THE DOCUMENTATION AND CONSERVATION OF THE CULTURAL HERITAGE: 3D LASER SCANNING AND GIS TECNIQUES FOR THEMATIC MAPPING OF THE STONEWORK OF THE FAÇADE OF ST. NICHOLAS CHURCH (PISA, ITALY)

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Abstract

The role of the Cultural Heritage is central in our society and culture, and all the interdisciplinary studies that can be useful for its restoration have an undoubtedly interest for the researchers. This paper reports the mapping of the stones, including marbles and brick masonry, used for building the façade of the medieval church of St. Nicholas (XI century A.D.), one of the most interesting church in Pisa also due to the nearby famous octagonal bell tower. Mapping of stone materials was undertaken using a CAD/GIS software package for storing and processing spatial information of the ashlars and their non-spatial data, obtained by both 3D laser-scanning data, combined with high-resolution images, and stone-to-stone observation.

Based on collected data, the façade of the church of St. Nicholas was mostly made up of rocks belonging to the metamorphic Tuscan sequence, quartzites and marbles from *Mt. Pisano* area. Black limestones quarried at some kilometres northwest from Pisa in the *Monti d'Oltre Serchio* area, white Apuan marbles and *Macigno* sandstones are also present, while intarsia are mainly made up of serpentinite and, suborbinately, red limestones inlayed in white Apuan and *Mt. Pisano* marbles.

Keywords: laser scanning/CAD/GIS/thematic mapping/building stone/marble/cultural heritage/medieval buildings.

Research aims

This paper presents the mapping of the building stones used in the façade of the St. Nicholas church in Pisa, in order to highlight the potential of 3D laser scanning and CAD/GIS (Computer Aided Design/Geographical Information System) techniques in the field of restoration and conservation of stonework. In particular, the paper focuses on the workflow from the 3D laser scanner data to the thematic mapping of the stones and other building materials.

1. Introduction

The theme of the documentation and conservation of the Cultural Heritage is deeply rooted in the contemporary society. In ~~a project in general and in~~ stonework's restoration ~~one~~ in particular, ~~a~~ detailed knowledge of the building materials and of their main characteristics is an essential pre-requisite for developing a good planning ~~in the near future~~. A correct organization of the work and of its phases and priorities, in fact, can make the real difference in a good project, allowing to achieve the best results also considering the economic issues. ~~A good and efficient analysis can be expensive, but all its cost are quite always saved during the construction phase of the restoration when, especially with ancient structures, a conscious and minimal interventions is required according to their considerable value. The theme of the economical resources is central, not only for mere commercial considerations, but also for the real possibility to proceed with the eventual restoration of the building~~. A good planning can, in fact, evaluate all the costs and give the real idea of the consistency of the operation that is nowadays a plus to move the public commissions that hold the great part of the Cultural Heritage, to put hand to the conservation of their vast properties. All the techniques useful to reach the real knowledge of the object are then essential and especially the more advanced ones can ensure better results. From this point of view, the information technology applied to Cultural Heritage can be regarded as providing a tool box of techniques and technologies of wide applicability to the achievement of stonework mapping and, more generally, to the management of a full restoration project. Many studies have demonstrated the utility of the laser scanning technology to generate virtual models of elements, buildings and cities [1], and in the investigation of world heritage sites [2-6] as well as in the high-resolution documentation of lithic artifact and archaeological finds [7-9]. On the other hand, Computer Aided Design (CAD) and Geographical Information System (GIS) techniques are increasingly used to enhance our understanding of the past producing a detailed documentation of recent restoration works [10-12].

After the survey of the façade had been completed and the main geometry of each ashlar was known, the building materials have mostly been identified by visual inspection, with the aid of both a tripod-mounted Zeiss Victory DiaScope 85 FL and a field stereomicroscope at 20x, and by mineralogical and petrographic analyses. For recognition of the stones used for building the façade of St. Nicholas church, the macroscopic characteristics widely described in several papers on the stones of medieval buildings in Pisa [13-16 and references therein] has been exploited, while for marbles usual and topical provenance methods such as textural features, accessory minerals and C-O stable isotope data [17-19] were applied. The stone mapping was carried out identifying the lithotype of each ashlar or stone fragment. Their spatial (i.e. the physical location of objects and the metric relationships between them) and non-spatial (i.e. attributes) information have been stored, processed and displayed into a specifically developed GIS project. For this, ArcGis 10.1 software package by ESRI (Environmental Systems Research Institute) ~~was~~ used.

2. The studied church

The church of St. Nicholas (Figure 1) represents a typical example of the wide and high quality Italian Heritage spread all over the country and is situated in the centre of Pisa (central Tuscany) near the *Lungarno Pacinotti*.

It is mentioned for the first time, as a dependency of the nearby abbey of St. Michael “alla Verruca”, in 1097, whereas the annexed monastery of St. Nicholas appears in medieval documents from 1130 [20-21].

In 1297 the religious complex of St. Nicholas passed from the Cistercian monks to the Augustinian friars: this event is commemorated by a medieval stone inscription currently located in the cloister of the monastery [21]. At the beginning of the 14th century the friars of St. Augustine enlarged the building [22]. In the 17th century the church was restored with the addition of altars and the valuable sacrament chapel by Matteo Nigetti, a Florentine architect assistant of Bernardo Buontalenti. The façade features pilaster strips, blind arches and lozenges, and it is decorated with 12th century intarsia. A covered passage connects the church of St. Nicholas to the *Torre De Cantone* and then to the *Palazzo delle Vedove*, which the Medici gentlewomen could use to reach the church without passing in the streets. Around 1170, an octagonal bell tower, the second most famous in the city after the Leaning Tower, was erected beside the church, perhaps due to the work of Deotisalvi [23], using quartzites and calcarenites laied by hydraulic lime mortars. Inside, there is a beautiful spiral staircase with small arches supported by twenty-four columns made up of granites, quartzites and marbles coming from both Apuan Alps district, *Mt. Pisano* quarries and Mediterranean quarrying areas. Today the bell tower is slightly tilting with its base under the current street level.

3. Methods

The key points of the desk study, field acquisition, post-processing and thematic mapping of the stones and other building materials, including the marble analyses, are detailed as below.

3.1 Desk study

3.1.1 Geometry

Before proceeding to the digital survey of the façade of St. Nicholas church, as for every object to be measured, an appropriate strategy must be developed to optimize the laser scanning acquisition. Taking into account the type of masonry, the area to be investigated (about 350 m^2) and the minimum resolution (< 5 mm) required for determining the geometry of each ashlar excluding intarsia, the choice of an opportune instrumentation was done. On the basis of the selected instrument (3D-HDS4500 Leica Geoystems), considering the low traffic in front of the façade and the possibility to use the windows of the opposite buildings, as points of view at different heights, we have decided to acquire a redundant number of scanning with twelve reference points. In this way, the whole surface of the façade was covered, minimizing the hidden or shaded areas.

3.1.2 Building materials

A preliminary observation of the building materials used for embellishing the façade of the studied church shown that the stones and the colored marbles could be identified on the basis of their macroscopic characteristics which are available in the literature through the research of several authors [13-16 and references therein].

With regard to white marbles, they showed the typical features of the Mt. Pisano and of the Apuan marbles, but to exclude the presence of marbles used in antiquity coming from the Mediterranean area, it was chosen to sample and to analyze some of them. Latest provenance studies on white marble were recently performed by several authors taking into account maximum grain size, accessory minerals and C-O stable isotopes [17-19]. Therefore, it was chosen to collect these data on some very small fragments by sampling in such a way as not to damage the façade.

3.2 Field acquisition

3.2.1 Sampling

Some small fragments of white marble were sampled using a light hammer and a small chisel from nine ashlars in the central and right lower part of the façade, up to about 3 m in height. Samples were taken only where there were almost detached flakes in order to avoid damage to the façade of the church.

Sampling of white marbles was needed to collect data on their mineralogical and petrographic characteristics (texture, grain boundary shape, maximum grain size, dolomite content and accessory minerals) by thin section observations and X-ray powder diffraction of bulk sample, and on their carbon-oxygen stable isotope ratios, which are useful data for identifying the ancient quarrying areas [17-19].

3.2.2 Laser scanning

Laser scanning is a quite recent innovation in spatial information data acquisition, its intensive usage in Cultural Heritage subjects has a story long a little more than 10 years. This set of procedures allows the surfaces of buildings and other spatial objects to be digitally captured with high resolution and accuracy. In addition, the laser scanning is undoubtedly less time consuming than the conventional survey methods such as topographic and photogrammetric techniques.

In this study, a tripod-mounted laser scanner (3D-HDS4500 Leica Geoystems) was used for one day of fieldwork to capture with high accuracy the geometric features of all the ashlars in the façade of the church.

The field of view of the used scanner is 310 degrees on the vertical and 360 degrees to on the horizontal around the scanning position. A laptop running Leica Geosystem Cyclone 7.1 was used in the fieldwork to control the scanner and to store the laser scanning data. The capture rate of the laser beam was up to five hundred thousand points per second. A Nikon D3x digital camera mounting an AF-S Nikkor 50 mm f/1.4 G lens was used for covering with a series of photographs the whole area scanned by the laser; highly visible targets were used for linking laser scanning data. The measurement accuracy was less than ± 5 mm at the scanning distance (< 15 meters).

The scans were captured from 9 different tripod positions (3 of them on the pavement opposite to the façade and 6 using the windows of both the first and second floor of the opposite building) with their locations chosen to guarantee a full coverage of the survey area. It was decided to do multiple scans from different positions to minimize as far as possible the space occlusions that they could not be reached by the laser beam. Every new scan area had to contain parts of previous scans, thus providing overlaps for subsequent alignment into a single reference system and for the following reduction of the scan set into one single point cloud.

3.3 Post-processing

3.3.1 Point cloud processing and map drawing

To obtain a detailed survey of the façade of the St. Nicholas church (Figure 1), including the features of each ashlar, the multiple scans were integrated into a single reference system by referencing together the scanned targets, later the point clouds were unified into a single point cloud. The objects of no relevance have been removed from the scans before to combine the multiple scans into a single point cloud (Figure 2a).

The map of the façade was drawn by using AutoCAD 2012 (AutoDesk) drawing tools, tracing out the outline of each stone object on the point cloud colored by matching the rectified photographs. Intarsia had separately drawn using rectified high-resolution photos, in this way the details from the pictures were not lost. Afterwards, the intarsia pictures were imported and advisably scaled into the general drawing.

All the objects of the façade (*i.e.* the stone ashlars) were drawn as closed polylines of which the perimeter and the area have been calculated.

A detailed map of the façade has needed a little long time also including several controls that were made on the fieldwork.

At the end of the drawing work, all the objects in DXF format were imported into a GIS project using ArcGis 10.1 conversion tool, useful to start the realization of the thematic mapping of stonework (Figure 2b).

3.3.2 White marble analyses

A small portion of each collected rock sample was used for producing a polished thin section using epoxy resin as impregnating agent. The thin sections were studied by optical microscopy (OM) using a Zeiss-Axioplane polarising microscope to observe the rocks up to 200 magnifications in order to evaluate maximum grain size (MGS) of carbonate crystals, their boundary shapes and to identify the accessory minerals. Scanning electron microscope equipped with an energy dispersive spectrometer (SEM/EDS) provided further information about the crystal features and the chemical composition of the accessory minerals. The remaining portion of the sample was hand-powdered in an agate mill and the powder was analyzed for determining mineralogical compositions by X-ray powder-diffraction (XRPD) using a Bragg-Brentano geometry and Ni-filtered CuK_α radiation, obtained at 40 kV and 20 mA.

Measurements of the isotopic ratios $^{18}O/^{16}O$ and $^{13}C/^{12}C$ in the marble samples were carried out using mass spectrometry of the rock carbonate phase. All selected samples were extracted using phosphoric acid and analysed at the Stable Isotope Mass Spectroscopy Laboratory of the Institute of Geosciences and Earth Resources, National Research Council of Italy. The results are expressed in terms of the deviation from a conventional standard, Pee Dee Belemnite, a carbonate fossil from South Carolina. This deviation, called δ, is expressed as $\delta^{13}C$ or $\delta\ ^{18}O$, measured in parts per thousand (or per mil., ‰) and calculated as follows:

$$\delta\ (‰) = [R\ sample/R\ standard - 1] \cdot 1000$$

where R= $^{13}C/^{12}C$ or $^{18}O/^{16}O$. The isotopic variability data are expressed as a scatter plot of $\delta^{18}O$ and $\delta^{13}C$ values. Analytical precision is ± 0.1‰ for both oxygen and carbon.

3.4 Thematic mapping of the stones and other building materials

Based on both 2D detailed map of the ashlars (Figure 2b) and stone-to-stone observation, the thematic mapping of the stones used for building the façade of the St. Nicholas church was realized. The spatial and non-spatial data were stored using ESRI ArcGIS 10.1, a software package even more used by geoscientists for analyzing geological and archaeological datasets.

Before to ultimate the graphic base, the digital map was yet edited to close the polylines, which had remained open by mistake, and to modify some hidden polygons, because they had not recognized like independent, but as a part of the polygons that contained them. This problem had resolved using the command 'Cut Polygon Features', available in the menu of the Editor. After the editing phase, a database containing records with the attributes of each object of the façade has been created and the attributes linked to the objects of the graphic base. The main fields of the database are as follows: 'Identifier', 'Perimeter', 'Area', 'Shape Factor' and "Materials'.

Three outputs respectively show perimeter (Figure 3a), area (Figure 3b) and shape factor (Figure 3c) of the building materials used for building the façade of the St. Nicholas church in addition to the main view of the stone map (Figure 4) and to the some details showing the precious intarsia (Figure 5).

4 Results and discussion

4.1 The geo-materials identified in the façade of the church

In this section the building materials observed in the façade of the St. Nicholas church are listed, reporting for each of them the main characteristics and decay.

4.1.1 Marbles

In the façade of the St. Nicholas church, marbles from *Mt. Pisano* area and Apuan Alps district have been recognised on the basis of their macroscopic characteristics, petrographic features and C-O stable isotope data (Table 1 and Figure 6).

From the macroscopic point of view, the *Mt. Pisano* marbles are ~~easily~~ distinguishable among the other ones because of the very fine grain size of the calcite crystals (MGS ~ 100 μm, samples SNF 1-3) as well as the presence of dolomite-rich veins, which enable the typical process of differential erosion [14]. Macroscopic characteristics and petrographic features of the other marbles observed in the façade of the church indicate a ~~sure~~ origin from the Apuan Alps district. They are fine-grained (MGS ranging from 400 to 700 μm, Table 1) white and, subordinately, gray marbles. The six analyzed samples (Table 1) show prevailing homeoblastic/granoblastic textures with grain boundary shapes ranging from straight to curved, but also polygonal textures with triple points (SNF 6) or homeoblastic/heteroblastic grain size uniformity with granoblastic texture characterized by grain boundary shapes ranging from straight to lobate are present (SFN 9). Petrographic features, including the maximum grain size of the calcite crystals (MSG < 2 mm), accessory minerals (pyrite ± quartz ± albite ± muscovite) and isotopic fingerprint ($\delta^{13}C$ and $\delta^{18}O$ ranging from 1.76 to 2.33‰ and from -1.58 to -2.23‰, respectively) close to those reported in literature for Apuan marbles [17-19, 24].

4.1.2 Quartzites

The *Mt. Pisano* Triassic quartzites, widely used together with *Caprona* and *Agnano* Breccias for building the Pisa's Case Torre (Tower Houses) throughout the Middle Ages [15-16], belong to the Verrucano meta-sedimentary sequence of the Northern Apennines. Two geological levels were used for building the façade of the St. Nicholas church, the member 2 – *Quarziti verdi* (Green quartzites) and the member 3 – *Quarziti bianco-rosa* (White-pink quartzites) of the *Quarziti del Monte Serra* Formation [25]. As reported by Franzini et al. [15], the quartzites are made up of prevailing quartz grains (from 44 to 86 % by weight) embedded in a matrix with a rather constant chemical composition, represented mainly by phyllosilicates (muscovite and chlorite) with minor amounts of feldspars, paragonite and pyrophillite. On exposure to the environment, the surface color of both the green and white-pink varieties alters to a light ochre-yellow shade.

From a functional point of view, the quartzite ashlars were employed as structural elements and subordinately as ornamental ones. Both varieties have very good mechanical properties and great resistance to degradation. Although the *Mt. Pisano* quartzites show an excellent resistance to the most part of the degradation processes, they are susceptible to aeolian abrasion and may undergo the formation of superficial dusty, dark-colored deposits, which are favored by the surface roughness. When they are within permanently humid masonry, the water capillary rise induces severe degradation phenomena and substantial loss of cohesion, and Na-sulphate efflorescence occur.

4.1.3 Black limestones

The *Monti d'Oltre Serchio* limestones, black in colour with surfaces altered to gray, belong to *Calcari grigio scuri con selci nere* Formation [26]. These rocks were widely used together with *Mt. Pisano* marbles to realize the gray-and-white striped style of the Pisan Romanesque architecture, characterising also Lucca and other Tuscan cities. The most ancient quarrying area was on the slopes of *Mt. Bastione*, where the formation reaches 300 m in thickness and includes fine-grained black limestones, with or without lists and nodules of black flint, and interbedded pseudoolitic and oolitic limestones. As a result of weathering, the black limestones become gray in color. The discoloration is fast, but requires, however, a few tens of years, as evidenced by the scars of World War II due to bomb damage, in the bottom of which the color is darker than that of adjacent areas.

4.1.4 Sandstones

Sandstones used in the studied façade are grey to light bluish-grey in colour when unaltered and, from a geological point of view, belong to the *Macigno* Formation (Upper Oligocene - Lower Miocene) that crops out extensively in the Northern Apennines, from *Pontremoli* to the *Chianti* area, with some occurrences in the southern Tuscan region [27]. Historically, these rocks have been extensively employed in Florence and other Tuscan cities for monumental buildings, churches, castles and towers. In the Pisa's medieval architecture, the *Macigno* sandstones were mostly used for ornamental elements (pilaster, pillars, columns, window and door frames) and as paving stone for squares and streets of the city centre. The *Macigno* sandstones consist of well-consolidated, fine- to very coarse-grained, poorly to moderately sorted siliciclastic rocks made of sub-angular detrital grains of quartz, plagioclase, K-feldspar, chlorite s.l., mica-like minerals (muscovite/illite and minor biotite), with minor amounts of rock fragments (<10% by volume), including granites, felsic volcanites and metavolcanites, low to medium metamorphic-grade rocks, ophiolites, quartz veins, limestones and shales [27-29]. Carbonates occur as both detrital clasts and authigenic cement. Mixed-layer chlorite/smectite and subordinate illite/smectite phases, as well as minor and sporadic kaolinite may be present as clay minerals. Neoformed pumpellyte, illite, epidote and chlorite have also been described, indicating incipient metamorphism. Despite its good technical properties, when used outdoors *Macigno* sandstones often undergo a typical process of decay, consisting of delamination characterised by a detachment of multiple thin stone layers sub-parallel to the stone surface (exfoliation), which in many cases may be exacerbated by the occurrence of significant amounts of expansible clay components [29].

4.1.5 Other building materials

Excluding brick masonry and mortars (some of which laid during recent grouting works), the other building materials identified in the façade of the St. Nicholas church are serpentinites of unknown origin, used as decorative stones for their marble-like qualities, a few ashlars of Agnano breccias [16] and small elements of red limestone probably belonging to the *Scaglia Rossa* Formation of the Tuscan sequence.

4.2 The GIS project of the stone mapping

The resulting GIS project shows that the façade of St. Nicholas church is about 340 m^2 wide, excluding the surface of the openings in the first and second orders, the four windows and the main door, and the surface of the rose window of the second order.

The façade has been realized with 1855 elements. Based on stone-to-stone observation, taking the macroscopic features reported in the literature for the stones of medieval buildings in Pisa into account [13-16 and references therein] and on both petrographic analyses and C-O stable isotope data on white marbles, the identified litotypes are as follows (Table 2 and Figure 4): *Mt. Pisano* marbles (579 ashlars, 18.37% of the stone surface), quartzites (516, 21.81%), serpentinites (412, 0.47%), limestones (223, 5.93%), Apuan marbles (97, 5.42%), *Macigno* sandstones (25, 1.48%) and *Agnano* breccias (3, 0.09%).

Table 2 and Figures 3a-3b point out that stones characterised by higher values of perimeter and area were used for realizing the elements of the main door of the church in the first order of the façade, while those with smaller dimensions are present in some ornamentations and in the frames of blind arches of the first and second order, and only barely constitute whole recurrences.

Table 3 reports the shape factors of the building materials observed in the façade of St. Nicholas church. The shape factors values, ranging from 0 to 1, have been computed as suggested by Russ [30] using the following formula: Shape factor = $4\ \pi$ Area/Perimeter^2. The maximum value of the form factor corresponds to a circle, while values lower than 1 are due to objects with more irregular shape (for example, a square stone ashlar is characterised by a shape factor value of 0.785, while the stones with a rectangular shape are characterized by lower values as smaller as larger is the difference between the length of their sides). Observing the average data of the shape factors, given in the last column of Table 3, the building stones exposed on the façade have values ranging from 0.26 (*Macigno* sandstones) to 0.79 (*Agnano* breccias). The average values of the other building stones are 0.70 for quartzites, 0.63 for red limestone, 0.62 for *Mt. Pisano* marbles and black limestone, 0.61 for Apuan marbles and 0.49 for serpentinites. The arrangement of the stones approximately of squared shape (blue colour) and highly elongated (red colour) seems to be related to the structural and ornamental function more than to the type of building material or to the constructive phase (Figure 3c).

5 Conclusion

This case study shows how the acquisition and processing of laser scanner data supported by high-resolution digital images, the CAD/GIS techniques and the stone-to-stone mapping may contribute to enhance our understanding of the building materials and techniques used in the past. Aside from the knowledge of the spatial information of the façade of St. Nicholas church, our work has provided a detailed mapping of stones, marbles and other building materials, which can be useful for a future conservation and restoration planning. The knowledge of the nature of stone materials used for building the façade of this church and of their provenance can serve for creating a comprehensive database of all the valuable buildings in Pisa; today data about *Palazzo Gambacorti* , *Baptistery* and *St. Frediano church* are already available [12 and references therein].

It is noteworthy that the GIS project can be easily developed for historical and archaeological purposes or used as useful base for storing information relating to future renovation works. As regard to education, the GIS project of the façade of St. Nicholas church may certainly be used as an efficient and relatively inexpensive educational tool to disseminate geo-archaeological information and it can contribute to publicize a tourist route in addition to that represented by the more famous medieval monuments in the well-known *Piazza dei Miracoli* in Pisa.

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Titles of tables

Table 1 - Mineralogical and petrographic features of the marbles worked for structural pourpose in the St. Nicholas church's façade.

Table 2 - Number, perimeter and area of the stone ashlars and other building materials used for building the façade of the St. Nicholas church.

Table 3 - Shape factor of the stone ashlars and other building materials used in the façade of the St. Nicholas church.

Captions for figures

Figure 1 - Photograph of the façade of the St. Nicholas church with on the left the octagonal bell tower.

Figure 2 - The façade of the St. Nicholas church: a) The point cloud of the façade as obtained for processing the laser scanner data coloured by the effects of the reflecting material surface properties; b) Drawing of the façade showing the ashlar features.

Figure 3 - Map of the main geometric features of stone ashlars and of other building materials used in the façade of the St. Nicholas church: perimeter (a), area (b) and shape factor (c).

Figure 4 - Stone mapping of the façade of the St. Nicholas church.

Figure 5 - Detail of the stone mapping of the façade of the St. Nicholas church showing some precious intarsia.

Figure 6 - Isotopic signatures of some white marbles used for architectural elements in the St. Nicholas church's façade. The isotopic fields for the main Mediterranean fine-grained marbles (average MGS < 2 mm) used in antiquity are those reported by [18], [31] and [32]: C = Carrara; Ca-1 = Campiglia M.ma; D = Dokimeion; Pa-1 Paros Stefani; Pe = Mount Pentelikon; Ti = Island of Tinos.

Table 1

Sample	Cal	Dol	Qtz	Pl	Ms	Ap	Py	Ox	GSU	Texture	GBS	Fabric
SNF-1	+++	+						tr	He	M		Mosaic
SNF-2	+++	++	tr					tr	He	M		Mosaic
SNF-3	+++	+						tr	He	M		Mosaic
SNF-4	+++				tr		tr		Ho	G, w-A	St-Cr	Mosaic, with rare triple points
SNF-5	+++		tr	tr	tr	tr	tr		Ho	G, I	St-Cr	Mosaic, with rare triple points
SNF-6	+++		tr	tr			tr	tr	Ho	G, I	St-Cr	Mosaic, with triple points
SNF-7	+++				tr		tr		Ho/He	G, I	St-Cr	Mosaic, with rare triple points
SNF-8	+++			tr	tr	tr	tr	tr	Ho	G, I	St-Lo	Mosaic
SNF-9	+++		tr	tr	tr	tr	tr	tr	Ho/He	G, I	St-Lo	Mosaic

GSU, *Grain-Size Uniformity* = Ho, homeoblastic; He, heteroblastic; Texture: G, granoblastic; S anisotropic; w-, weakly-; GBS, *Grain-Boundary Shape* = St, straight; Cr, curved; Lo, lobate; MGS = calcite; Dol = dolomite; Qtz = quartz; Pl, plagioclase; Ms, muscovite; Ap, apatite; Py, pyrite; present; +, scarce; tr, trace; $\delta^{13}C$ and $\delta^{18}O$ = carbon (C) and oxygen (O) isotopic values.

MGS (mm)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)	Origin
0.1	1.8	-1.9	Mt. Pisano
0.1	2.0	-1.9	Mt. Pisano
0.1	2.5	-1.3	Mt. Pisano
0.4	2.1	-1.8	Carrrara
0.5	2.1	-1.8	Carrara
0.5	1.8	-1.6	Carrrara
0.5	2.1	-2.0	Carrrara
0.6	1.8	-2.2	Carrrara
0.7	2.3	-1.8	Carrrara

, sutured; M = microgranular; I, isotropic; A, = *Maximum Grain Size* of calcite crystals*;* Cal Ox, oxide and hydroxide; +++, abundant; ++,

Table 2

Litotype	Ashlars	Perimeter (m)				Area (m^2)			
		Min	Max	Average	Total	Min	Max	Average	Total
Mt. Pisano marbles	579	0.04	9.44	1.35	780.66	<0.01	0.56	0.11	62.69
Mt. Pisano quartzites	516	0.32	3.83	1.55	801.13	0.01	0.54	0.14	74.44
Serpentinites	412	0.04	4.97	0.31	129.47	<0.01	0.06	0.00	1.59
Black limestones	198	0.16	5.08	1.41	278.81	<0.01	0.55	0.10	20.23
Apuan marbles	97	0.01	24.39	1.82	176.15	<0.01	2.64	0.19	18.50
Macigno sandstones	25	1.05	5.32	3.25	81.32	0.05	0.47	0.20	5.06
Red limestone	25	0.05	0.16	0.11	2.65	<0.01	0.00	0.00	0.01
Agnano breccias	3	1.00	1.45	1.24	3.72	0.06	0.13	0.10	0.29
Mortars	-	-	-	-	755.91	-	-	-	10.63
Brick masonry	-	-	-	-	211.06	-	-	-	147.84
Total	1855				3220.89				341.27

%
18.37
21.81
0.47
5.93
5.42
1.48
<0.01
0.09
3.12
43.32
100.00

Table 3

Litotype	Ashlars	Shape factor		
		Min	Max	Average
Mt. Pisano marbles	579	0.01	0.99	0.62
Mt. Pisano quartzites	516	0.12	0.87	0.70
Serpentinites	412	0.03	1.00	0.49
Black limestones	198	0.14	0.85	0.62
Apuan marbles	97	0.03	0.85	0.61
Macigno sandstones	25	0.10	0.63	0.26
Red limestone	25	0.30	0.98	0.63
Agnano breccias	3	0.76	0.81	0.79
Mortars	-	0.00	0.79	0.20
Brick masonry	-	0.05	0.85	0.36

Shape factor = $4 \cdot \pi \cdot$Area /Perimeter^2

Figure 1
965x1286mm (72 x 72 DPI)

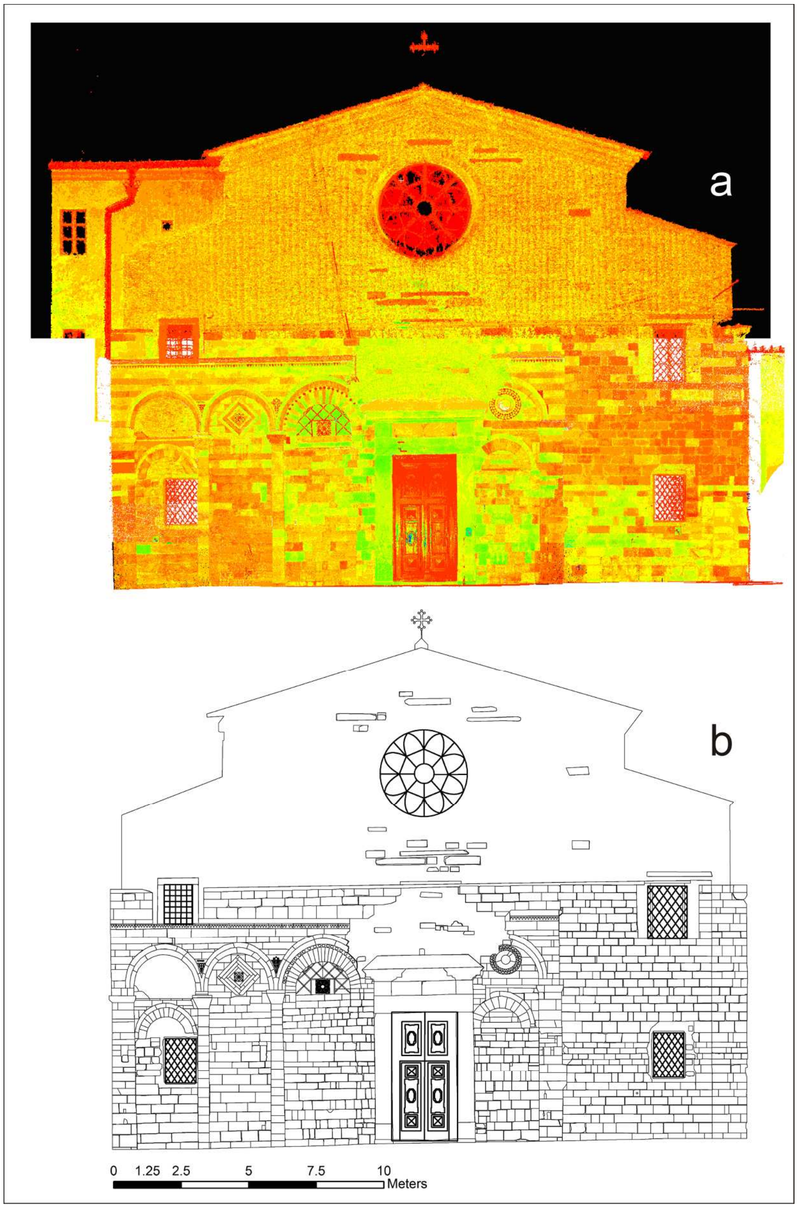

Figure 2
154x233mm (300 x 300 DPI)

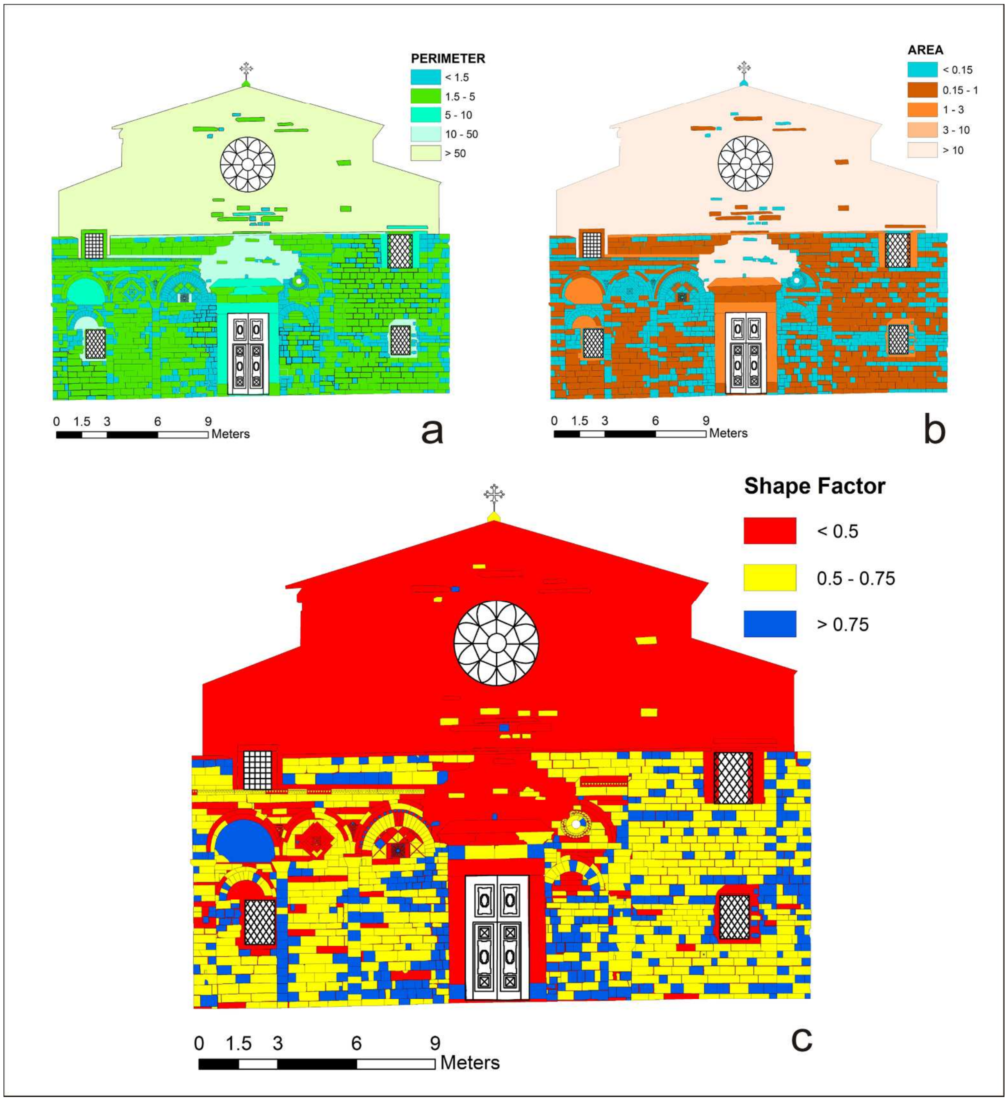

Figure 3
209x229mm (300 x 300 DPI)

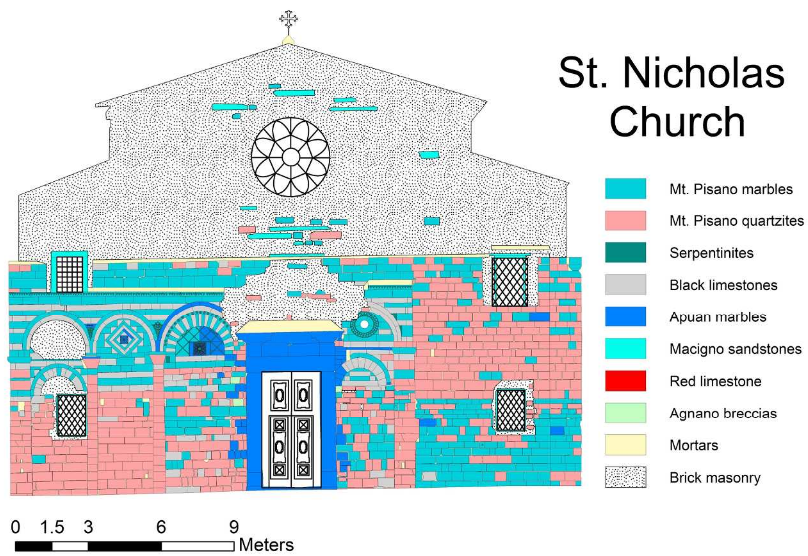

Figure 4
210x148mm (300 x 300 DPI)

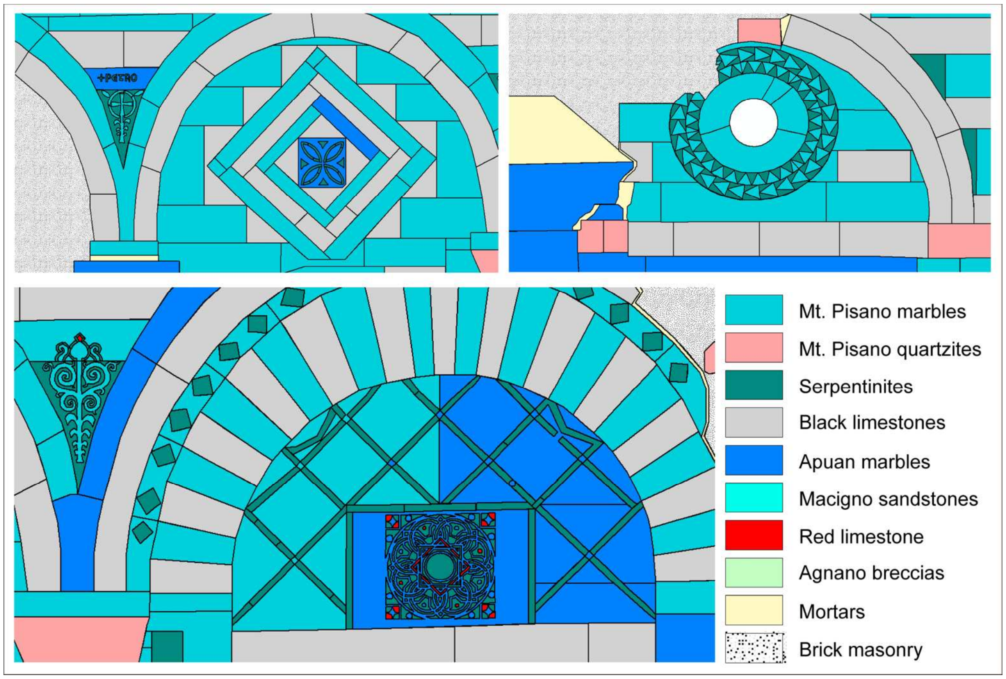

Figure 5
191x128mm (300 x 300 DPI)

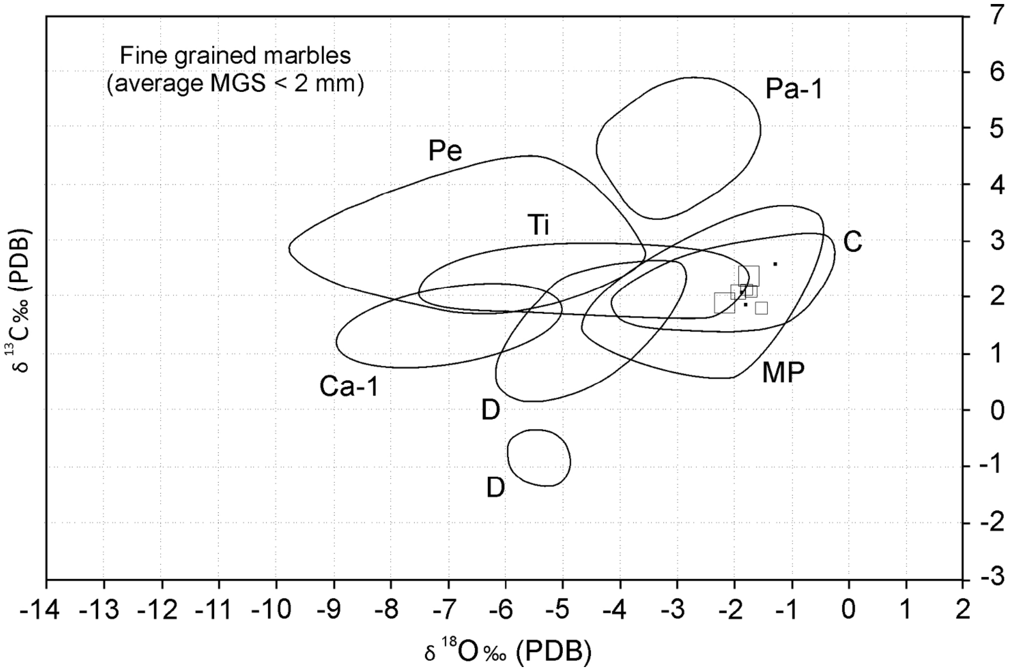

Figure 6
171x113mm (300 x 300 DPI)