that pays attention to production indicators that are often overlooked, even with the key advantage of digital technologies.

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