Conservation Analysis Using Photogrammetric Post Processing Techniques: The Example of Early Medieval Low Relief in SS. Assunta e S. Bartolomeo Church in Badia Prataglia, Tuscany

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The purpose of the following paper is to develop an integrated system for the state of conservation of the low relief in SS. Assunta e S. Bartolomeo Church in Badia Prataglia (Poppi) in Tuscany by incorporating observable and interpretative data. This decoration (dated to 9th-10th AD) is located in the Early Medieval crypt of the Church, on an architrave above a little alcove. Over the years the rising damp has caused serious damages to the architrave and the capitals, threatening the preservation of the low relief itself. The survey project, to which this paper also belongs, started in 2012 following a previous photogrammetric work on the Church and the discovery of an old picture of this sculpture in an article of Alberto Fatucchi, scholar of the history of Tuscany. From this old picture (1977) we noticed the different state of conservation of the low relief (due to humidity) and for this reason we decided to plan another photogrammetric survey in 2016, in order to understand the changes of thickness of the low relief over the time. Survey plays a central role allowing archaeologists to translate metrical observations into historical interpretations of the low relief. For this reason, all the images have been processed in order to create a 3D model of the low relief and then to obtain a Digital Elevation Model of it. DEM analysis was fundamental for the data comparison, in fact regarding results, they helped us to know the action of the rising damp over four years. Working with a calibrated not professional camera, using low-cost budget and open source/free tools, we obtained good and accurate results.

Key words:
Badia Prataglia, Conservation, Early Middle Ages, Low-Cost, Photogrammetry.

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INTRODUCTION

The main goal of this work was the detection of the thickness changes of a low relief in SS. Assunta e S. Bartolomeo Church in Badia Prataglia (Poppi) in Tuscany. However, the idea of this project was carried out after reading a book (*La Diocesi di Arezzo, Corpus della scultura altomedievale*) of Alberto Fatucchi [Fatucchi 1977], who is one of the most important Italian scholars of history of Tuscany. Inside this book we found a black and white picture of the architrave taken by Alberto Fatucchi himself in the 1970s. Looking at this photo, without any measurements, we can anyway deduce the thickness of this relief from the shadows inclination and the contrasts of the black and white tones.

In order to detect these changes, we planned to use photogrammetric techniques, comparing the 2016 survey with a previous one made in 2012 for ensuring that the highly method adopted was as reliable as possible.

BADIA PRATAGLIA: CONTEXT AND HISTORY

Badia Prataglia is a small town in Tuscany, located in the province of Arezzo at the border with Emilia Romagna region, in particular into Casentino woodland, near the Camaldoli Hermitage. Badia Prataglia is also included into a protected natural reserve inside the National Park “Parco Nazionale delle Foreste Casentinesi”.

The first document about the Badia Prataglia Abbey is dated around 1001/1002 AD and it is a certificate of Otto III of Saxony [Piccinni 1999]; in this certificate and in others documents are contained mainly land concessions dated to 986 AD, and subscripted from Ugo count of Tuscany to Santa Maria e San Benedetto of Prataglia.

Indeed, the Early Medieval foundation of this Church, in the middle of a big woodland in Casentino, is nearly before the 10th century and it was founded by the Benedictine monks of Montecassino Abbey.
However, the history of Badia Prataglia is marked by several land concessions. Around the 11th century there were about ten land concessions (such as the near location of Partina and Gello) in support of Prataglia [Wickham 1997] which increased the political influence of the Abbey and led to the inevitable conflict with the near Camaldoli Hermitage that was having in that period a stronger religious and political position [Salmi 1958]. Moreover, the conflict with Camaldoli was so rough that it needed the intervention of the bishop of Arezzo.
In addition to the importance of Badia Prataglia, the historian Wilhelm Kurze described the Abbey like a private and preferential monastery (he used the German word *Eigenkloster*) property of the bishops of Arezzo [Kurze 1973].
The original architectural project of the church was based on the presence of three aisles with the apse facing the eastern side. The low-level crypt is dated to the 10th century AD and it was restored around the 1910 (before this year the crypt was buried); this is the only part of the Medieval Abbey that survived. The crypt is located exactly under the choir and it is composed by three aisles and two spans with round arches and groined vaults. The vaults are supported by twelve columns (in particular two columns and ten semi-columns), and only two of them are located in the central area of the crypt.

DECORATIONS

The low-level crypt presents beautiful decorations: the main capitals, in the central area of the crypt, are significant first of all, because they are architectural elements probably reused from a late Roman building - perhaps the first abbey was built on an earlier late Roman one - that allow us to deepen the study of reuse dynamics and secondly because capitals are made with marble (maybe imported from of Luni), instead of the local sandstones coming from Monte Falterona (however used for the others decorations).
A capital in the central area shows on its upper part clear re-decorated signs result of Pre-Romanesque manufacturing processes. The surrounding semi-columns, and its decorations, are very degraded (and lost) due to humidity actions. Finally, the great part of these elements has leaves and herringbone decorations made with drill and tip.
Moreover, inside the crypt there is an important decoration called “Orante” that represents a prayer in a very simple way (it is typical of Early Middle Ages Christian iconography decorations). In the same masonry there is an architrave, facing the “Orante” decoration.
The aforementioned architrave is located to the left side facing the altar, above a little alcove and near the “Orante” decoration, and it is 110,5 cm long, 32 cm high, 29,4 cm deep. Briefly, the decoration of the front has a braid of knotted circles running horizontally with a D-shaped terminal at either end of the architrave (the semi-circle on the right is more damaged owing to rising damp). The braid is therefore composed by two linked little strings. Comparing this kind of decoration with others in Tuscany and Emilia Romagna we can date this architrave to the 9th-10th century AD [Ciampoltrini 1991 and Budriesi 2005].
As far as the materials are concerned, the “Orante” and architrave decorations are made with the Casentino sandstone that it is referred to “*Monte Falterona*” Sandstone group (*Arenarie del Monte Falterona*).
The architrave was made probably with sandstone of the sub-group *“Membro di Camaldoli”*: this kind of sandstone is generally light grey-green and it has a coarse base, without clastic conglomerates and carbonate matrix. Anyway, the use of this kind of sandstone caused the deterioration (not only due to humidity) and the detachment of material, allowing also the fragmentation of Casentino sculptures in general (geologic information taken from “*Carta Geologica D'Italia, scala 1:50.000, foglio 264, Borgo San Lorenzo; ISPRA, Servizio Geologico D'Italia, 2010”*).
The decorations inside the crypt of Badia Prataglia show different motifs but they are made with the same executive technique. The architrave and the “Orante” decorations have almost the same tip diameter (0.5 cm) and the other signs of instrument signs change proportionally to its value. The architrave presents different decorations: two kinds of thickness from the background that diverges from about 0.5 cm - 0.6 cm on average. The analysis of the tip diameter, height, dimension and interval of signs of instruments could help us to locate the realization of decorations on the same chronological period. Moreover, these decorations could be made by a single group of workers, who was active in Casentino around the 9th-10th century [Diara 2016].

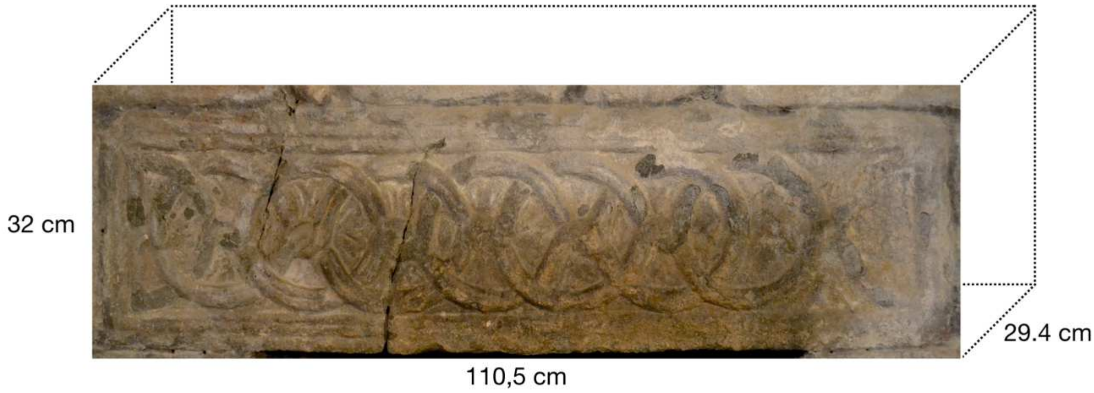


Fig. 1. The architrave and its measurements

METHODOLOGY

Starting point and acquisition

As said before, this project started by accident. In 2012 the crypt was surveyed from a research team of the University of Siena who studied the Badia Prataglia Church and other contexts in Casentino; it was surveyed using photogrammetry for other purposes. Comparing different sources (comparing this survey to the Alberto Fatucchi old photo) we noticed the change of thickness, due to humidity of the crypt, during the years. Therefore, in 2016 we planned another low-cost photogrammetric survey (without total station) and analysis in order to register others changes ad evaluate the state of conservation of the architrave.
But why using photogrammetry? For different aspects, first of all because the early survey was an image-based survey and we wanted to obtain a good RGB restitution product (photographic colours red, green and blue) and orthophotos, having a low-cost budget and using open source software. Indeed, photogrammetry techniques can offer significant reduction in the cost of archaeological surveys and in the enhancement of survey result.
Briefly, photogrammetry is an image-based technique that allows to obtain metric information starting from images, as well as the geometric and volumetric data of objects and it is based essentially on photographic sensors [Diara 2013].

Table 1. Nikon D3100 optical sensors details

Camera sensor Type	CMOS (complementary metal oxide semiconductor)
Camera sensor Resolution (MP)	14.2
Camera sensor Size (mm)	15.4 x 23.1

Metric survey (LiDAR or photogrammetric techniques) in Cultural Heritage contexts become a fundamental step because it allows recording and reconstructing accurately geometries of every object or building for further analysis. The accuracy and reliability of the survey data depend mostly on the quality of the recorded images (in terms of resolution) and on the quality of the used camera (sensors and lenses calibration). Moreover, the quality of the survey is also influenced by many factors, like the technical ability of the operator to surround shadows, reflections, glare and others. Furthermore, the quality of the images depends mainly on the kind of camera: a better camera will produce better images as well as better readable results and reconstructions [Diara 2013].

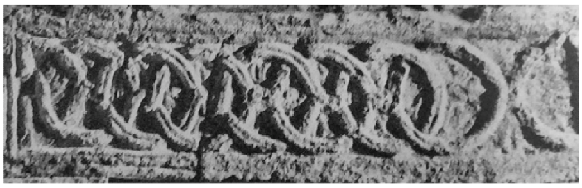


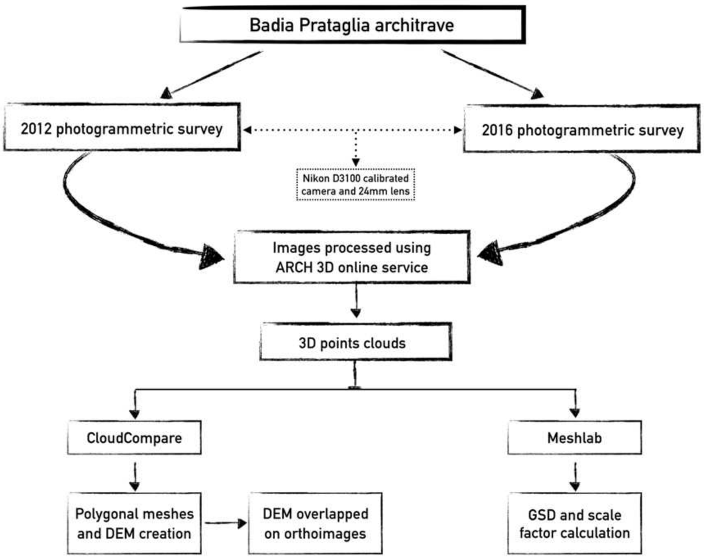
Fig. 2. The architrave in the 1970s (photo by A. Fatucchi, 1977)

Fig. 3. The architrave in 2012 (photo by F. Diara, 2012)

Fig. 4. The architrave in 2016 (photo by F. Diara, 2016)

The first phase of the project was the photogrammetric acquisition in 2012 (carried out for others purposes) and in 2016 using a not full frame reflex camera, in particular Nikon D3100 and Nikkor lens AF-S 24-85mm f/3.5-4.5 G ED, with focal length blocked at 24 mm. At the end we collected 20 images, with NEF Nikon format, for each situation: 10 images for each year with targets in order to measure the main distances of the architrave.

Table 2. Methodologic workflow of this project



Processing operations

All images have been processed using ARCH 3D online service (www.arch3dch.weebly.com), that it is based on photogrammetric open source tools of MicMac (developed at French National Geographic Institute and French National School for Geographic Sciences, https://micmac.ensg.eu/index.php/Accueil). However, we used a personal (not public) standalone offline version of ARCH 3D. Using this kind of service, we obtained only 3D points clouds starting from images (Fig.7 and 9). The ARCH 3D workflow (from images alignment to final 3D model) is similar to the MicMac method (), the only differences are the following: RGB photographic values are optimized as regards brightness and contrast; point cloud cleaning, re-sampling and optimization. Camera calibration parameters have been set automatically. We decided to import manually just the focal length, pixel size and image size (Tab.3) and we have set camera orientation defining the custom camera rotation (setting horizontal plane and axis direction) and the camera scale factor.

Table 3. Camera calibration parameters

Camera focal length:	24mm
Camera pixel size:	4.94 µm
Camera image size:	4608 x 3072 pixel

Auto-calibration of camera report (pictures of 2012):


```
<?xml version="1.0" ?>
<ExportAPERO>
    <CalibrationInternConique>
        <KnownConv>eConvApero_DistM2C</KnownConv>
        <PP>2353.54062344588556 1552.541143660957</PP>
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            <ModRad>
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                <CoeffDist>6.01736008227289519e-17</CoeffDist>
                <CoeffDist>6.42277458097669862e-24</CoeffDist>
            </ModRad>
        </CalibDistortion>
    </CalibrationInternConique>
</ExportAPERO>
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We decided to create 4 models in total: 2 points clouds without targets (visible in Fig. 5) and 2 points clouds with targets just to compare and measure distances (point cloud creation report in Tab.6) – and we used Meshlab (www.meshlab.net) in order to calculate the level of detail of points clouds. In fact, the Global Sampling Distance (GSD) is the average density of the points cloud grid and it has been calculated in this way: inside Meshlab when you measure any object you do not have a real measure unit but only custom numbers, referred to local coordinate x, y, z inside software and the 3D model. Therefore, the only way to calculate and measure distances (without total station) is to have the real dimensions of objects.

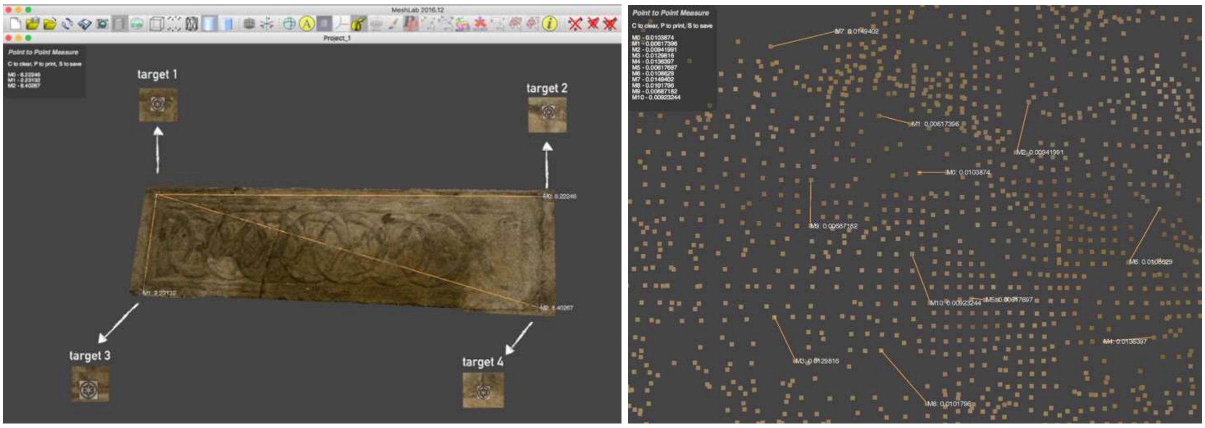

Fig. 5-6. Dimensions inside Meshlab (2016 points cloud)

At the end of the process, we calculated the scale factor of the 3D model and this involves the average ratio between *real dimension* and *software value* (Tab.4-5). We applied the same methodology to 2012 and 2016 models. Regarding the 2012 points cloud, the average GSD is about 1.9 mm (±1.93 mm), while for the 2016 model is about 1.5 mm (±1.54 mm).

Table 4. 2016 – Scale factor calculation (referred to Fig.5)

	Real dimensions	Meshlab value	Scale factor (cm)	Scale factor AVG (cm)
Length (target 1-2)	110,5 cm	8.22246	13.43	41,62 / 3 = 13,8733
Height (target 1-3)	32,0 cm	2.23132	14.34	
Diagonal (target 1-4)	116,4 cm	8.40267	13.85	

The architrave is 110,5 cm long x 32,0 cm high and has 116,4 cm as diagonal (distance taken from target 1 and 4, Fig.5). Measuring exactly the same distance in Meshlab (on 2016 points clouds model) we obtained 8.22246 as length, 2.23132 as height and 8.40267 as diagonal (as you can see on Fig.5).
Therefore, we chose to measure points distances selecting the same points cloud area as a sampling part (for 2012 and 2016 model).

Table 5. 2016 - Scale transformation of points distance (referred to Fig.6)

Point distance	Meshlab value	Scale factor AVG (cm)	Real value (cm)	Real value (mm)
M0	0.0103874	13,8733	0.144	1.44
M1	0.0061739		0.086	0.86
M2	0.0094199		0.131	1.31
M3	0.0129816		0.180	1.80
M4	0.0136397		0.189	1.89
M5	0.0061769		0.086	0.86
M6	0.0108629		0.151	1.51
M7	0.0149402		0.207	2.07
M8	0.0101796		0.141	1.41
M9	0.0068718		0.095	0.95
M10	0.0092324		0.128	1.28
Average GSD: 15.38 / 10 = ±1.54 mm				

Table 6. Summary of points cloud creation

2012 model	**2016 model**
Nikon D3100 and Nikkor lens 24mm	Nikon D3100 and Nikkor lens 24mm
10 images (without control targets)	10 images (without control targets)
Points cloud: 6.241.698 points	Points cloud: 6.751.131points
GSD: ±1.93 mm	GSD: ±1.54 mm


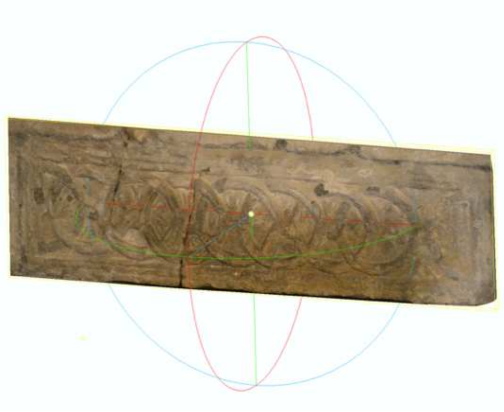

Fig.7-8. Points cloud (left) and polygonal mesh (right) of the architrave model (2012)


Fig. 9-10. Points cloud (left) and polygonal mesh (right) of the architrave model (2016)

Post-processing operations and photo rectification:

Starting from points clouds, aligned in XY plane, we created 3D polygonal geometries (Fig. 8 and 10) in Cloud Compare (www.danielgm.net/cc)open source software using Delaunay triangulation process (XY plane). This process ensures good results with points clouds created starting from SIFT (Scale Invariant Feature Transform) image matching algorithm [Karagiannis et al. 2016].

Afterwards, as a second post-processing step we processed both 3D models in order to obtain the Digital Elevation Models (DEM), which is the digital and colours representation of the height distribution of a surface/plane or a terrain. This kind of technique is very useful in conservation analysis and comparison between different moments of an object or a building, as demonstrated by many digital analysis projects [Balzani et al. 2017].

Later, we extracted the radiometric scalar field from polygonal meshes inside Cloud Compare software, after the XY plane alignment. The scalar numeric ramp has been set customizing and converting values (as described into Cloud Compare wiki manual, available on Cloud Compare web site) in order to have it expressed in cm units.

As for the photo rectification, main photos of the architrave (for 2012 and 2016) have been rectified using RDF software (developed by IUAV University of Venice, inside Circe photogrammetry laboratory, www.iuav.it/SISTEMA-DE/Laboratori2/cosa-offri/software/index.htm) that allows to perform the analytic or geometric photo rectification of planar objects. The analytic method works with coordinates of image, object and union coordinates. Using this method, we can essentially define every coordinate of the objects (.ogg file) with the corresponding points on images. In a further phase, in order to rectify pictures of the architrave, we decided to use the geometric rectification, defining vertical and horizontal straight lines on main images of 2012 and 2016.

The geometric rectification consists in vertical and horizontal straight lines (defined by user) and therefore on x/y ratio and connection of a known real dimension of object inside picture and its measurements in pixels.

Table 7. Main summary of the triangulation process

2012 model	**2016 model**
Cloud Compare Software	Cloud Compare Software
Delaunay triangulation	Delaunay triangulation
Point cloud: 6.241.698 points	Point cloud: 6.751.131points
Polygonal mesh: 10.675.831 faces	Polygonal mesh: 11.823.767 faces

ANALYSIS AND RESULTS

From the analysis of DEM, scalar radiometric field (Fig. 13-14) shows the differences of thickness: values in blue are referred to protruding parts while values in red are referred to deeper parts.
Reading the values of 2012, the entire thickness of the architrave is included between 0.1cm - 1.46 cm and the high percentage of thickness is included between 0.35 cm - 0.5 cm.
Anyway, the situation of the architrave in 2016 changed: now thickness ranges from 0.1 cm to 1.15 cm and the high percentage of thickness is included between 0.4 cm - 0.6 cm.
Comparing these values, we were able to notice differences within four years. Starting from 2012 and finishing in 2016 we have almost 18-20% of thickness lost in four years (Fig. 12), that correspond to -0.3 cm (-3 mm). Moreover, we can deduce how the rising damp modified the decorations of the architrave in few years. Thus, depth has changed quickly:

- Thickness values between 1.46 cm and 1.15 cm have been reduced to lower values (Fig. 11) and the changing of thickness is also visible watching colorimetric differences (Fig. 15).

In conclusion, final data extracted from the architrave (obtained from free and open source technologies) confirm what we have registered visually during the second survey. There are essentially two different situations in which wet and dry conditions changed during the years: in 2012 wet area (due to humidity) was homogeneous and a little invasive and aggressive while in 2016 wet area was much more aggressive and invasive to the left and to the bottom, despite the central upper part of the architrave, that is drier than 2012 (Fig. 3-4; 13-14).

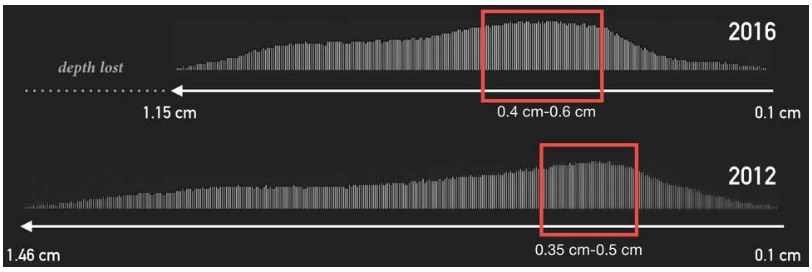

Fig. 11. DEM spectrum of models: visual difference of thickness during the years

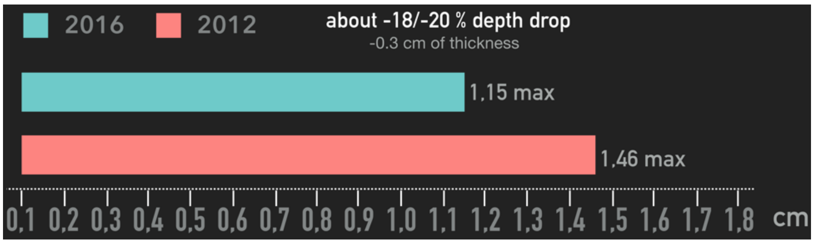

Fig. 12. DEM values comparison and percentage of depth drop in only four years

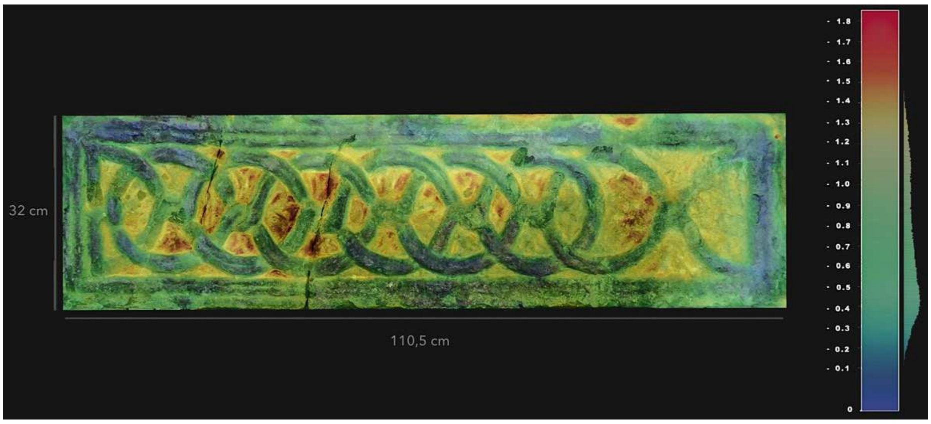

Fig. 13. photo-DEM of the architrave (2012 model)

Fig. 14. photo-DEM of the architrave (2016 model)

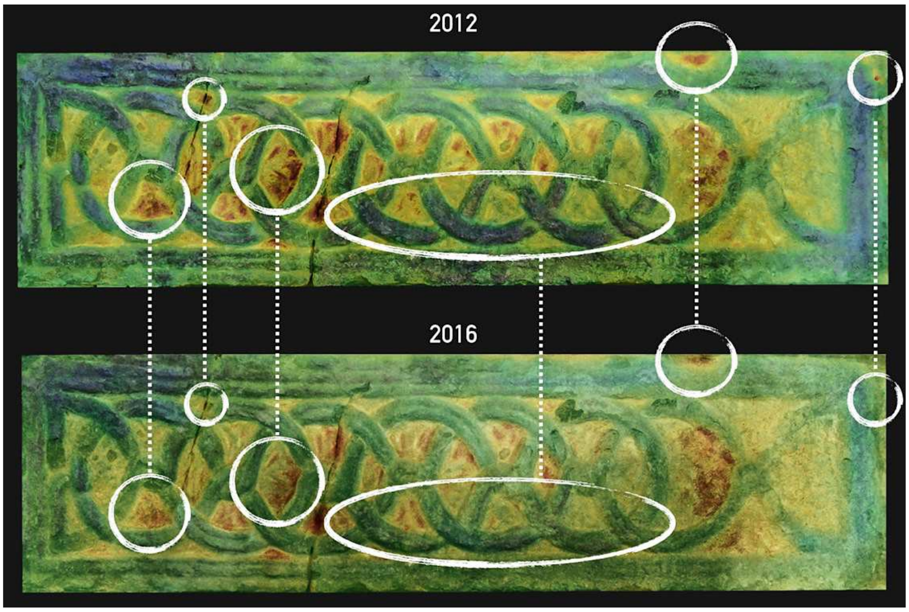

Fig 15. Macro differences of photo-DEM of 2012 and 2016

CONCLUSIONS

This kind of photogrammetric post-processing and low-cost approach was useful (extracting process and post process metric information from images) to understand the variation of thickness in four years starting from images (acquired for other purposes) and 3D model.
Despite we worked with a calibrated not professional camera, with low-cost budgets and using open source/free tools, we were able to obtain significant and accurate results. The use of open source and free services was a forced choice as well as a challenge: could Cultural Heritage researchers carry out scientific studies with low-cost equipment? If it can be done, and with the equality of results, how can these studies be compared with others carried out with high-cost technologies? Do they have the same importance? There is a problem behind our methodological choice if we use high-cost equipment that lead us to obtain the same results of a study carried out with low-cost technologies.
In the Cultural Heritage area many low-cost analysis (including emergency state surveys) have often proved to be the most reliable of the field, allowing obtaining more complete and accurate results than different researches.
Three-dimensional photographical survey in archaeology and in architecture is a fundamental moment of study because it allows reconstructing shapes and geometries. It can be helpful in case of damaged buildings or degraded archaeological objects, because photogrammetric survey (including low-cost surveys) helps obtaining volumetric data useful for future reconstruction or restoration, and it can be also helpful to freeze a particular situation.
Thanks to new digital technologies (mid-cost, low-cost, open source) it is possible to produce and process data in a synthetic and clear way. The technological changes and the massive diffusion of freeware and open source software (for example 3D viewers and other photogrammetric tools) aided the documentation and communication in Cultural Heritage field [Diara 2014] for example in archaeology or historical architecture, photographic survey revolutionized the way to produce documentation, analysis and then the teaching method. Nowadays, it becomes maybe the main methodology to do research, creating the possibility to investigate archaeological sites or historical buildings [MacDonald et al. 2012].
Taking note of extracted data from DEM analysis, it would be necessary to install a micro climate control device inside the crypt in order to monitor and preserve the sandstone decorations, but it is not easy for different aspects, especially for economic and logistic reasons.
Furthermore, as a future step, we will try to find and collect other images of the architrave, because in other publications and on the internet, there are a lot of images of the crypt of Badia Prataglia but not focused on the architrave.
Moreover, it would be useful to create a real model of the architrave using a 3D printer, based on 2012 pictures and model. Doing that, we could ideally freeze and stop the situation of the architrave related to 2012 (best documented situation of it) in a real touchable model. As a future step of knowledge, it would be so helpful to try to understand the original thickness of the decorations (also the thickness in the 1970s) in order to register the entire depth drop during the years creating a real comparison path.

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