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BRIEF REPORT

The frieze of the Art of War in the Ducal Palace of Urbino: conservation issues, materials, and executive techniques

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Abstract

The frieze of the Art of War was originally positioned along the sides of the facade of the Ducal Palace in Urbino (Marche, Italy), and it is currently located in the palace's Chancellery Room. The frieze, probably elaborated by Federico da Montefeltro around 1474, consists s of stone bas-reliefs illustrating a rich iconographic repertoire depicting numerous engineering machines and symbols related to the military and political spheres. The present work aims to deepen the knowledge of the Art War frieze and to clarify some doubts regarding the original shape of the bas-reliefs, the constituent material, and the executive technique; conservation issues were also considered. Polarized light microscopy observations were carried out on the stone materials, identifying the use of a packstone referable to the Calcare Massiccio A Formation (Hettangian-Lower Pliensbachian p.p.). This stone, locally known as *Piobbico Travertine*, was excavated in the Val d'Abisso quarries, part of the Umbria-Marche ridge. Ca-oxalates were detected by Fourier transform infrared analysis in the brownish patinas that mainly cover the surfaces of the bas-reliefs; they could be related to ancient conservation treatments and/or to biological agents. Regarding the execution technique, a thorough autoptic examination allowed for a better understanding of the original conformation of the bas-reliefs and the carving process. Stylistic and executive differences in the execution of the same detail were observed in different bas-reliefs, confirming the activity of various sculptors. Different decay typologies were used to consider the debate regarding the original arrangement of the frieze on the facade, validating the most accredited hypothesis.

Keywords Renaissance bas-reliefs · Urbino · Calcare Massiccio Formation · Micro-invasive investigation · Conservation issues

Historical background

The frieze of the Art of War was originally placed on the plinth that ran along the sides of the facade of the Renaissance Ducal Palace (Figs. 1a, b and S1a) in Urbino (Marche, Italy) up to the facade of Castellare (Polichetti 1986) in front of to the church of San Domenico. A varied iconographic repertoire (Fig. 2) is displayed in the frieze depicting numerous engineering machines for construction and warfare and symbols related to the military and political themes (Pietrini et al. 2023).

There is no certain information about the design of the frieze, and the debate related to its execution appears even more complex. Scholars argue that the conception of the stone frieze corresponds to an accurate iconographic program probably elaborated around 1474 by Federico da Montefeltro, before the arrival of Francesco di Giorgio Martini (Bernini Pezzini 1985; Taglialagamba 2023). Bernini Pezzini (1985) argued that it is possible to distinguish almost two consecutive phases of execution: one before Francesco di Giorgio Martini and one related to his activity in Urbino. Aureli (2023) rejects this interpretation because of the close and very strong similarity between the bas-reliefs and the system of portals and angular parasitic that support the entablature while attributing the unevenness of execution of the panels exclusively to the intervention of several artists.

Taglialagamba (2023) has proposed a heraldic and emblematic reading of the bas-reliefs, suggesting 1480 as the terminus ante quem for the design of the frieze. According to these scholars, the drafting of the iconographic program aimed to celebrate both Federico da Montefeltro politically and his stature as a man of war, including the

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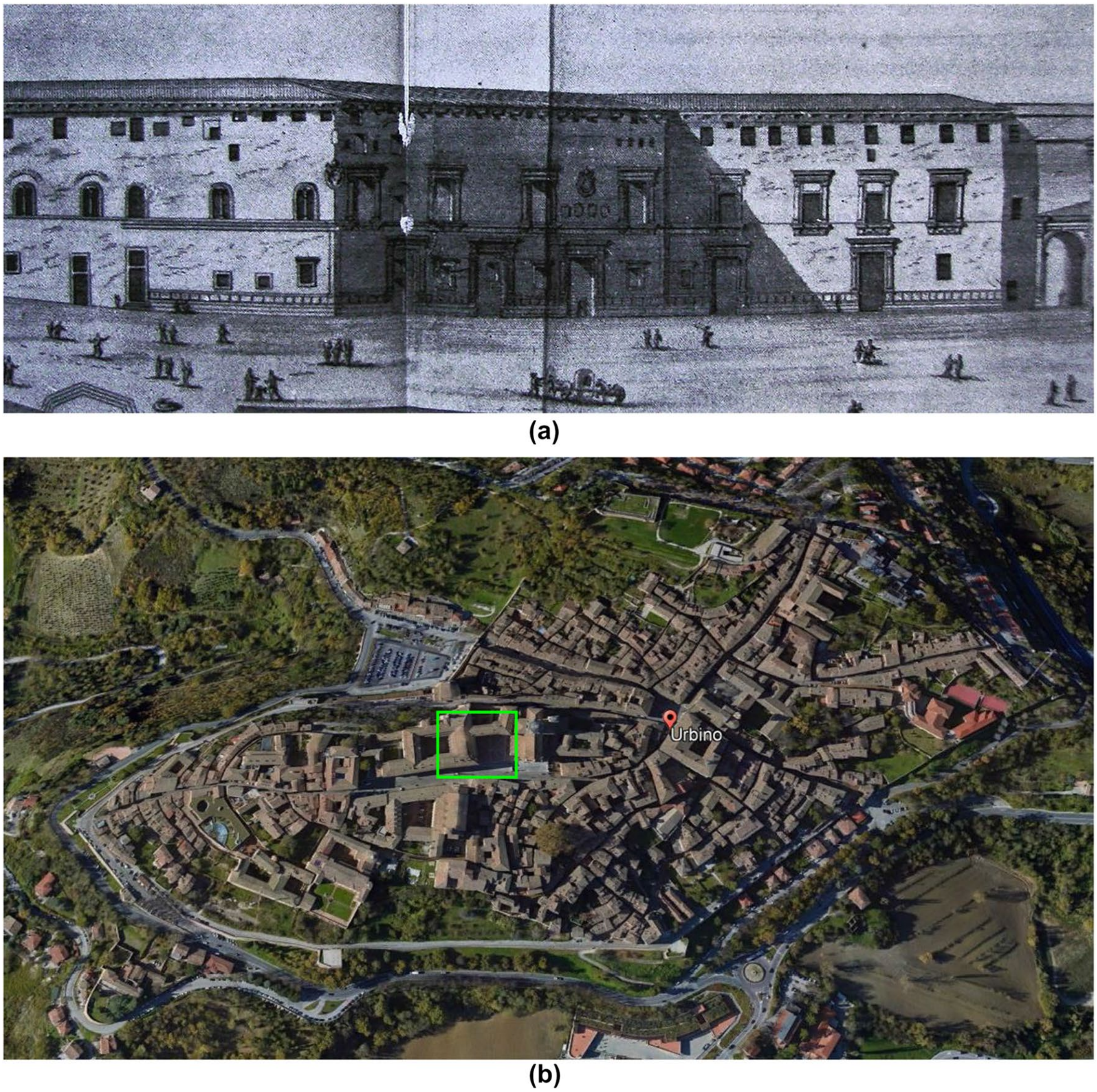

Fig. 1 **a** Engraving of the Ducal Palace in Urbino (Marche, Italy) taken from Bianchini (1724); **b** current plan of Urbino, 1: Ducal Palace. The square green line highlights the area in which the bas-reliefs were originally positioned

foresight of his dense network of alliances. Molari and Molari (2023) suggested the subjects depicted in the bas-reliefs were selected by Duke Federico da Montefeltro for the purpose of generating and disseminating ideas in the minds of those who would be able to interpret them. Luca Pacioli in his work reports that «... Federico Feltrense... a frieze of the living and beautiful stone by the hands of worthy stone carvers and sculptors, neatly arranged...» (Bernini Pezzini 1985). This confirms that the execution of the frieze was not entrusted to a single artist but to a group of sculptors. Moreover, the statement makes a distinction between two groups of workers: the sculptors and the stonemasons (probably less skilled than the former). In the course of time, different scholars have tried to solve the question of attribution: Giorgio Vasari, for example, mentions a certain "Francesco," presumably to be identified with Francesco di Giorgio Martini (Vasari 1568), while Baldi (1590) argued that the sculptor Ambrogio Barocci, great-grandfather of the famous Urbino painter Federico, had made the frieze together with his brother Simone on the basis of drawings provided by Martini. After some time, Rotondi (1950) generically attributed the paternity of the bas-reliefs to a Lombard environment, while Bernini Pezzini (1985) ascribed them to different sculptors, probably the same ones who made the entire ornamental apparatus of the palace. In detail, a part of the stone panels, characterized by robust modelling and rich decorative elements, is attributed to Ambrogio Barocci and his circle; another group of panels,

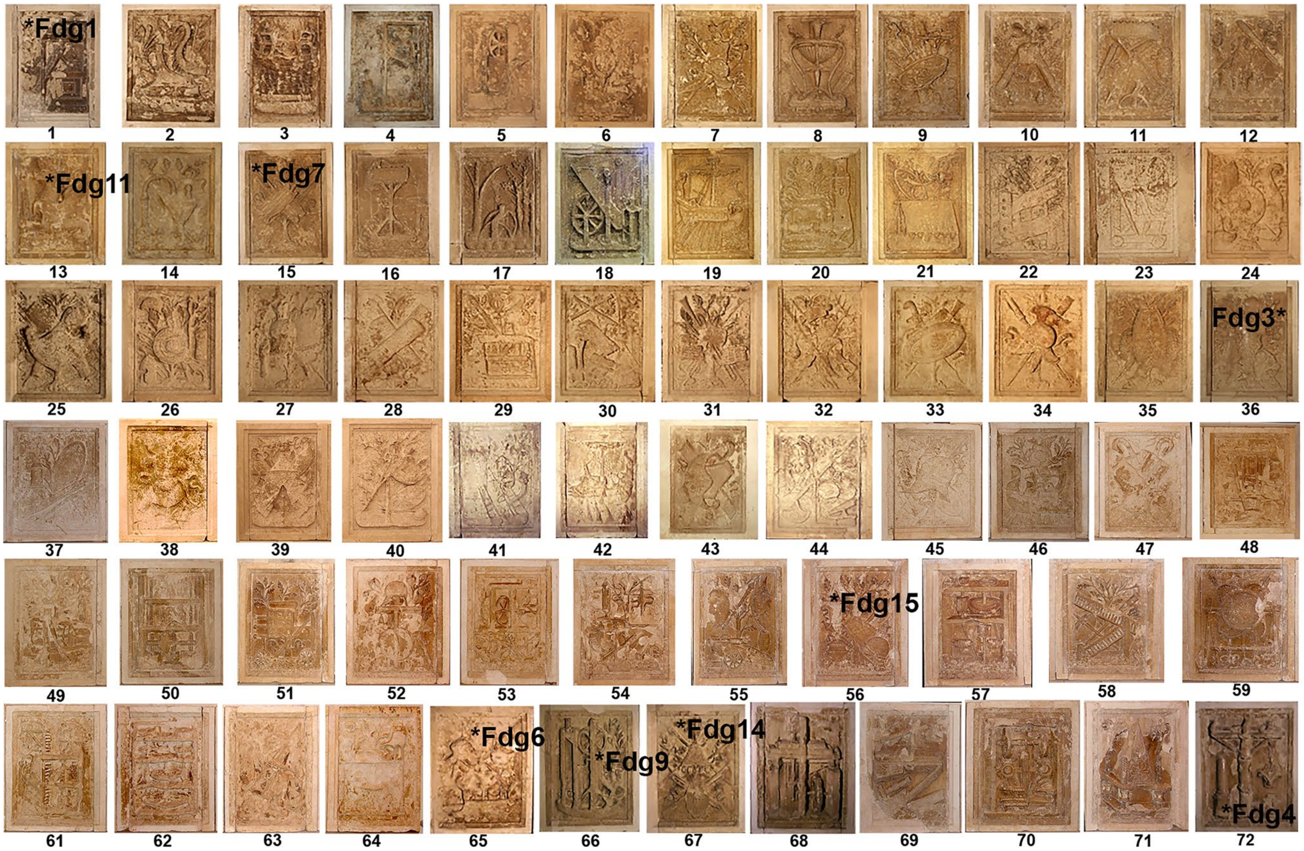

Fig. 2 Bas-reliefs of the Art of War frieze, Ducal Palace of Urbino, with their progressive number and the sampling location

on the other hand, is attributed to some Sienese stonemasons, because of their incisive linear modelling and deep perspective rendering. Finally, Bernini Pezzini also reported the production of some roughly executed bas-reliefs (No. 23-29). Molari attributed the execution of the stone panels to both Francesco di Giorgio and the stonemasons working in the palace, probably directed by Barocci (Molari and Molari 2006).

No literary source reports the order in which the stone panels were displayed on the facade and the chronology of their placement. The frieze is mentioned for the first time in a brief indication in Luca Pacioli's De divina proporzione (Bernini Pezzini 1985); moreover, in the accurate description of the Ducal Palace provided by Baldi (1590), the continuity of the stone seat and thus of the bas-reliefs along the winged facade was reported.

Regarding the stone used for the realization of the Art of War frieze, Baldi (1590) revealed the use of *Piobbico Travertine* and the location of the quarry: «This stone although it seems to be of the same species as that which is quarried at Tivoli, from which it takes its name, is different in some parts; for ours is much finer and not pitted, and spongy like that, but firm and similar. Moreover, it surpasses it in whiteness, for where the former is of a colour tending to the pale, the latter is as white as snow: in this, however, both after being extracted from the stone quarry and left in the air become hard... Travertine is quarried ten or twelve miles from Urbino from a mountain, which is called Nerone... This is on the banks of the Metauro River, above a castle called Piobico. On the top of this mountain are quarries of Travertine, and there are seen quarries, and very deep caverns formed for the columns and other stones excavated for the use of this factory.» (Baldi 1590). The impervious site was known since Roman times but was of great importance in the Renaissance period (Rodolico 1953; Selli 1954).

The most important historical quarries, currently inactive, are located in the area of Nerone Mountain anticline (Val d'Abisso, Infernaccio quarry), on the northern slope of Nerone Mountain, 1.5 km from Piobbico, 35 km from Urbino (Fig. S1b) (Bani 1989; Raffaelli 2003). These quarries are consistent with lithofacies A of Calcare Massiccio Formation (Amadori 1985a and references therein; Amadori 1985b).

According to the literature, the Jurassic Calcare Massiccio Formation (Hettangian-Lower Pliensbachian p.p.) is divided into three lithostratigraphic subunits: A, B (Nerone Mountain) and C (Burano) (Amadori 1985a; Amadori 1985b; Brandano et al. 2016, Santi et al. 2021 and reference therein). Calcare Massiccio A (lower member) is composed of beds of whitish metric massive limestone (3–4 to 15 m thick) with oncoids and peloids (Centamore et al. 1986; Santi et al. 2021). Lithofacies B (upper member) consists mainly of massive or poorly stratified bioclastic limestone beds (10 to 30 m thick) with small oncoids and variable peloids (Centamore et al. 1986; Santi et al. 2021). Lithofacies C is mainly composed of whitish-light brown massive limestones (4 to 5 m thick) with abundant oncoids and peloids (Centamore et al. 1986; Santi et al. 2021).

Transportation of the stone materials from the quarries was done by sliding the limestone blocks on sledges properly anchored by ropes to posts into the rock, to the road (Busdraghi and Wezel 2002).

Since antiquity this stone (Calcare Massiccio A) has been erroneously called *Piobbico travertine* probably because of its vacuolar texture (Baldi 1590) and different hardness; in particular, it has been locally referred to *Female* and *Male Piobbico travertine* depending on the ease with which it can be carved (Selli 1954; Amadori 1985a; Amadori 1985b). The former is classified as packstone with a grain size of 100 µm to 0.4 mm and it is composed of well-graded peloids and ooids, intraclasts, and bioclasts. The second is classified as grainstone with a variable grain size (100 µm to 1 mm) and is composed of ooids, intensely micritised, intraclasts, bioclasts and algal fragments, bound by a spatic cement. Since the total porosity of *Piobbico Male travertine* is lower (3–8%) than that of *Piobbico Female travertine* (20–28%) (Amadori 1985a, b; Santi et al. 2021 and references therein) the former lithology should be harder than the latter. From a geotechnical point of view, *Piobbico Female travertine* has a medium hardness that offers the sculptor the possibility of obtaining the maximum variety of surface shades and textures. An important peculiarity of this material is its brittleness: this is due to its high tensile strength and fair aptitude to retain details (Amadori 1985a).

Conservative history

Seventy-two bas-reliefs decorated the plinth that ran along the sides of the facade of the Ducal Palace in Urbino from its creation (late fifteenth century) until 1756 when they were detached and transferred for conservation purposes to the new Lapidary Museum in the Soprallogge. This was an important significant protection operation carried out by Cardinal Giovan Francesco Stoppani, papal legate in Urbino (Aureli 2023; Taglialagamba 2023), who included the Art of War frieze within a program of conservation of ancient stone artefacts.

The operation of detaching the frieze from the stone seat, entrusted to the Rimini architect Giovan Francesco Buonamici, as he himself stated was not particularly smooth «...some were found broken, and one could no longer be used...» (Bernini Pezzini 1985) referring in particular to stone panel No. 60, no longer extant and known only thanks to an engraving by Gaetano Piccini (Eiche 1990; Aureli 2023; Molari and Molari 2023). The original sequence of the panels is currently only conceivable on the basis of the publication of Bianchini (1724) and Bernini Pezzini (1985). According to Aureli (2023), the individual stone panels were not directly juxtaposed next to each other but interspersed with intermediate vertical elements whose features are unknown; their presence is confirmed by the iconographic sources of the facade and was required due to the extension of the plinth.

Thanks to its relocation, the frieze was preserved from interacting with the environment «... and it was well that the provident restorer of this building had the thought to save them from further damage, while those were threatened with total ruin and consumption» (Bernini Pezzini 1985). Seventy-one bas-reliefs were therefore walled inside special panels, built at the base of the walls of the Soprallogge (noble floor), in contact with the floor, and decorated with perimeter pilasters in stucco (Fig. S2a), so as to resume the original frieze (Bernini Pezzini 1985). This arrangement, unlike the original one, was made according to an aesthetic criterion typical of the 18th century, giving the stone panels a purely decorative function.

The frieze remained on the Soprallogge for about two centuries and in 1944 it was transferred from the Lapidary Museum to the ground floor (Fig. S2b). The well-preserved bas-reliefs were located in the rooms facing the Pasquino courtyard and displayed according to the subjects represented; all the others were placed in the storage rooms of the Ducal palace. Around 1980, after a restoration intervention, the stone panels were placed in the Chancellery room.

Currently, the bas-reliefs maintain the latter arrangement, placed side by side according to the numbering provided by Bianchini (1724). The first forty-eight panels are arranged inside the first room, while the other thirteen are located in the adjacent room. They are placed on white Plexiglas bases and anchored to the walls by metal brackets inserted on the back (Fig. S2c).

The bas-reliefs have the same dimension in height (about 84 cm) but vary in width (D'Apice 2008; Baratin et al. 2013; Amadori and D'Apice 202). Few of them are composed of a single element (Nos. 2, 4, 9, 14, 25, 27, 33, 34, 37, 43, 47, 50, 65, 70, 72) of different widths, while all rest are composed of a variable number of pieces; for example, stone panel No. 43 is 95 cm wide and consists of a single block (Fig. S3a), while bas-relief No. 3 is 64.5 cm wide and is divided into three parts (Fig. S3b). In most cases, the side frames seem not to match the central block; this inconsistency is also confirmed by the different shades between the two pieces. Further information on the original conformation of the blocks emerges from the observation of stone panels No. 48 and

No. 49 (Fig. S4a,b). Bas relief No. 49 consists of two blocks: the first corresponds to the right edge, while the other, on which the depiction is carved, also has one of the two edges of the adjacent panel (No. 48). Probably, the bas-relief was not only created off-center within the block but also lacks the right edge; however, the piece would include the edge of the adjacent stone panel (No. 48). This hypothesis can only be valid if we assume that most of the blocks underwent cutting operations that today do not allow us to trace their original conformation (Amadori and D'Apice 2023).

Considering the vicissitudes of the frieze and its relocation over time, it is possible that the different stone elements were assembled inaccurately over time. Based on a period photo (Fig. S4c), the eighteenth-century arrangement of two stone panels (Nos. 44 and 36) can be seen, the insertion of a stone dowel (made especially for their assembly) into the wainscoting of the Soprallogge walls is evident. Both the right margin of the bas-relief No. 44 and the left margin of No. 36 are currently completely missing (Fig. S4d).

Sampling and methods

The frieze of Art of War is a unique artifact and sampling was greatly reduced because of this uniqueness. According to UNI Recommendations (UNI-EN 16085 2012), nine representative samples were carefully collected from the frieze (Table 1, Fig. 2). The micro samples were collected from partially detached surface areas that were no longer suitable for future restoration, following the Superintendency's recommendations and the critical conservation requirements of the minimum intervention strategy. Location, description of the sample, and analyses performed are shown in Table 1.

Polarized light microscopy observations were carried out with an Olympus BX51 microscope equipped with fixed ocular (10× magnification) and objective at different magnifications (5×, 10×, 20×, 50×) connected directly to an Olympus SC50 camera and Stream Basic software for image acquisition. Observations in transmitted and reflected light on thin and cross sections allowed the identification of the typology and the characteristics of the stone samples.

Table 1 List and description of micro samples collected in the stone bas-reliefs and related investigations

Sample name	Bas-relief number	Sampling area	Scientific investigations
Fdg1	1	Tree	PLM, SEM-EDS
Fdg3	36	Right side	PLM, SEM-EDS
Fdg4	72	Left column	FT-IR
Fdg6	65	Frame	FT-IR
Fdg7	15	Frame	FT-IR
Fdg9	66	Cog wheel	FT-IR
Fdg11	13	Basket base	FT-IR
Fdg14	67	Left leaf	FT-IR
Fdg15	56	Trunk	FT-IR

Morphological observations and chemical microanalyses were carried out on both the sample and cross section using a scanning electron microscope (Philips 515) equipped with an energy-dispersive X-ray spectrometer (EDX) by Link Analytical Oxford (Link, UK), model 6103. Sample and cross section were investigated after air drying and gold-sputtering. The analyses were performed at acceleration voltage from 5 to 15 kV with a variable working distance (0.1 to 5.4 mm), 40 µA filament current, 100 s acquisition time.

Fourier transform infrared analysis was carried out on some samples using a Perkin-Elmer mod. Spectrum 1000 spectrometer equipped with Spectrum software for data processing. The micro-samples, selected under a stereomicroscope (Nikon mod. SMZ745T), were analyzed as such, without further manipulation in transmission mode using a diamond anvil cell (Specac, Slough England). The working spectral range was 4000 to 370 cm^{-1}, with a resolution of 2 cm^{-1} and 32 scans.

A microclimate monitoring (DM. 10.5.2001 2001; UNI 10829; UNI EN 15757) was carried out in the Chancellery room, on the ground floor, in order to monitor the indoor microclimatic conditions. A data logger was used to collect temperature (T) and relative humidity (RH) values from December 2019 to November 2020, with a time step of 15 min.

Results

Materials

On the basis of polarized light microscope investigation (Fig. 3a, b), the samples collected from the bas-reliefs (samples Fdg1 and Fdg3, Table 1) can be classified as packstone (Dunham 1962). The texture is composed of peloids, ooids, strongly recrystallised, associated in clearly subordinated amounts with intraclasts, bioclasts and small oxides. The ooids, which vary in size from 100 µm to about 400 µm, are often micritic. The intergranular space is occupied by a microsparitic matrix partially replaced by a neomorphic sparite (Fig. 3c). The samples also appear to be characterized by moderate primary and secondary intergranular porosity. PLM observations ascertained that the samples Fdg1 and Fdg3 (Table 1) are attributable to the Calcare Massiccio A Formation, locally known as *Female Piobbico Travertine* (Amadori 1985a; Amadori 1985b; Bani 1989; Raffaelli 2003).

The surface of the stone is sometimes wavy and covered by reprecipitated calcite, demonstrating the action of dissolution and reprecipitation processes that occurred during

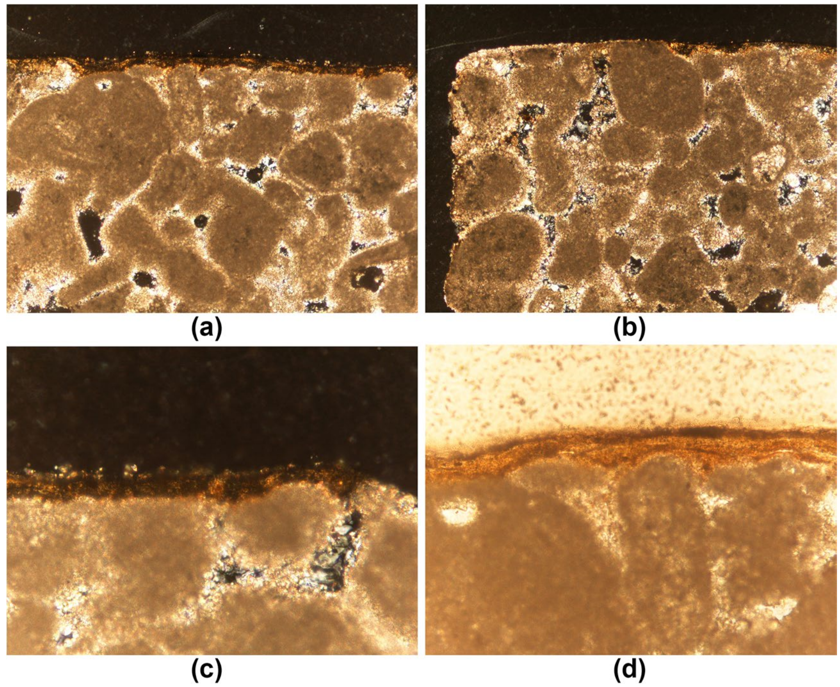

Fig. 3 Micrographs of sample FdG3 thin section in transmitted light: stone texture, **a** Nicols X and **b** Nicols; patina detail, **c** Nicols X and **d** Nicols

outdoor exposure (Fig. 3b). Interstitial pores sometimes appear partially filled with calcite and gypsum formed by recrystallization and sulphation phenomena (Fig. 3c).

Yellowish-brownish patinas partially covered the stone surface of the bas-reliefs (Figs. 3d and S5a). SEM investigation carried out on the cross-section (sample Fdg3) revealed the presence of cracks and micro-cracks confirming the decohesion phenomena observed in most of the surface patinas (Fig. S5b). EDS mappings (Fig. S5b–d) showed the presence of Ca related to the limestone, while Si could be related to the consolidation treatment applied in the 1980s. The presence of S is attributable to the sulphation phenomena. EDS analysis confirms the presence of Ca, S, Si, Al, Mg, K and Cl (Fig. S5e, f) related to stone material and exogenic deposits. Fe was detected in the red traces visible on both the patina and deteriorated surfaces of some bas-reliefs (Fig. 4a). FTIR analysis showed the presence of calcium oxalate, mainly trihydrate, monohydrate and probably dihydrate, sulfates, and silicates (Fig. 4b). Caoxite, a rare trihydrate Ca-oxalate, was detected due to strong signals at ~ 1323–1324 cm^{-1} and OH stretching at 3526, 3422, and ~ 3270 cm^{-1} (Conti et al. 2015). The presence of Ca-oxalates could be related to a consequence of the oxidative degradation of ancient organic treatments applied on the stone surface during the centuries (Camaiti et al. 1996) or it could be a product of past lichens colonization (Cariati et al. 2000), since rare crusted lichens are currently visible on the surfaces of the bas-reliefs originally placed on the north wall façade. In addition to gypsum, an acryl-silane resin (Wu et al. 2014) was detected in samples Fdg4 and Fdg14 (Fig. 4b) while dialkylsilane oligomer (Launer and Arkles 2013) was identified in sample Fdg15 (Fig. 4c) related to recent interventions of restoration.

Executive techniques

According to the technique of stone carving (Rockwell 1989), each block was probably sawed along the frontal plane so as to obtain a smooth contour surface, leaving the central space still rough; then, the frame was made with a chisel (Fig. S6a). Next, a perfectly polygonal element was probably carved on which the contours of the details were sketched by chisel and string/running drills (for the more prominent elements). The contours were then carved down to the bottom plane. It is assumed that the bottom was further carved to create a uniform surface, with the exception of the small intermediate spaces between some elements that were probably carved at a later time (D'Apice 2008).

Regarding the execution stages, due to the poor state of conservation of the frieze, we considered only the traces of the tool still visible on the well-preserved surfaces (Amadori and D'Apice 2022). The sculptor probably defined the forms with a point chisel and flat chisel, starting with the outermost and thickest ones and ending with the innermost ones on the lower plane. The hypothesis that this technique and not the reverse one was used stems from the fact that the thickness of the reliefs in relation to the bottom plane is not the same; this would also suggest that no precise method was used to calculate the depths. Probably, after the execution of the primary and thicker parts (Fig. S6b), the internal details

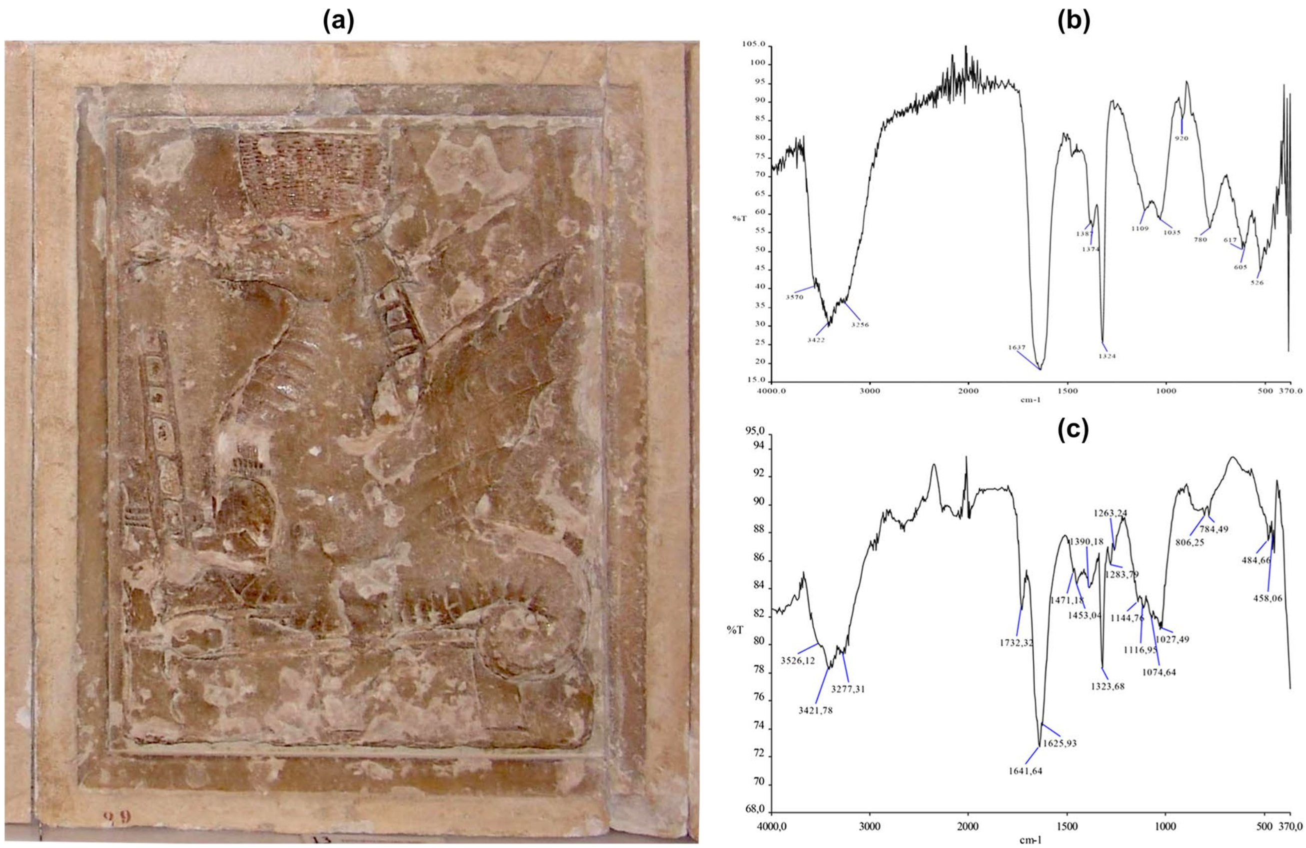

Fig. 4 **a** Bas-relief No. 13 with red traces; FT-IR spectra; **b** sample Fdg14 bas-relief No. 67; **c** sample Fdg15 bas-relief No. 56

(Fig. S6c) were sculpted based on the already sketched outlines. It is assumed that the sculptor proceeded by zones, evaluating the thickness of the decorative elements from time to time and adapting them to that of the surrounding composition. Based on the traces observed on the surfaces of the bas-relief, it is likely that string/running drills (Fig. 5a), roundel chisel (Fig. 5b), claw chisel (Fig. 5c), pointed chisel (Fig. 5d), channelling tool, tooth chisel, and rasp were used. The finishing technique sometimes seems rather quick and imprecise.

By distinguishing the various groups of bas-reliefs on the basis of specific characteristics and comparing the same subject (flowers, leaves, etc.) carved in different panels, it was possible to underline some differences in both stylistic and executive (Amadori and D'Apice 2023). For example, the five-petaled floral element represented in bas-relief No. 39 is more accurately finished than in No. 59, in which the flower appears almost stylized; moreover, in the former case, a string drill was used, in the latter a chisel (Fig. 6a, b). In addition, the oak leaf, depicted in bas-reliefs No. 46, is thicker and has a smoother surface than the leaf in stone panel No. 55, which has a slight central rib and a more naturalistic appearance (Fig. 6c, d).

State of conservation of the frieze and its original arrangement on the façade

Urbino (Fig. 1b) lies on two hills (average altitude 450 a.s.l.) connected by a saddle that slopes for 30 km from the Apennines to the Adriatic Sea (Bernardi et al. 1985). The city has a transitional sub-continental climate with medium to high humidity (71%), characterized by wind gusts that sometimes exceed 100 km/h on average 10 times. The average annual temperature is 12.6 °C with not very cold winters (average 4.3 °C) and frequent snowfalls (average 69 cm). Rainfall is well distributed throughout the year, more abundant in autumn, less in summer, and very similar in winter and spring.

The Ducal Palace (Fig. 1b) is located on the top of one of the two mentioned hills and is south-north in length and east-west in width. Due to the climate conditions of the area, the different typologies of decay that affected the frieze of the Art of War are mainly attributable to their original position along the sides of the facade of the Ducal Palace (Figs. 1a and S1) because of the different exposure to weathering, even though it has been there for a limited time, ~ 200 years. In addition, the frequent movement of

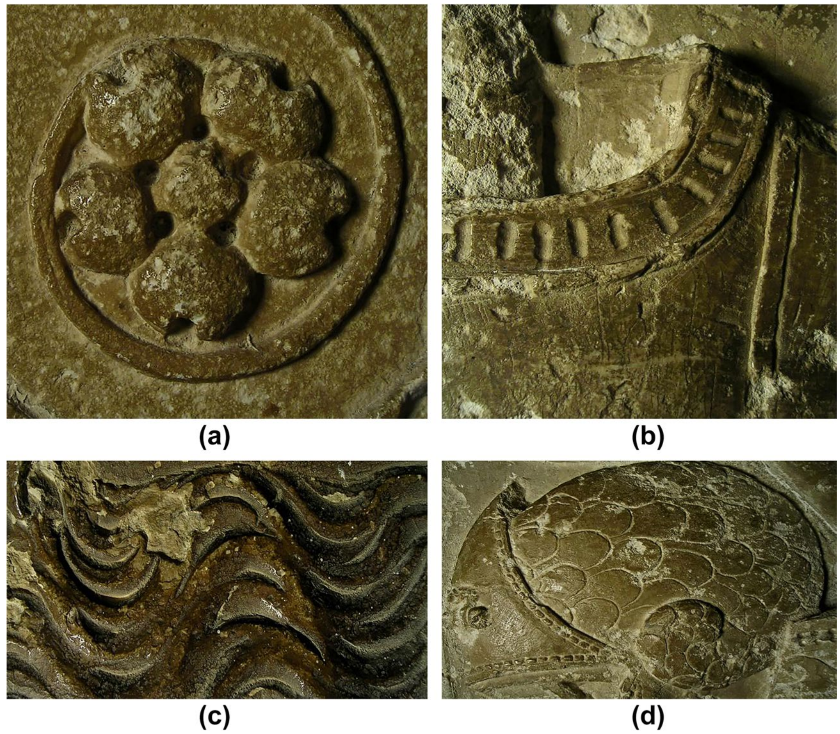

Fig. 5 **a** Floral decorative detail in stone panel No. 43; **b** finishing of the edge of the cuirass in stone panel No. 38; **c** crests of water in No. 1; **d** decoration of the helmet in bas-relief No. 39

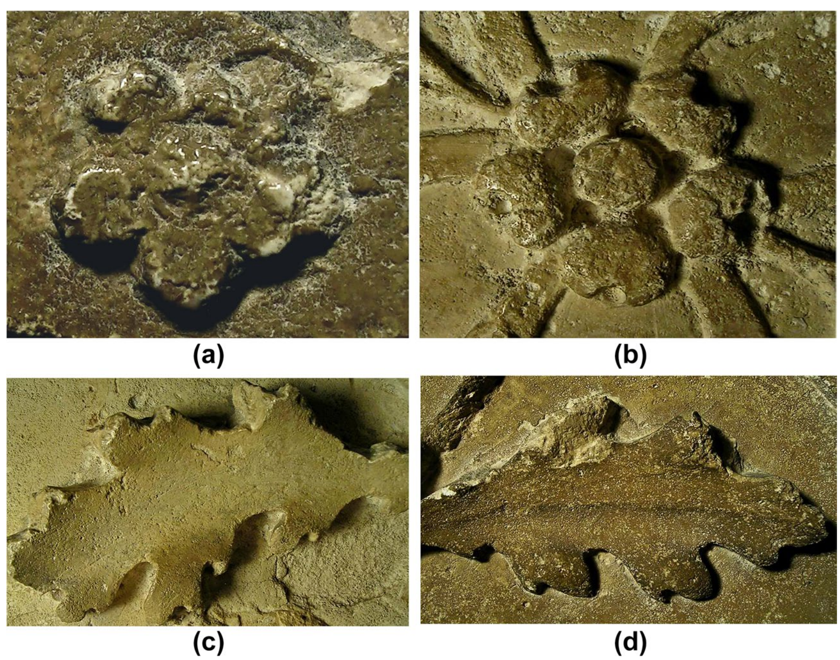

Fig. 6 Five-petalled flower in bas-reliefs **a** No. 59 and **b** No. 39; oak leaf in **c** No. 46 and **d** No. 55

the stone panels has also contributed to the deterioration of their state of conservation.

Currently, the main typologies of decay (ICOMOS 2008) visible on the surface of the bas-reliefs are loss of parts (Fig. S3b), abrasion (Fig. S7a), differential erosion (Fig. S7b), alveolization (Fig. S7c), detachment (Fig. S7d), mechanical damage, etc. (Fig. S6), sometimes so intense that the original features are lost; biological attack is limited to the rare presence of lichens and fungal species (Fig. S7e, f) on those bas-reliefs originally located on the north wall facade. Most of the stone panels are covered with yellowish-brownish patinas (Amadori et al. 1989). These patinas are compact, vary in thickness and follow the morphology of the substrate, sometimes constituting a faithful replica of it

(Fig. S8a, b). However, the hue and intensity of the patinas gradually change from one bas-relief to another; this would confirm that their formation may be mainly related to the two centuries of exposure on the facade. Comparing a period photo (Fig. S9a) and a current photo (Fig. S9b, c), in which stone panels No. 49 and No. 25 are visible, the state of preservation of the surfaces differs little: the patinas show the same extent and are absent in the areas where the surface is eroded (Fig. S9).

The different typologies of decay and variations in patina hues were used to identify possible correlations between atmospheric parameters (sunlight, temperature, rainfall) and the original exposure of the bas-reliefs. Starting from Gaetano Piccini's engraving (Fig. S10a) (Bianchini 1724) and in the absence of information on weather conditions in Urbino during the two centuries in which the frieze was exposed, the hypothesis regarding its original position was evaluated taking into account the current environmental characteristics and past architectural features of the area (Amadori and D'Apice 2022). Based on the position of the facade, the areas most exposed to sunlight are those facing east (areas: A, F, G) and south-east (area H), while the other areas facing north (areas B, C, D, E) are always in shade (Fig. S10b). It should be considered that the dynamic of degradation phenomena is greatly influenced by the incidence of winds: this interferes with the inclination and penetration pattern of rainfall and with the cycles of solubilization and recrystallization of salts.

Returning to Bianchini's "sequence" (Bianchini 1724), the first eighteen bas-reliefs (No. 1 to No. 18) should be present along the first section of the facade (A) in which the solar radiation and related phenomena are the main cause of the surface degradation. According to Molari (Molari and Molari 2022) the stone slabs in this section were 17 instead of 18. Patinas, detachments and losses of material characterize the first eight panels (No.1 till No.8), albeit with different extensions and intensities (Fig. 2). Abrasive or erosive phenomena mainly concern smaller elements, which are easily affected by temperature variations and therefore tend to expand further. The poor state of conservation of some stone panels (Figs. S3b and S11a) is probably attributable to a malfunction of the water drainage system (Bernini Pezzini 1985). In addition, it should be hypothesized that the missing elements could also be linked to anthropic factors: these bas-reliefs adorned the back of the seat and the ball game officially took place in Piazza Rinascimento (Bernini Pezzini 1985). Starting from bas-reliefs No. 8 to 18, slight gaps are observed; the stone surfaces are covered by patinas, suggesting exposure to stronger winds (Fig. S11b). The state of conservations of the bas-reliefs originally positioned in this area (section A), allowed us to hypothesize that the wind flows coming from the north (today's Via Pucinotti) and from the south-east (today's Via S. Domenico) contributed differently to the decay depending on their position (Fig. 1b).

Comparing the state of conservation of the next three bas-reliefs (Nos. 19–21), belonging to section B (Bianchini's "sequence"), a similarity with the eighteen stone panels of section A is evident (Figs. S8b and S11c). We could hypothesize that these last three elements were originally placed at the end of section A (D'Apice 2008; Baratin et al. 2013).

Starting with stone panel No. 22 (Fig. S11d), the patinas present different shades (tending towards grey-ochre) and the surfaces are mainly characterized by erosive phenomena. We can therefore hypothesize that the first stone panel on the north wall (section B) was No. 22. According to Bianchini (Bianchini 1724), 24 bas-reliefs (Nos. 19–42) made up the section of the north wall (B, C, D, E). Obviously, it is rather difficult to confirm the exact total number and elements within each section but the bas-reliefs from No. 22 to No. 43 show the same typologies of decay (erosion, alveolization, surface abrasion, and thinning or absence of patina), confirming that they were particularly exposed to the rain runoff (Figs. 2, S3a, S4b, S7a, and S11d). Furthermore, the presence of rare crustose lichens and fungal species (Fig. S7e, f) provided further confirmation of the atmospheric conditions to which the north wall was subjected. These biological forms generally colonize surfaces particularly exposed to air circulation and meteoric runoff. Some exceptions are represented by bas-reliefs from No. 33 to No. 36 where surface abrasion appears to be attenuated.

Sections F, G, and H are exposed to the east, and the bas-reliefs present more or less the same degradation phenomena as section A, mainly due to the following factors: exposure to sunlight and condensation humidity. It is interesting to note strong detachment and abrasion, especially the bas-reliefs from No. 68 to No. 72 of section H (Fig. S11e). This may be due to exposure to direct solar radiation warming these surfaces due to a slight southward orientation. Some bas-reliefs (Nos. 61–65) appear completely damaged, perhaps due to a dripping problem (Fig. S11f). Bianchini (1724), placed thirteen panels (Nos. 47–59) inside section G. Since the bas-reliefs No. 48 and No. 49 belonged to a single stone block, as revealed by the study of the executive techniques, they were presumably arranged within the section G (Fig. S4a, b).

Finally, on the basis of the data acquired in this study, the presumed distribution of the bas-reliefs within the different sections does not differ significantly from Bianchini's "sequence" (Bianchini 1724): starting from the door in front of the S. Domenico church, they may be placed 21 bas-reliefs (section A), then 22 or 23 stone panels on the side of the main entrance of the north wall (section B), followed by 4 or 5 stone panels probably positioned on the east wall (section F), 13 bas-reliefs between the false door and the door of the former Art Institute (section G) and 13 on the Castellare side (section H).

Microclimate monitoring

According to microclimate monitoring, carried out in the Chancellery room (Fig. S12a, b) from November 2019 to December 2020 (Fig. S13a–f), important temperature excursions occurred especially between April and November (UNI EN 1999, UNI EN 2010). This parameter always remained below 30 °C as recommended for the conservation of the stone artefacts (DM. 10.5.2001, 2001). Compared to T, RH is characterized by greater oscillations, mainly between July and November (Fig. S13b, c, e, f); generally, it has an average value of 50–60% (therefore respecting the recommended range) but in some cases, it even reaches 70% and 30%. Therefore, the summer season is characterized by more intense temperature variations while fluctuations in relative humidity are frequent in the winter period.

While the two physical quantities (T and UR) should be indirectly correlated, the anomalous trend of these parameters in certain periods of the year, such as in November (Fig. S13c, f), can be explained by the external Urbino climate condition. It is worth remembering that in Urbino the rainiest season lasts around 9 months, from the end of August to mid-June. November is the wettest and rainiest month of the year.

Conclusion

The frieze of the Art of War is a unique artefact sculpted in a particularly lively Renaissance context and open to technical-scientific innovations and architectural experimentation. The iconographic program that characterizes the 72 bas-reliefs represents the progress achieved in the military and engineering arts in that period.

The PLM investigations confirmed that the bas-reliefs were carved using Calcare Massiccio (type A), locally formerly called *Female Piobbico travertine*, which was quarried from the quarries located in Val d'Abisso on the northern slope of Nerone Mountain, 35 km far from Urbino.

The presence of calcium oxalate may be related to an ancient conservation treatment or/and to a biological activity of lichens/fungi. The red traces are considered a subsequent intervention as their presence was also detected in the detached area where the original surface no longer exists.

As regards the original conformation of the blocks, they did not have the same shape nor the same width and it is probable that some of them were intended for a single bas-relief while others were destined for at least two. The careful examination of the stone surfaces has allowed to reconstruct the phases of their execution, including the delineation of the rectangular frame intended for the representation, the sketching of the contours of the main details, the reduction of the bottom area to a uniform level, the completing of the representation and the finishing of the surfaces. The main tools used in the various stages of execution were string/running drills, different types of chisels, channelling tools, and rasp. Even the observation of the traces left by the tools on the surfaces during the finishing phase, although it was only possible in some stone panels (Nos. 1, 3, 9, 14), contributed to obtaining adequate indications for the attribution debate. In fact, the presence of stylistic and executive differences in the creation of the same details revealed by comparing the same sculpted subject (flowers, leaves, etc.) made it possible to confirm that the finishing of the surfaces was carried out by different sculptors.

The main causes of deterioration of the bas-reliefs are mainly due to weathering phenomena that occurred in correspondence with the frieze during the two centuries of its position on the facade. The different types of decay observed on the stone surface also proved to be a useful method for addressing the debate linked to the original arrangement of the frieze on the facade. Excluding that the ordering of the stone panels has changed during the two centuries of their display on the facade, the eighteenth-century sequence proposed by Bianchini has been substantially confirmed.

According to microclimate monitoring data, although the temperature and relative humidity parameters respected the recommended range, the data variations did not always occur in a constant manner, thus running the risk of compromising the long-term integrity of the stone surface, which is particularly predisposed to phenomena of detachment.

As part of a valorization project, by the end of the year, the stone bas-reliefs are expected to be moved from the Chancellery room to the Soprallogge on the main floor, the same place where they were placed by Cardinal Giovan Francesco Stoppani in the eighteenth century. Obviously, it is advisable to carry out a microclimatic monitoring of the new location to check the temperature and relative humidity before moving the bas-reliefs.

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Data availability The authors declare that the data supporting the findings of this study are available within the paper and its Supplementary

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Declarations

Ethics approval Not applicable.

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