**Provenance of marbles used for building the internal spiral staircase of the bell tower of St. Nicholas Church (Pisa, Italy)**

Marco Lezzerini1,4\* • Fabrizio Antonelli2 • Gianni Gallello3 • Mirco Ramacciotti3 •Luca Parodi3 • Antonio Alberti3 • Stefano Pagnotta1 • Stefano Legnaioli4 •Vincenzo Palleschi4

1 Department of Earth Sciences, University of Pisa, Via S. Maria 53, 56126 Pisa, Italy

2 LAMA – Laboratory for Analysis of the Ancient Materials, DACC, University Iuav of Venice, San Polo, 2468, 30125 Venice, Italy

3 Department of Analytical Chemistry, University of Valencia, 50 Dr. Moliner Street, 46100 Burjassot, Valencia, Spain

4 Applied and Laser Spectroscopy Lab., ICCOM-CNR, Via G. Moruzzi 1, 56124 Pisa, Italy

Corresponding Author: Marco Lezzerini\*

Email: marco.lezzerini@unipi.it

**Abstract**

The aim of this study is to investigate the provenance of marbles used as architectural elements (bases, shafts and capitals of columns) for building the internal spiral staircase of the medieval bell tower of St. Nicholas Church at Pisa, Italy. Accordingly, the 45 collected marble samples have been analysed by optical microscopy, X-ray powder diffraction and mass spectroscopy for carbon and oxygen stable isotope ratio analysis; additionally, SEM–EDS analysis have been performed to complement data about accessory minerals. By comparison with literature data on the main sources of the white Mediterranean marbles used in ancient times, the results show that the analysed samples are mainly white crystalline marbles from Carrara (Italy) and, subordinately, from other Tuscan and Eastern Mediterranean quarrying areas. In fact, Mt. Pisano and Campiglia M.ma (Tuscany, Italy) and Marmara (Turkey), Paros, Mt. Penteli, Thasos (Greece) are minor sources. The other coloured stones identified on the strength of their macroscopic features are quartzites from Mt. Pisano area and granitoids from Sardinia and Island of Elba (Italy). Occasionally, a very limited number of architectonical elements made up of Acquabona limestone from Rosignano Marittimo (Livorno,Italy), red limestone with ammonites (the so-called ‘‘Rosso Ammonitico’’) and black limestone belonging to the Tuscan Nappe sequence, outcropping at northwest of Pisa in the nearby Monti d’Oltre Serchio area, are present.

**1 Introduction**

Since ancient times, marble was used for its beauty in architecture and sculpture, extracting it from historical quarries opened in the Mediterranean area [1–3]. With the aim of collecting and providing useful discriminative criteria for the most relevant marbles used in antiquity, several authors have proposed multiple analytical approaches, including the critical comparison among different diagnostic features, such as petrographic fabric [4–6], geochemical data [7], accessory minerals [8], isotopic data [4, 9–12]. Within the framework of a multidisciplinary study in the field of art history and restoration of the St. Nicholas church—promoted by the Soprintendenza Archeologia, Belle Arti e Paesaggio per le province di Pisa e Livorno, the Department of Earth Sciences at the University of Pisa was entrusted with a comprehensive characterization of the building materials, including stones, marbles and mortars used for building the church and its bell tower [13, 14]. The first documentary attestation of the St. Nicholas church as a dependence in Pisa of the Benedictine monastery of San Michele alla Verruca dates from June 17th, 1097 [15]. Likewise, the first evidence of the monastery adjacent to the St. Nicholas church is contained in a cartula venditionis drawn up in 1130 and prepared in Pisa ‘‘infra claustra Sancti Nicolai’’. In 1295, the church and the monastery of St. Nicholas passed by the Cistercian monks of the Verruca to the Augustinian friars, although the transaction was finally approved by Pope Boniface VIII 2 years later. In the first decades of the fourteenth century [16–20], the Hermits of St. Augustine started work on the extension and reorganization of the monastic complex. The bell tower (Fig. 1a), slightly tilting with its base under the current street level such as the most famous Leaning Tower, is a medieval four-storey structure (total height: 34 m; external diameter: 5 m; internal diameter: 3 m), which most likely dates back to 1170 [17]. Inside, a beautiful spiral staircase with small arches supported by columns (Fig. 1b) was built with about one hundred architectonical elements made up mainly of marble, but also of granite, quartzite and limestone (Fig. 1c–f). The archaeometric analyses were accompanied by archaeological and stratigraphic investigations of the internal masonry structures, aimed at the reconstruction of the main building phases that have affected the bell tower and the identification of the construction techniques adopted at the time of its construction, and during the subsequent reorganization and restoration works. The study of the architectural elements used in the spiral staircase— compared with archaeometric analyses on the main rocks—also allowed us to recognize the frequent use of recycled materials for the construction of the bell tower. The present article refers to the obtained results, focused on assessing the stone materials used for building the internal spiral staircase, i.e. identifying the nature and provenance of bases, shafts and capitals employed in the assemblage of the columns. For carrying out the study, the identification of the coloured lithotypes was done by naked-eye examination of the macroscopic features, comparing them with those shown by the stones used in the medieval buildings at Pisa [21–24]. On the contrary, provenance of white marbles was assessed on the basis of usual and topical provenance methods, as diagnostic fabric parameters (i.e.: microstructure, boundary types and maximum grain size of the carbonate crystals), calcite and dolomite presence/absence, detection of peculiar accessory minerals, and variation in abundances of carbon and oxygen isotopes; C–O isotopes are in fact considered asignature derived from geological history and thus able to cluster marbles with common geographical provenance [25–27]. Archaeological data shows that the structure of the bell tower of the St. Nicholas Church at Pisa, with the exception of the cusp, is essentially related to the first constructive stage of foundation. In fact, the well preserved masonry is homogeneous and continuous, without noticeable replacements with new stone materials. The bell tower was built combining the use of Mt. Pisano quartzite and calcarenite Panchina, according to the specific physical and mechanical properties of these two lithotypes [23, 24]. The exclusive use of quartzite for building the main structure, up to the belfry, including all the steps of the spiral staircase, is matched by the almost total use of calcarenite Panchina in the system of the rampant arches and in the masonry at the top of the bell tower. The deliberate choice of using these two lithotypes for building the structure of the bell tower is accompanied by the use of materials and architectural elements of spolia for the assemblage of the columns of the spiral staircase.

**2 Materials and methods**

One hundred and four architectural elements were examined observing their main macroscopic features and 45 marble samples were collected for a detailed study by optical microscopy (OM), X-ray powder diffraction (XRPD), scanning electron microscopy equipped with a dispersive microanalytical system (SEM/EDS), and mass spectroscopy for carbon and oxygen stable isotope ratio analysis (SIRA). Thin section study using a Zeiss-Axioplan polarizing microscope was performed to measure the maximum grain size (MGS) of the calcite/dolomite crystals and to observe the petrographic features of the rocks, i.e. grain-size uniformity, type of texture, grain-boundary shape, and accessory minerals. The terminology used to describe the marble texture is that adopted by Antonelli and Lazzarini [4]. The grain sizes of the studied rocks are reported according to the scheme proposed by the British Geological Survey based on the Wentworth scale [28]. XRPD, using a Bragg–Brentano geometry and Ni-filtered Cu Ka radiation at 40 kV and 20 mA, was used to identify the main mineralogical phases (i.e. calcite and dolomite) in the marble samples. Qualitative data about the possible accessory minerals in white marbles were acquired by SEM observations and microanalysis using a Philips XL30 instrument equipped with an energy dispersive spectrometry EDAX (standardless software DXi4) with 20 kV acceleration voltage, 0.1 nA beam current, and 100 s live time. Carbon and oxygen stable isotopes were measured by mass spectrometry [29]. Carbonate powders were reacted with 100% phosphoric acid at 70 C using a GasbenchII connected to a ThermoFinnigan Five-Plus mass spectrometer. The isotopic ratios of carbon and oxygen were measured in accordance with the international standard Pee Dee Belemnite (PDB) and expressed in delta values d13C% and d18O% [30]. The standard error for the delta values is ±0.1% for both carbon and oxygen. The results of mineralogical, petrographic and isotopic analyses were carefully compared with data reported in the literature, collecting data about Mediterranean marbles used in antiquity [4, 25–27, 31–33].

**3 Results and discussion**

The main geometric features of the columns, including data on bases, shafts and capitals, are reported in Table 1, together with a preliminary classification of the building stones as identified by naked-eye examination and under a field microscope. The 28 columns of the internal staircase are composed of 104 elements, including bases (labelled as a), shafts (labelled as b), and capitals (labelled as c). It has to be highlighted that possibly due to reuse routines, some of the aforementioned elements are due to more than one unit. In addition to 28 bases, 28 shafts and 28 capitals there are: (a) one base and one capital of the ground floor; (b) five bases and one shaft of the first floor; (c) two bases, two shafts and two capitals of the second floor; (d) one base of the third floor; (e) two bases and three shafts of the belfry. Overall, the height of the analysed columns ranges from 169 cm (column 25) to 340 cm (column 1) with 275 cm as average value. Excluding the columns 1 and 23–28, the height of the vertical support ranges from 264 cm (column 21) to 310 cm (column 12) with an average value of 290 cm. As regards the shaft, the circumference measured at medium height range from 51 to 108 cm and from 71 to 107 cm for all the columns, except columns 1 and 23–28.The presence of vertical architectonical elements of different height, size and lithology (marble, granite, quartzite and limestone) highlights that the planner and the builders settled on the reuse of ancient stones rather than on the use of new quarrying materials for building the internal staircase. The study of identification and provenance of the stones provided the results as follows (Fig. 2).

**3.1 White crystalline marbles**

Based on macroscopic features, we have identified 64 architectural elements (16 bases, 24 shafts, 24 capitals) made of crystalline marbles. Overall, 45 items were sampled: 10 bases (62.5% of the total number of bases), 15 shafts (62.5% of the total) and 20 capitals (83.3% of the total). All the items resulted made of pure white marble except the samples 8b1, 15b1, 17b1, 19b1, 21b1, 24b1, 24c1, which were characterized by the presence of parallel grey stripes (foliation). The main mineralogical and petrographic features obtained by XRPD, optical microscopy and SEM analysis, along with the C–O isotopic ratios of all analysed marble samples are reported in Table 2, while in Fig. 3 microphotographs of representative thin sections are shown. According to reference data reported in the literature for white marbles used in antiquity [4, 25–27], the measured maximum grain size (MGS) values ranging from 0.10 (samples 22a1, 27a2, 26c1 and 28c1) to 3.40 mm (sample 14c1), combined with other petrographic features (such as texture, grain boundary shapes, triple points, twins) strongly suggest that the analysed marbles come from several Mediterranean sources (where P–T metamorphic conditions induced a more or less recrystallization of the calcite/dolomite crystals). The analysed marbles show a large variability of textures, which are prevalently heteroblastic, only subordinately homeoblastic, granoblastic microstructures with boundary shapes ranging from right to embayed (lobate) and, subordinately, mortar (samples 8b1, 15b1, 17b1, 19b1, 21b1, 24b1, 24c1) and mosaic (samples 11c1, 14c1) fabrics. Some marble samples show a microgranular texture (samples 22a1, 27a2, 26c1 and 28c1).From mineralogical point of view, the studied marbles exhibits calcite as main component, even in some samples also dolomite has been detected as subordinate phase (Fig. 4). In some cases, SEM observations and qualitative EDS analysis have allowed us to confirm or reveal the nature of the few accessory minerals (often already detected by optical microscopy), mainly represented by quartz, plagioclase, graphite, and pyrite (see Table 2). The delta values of carbon and oxygen isotopes range from 1.61 (sample 27b1) to 3.56% (sample 3c1) and from -9.66% (sample 3c1) to -0.99% (sample 21c1), respectively. By plotting the isotopic data into reference isotopic fields [4, 26, 31, 32], a match with Carrara and Marmara marbles, partially overlapping the fields corresponding to other ancient quarrying areas such as those of Paros and Thasos, can be observed (Fig. 5). Table 3 reports the most probable provenance of marbles used for architectonic elements of the columns as obtained combining mineralogical and petrographic features and C–O isotopic data. The collected data point out that most of the bases are made up of Apuan marble (Carrara, Italy; 80% of the total) and subordinately of Mt. Pisano marble (Pisa, Italy; 20% of the total). Greek marbles from Mt. Penteli (7% of the total), Turkish Proconnesian marble from Marmara (40% of the total) and Lunense marble from Carrara (53% of the total) were used for carving the column shafts, while Carrara (70% of the total), Mt. Pisano (10% of the total), Marmara (10% of the total), Paros (5% of the total) and Campiglia M.ma (5% of the total) are the most likely sources of the marbles used for capitals.

**3.2 Other building and decorative stones**

Based on the observations of the macroscopic features, forty column elements made up of granite, quartzite and limestone were identified: 22 bases, 10 shafts and 8 capitals. The provenance of these stones was assumed as follows:

– Granites (six column shafts): three samples (1b1, 9b1, 11b1) are from Island of Elba (Tuscany, Italy), probably from the Mt. Capanne area, where the socalled granitello antico was quarried [34]; three samples (7b1, 12b1, 13b1) are from Sardinia (Italy), probably from the Capo Testa district, where the pink variety of the local granite was abundantly exploited since Roman times [35].

– Quartzites (20 bases, 3 shafts and 7 capitals): all the observed samples show macroscopic features corresponding to those described by Franzini et al. [23] for the rocks belonging to the ‘‘Quarziti bianco-rosa’’ Formation cropping out in the nearby Mt. Pisano area; consequently, we can assume this area as provenance locality. Effectively, the historical sources correlate the quartzite quarrying on the hill just north of the town ofCrespignano (S of Calci) with the proprieties of San Michele alla Verruca monks. In a document dated August 11, 1147, the property of the abbots of the Verruca of land in the locality Crespignano, in a place called Pinetulo, is attested. The papal bull of Innocent III in 1209, among others, remembers the rights of the monastery on St. Martin Church of Crespignano. This bull refers to previous papal bulls, in which the quartzite quarrying area is probably of property of the monks of San Michele alla Verruca for over a century [15]. The monks could therefore take advantage of the quartzite quarry in the period that we have indicated as possible time of construction of the bell tower.

– Limestones (2 bases, 1 shaft and 1 capital): these are: (a) snow-white limestone (sample 23c1) probably coming from Acquabona quarrying area [21] near Rosignano Marittimo (Livorno, Italy); (b) black chert limestone (sample 27a1) similar to that from Monti d’Oltre Serchio (Pisa, Italy) [24]; (c) red limestones with ammonites (samples 6b1, 12a2) belonging to the Rosso Ammonitico Formation of the Tuscan Nappe sequence; the quarrying area of this latter is still of unknown origin, even if it extensively outcrops northwest of Pisa in the nearby Monti d’Oltre Serchio area [24].

**4 Conclusions**

This work highlights that macroscopic features, petrographic thin section analyses and isotopic data of carbonand oxygen stable isotopes, complemented also by mineralogical data, are useful for determining the provenance of the lithotypes used as vertical architectural elements of the spiral staircase of the St. Nicholas church at Pisa. The collected data indicate that 64 stone elements on a total of one hundred and four employed for the assemblage of the columns are made up of calcite/dolomite-rich marbles, many of them already used by the Romans, while for the remaining forty elements granites, quartzites and limestones locally quarried were used. The presence of Mediterranean marbles used in antiquity suggests a precise choice of materials more than an occasional use of marble spolia for realizing the spiral staircase. The identified stone materials suggest some hypotheses about the period of construction of the bell tower. The absence of Mt. Pisano marble as a building material for columns, except for three bases and two capitals of the belfry, makes it possible to hypothesize the foundation date of the bell tower. It could be attested in the early thirteenth century, a period in which Mt. Pisano marble from local quarries was widely used in Pisa for columns and other architectural elements [22], as also testified by the initial constructive phase of the famous Leaning Tower (1173). Likewise, the occasional use of Roman brick reused in the main fac¸ade made up of quartzite suggests a time before the start of serial production of Pisan medieval bricks, attributable at the late XII century–early XIII century [19]. Thus, taking into account the even more sporadic use of calcarenite Panchina in Pisa’s building since the second half of the XII century [24] and the right of quarrying quartzite by San Michele alla Verruca monks, this data seems to place the foundation of the bell tower between the second half and the end of the XII century, rather than in early XIII century.

**Acknowledgements**

The sampling was carried out under permit from the Soprintendenza Archeologia, Belle Arti e Paesaggio per le province di Pisa e Livorno. This work was partially funded by University of Pisa through project PRA 2016 (Chief: C. Montomoli).

**References**

1. K.J. Matthews, L. Moens, S. Walker, M. Waelkens, P. De Paepe, in Ancient Stones: Quarrying, Trade and Provenance, vol. 4, ed. by N. Herz, M. Waelkens, L. Moens (Acta Archaeologica Lovaniensia Monographiae, Leuven, 1992), pp. 203–212

2. L. Moens, P. Roos, J. De Rudder, P. De Paepe, J. Van Hende, M. Waelkens, in Classical Marble: Geochemistry, Technology, Trade. NATO ASI Series, ed. by H. Hertz, M. Waelkens (Kluwer, Dordrecht, 1988), pp. 243–250

3. K. Germann, G. Gruben, H. Knoll, V. Valis, F.J. Winkler, in Classical Marble: Geochemistry, Technology, Trade. NATO ASI Series, ed. by H. Hertz, M. Waelkens (Kluwer, Dordrecht, 1988), pp. 252–262

4. F. Antonelli, L. Lazzarini, Rend Lincei 26, 399–413 (2015)

5. T. Koralaya, S. Kılınc¸arslan, J. Cult. Herit. 17, 42–52 (2016)

6. D. Attanasio, M. Bruno, W. Prochaska, A.B. Yavuz, Archaeometry 57, 217–245 (2015)

7. A. Ebert, E. Gnos, K. Ramseyer, C. Spandler, D. Fleitmann, D. Bitzios, D. Decrouez, Archaeometry 52, 59 (2010)

8. S. Capedri, G. Venturelli, Archaeometry 46, 517–536 (2004)

9. D. Attanasio, M. Brilli, N. Ogle, The Isotopic Signature of Classical Marbles (L’Erma di Bretschneider, Rome, 2006)

10. H. Craig, V. Craig, Science 176, 401–403 (1972)

11. N. Herz, Archaeometry 29, 35–43 (1987)

12. K. Al-Bashaireh, A.Q. Al-Housanb, J. Cult. Herit. 16, 591–596 (2015)

13. M. Lezzerini, S. Legnaioli, G. Lorenzetti, V. Palleschi, M. Tamponi, Constr. Build. Mater. 69, 203–212 (2014)

14. M. Lezzerini, F. Antonelli, S. Columbu, R. Gadducci, A. Marradi, D. Miriello, L. Parodi, L. Secchiari, A. Lazzeri, Int. J. Arch. Herit. 10, 9–19 (2016)

15. G. Giuliani, in L’Aratro e il Calamo. Benedettini e Cistercensi sul Monte Pisano ed. by S. Gelichi, A. Alberti (Felici, Pisa, 2005), pp. 11–33

16. G. Garzella, Pisa com’era: topografia e insediamento (Liguori, Napoli, 1990)

17. P. Pierotti, L. Benassi, Deotisalvi. L’architetto pisano del secolo d’oro (Pisa, Pacini, 2001), p. 240

18. G. Rohault de Fleury, Les monuments Pisans au Moyen Age (Paris, 1866)

19. J.A. Quiro´s-Castillo, in IV Congresso Nazionale di Archeologia Medievale, ed. by R. Francovich, M. Valenti (All’Insegna del Giglio, Firenze, 2006), pp. 563–569

20. M.L. Testi Cristiani, Nicola Pisano, architetto scultore. Dalle origini al pulpito del battistero di Pisa (Pacini, Pisa, 1987)

21. A. Baldanza, A. Gioncada, M. Lezzerini, Period. Miner. 81, 1–17 (2012)

22. M. Franzini, M. Lezzerini, Eur. J. Miner. 15, 217–224 (2003)

23. M. Franzini, M. Lezzerini, L. Mannella, Eur. J. Miner. 13, 187–195 (2001)

24. M. Lezzerini, Memorie Serie A 110, 43–50 (2005)

25. L. Moens, P. De Paepe, M. Waelkens, in Ancient Stones: Quarrying, Trade and Provenance, ed. by M. Waelkens, N. Herz, L. Moens (University Press, Leuven, 1992), pp. 247–255

26. C. Gorgoni, L. Lazzarini, P. Pallante, B. Turi, in Asmosia 5: Interdisciplinary Studies on Ancient Stone, ed. by J.J. Herrmann, N. Herz, R. Newman (Archetype, London, 2002), pp. 115–131

27. S. Capedri, G. Venturelli, A. Photiades, J. Cult. Herit. 5, 27–47 (2004)

28. C.K. Wentworth, J. Geol. 30, 377–392 (1922)

29. J.M. McCrea, J. Chem. Phys. 18, 849 (1950)

30. H. Craig, Geochem. Cosmochem. Acta 12, 133 (1957)

31. L. Lazzarini, F. Antonelli, Archaeometry 45, 541–552 (2003)

32. M. Franzini, M. Lezzerini, F. Origlia, Eur. J. Miner. 22, 881–893 (2010)

33. M. Lezzerini, G. Di Battistini, D. Zucchi, D. Miriello, Appl. Phys. A 108, 475–485 (2012)

34. G. Tedeschi-Grisanti, in Niveo de marmore: l’uso artistico del marmo di Carrara dall’XI al XV secolo, ed. E. Castelnovo (Carrocci, Genova, 1992), pp. 43–51

35. D. Poggi, L. Lazzarini, Marmora 1, 49–68 (2005)



















