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

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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.

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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 a signature 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

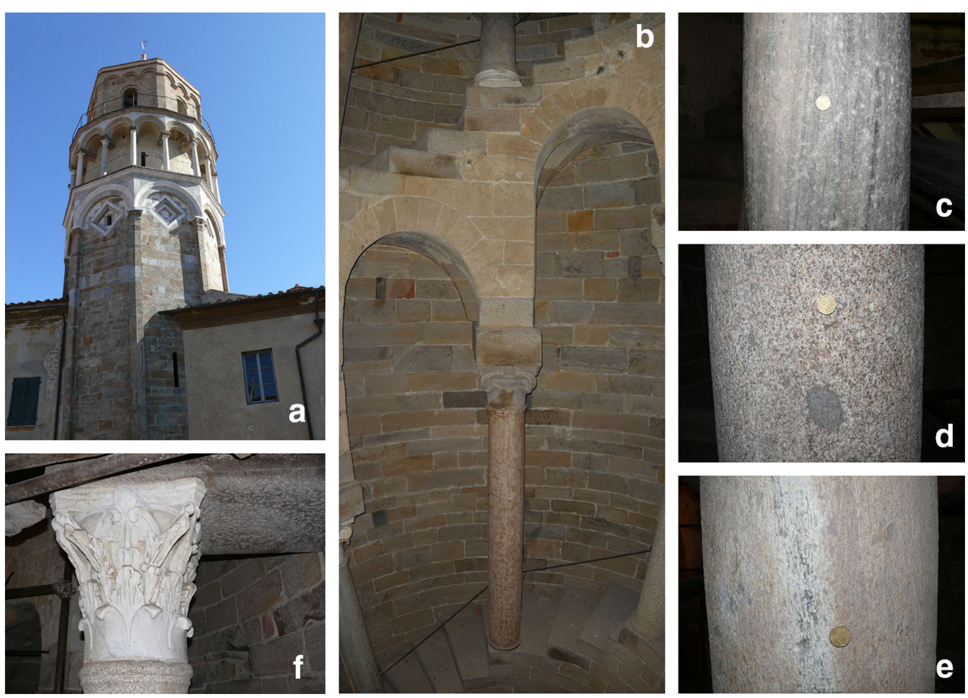

Fig. 1 **a** The bell tower of the St. Nicholas Church; **b** spiral staircase coming up to the belfry (the shaft of the column 6b1 in the centre of photograph is made up of red limestone with ammonites); **c–e** detail of columns 2, 9 and 10 showing the macroscopic features of the proconnesian marble, white granite and white–pink quartzite, respectively; **f** capital of column 11 made up of white fine-grained marble

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 polarising 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 Kα 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 Gasbench II 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 δ^{13}C‰ and δ^{18}O‰ [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

Table 1 Main geometric features of the architectonical elements of the internal spiral staircase of the bell tower of St. Nicholas Church and classification of the building materials (marble, granite, quartzite and limestone) as identified by visual examination and under a field microscope

	Element	Base (a)				Shaft (b)				Capital (c)				Lithotype
		C_1	L	W	H	C_1	C_2	C_3	H	C_1	L	W	H	
Ground floor	1a1		34.5	28	19									Mt. Pisano white–pink quartzite
	1b1					102	108	93	290					Elban white granite
	1c1									85	43	43	30.5	White marble
	2a1		33	28	18.5									Mt. Pisano white–pink quartzite
	2b1					98	98	87	239					Foliated white marble
	2c1									84.5	38	38	33.5	White marble
	3a1		33.5	29	19									Mt. Pisano white–pink quartzite
	3a2		32	32.5	6.5									White marble
	3b1					95	93	98	229					White marble
	3c1									86	41	41	32	White–pink marble
	4a1		34	30.2	18.5									Mt. Pisano white–pink quartzite
	4b1					92	91	82	237					Grey marble
	4c1									83	34	34	28	White marble
	4c2										35	34	6.5	White marble
	5a1		34	32	18									Mt. Pisano white–pink quartzite
	5b1					90	89	78	234					Foliated white–grey marble
	5c1									72	36	36	36	White marble
	6a1		33	35	18									Mt. Pisano white–pink quartzite
	6b1					99	96	89	239					Red limestone
	6c1									91	46	46	33	Mt. Pisano white–pink quartzite
	7a1		33.5	22	18									Mt. Pisano white–pink quartzite
	7b1					106	102	96	242					Sardinian pink granite
	7c1									95	48	48	33.5	Mt. Pisano white–pink quartzite
	8a1		33.5	34	16									Mt. Pisano white–pink quartzite
	8b1					92	91	79	234					Foliated white–grey marble
	8c1									82	44	44	30	Mt. Pisano white–pink quartzite
First floor	9a1		37.5	24.5	19									Mt. Pisano white–pink quartzite
	9b1					108	107	99	249					Elban white granite
	9c1									91	43	43	32	Mt. Pisano white–pink quartzite
	10a1		37	37	19									Mt. Pisano white–pink quartzite
	10b1					104	104	94.5	253					Mt. Pisano white–pink quartzite
	10c1									98	43	43	31	Mt. Pisano white–pink quartzite
	11a1		38	32.5	18									Mt. Pisano white–pink quartzite

Table 1 continued

	Element	Base (a)				Shaft (b)				Capital (c)				Lithotype
		C_1	L	W	H	C_1	C_2	C_3	H	C_1	L	W	H	
	11a2		39	40	11.5									White marble
	11a3	128			5.5									White marble
	11b1					105	105	98.5	217					Elban white granite
	11c1									103.5	49	49	52	White marble
	12a1		38	13	18.5									Mt. Pisano white–pink quartzite
	12a2		37	38	11									Red limestone
	12b1					103	105	100	200					Sardinian pink granite
	12b2					100	99	98	30					Mt. Pisano white–pink quartzite
	12c1									102.5	41	41	50	Mt. Pisano white–pink quartzite
	13a1		39.5	29.5	18.5									Mt. Pisano white–pink quartzite
	13a2		36.5	40	5.5									White marble
	13a3	119			12									White marble
	13b1					98	97	87	237					Sardinian pink granite
	13c1									82.5	33	33	29	White marble
	14a1		33	33.5	16.5									Mt. Pisano white–pink quartzite
	14b1					93	92	80	235					Mt. Pisano white–pink quartzite
	14c1									75.5	32	32	31	White marble
	15a1		28	28	8									White marble
	15b1					76	73.5	62	250					Foliated white–grey marble
	15c1									66.5	31	31	25	White marble
Second floor	16a1		29.5	28	4									White marble
	16b1					75	74	65	254					White marble
	16c1									67.5	33	33	27	White marble
	17a1		28	29.3	10.5									White marble
	17b1					69	71	60	248					Foliated white–grey marble
	17c1									60	32.5	31.5	22.5	White marble
	18a1		32	19	18									Mt. Pisano white–pink quartzite
	18b1					85	87	80	201					White marble
	18b2					80	78.5	73	58					White marble
	18c1									76	34	34	28	White marble
	19a1		32.5	31.5	18									Mt. Pisano white–pink quartzite
	19a2		33.5	39	24									White marble
	19b1					83	84	73	213					Foliated white–grey marble
	19c1									71	40	40	30	White marble
	19c2										43.5	42	8	White marble
	20a1		35	31	18									Mt. Pisano white–pink quartzite
	20a2		35	36.5	19.5									White marble
	20b1					83	79	73	215					White marble

Table 1 continued

	Element	Base (a)				Shaft (b)				Capital (c)				Lithotype
		C_1	L	W	H	C_1	C_2	C_3	H	C_1	L	W	H	
	20c1									72	37	37	27	White marble
	21a1		34	36	19									White marble
	21b1					78	80	72	207					Foliated white–grey marble
	21c1									65	34	34	31	White marble
	21c2										41.5	40.5	7	White marble
	22a1		31	31.5	12									White marble
	22b1					87	87.5	88	121					White marble
	22b2					88	84	78	118					White marble
	22c1									78	37	33	25.5	White marble
Third floor	23a1		35	25	17									White marble
	23b1					82	89	80.5	199					White marble
	23c1									73	32	32	21	Acquabona snow-white limestone
	24a1		29	19	18									Mt. Pisano white–pink quartzite
	24a2		25.5	22	13									Mt. Pisano white–pink quartzite
	24b1					66	66	60	125.5					Foliated white–grey marble
	24c1									64	28.5	26	23	Foliated white–grey marble
Belfry	25a1		25	25	8									White marble
	25b1					57	56	55	62.5					White marble
	25b2					55	51	46.5	81.5					White marble
	25c1									49	26	26	17	White marble
	26a1		34	32	8									Mt. Pisano white–pink quartzite
	26b1					70	70	69.5	71					White marble
	26b2					69.5	66.5	60	118					White marble
	26c1									60	32	30	24	White marble
	27a1		32	32	11									Black limestone
	27a2	95			11.5									White marble
	27a3	84			4									White marble
	27b1					72	72	60	178					White marble
	27c1									60	33	33	24.5	White marble
	28a1		31	31	11									Mt. Pisano white–pink quartzite
	28b1					71	70	69	104					White marble
	28b2					69	66	61	98					White marble
	28c1									62	33	33	24	White marble

The element name has been assigned following the architectural clustering: the first Arab number (1, 2, 3) recalls the number of the column; a, b, and c stands for base, shaft and capital, respectively; the latter Arab number (1, 2, 3) indicates the possible sub-units recognized (from bottom to up) in a same base, shaft or capital

C (cm), circumference (1 = bottom; 2 = medium; 3 = top); *L* (cm), length; *W* (cm), width; *H* (cm), height

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

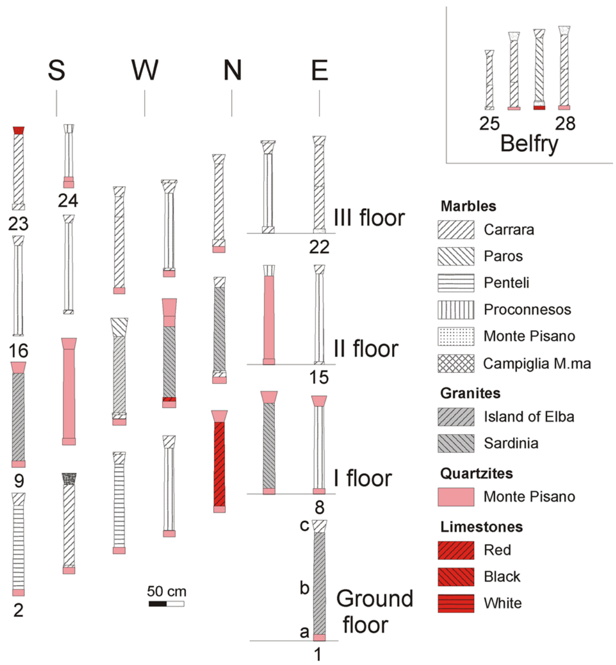

Fig. 2 Detailed mapping and distribution of marbles, granites and other stones used for the construction of the columns of the spiral staircase of the bell tower of the St. Nicholas Church at Pisa

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 so-called *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 of Crespignano (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

Table 2 Mineralogical and petrographic features identified by both petrographic observation, XRPD and SEM–EDS qualitative analysis, along with C–O isotopic ratios for studied marbles, grouped according the architectural elements of the columns (bases, shafts and capitals)

	Element	Cal	Dol	Qtz	Pl	Mu	Py	Gr	Ap	Texture	GBS	Triple points	Twinned crystals	MGS (mm)	$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)
Bases	11a2	xxx			tr					He, G, I	Cr	Rare	Rare	0.70	−1.37	1.78
	13a2	xxx								He, G, I	Cr		Present	0.70	−1.64	2.64
	15a1	xxx								He, G, I	St–Em	Rare	Present	0.55	−1.86	1.96
	16a1	xxx								He/He, G, I	St–Cr	Rare	Rare	0.90	−1.97	1.84
	19a2	xxx	x		tr	tr	tr			He, G, I	Cr–Em		Present	0.65	−1.15	2.28
	20a2	xxx								He, G, I	Cr/St		Rare	0.70	−1.72	1.99
	21a1	xxx		tr	tr		tr			He, G, I	St–Em		Present	0.70	−1.73	2.30
	22a1	xxx								M				0.10	−1.79	2.00
	23a1	xxx								He, G, I	Cr		Rare	0.70	−1.49	2.13
	27a2	xxx								M				0.10	−2.50	2.17
Shafts	2b1	xxx	tr	tr		tr				w-He, G, w-A	St–Cr	Rare	Present	0.60	−6.38	2.52
	3b1	xxx								Ho/He, G, w-A	Cr–St	Rare	Rare	0.60	−1.79	2.08
	8b1	xxx					tr	tr		He, G (Mortar), I	Cr–Em		Deformed	1.40	−1.64	2.59
	15b1	xxx						tr		w-He, G (Mortar), I	Cr–Em		Present	1.10	−1.55	3.31
	17b1	xxx				tr		tr	tr	He, G (Mortar), I	Cr–Em		Present	1.90	−1.38	3.50
	18b1	xxx			tr					Ho/He, G, I	St–Cr		Rare	0.75	−1.35	2.28
	19b1	xxx	tr					tr		He, G (Mortar), I	Cr–Em		Deformed	1.50	−3.69	2.80
	20b1	xxx	x				tr			He, G, I	St–Em		Rare	0.75	−2.05	2.50
	21b1	xxx						tr	tr	He/He, G (Mortar), I	Cr–Em		Present	1.90	−1.64	2.83
	22b1	xxx								He, G, I	Cr			0.40	−2.02	1.91
	22b2	xxx		tr	tr		tr			He, G, I	Cr–St			0.40	−1.68	2.15
	23b1	xxx					tr			He, G, I	Cr		Rare	0.70	−1.40	2.11
	24b1	xxx						tr		He, G (Mortar), I	St–Em		Present	1.90	−2.33	1.79
	26b2	xxx					tr			He/Ho, G, I	St–Cr		Rare	0.50	−1.85	2.13
	27b1	xxx								He, G, I	St–Cr		Rare	0.40	−1.69	1.61
Capitals	1c1	xxx					tr			Ho, G, I	St–Cr	Present	Present	0.45	−2.40	2.34
	2c1	xxx								Ho/He, G, I	St–Cr	Rare	Rare	0.40	−2.10	1.80
	3c1	xxx								Ho, G, I	St	Present	Present	0.50	−9.66	3.56
	4c2	xxx								He, G, I	Cr–Em	Present	Present	0.75	−2.00	2.01
	5c1	xxx			tr					He, G, I	Cr–St		Rare	0.70	−1.53	1.87
	11c1	xxx				tr			tr	He, G (Mosaic), I	Cr–Em		Present	2.50	−1.21	2.16
	13c1	xxx	tr							He, G, I	Cr–St	Rare	Rare	0.40	−2.35	1.90
	14c1	xxx								He, G (Mosaic), I	Cr–Em		Deformed	3.40	−2.20	2.28
	15c1	xxx	tr							Ho, G, I	St–Cr		Rare	0.30	−1.63	2.19
	16c1	xxx					tr			He, G, I	Cr		Present	1.00	−1.31	2.46
	19c1	xxx			tr					Ho/He, G, I	Cr–St		Rare	0.80	−1.63	2.21
	20c1	xxx								He, G, I	St–Em		Present	0.70	−1.68	2.28
	21c1	xxx								He/He, G, I	Cr		Present	0.80	−0.99	2.37
	21c2	xxx			tr		tr			He/He, G, I	Cr–St		Present	0.80	−1.54	2.26
	22c1	xxx								He, G, I	Cr		Rare	0.70	−1.60	2.17
	24c1	xxx				tr		tr	tr	He, G (Mortar), I	Cr–Em		Present	2.55	−1.21	2.63
	25c1	xxx	x		tr					He/Ho, G, I	Cr		Present	0.65	−2.05	2.12
	26c1	xxx	tr							M				0.10	−2.28	2.38
	27c1	xxx					tr			He, G, I	St–Cr		Rare	0.60	−1.18	1.98
	28c1	xxx	tr							M				0.10	−2.00	2.12

The number of (x) is related to the mineralogical phase abundance: xxx = main; x = scarce/rare; tr = trace

Ap apatite, *Cal* calcite, *Dol* dolomite, *Gr* graphite, *Mu* muscovite, *Pl* plagioclase, *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, *Em* embayed, *MGS Maximum Grain Size*

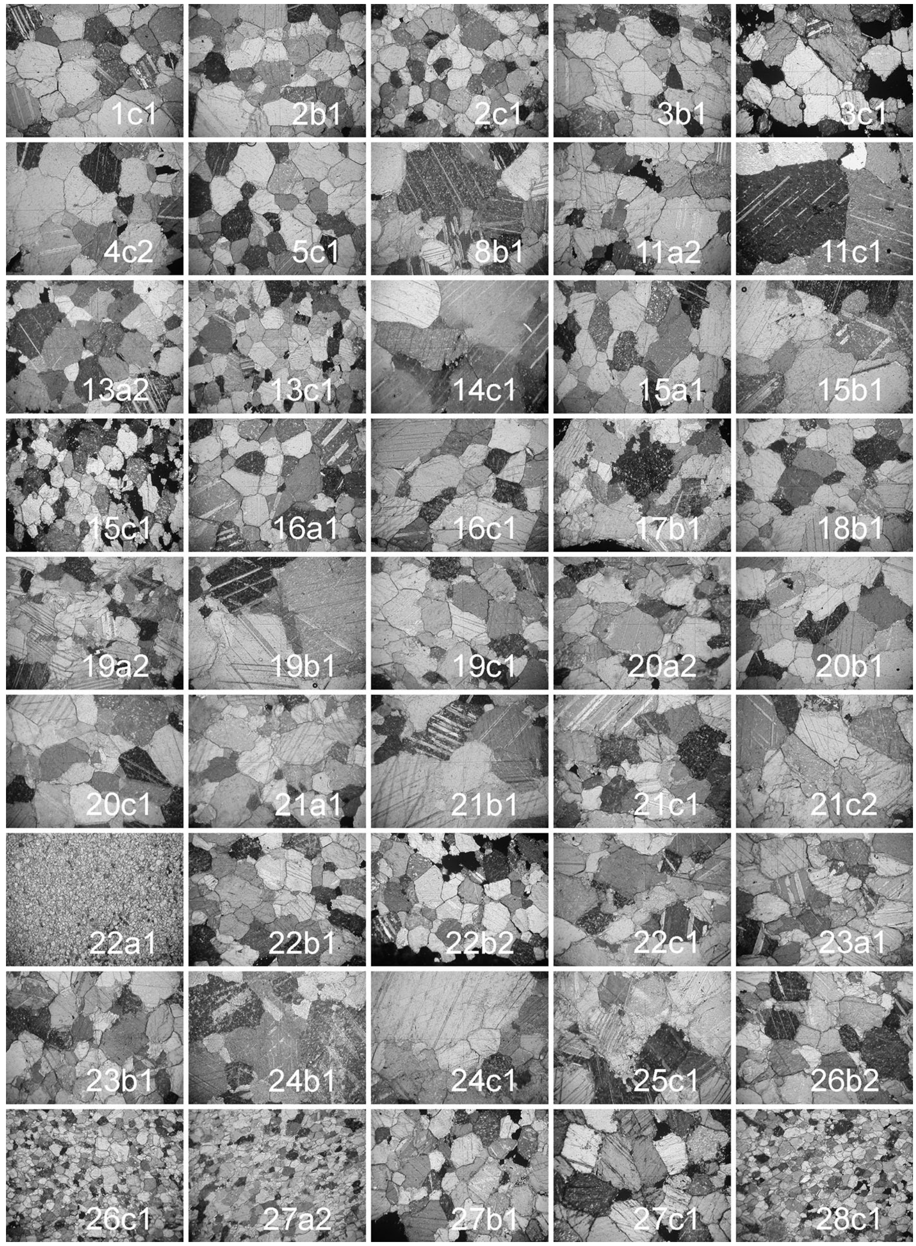

Fig. 3 Microphotographs of thin sections showing the main textural features of the investigated white marbles. Crossed polarised light, the long side of all images is 1.2 mm

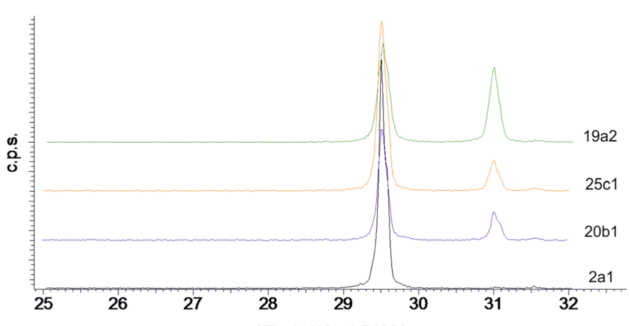

Fig. 4 XRPD patterns collected on some studied samples, representative of white marble with different calcite/dolomite abundances, as examples

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 carbon and oxygen stable isotopes, complemented also by

Table 3 Provenance of marbles from the column elements (bases, shafts and capitals) according to C–O isotopic composition, MGS and petrographic features

	Element	A: C–O isotopic composition	B: MGS combined with A	C: petrographic features combined with A and B
Bases	11a2	C, MP, Pa 2(3), Pr-1	C, Pa 2(3)	C
	13a2	C, MP, Pa 2(3), Pr-1, T-2	C, Pa 2(3)	C
	15a1	C, MP, Pa 2(3), Pr-1	C	C
	16a1	C, MP, Pa 2(3), Pr-1	C, Pa 2(3), Pr-1	C
	19a2	C, MP, Pa 2(3), Pr-1, T-1	C, Pa 2(3)	C
	20a2	C, MP, Pa 2(3), Pr-1	C, Pa 2(3)	C
	21a1	C, MP, Pa 2(3), Pr-1, T-1	C, Pa 2(3)	C
	22a1	C, MP, Pa 2(3), Pr-1	MP	MP
	23a1	C, MP, Pa 2(3), Pr-1, T-1	C, Pa 2(3)	C
	27a2	C, MP, N, Pa 2(3), Pr-1, T-1	MP	MP
Shafts	2b1	N, Pe, Pr-2	Pe	Pe
	3b1	C, MP, Pa 2(3), Pr-1	C, Pa 2(3)	C
	8b1	C, MP, Pa 2(3), Pr-1, T-2	C, Pa 2(3), Pr-1	Pr-1
	15b1	MP, Pr-1, T-2, T-3	Pr-1, T-3	Pr-1
	17b1	MP, Pr-1, T-2, T-3	Pr-1, T-3	Pr-1
	18b1	C, MP, Pa 2(3), Pr-1, T-1	C, Pa 2(3)	C
	19b1	N, Pa 2(3), Pe, Pr-1	Pa 2(3), Pe, Pr-1	Pr-1
	20b1	C, MP, Pa 2(3), Pr-1, T-1	C, Pa 2(3)	C
	21b1	C, MP, Pa 2(3), Pr-1, T-2	Pa 2(3), Pr-1, T-3	Pr-1
	22b1	C, MP, Pa 2(3), Pr-1	C	C
	22b2	C, MP, Pa 2(3), Pr-1, T-1	C	C
	23b1	C, MP, Pa 2(3), Pr-1, T-1	C, Pa 2(3)	C
	24b1	C, MP, N, Pa 2(3), Pr-1	Pa 2(3), Pr-1	Pr-1
	26b2	C, MP, Pa 2(3), Pr-1, T-1	C	C
	27b1	C, MP, Pa 2(3), Pr-1, T-1	C	C
Capitals	1c1	C, MP, Pa 2(3), Pr-1, T-1	C	C
	2c1	C, MP, Pa 2(3), Pr-1	C	C
	3c1	Ca-2, N	Ca-2	Ca-2
	4c2	C, MP, Pa 2(3), Pr-1	C, Pa 2(3)	C
	5c1	C, MP, Pa 2(3), Pr-1	C, Pa 2(3)	C
	11c1	C, MP, Pa 2(3), Pr-1, T-1	Pr-1, Pa 2(3), T-1	Pa 2(3)
	13c1	C, MP, N, Pa 2(3), Pr-1	C	C
	14c1	C, MP, Pa 2(3), Pr-1, T-1	Pa 2(3), Pr-1, T-1	Pa 2(3)
	15c1	C, MP, Pa 2(3), Pr-1, T-1	C	C
	16c1	C, MP, Pa 2(3), Pr-1, T-1	C, Pa 2(3), Pr-1	C
	19c1	C, MP, Pa 2(3), Pr-1, T-1	C, Pa 2(3)	C
	20c1	C, MP, Pa 2(3), Pr-1, T-1	C, Pa 2(3)	C
	21c1	C, MP, Pa 2(3), Pr-1, T-1	C, Pa 2(3)	C
	21c2	C, MP, Pa 2(3), Pr-1, T-1	C, Pa 2(3)	C
	22c1	C, MP, Pa 2(3), Pr-1, T-1	C, Pa 2(3)	C
	24c1	C, MP, Pa 2(3), Pr-1, T-2	Pa 2(3), Pr-1, T-2	Pr-1
	25c1	C, MP, Pa 2(3), Pr-1, T-1	C, Pa 2(3)	C
	26c1	C, MP, Pa 2(3), Pr-1, T-1	MP	MP
	27c1	C, MP, Pa 2(3), Pr-1	C, Pa 2(3)	C
	28c1	C, MP, Pa 2(3), Pr-1, T-1	MP	MP

C Carrara, *Ca-2* Campiglia M.ma, *MP* Monte Pisano, *N* Naxos, *Pe* Penteli, *Pr* Proconnesos, Marmara (*Pr-1* main marble, *Pr-2* marble from Camlik area); *Pa* Paros (*Pa-2* Chorodaki valley, *Pa-3* Aghias Minas valley), *T* Thasos (*T-1* Fanari district, *T-2* Aliki district, *T-3* Vathy-Saliara district)

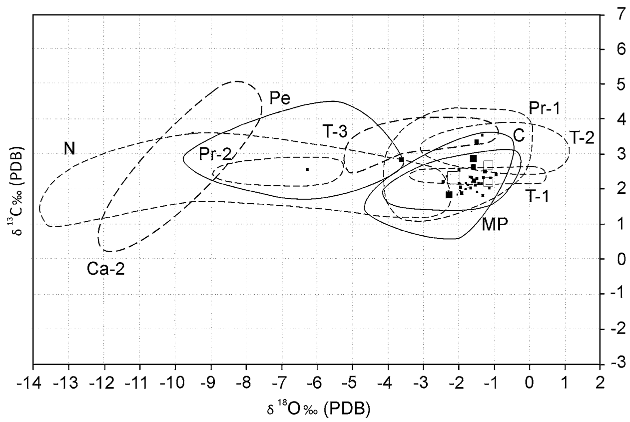

Fig. 5 $\delta^{18}O$ versus $\delta^{13}C$ diagram for Mediterranean marbles used in antiquity and for the marble samples coming from the spiral staircase of the bell tower of the St. Nicholas Church at Pisa (*filled squares* MGS < 2 mm; *empty squares* MGS > 2 mm). Reference isotopic fields from Gorgoni et al. [26], with supplementary data after Antonelli & Lazzarini [4], Lazzarini & Antonelli [31], Lezzerini et al. [32]: *C* Carrara; *Ca-2* Campiglia M.ma; *MP* Mt. Pisano; *N* Naxos; *Pe* Mt. Penteli; *Pr* Proconnesos, Marmara (*Pr-1* main marble; *Pr-2* marble from Camlik area); *Pa* Paros (*Pa-2* Chorodaki valley; *Pa-3* Aghias Minas valley); *T* Thasos (*T-1* Fanari district; *T-2* Aliki district; *T-3* Vathy-Saliara district)

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 façade 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.

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