SOCIETÀ TOSCANA DI SCIENZE NATURALI
RESIDENTE IN PISA

ATTI DELLA SOCIETÀ TOSCANA DI SCIENZE NATURALI

MEMORIE • SERIE A • VOLUME CXXII • ANNO 2015

Edizioni ETS

UNIVERSITÀ DI PISA
MUSEO DI STORIA NATURALE

Con il contributo del Museo di Storia Naturale dell'Università di Pisa

Fondazione
Cassa di Risparmio
di Lucca

e della Fondazione Cassa di Risparmio di Lucca

INDICE - *CONTENTS*

Atti Soc. Tosc. Sci. Nat., Mem., Serie A, 122 (2015)
pagg. 55-62, fig. 7, tab. 2; *doi: 10.2424/ASTSN.M.2015.20*

Mirco Ramacciotti (*), Marcello Spampinato (**), Marco Lezzerini (*)

THE BUILDING STONES OF THE APSIDAL WALLS OF THE PISA'S CATHEDRAL

Abstract - *The building stones of the apsidal walls of the Pisa's Cathedral.* This paper reports the preliminary data about the stones used in the apsidal walls of the Cathedral of Pisa. The research was made during the study and restoration works of the monument, under the supervision of the Opera della Primaziale Pisana.
The collected data shows the prevalence of stones commonly used in the historical buildings of the city. The main lithotypes are the marbles from the Monte Pisano and from the Apuan Alps. Moreover, there are numerous ashlars of Proconnesian marble and two capitals of Pentelic and one of Paros marbles, three lithotypes used during the Roman Age and coming from the Eastern Mediterranean. The wall of the loggia of the third storey is almost entirely made up of a calcarenite (*Panchina*) coming from the area South of Livorno. Black limestone from the Monti d'Oltre Serchio, and serpentinite and red marly limestone outcropping in different areas of Tuscany, were also identified.

Keywords - Building materials, applied petrography, archaeometry, architecture, Middle Ages, Tuscany, Italy

Riassunto - *Le pietre delle murature dell'abside del Duomo di Pisa.* In questo articolo sono riportati i dati preliminari relativi alle pietre usate nei paramenti murari dell'abside del Duomo di Pisa. Le ricerche sono state effettuate nell'ambito del cantiere di restauro e di studio del monumento, diretto dall'Opera della Primaziale Pisana. I dati mostrano la prevalenza di pietre usate comunemente negli edifici storici della città. I litotipi principali sono i marmi del Monte Pisano e delle Alpi Apuane. Vi sono inoltre numerosi conci di Marmo Proconnesio e un capitello di marmo Pentelico e uno di marmo di Paros, tre pietre usate in epoca romana e provenienti dal bacino orientale del Mediterraneo. Il muro della loggia del terzo ordine è quasi interamente costruito con una calcarenite (Panchina) proveniente dall'area a Sud di Livorno. Sono stati inoltre identificati il calcare nero dei Monti d'Oltre Serchio e una serpentinite e un calcare marnoso rosso che affiorano in diverse zone della Toscana.

Parole chiave - Materiali da costruzione, petrografia applicata, archeometria, architettura, medioevo, Toscana, Italia

Introduction

The identification and the characterization of the lithotypes of a monument have an important role in conservation works. The chemical, mineralogical, petrographic data and the identification of deterioration phenomena are in fact fundamental to choose the best strategies of intervention.
For this purpose, the use of appropriate software such as CAD (Computer Aided Design) and GIS (Geographical Information System) have become more and more common to map historical structures due to their high informative potentialities (Katsianis *et al.*, 2008; Siart *et al.*, 2008; Tian *et al.*, 2008; Giammartini, 2010; Lezzerini *et al.*, 2016). In fact, these tools permit to organise georeferenced data collected during the study and the restoration of a building, and they give also the possibility to consult database linked to a graphic support.
The naked-eye observation of coloured marbles is quite often sufficient to detect their provenance. Sometimes, the archaeometric data, such as maximum grain size and texture obtained by optical microscopy observation, accessory minerals, and oxygen and carbon stable isotopes, is useful to identify the provenance of white marbles (Craig, 1957; Craig & Craig, 1972; Lazzarini *et al.*, 1980; Matthews *et al.*, 1992; Attanasio *et al.*, 2000; Franzini & Lezzerini, 2002; Lazzarini, 2004; Attanasio *et al.*, 2006; Attanasio *et al.*, 2008; Gorgoni *et al.*, 2002; Capedri & Venturelli, 2004; Capedri *et al.*, 2004; Ebert *et al.*, 2010). By applying these methods, many white marbles from different Mediterranean areas were identified in several archaeological and monumental contexts (Antonelli *et al.* 2009; Antonelli *et al.*, 2010; Maniatis *et al.*, 2010; Lezzerini *et al.*, 2012; Al-Bashaireh, 2011; Miriello *et al.*, 2012; Pensabene *et al.*, 2012; Attanasio *et al.*, 2013; Al-Bashaireh & Al-Housan, 2014; Antonelli *et al.*, 2014; Columbu *et al.*, 2014).
This paper reports the preliminary data on the lithotypes used in the apse of the Cathedral of Pisa (Figure 1), one of the most important monument of the Romanesque architecture and part of a historical complex which has been included in the Unesco "World Heritage List" since 1987. According to Alberti & Paribeni (2011), the area of Piazza del Duomo

(*) Dipartimento di Scienze della Terra, Università di Pisa, Via S. Maria 53, 56126 Pisa (Italia).
(**) Laboratorio di Analisi, Via S. Maria del Giudice Trav. III 15/A, Lucca (Italia).
Corresponding author: e-mail: mirco.ramacciotti@gmail.com

Figure 1 - The apse of Pisa's Cathedral.

has been occupied since the Etruscan Age, and Roman villas embellished with precious marbles, mosaics and painted plasters were found. During the archaeological excavations, the remains of a more ancient baptistery and of an older cathedral were also unearthed in the square, whose built is dated back to the 6th and to the 10th centuries, respectively. Conversely, the existing monumental complex was built from the second half of the 11th to the 14th centuries, and consists of the Cathedral, the Baptistery, the famous Leaning Tower and the Monumental Cemetery (Garzella *et al.*, 2014).

Materials and methods

Thirty-eight marble samples were collected from the external wall of the apse (Table 1). For each sample, thin sections were analysed through optical microscopy (OM) using a Zeiss-Axioplane polarizing microscope to measure the maximum grain size (MGS) of the carbonate crystals (Wentworth, 1922) and to observe their texture as well as to identify the main accessory minerals. A 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.

X-ray powder-diffraction (XRPD) using a Bragg-Brentano geometry and Ni-filtered CuKα radiation, obtained at 40 kV and 20 mA, was used to determine the main mineralogical composition of the marbles.

Measurements of the $^{18}O/^{16}O$ and $^{13}C/^{12}C$ isotopic ratio of the marbles were carried out through mass spectroscopy (McCrea, 1950) in the Stable Isotope Mass Spectroscopy Laboratory of the Institute of Geosciences and Earth Resources, National Research Council of Italy. The results were expressed as $\delta^{13}C$ or $\delta^{18}O$, measured in parts per thousand (‰) referring to the conventional standard Pee Dee Belemnite (PDB). The isotopic data is reported as a scatter plot of $\delta^{18}O$ and $\delta^{13}C$ values. Analytical precision is ± 0.1‰ for both oxygen and carbon (Craig, 1957). The results of mineralogical, petrographic and isotopic analyses were compared with the most up-to-date databases for the white Mediterranean ancient marbles (Herz, 1987; Moens *et al.*, 1995; Gorgoni *et al.*, 2002; Capedri *et al.*, 2004; Franzini *et al.*, 2010; Yavuz *et al.*, 2011; Lezzerini *et al.*, 2012).

Table 1 - Sampling.

Sample	Storey	Sector	Element	Course	Ashlar
1	I	3	b	1	1
2	I	9	b	1	1
3	I	3	b	2	1
4	I	3	b	2	2
5	I	3	b	3	2
6	I	3	b	4	1
7	I	5	b	5	1
8	I	3	b	8	1
9	I	3	b	9	1
10	I	1	c	1	1
11	I	3	c	1	1
12	I	5	c	1	1
13	I	7	c	1	1
14	I	9	c	1	1
15	I	11	c	1	1
16	I	13	c	1	1
17	I	15	c	1	1
18	I	17	c	1	1
19	I	19	c	1	1
20	I	1-3	w	1	2
21	I	1-3	w	2	2
22	I	3-5	w	2	4
23	I	3-5	w	3	3
24	I	3-5	w	4	3
25	I	1-3	w	4	3
26	I	3-5	w	5	1
27	I	3-5	w	6	2
28	I	1-3	w	6	3
29	I	1-3	w	9	3
30	I	1-3	w	11	2
31	I	3-5	w	12	3
32	I	3-5	w	16	4
33	I	3-5	w	19	3
34	III	2-3	m	1	1
35	III	1-2	m	1	1
36	III	2-3	m	1	2
37	III	1-2	m	2	1
38	III	1-2	w	9	3

Element: b = column shaft, c = column capital, m = moulding; w = wall; Course: The number represents the position from the bottom to the top; Ashlar: The number represents the position from theright to the left.

Results

In the external walls of the Pisa's Cathedral we have recognized the presence of the following main lithotypes:

Marbles. Monte Pisano marble (MPM) and white Apuan marble (WAM) were identified (Figure 2). The MPM is characterized by very fine grain size with calcite crystals ranging from 50 to 110 μm and a typical microgranular texture. The colour of the ashlars is whitish to light grey, and their surfaces frequently show in relief dolomite-rich veins and nodules (Franzini & Lezzerini, 2003). MPM was widely used in the medieval buildings of Pisa, such as the other monuments of Piazza del Duomo, and in Lucca, for example in the churches of San Frediano and San Martino.

Figure 2 - Detail of the wall of the first storey, showing Monte Pisano marble, Carrara marble and Proconnesian marble.

Table 2 - Petrographic, mineralogical and isotopic data.

Sample	Cal	Dol	Other minerals	Texture	GBS	Triple points	Twinned crystals	MGS (mm)	$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)	Origin
1	Only		Mu, Py, Ox, Ap	He-Ho, G, I	Cr		present	0.50	-1.06	2.01	Carrara (Italy)
2	Only		Py	Ho, G, I	St-Cr		present	0.60	-1.65	1.59	Carrara (Italy)
3	Main	Sub	Py	Ho, M, I				0.09	-1.15	2.87	Monte Pisano (Italy)
4	Only		Py, Ox	Ho, G, I	St-Cr	present	present	0.58	-1.17	1.79	Carrara (Italy)
5	Only		Py	Ho, G, I	St-Cr	present	present	0.74	-1.75	2.20	Carrara (Italy)
6	Only		Py, Pl, Mu, Ap	Ho, G, I	St-Cr		present	0.44	-1.76	2.06	Carrara (Italy)
7	Only		Py	He, G, I	Lo		deformed	1.48	-0.89	2.72	Marmara (Turkey)
8	Only		Py, Ox	Ho-He, G, I	Cr-St		present	0.75	-1.79	2.14	Carrara (Italy)
9	Only		Py, Mu, Ap(?)	Ho, G, w-A	St-Cr		present	0.40	-1.84	2.09	Carrara (Italy)
10	Only		Py, Ap	He, G, I	St-Cr-Lo		present	2.28	-2.34	3.15	Marmara (Turkey)
11	Only		Py, Mu	Ho, G, I	St-Cr	rare	rare	0.52	-1.99	2.05	Carrara (Italy)
12	Only		Mu, Py, Pl	Ho, G, I	St-Cr		rare	0.56	-0.95	2.24	Carrara (Italy)
13	Only		Py	Ho, G, I	St-Cr		present	0.69	-0.83	1.62	Carrara (Italy)
14	Only		Py, Mu	Ho, G, I	St-Cr		present	0.49	-1.72	2.15	Carrara (Italy)
15	Only		Pl, Py	Ho-He, G, I	St-Cr		rare	0.69	-1.33	1.12	Carrara (Italy)
16	Only		Py, Mu, Pl	Ho-He, G, I	St-Cr	rare	rare	0.55	-2.15	1.61	Carrara (Italy)
17	Only		Mu	Ho-He, G, w-A	St-Cr		rare	0.71	-6.92	2.75	Penteli (Greece)
18	Only		Py	Ho, G, I	St-Cr	rare	rare	0.50	-2.89	2.00	Carrara (Italy)
19	Only			He, G, I	St-Cr	rare	rare	1.41	-1.83	2.14	Paros (Greece)
20	Main	Sub	Py	He, G, I (Mortar)	Lo-Cr		present	2.34	-2.65	2.12	Marmara (Turkey)
21	Only		Py, Pl, Ox	Ho, G, I (Mosaic)	St-Cr	present	rare	0.44	-0.58	1.76	Carrara (Italy)
22	Only		Py, Ox, Mu	Ho-He, G, I	St-Cr		present	0.61	-0.81	1.80	Carrara (Italy)
23	Only		Py, Ox, Mu, Ap	Ho, G, I	St-Cr		present	0.71	-1.80	2.33	Carrara (Italy)
24	Only		Py, Ox, Pl, Mu	Ho-He, G, I	St-Cr	present	present	0.77	-0.71	1.74	Carrara (Italy)
25	Main	Sub	Py, Ox, Ap	Ho, G, I	St-Cr	rare	present	0.50	-1.79	2.27	Carrara (Italy)
26	Only		Py, Mu, Ox, Ap	Ho, G, I	St-Cr	rare	present	0.60	-2.23	1.85	Carrara (Italy)
27	Only		Py, Ox	Ho, G, I	St-Cr	rare	present	0.44	-1.42	2.03	Carrara (Italy)
28	Only		Py, Ox	Ho-He, G, w-A	Lo-Cr		present	0.85	-1.79	2.47	Carrara (Italy)
29	Only		Ox	Ho, G, w-A	St-Cr	rare	present	0.82	-1.18	1.63	Carrara (Italy)
30	Main	Sub	Py, Mu, Pl, Ap	He, G, w-A	Lo-Cr		present	1.88	-2.63	2.11	Marmara (Turkey)
31	Only		Py, Mu	He, G, I	Lo-Cr		deformed	1.76	-0.30	2.90	Marmara (Turkey)
32	Main	Sub	Ox	Ho-He, M, I				0.10	-3.17	2.14	Monte Pisano (Italy)
33	Main	Sub	Py, Ox	Ho-He, M, I				0.15	-2.88	2.23	Monte Pisano (Italy)
34	Only		Py	He, G, I	Lo-Cr		deformed	1.84	-1.81	2.59	Marmara (Turkey)
35	Main	Sub		Ho, M, I				0.13	-2.72	0.85	Monte Pisano (Italy)
36	Main	Sub		Ho, M, I				0.09	-2.10	0.71	Monte Pisano (Italy)
37	Only		Py	He, G, I	Lo-Cr		deformed	2.15	-1.60	3.34	Marmara (Turkey)
38	Main	Sub	Py, Ox	Ho, M, I				0.16	-2.03	2.50	Monte Pisano (Italy)

Ap = apatite, Cal = calcite, Dol = dolomite, Mu = muscovite, Ox = oxides and idroxides; Pl = plagioclases, Py = pyrite, Qtz = quartz; Ho, homeoblastic; He, heteroblastic; G, granoblastic; I, isotropic; M = microgranular; A, anisotropic; w-, weakly-); GBS, Grain Boundary Shape = St, straight; Cr, curved; Lo, lobate; MGS = Maximum Grain Size.

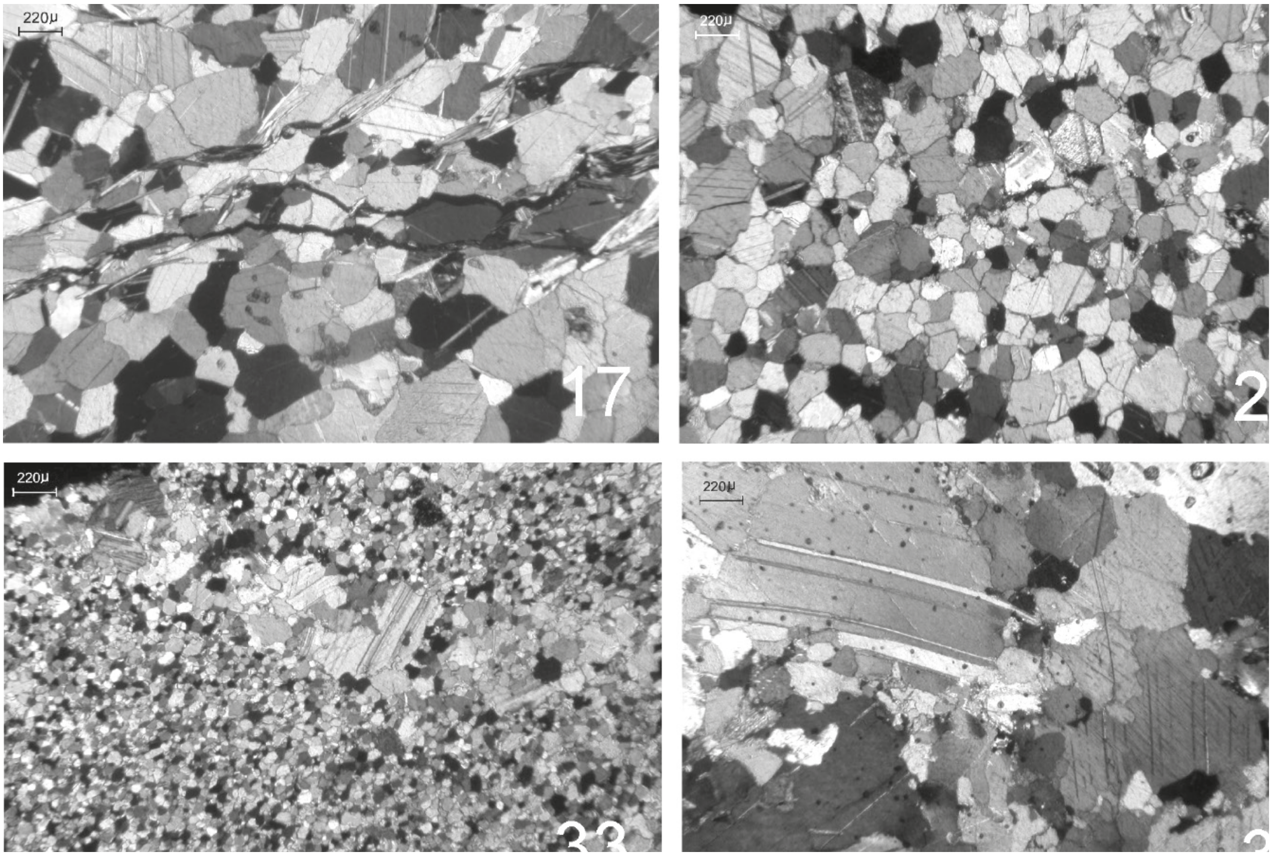

Figure 3 - Thin sections of four different samples of marble (crossed nicols). 17) Penteli; 27) Carrara; 33) Monte Pisano; 37) Marmara.

The WAM has instead an average grain size ranging from 150 to 400 µm and the varieties recognized on the basis of the macroscopic features (white, greyish and greyish-veined) suggest the provenance from more than a quarry of the Carrara basin.
The identified eastern Mediterranean marbles are the Proconnesian (Figure 2), the Paros and the Pentelic ones. The Proconnesian marble is a Turkish marble coming from Marmara Island. It has a typical mortar texture and a calcite MGS that is higher than 2 mm. The Pentelic marble was quarried on the Mount Pentelikon, NW Athens, and it is characterized by fine grain size and by mainly granoblastic texture with some lepidoblastic streaks due to the presence of oriented muscovite/sericite crystals that are often organised in greenish trains (Gorgoni *et al*., 2002; Attanasio *et al*., 2008). The Paros marble was quarried in the Cycladic island of the same name (Greece) and was used since the Neolithic and then during the Roman age; it is characterized by fine to medium grain size (Gorgoni *et al*., 2002).
The results of the mineralogical, petrographic and isotopic analyses are summarized in Table 2. The XRPD analysis shows that the white marble samples are made up of calcite, with the exception of samples 3, 20, 25, 30, 32, 33, 35, 36 and 38 which contain both calcite and dolomite. Pyrite is present as accessory mineral in many samples, while samples 6, 12, 16, 21, 24 and 30 also contain plagioclases.
Petrographic examination (Figure 3) shows that samples 7, 10, 19, 20, 30, 31, 34 and 37 are coarser grained (MGS ranges between 1.41 to 2.34 mm, Table 2). Several of them show a typical mortar and heteroblastic texture with mostly embayed to sutured boundaries (7, 10, 20, 30, 31, 37). These characteristics are similar to those of Proconessos-1 marble. In addition, samples 7, 31, 34 and 37 show deformed polysynthetic twins, while the sample 17 contains muscovite and shows two different grain size distributions of the calcite crystals. In some areas, the larger crystals are small in size (about 1 mm) and sporadically dispersed in a very fine matrix, while in other areas, larger crystals (2-3 mm) are distributed in a fine matrix and alternate with areas of smaller crystals. Gorgoni *et al.* (2002) observed similar features in the marble from Mount Pentelicus. In contrast, sample 19 (MGS = 1.41 mm) is heterob-

Figure 4 - Detail of the wall of the second loggia made up of prevalently calcarenite *Panchina* and one black limestone ashlar.

Figure 5 - Detail of the ornamental area of the first storey.

lastic and granoblastic in texture and the crystals have straight to curved boundaries. These petrographic features correspond quite well with the Paros-2 marble (Gorgoni *et al.*, 2002).
Oxygen and carbon stable isotope data of the sampled marbles compared with that on marbles from the major ancient quarries of the Mediterranen area confirms the presence of Proconessos-1, Pentelic, Paros, Carrara and Monte Pisano marbles.

The other stones. There are two different kind of limestone: a black and a red ones. Black limestones (Figure 4) outcrop in different areas around Pisa, although the presence of black flint suggests a provenance from the Monti d'Oltre Serchio rather that from the Monte Pisano. The rock was originally black, but the atmospheric phenomena altered its surface to light grey. The red limestone (Figure 5) belongs to the Scaglia Formation of the Tuscan Nap Sequence, but its outcrops are uncertain. Its main Tuscan ancient quarries were in San Giusto at Monterantoli and Monsummano (Florence) and it was used also in some of the most important churches of Florence, such as Santa Maria Novella and Santa Maria del Fiore (Bastogi & Fratini, 2004).
The external wall of the loggia of the third storey is almost completely made up of the calcarenite *Panchina* (Figure 4), a stone that outcrops in the coastal area south of Livorno. This rock consists of a calcareous matrix and by fossils and clasts up to few centimeters. Even though the *Panchina* is a stone characterized by good compressive strength, the presence of not well cemented areas leads to the formation of cavities on the surface that were sometimes filled up with mortar, such as in the church of San Frediano (Lezzerini, 2005). The use of this stone was very common during the Middle Ages in Pisa until the half of the 12th century (Franzini, 2003).
The serpentinite (Figure 5) is characterized by black and dark green colours. It is frequently associated with black and red limestones in the ornamentation of medieval monuments of Pisa and of other cities in Tuscany (Bastogi & Fratini, 2004). This rock outcrops in several areas of the Northern Appennines and its provenance is still uncertain. The most important Tuscan quarries were opened in Figline di Prato (Prato) and Impruneta (Florence) where the so-called Green Marble of Prato was quarried (Bastogi & Fratini, 2004).
The main features of the ashlars of the apse cathedral permitted to exclude the use of other common historical building stones of Pisa, such as the Acquabona limestone (Baldanza *et al.*, 2012), the Agnano breccias (Franzini *et al.*, 2002), the quartzites from the Monte Pisano (Franzini *et al.*, 2001), the Maiolica and the Nummulitico of the lower valley of Serchio river (Franzini *et al.*, 2007) and the Macigno sandstone (Lezzerini *et al.*, 2008; Leoni et *al.*, 2010).

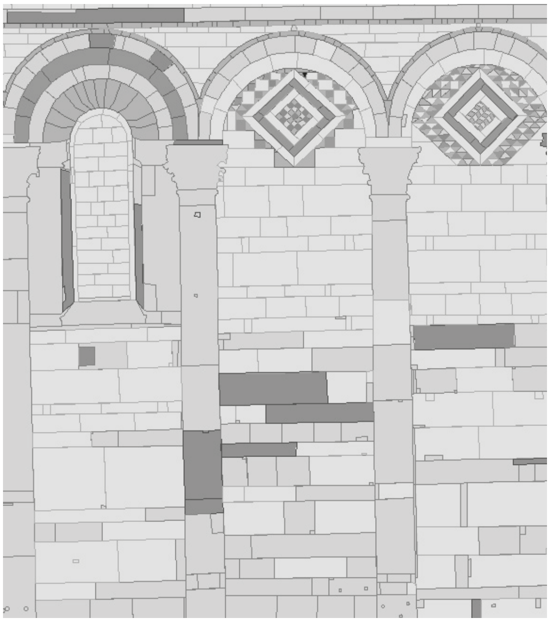

Figure 6 - Detail of the ashlar CAD-map of the first storey (Legenda - yellow: Monte Pisano marble, pale blue: Apuan marble, reddish violet: Eastern marbles, green: serpentinite, pink: red limestone, violet: black limestone, red: replacement stone).

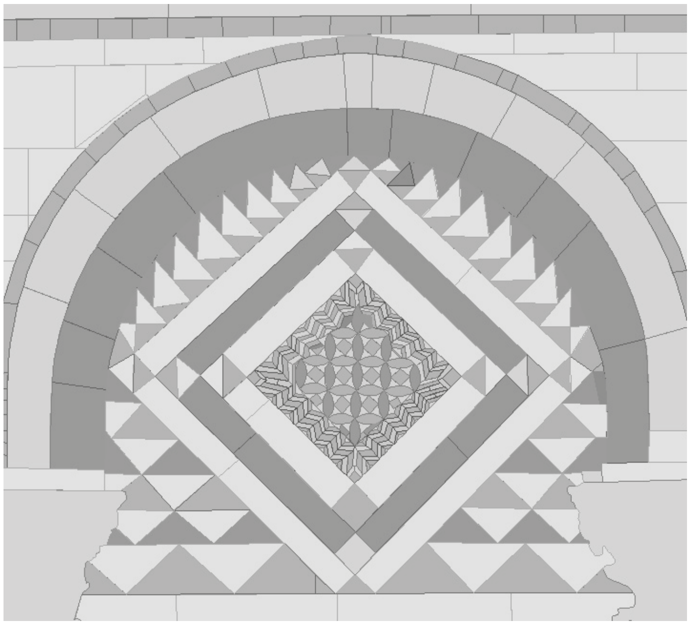

Figure 7 - Ashlar CAD-map of a tarsia of the first storey (Legenda - look at the caption of Fig. 6).

Discussion and conclusions

The external wall of the first storey of the apse is mainly characterized by white marbles. The presence of large ashlars disposed in non-regular courses in the first half of the blind arcades (from the base to the windows), as well as the presence of different varieties of white marbles (Figure 6), suggest the prevalence of reemployed stone materials (Franzini & Lezzerini, 2003).
The Monte Pisano marble was mainly used in the structural elements, even though its presence was also detected in the tarsias, in the blind arches, in a capital and, sporadically in the semicolumns and in the windows jambs. The other marbles (Apuan, Paros, Pentelic, Proconnesian marbles) were widely used in the ornamental areas, in the cornice between the first and the second storey, and in the first half of the wall. The presence of the black and red limestones as well as of the serpentinite is limited to the ornamentation (Figs. 5-7).
The wall of the first loggia is made up of Monte Pisano marble, except for some ashlars of Proconnesian and Apuan marbles. This wall is subdivided in two areas by a horizontal course of black limestone blocks. The jambs of the windows are made up of Apuan marble. The ashlar dimensions are quite regular.
The wall of the second loggia were built with quite regular blocks of calcarenite *Panchina*, except for the blocks where the architraves rest that are made up of black limestone and Monte Pisano marble (Figure 4). The *Panchina* ashlars show the presence of mortar remains. During the Roman period and the Middle Ages, mortars for Valdarno buildings were made by firing the Monte Pisano marble and the marly Alberese limestone. While the Alberese limestone was baked in the area of Florence (Fratini *et al.*, 1994), the other rock was generally used in Pisa (Franzini & Lezzerini, 2003).
In conclusion, most building stones of the Pisa's Cathedral apse are quite common in the medieval churches of Pisa. The collected data shows the prevailing use of Tuscan lithotypes such as the marbles from the Monte Pisano and from the Apuan Alps, the calcarenite *Panchina* from the area south of Livorno, the black limestone from the Monti d'Oltre Serchio, the serpentinite and the reddish marly limestone belonging to the Tuscan Nap Sequence. Moreover, eastern Mediterranean white marbles such as Proconnesian, Paros and Pentelic marbles were also identified.

Acknowledgements

The authors would like to thank the *Opera della Primaziale Pisana* for the possibility to conduct this research during the restoration works.

REFERENCES

Al-Bashaireh K., 2011. Provenance of marbles from the octagonal building at Gadara "Umm-Qais", Northern Jordan. *Journal of Cultural Heritage*, 12: 317-322.

Al-Bashaireh K., Al-Housan A.Q., 2014. Provenance investigation of white marbles of chancel screens from Rihab Byzantine churches, northeast Jordan. *Journal of Cultural Heritage*, 16: 591-596.

Alberti A., Paribeni E., 2011. Archeologia in Piazza dei Miracoli. Gli scavi 2003-2009. Felici Editore, Ghezzano, pp. 648.

Antonelli F., Lazzarini L., Cancelliere S., Dessandier D., 2009. Volubilis (Meknes, Morocco): Archaeometric study of the white and coloured marbles imported in the Roman age. *Journal of Cultural Heritage*, 10: 116-123.

Antonelli F., Lazzarini L., Cancelliere S., Dessandier D., 2010. On the white and coloured marbles of the Roman town of Cuicul (Djemila, Algeria). *Archaeometry*, 52: 575-596.

Antonelli F., Columbu S., Lezzerini M., Miriello D., 2014. Petrographic characterization and provenance determination of the white marbles used in the Roman sculptures of *Forum Sempronii* (Fossombrone, Marche, Italy). *Applied Physics A.*, 115: 1033-1040.

Attanasio D., Armiento G., Brilli M., Emanuele M.C., Platania R., Turi B., 2000. Multi-method marble provenance determinations: the Carrara marbles as a case study for the combined use of isotopic, electron spin resonance and petrographic data. *Archaeometry*, 42: 257-272.

Attanasio D., Brilli M., Bruno M., 2008. The properties and identification of marble from Proconnesos (Marmara Island, Turkey): a new database including isotopic, EPR and petrographic data. *Archaeometry*, 50: 747-774.

Attanasio D., Brilli M., Ogle N., 2006. The isotopic signature of classical marbles. L'Erma di Bretschneider, Roma, pp. 336.

Attanasio D., Bruno M., Prochaska W., Yavuz A.B., 2013. The Asiatic marbles of the Hadrian's Villa at Tivoli. *Journal of Archaeological Science*, 40: 4358-4368.

Baldanza A., Gioncada A., Lezzerini M., 2012. Historical building stones of the western Tuscany (Italy): the Acquabona Limestones from Mts. Livornesi. *Periodico di Mineralogia*, 81: 1-17.

Bastogi M., Fratini F., 2004. Geologia, litologia, cave e deterioramento delle pietre fiorentine. *Memorie Descrittive della Carta Geolologica d'Italia*, 66: 27-42.

Capedri S., Venturelli G., 2004. Accessory minerals as tracers in the provenancing of archaeological marbles, used in combination with isotopic and petrographic data. *Archaeometry*, 46: 517-536.

Capedri S., Venturelli G., Photiades A., 2004. Accessory minerals and $\delta^{18}O$ and $\delta^{13}C$ of marbles from the Mediterranean area. *Journal of Cultural Heritage*, 5: 27-47.

Columbu S., Antonelli F., Lezzerini M., Miriello D., Adembri B., Blanco A. (2014): Provenance of marbles used in the *Heliocaminus* Baths of Hadrian's Villa (Tivoli, Italy). *Journal of Archaeological Science*, 49: 332-342.

Craig H., 1957. Isotopic standards for carbon and oxygen and correlation factors for mass-spectrometric analysis of carbon dioxide. *Geochimica et Cosmochimica Acta*, 12: 133-149.

Craig H., Craig V., 1972. Greek marbles: determination of provenance by isotopic analysis. *Science*, 176: 401-403.

Ebert A., Gnos E., Ramseyer K., Spandler C., Fleitmann D., Bitzios D., Decrouez D., 2010. Provenance of marbles from Naxos based on microstructural and geochemical characterization. *Archaeometry*, 52: 209-228.

Franzini M., 2003. Le pietre toscane nell'edilizia medievale della città di Pisa. *Memorie della Società Geologica Italiana*, 49: 233-244.

Franzini M., Gioncada A., Lezzerini M., 2007. Le pietre dell'edilizia medievale pisana e lucchese (Toscana occidentale). 5 - La Maiolica ed il Nummulitico della bassa valle del fiume Serchio. *Atti della Società Toscana di Scienze Naturali Memorie,* Serie A 112: 9-19.

Franzini M., Lezzerini M., 1998. Le pietre dell'edilizia medievale pisana e lucchese (Toscana occidentale). 2. I calcari selciferi del Monte Pisano. *Atti della Società Toscana di Scienze Naturali Memorie,* Serie A 105: 1-8.

Franzini M., Lezzerini M., 2002. The Triassic marble from the Punta Bianca promontory (La Spezia, Italy). Did Roman quarrying of "Lunensis marble" begin here?. *Periodico di Mineralogia*, Special Issue: Archaeometry and Cultural Heritage, 71: 137-144.

Franzini M., Lezzerini M., 2003. The stones of medieval buildings in Pisa and Lucca provinces (western Tuscany, Italy). 1 – The Monte Pisano marble. *European Journal of Mineralogy*, 15: 217-224.

Franzini M., Lezzerini M., Mannella L., 2001. The stones of medieval buildings in Pisa and Lucca (western Tuscany, Italy). 3 – Green and white-pink quartzites from Mt. Pisano. *European Journal of Mineralogy*, 13: 187-195.

Franzini M., Lezzerini M., Marandola F., 2002. The stones of medieval buildings in Pisa and Lucca (western Tuscany). 4 – Agnano breccias from Mt. Pisano. *European Journal of Mineralogy*, 14: 447-451.

Franzini M., Lezzerini M., Origlia F., 2010. Marbles from the Campiglia Marittima area (Tuscany, Italy), *European Journal of Mineralogy*, 22: 881-893.

Fratini F., Giovannini P., Manganelli Del Fa', 1994. La pietra da calce a Firenze: ricerca e caratterizzazione dei materiali per la produzione di "calcina forte" e "calcina dolce". Scienze e Beni Culturali, X. Bilancio e Prospettive, Atti del Convegno di Studi, Bressanone, 5-8 luglio 1994. Padova, 189-199.

Garzella G., Caleca A., Collareta M., 2014. La Cattedrale di Pisa. Pacini, Ospedaletto, pp. 287.

Giammartini B., 2010. Mapping of the stones in the main façade of St. Giuliana castle (Umbertide, Italy). *Periodico di Mineralogia*, Special Issue: 11-20.

Gorgoni C., Lazzarini L., Pallante P., Turi B., 2002. An updated and detailed mineropetrographic and C-O stable isotopic reference database for the main Mediterranean marbles used in antiquity. In Herrmann Jr. J.J., Herz N., Newman R. (eds.), ASMOSIA 5. Interdisciplinary Studies on Ancient Stone. Archetype Publications, London, 115-131

Herz N., 1987. Carbon and oxygen isotopic ratios: a data base for Classical Greek and Roman marble. *Archaeometry*, 29: 35-43.

Katsianis M., Tsipidis S., Kotsakis K., Kousoulakou A., 2008. A 3D digital workflow for archaeological intra-site research using GIS. *Journal of Archaeological Science*, 35: 655-667.

LAZZARINI L., 2004. Archaeometric aspects of white and coloured marbles used in antiquity: the state of the art. *Periodico di Mineralogia*, 73: 113-125.

LAZZARINI L., MOSCHINI G., STIEVANO B.M., 1980. A contribution to the identification of Italian, Greek and Anatolian marbles though a petrological study and the evaluation of Ca/Sr ratio. *Archaeometry*, 22: 173-183.

LEONI L., LEZZERINI M., BATTAGLIA S., CAVALCANTE F., 2010. Corrensite and chlorite-rich Chl-S mixed layers in sandstones from the 'Macigno' Formation (northwestern Tuscany, Italy). *Clay minerals*, 45, 87-106.

LEZZERINI M., 2005. Mappatura delle pietre presenti nella facciata della chiesa di San Frediano (Pisa, Italia). *Atti della Società Toscana di Scienze Naturali. Memorie,* Serie A 110: 43-50.

LEZZERINI M., ANTONELLI F., COLUMBU S., GADDUCCI R., MARRADI A., MIRIELLO D., PARODI L., SECCHIARI L., LAZZERI A., 2016. Cultural Heritage Documentation and Conservation: Three-Dimensional (3D) Laser Scanning and Geographical Information System (GIS) Techniques for Thematic Mapping of Façade Stonework of St. Nicholas Church (Pisa, Italy). *International Journal of Architectural Heritage*, 10:1: 9-19 (DOI: 10.1080/15583058.2014.924605).

LEZZERINI M., DI BATTISTINI G., ZUCCHI D., MIRIELLO D., 2012. Provenance and compositional analysis of marbles from the medieval Abbey of San Caprasio, Aulla (Tuscany, Italy). *Applied Physics A*, 108: 475-485.

LEZZERINI M., FRANZINI M., DI BATTISTINI G., ZUCCHI D., 2008. The "Macigno" sandstone from Matraia and Pian di Lanzola quarries (north-western Tuscany, Italy). A comparison of physical and mechanical properties. *Atti della Società Toscana di Scienze Naturali. Memorie,* Serie A 113: 71-79.

MANIATIS Y., TAMBAKOPOULOS D., DOTSIKA E., STEFANIDOU-TIVERIOU TH. 2010. Marble provenance investigation of Roman Sarcophagi from Thessaloniki. *Archaeometry*, 52: 45-58.

MATTHEWS K.J., MOENS L., WALKER S., WAELKENS M., DE PAEPE P., 1992. The re-evaluation of stable isotope data for Pentelic marble. In Waelkens M., Herz, N., Moens, L. (eds.), Ancient Stones: Quarrying, Trade and Provenance (No. 4). Leuven, Leuven University Press, 203-212.

MCCREA J.M., 1950. On the isotopic chemistry of carbonates and a paleotemperature scale. *Journal of Chemical Physics*, 18: 849-865.

MIRIELLO D., ALFANO I., MICELI C., RUFFOLO S.A., PINGITORE V., BLOISE A., BARCA D., APOLLARO C., CRISCI G.M., OLIVA A., LEZZERINI M., DE CHIRICO F., MARI N., MURAT C., 2012. Analysis of marble statues from the San Bruno Church (Serra San Bruno, Southern Italy): provenance and degradation. *Applied Physics A*, 106: 171-179

MOENS L., DE PAEPE P., WAELKENS M., 1995. A multi-disciplinary contribution to the provenance determination of ancient Greek and Roman marble artifacts. *Israel Journal of Chemistry*, 35: 167-174.

PENSABENE P., ANTONELLI F., LAZZARINI L., CANCELLIERE S., 2012. Provenance of marble sculptures and artifacts from the so-called Canopus and other buildings of "Villa Adriana" (Hadrian's Villa, Tivoli, Italy). *Journal of Archaeological Science*, 39: 1331-1337.

SIAT C., EITEL B., PANAGIOTOPOULOS D., 2008. Investigation of past archaeological landscapes using remote sensing and GIS: A multi-method case study from Mount Ida, Crete. *Journal of Archaeological Science*, 35: 2918-2926.

TIAN Y., WEN C., HONG S., 2008. Global scientific production on GIS research by bibliometric analysis from 1997 to 2006. *Journal of Informetrics*, 2: 65-74.

YAVUZ A.B., BRUNO M., ATTANASIO D., 2011. An updated multi-method database of Ephesos marbles, including white, greco scritto and bigio varieties. *Archaeometry*, 53: 215-439.

WENTWORTH C.K., 1922. A scale of grade and class terms for clastic sediments. *The Journal of Geology*, 30: 377-392.

(*ms. pres. 10 giugno 2015; ult. bozze 18 settembre 2015*)

Edizioni ETS
Piazza Carrara, 16-19, I-56126 Pisa
info@edizioniets.com - www.edizioniets.com
Finito di stampare nel mese di giugno 2016