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Abstract

This study is part of an ongoing research aimed to examine a number of important defence towers situated along the western Sardinian coast, Italy, built in 16^{th}-17^{th} century. They have been studied through the analysis of masonries by an historical, architectural, technical and petrographical-chemical point of view, through a methodology based on a stratigraphical approach.

The main aim is the understanding of the traditional building techniques used during the above mentioned centuries, for warranting proper restoration projects.

Keywords: Stratigraphy, Chronology, Building Stones, Mortar Petrography, Weathering.

Introduction

The towers investigated are part of the historic coastal defence system dating between the beginning of the 16th and end of the 17th century, under the rule of Spain (Giannattasio and Grillo 2010 (a); Giannattasio and Grillo 2010 (b); Giannattasio and Grillo 2011; Giannattasio and Grillo 2013). These series of fortifications, rich in their historical and architectural quality, were constructed due to the social need for defence. Unfortunately, they are suffering from rapid deterioration of their stone fabric as a result of disuse and abandonment since the 19th century when the towers lost their defence purpose. Specifically, in this paper we present the investigations of the coastal towers on the shoreline between Bosa and Santa Caterina di Pittinurri, i.e. eight towers, named Argentina, Iscra Ruia, Bosa, Columbargia, Foghe, Capo Nieddu, Pittinurri and Su Puttu (Figures 1-2). All towers have been built with local stone material, Neogene volcanic rocks, Miocene carbonatic formations and Quaternary "Panchina Tirreniana" cropping in this part of the island.

Figure 1. *Columbargia Tower. Panoramic View of the Tower, its Structure and Detail of the 'Cantieri' Masonry. Photos: S.M. Grillo*

Historical Profile and Typologies of the Sardinian Defensive System

The 16th-17th century is very important for the development of the protection system, because the island represented a strategic ambit at that time, by a commercial and political point of view (Pillosu 1957; Fois 1981; Montaldo 1992; Russo 1992; Rassu 2000). In fact, although the implementation of the towers system covers a period of almost five centuries, it can be said that the building process became more intense in this period.

Specifically, during the second half of the 16th century Marco Antonio Camós (Pillosu 1961) was instructed by the viceroy Juan Coloma d'Elba to quantify the existing towers and to register their conditions. The viceroy's aim was to convince the authority to ameliorate the defense system, in order to protect Sardinia as well as Spain.

Afterwards a more concrete unitary fortification plan was promoted by the Viceroy Miguel de Moncada; after examining the entire coast of Sardinia, he drew up a careful report on the state of the defense system and formulated proposals for its implementation.

Thus a concrete development process started up, the defense system of the Kingdom of Naples serving as example.

This process continued until 1587, when the dominator decided to institute a central organization, the ‘Reale Amministrazione delle Torri’, which for centuries administered the Sardinian defensive system. Between the second half of the 16th century and the first half of the 17th century, the largest number of Sardinian towers was built.

From the beginning this process was characterized by a scarcity of economic resources and the constant difficulty in finding workers who agreed to carry out the building work in marshy, unhealthy places plagued by constant attacks. (Mele 2000; Mele 2010).

The scarcity of material and demographic resources and the necessity of shorter construction times influenced several project choices leading to less sophisticated technical and architectural solutions.

Prevalently these constructions show a circular plan, with a cut-off conical or a cylindrical façade (respectively representing 63 % and 6% of the Sardinian towers), still in coherence with the past catalane culture, even if in the same years in the other Italian contexts the military engineering praxis focused on the realization of quadrilateral buildings.

The cut-off conical shape responded to requirements of inexpensiveness and simplicity of construction. Therefore its realization had a much lower cost compared to the tower with a square base, while at the same time satisfying the basic military requirements (Rassu 2005).

Figure 2. *Argentina, Bosa and Pittinurri Towers. Photos: S.M Grillo*

Although the cut-off conical shape is the most common, the abacus of the typologies of the Sardinian towers is very heterogeneous. In the western coast the geometry consisting of a cut-off conical basis on which is set a cylindrical shape is also widespread (19% of total towers). The junction between the two solids is sometimes solved by inserting a stone molding with torus section. Most of the towers analyzed in this study belong to this category, which is the type commonly adopted also in the coastal towers of the Southern Corsica (Murru 2014).

The size and proportional relationships vary considerably depending on several factors, such as the funds available, the importance of position and in general the different functions they had and the allocation of artillery.

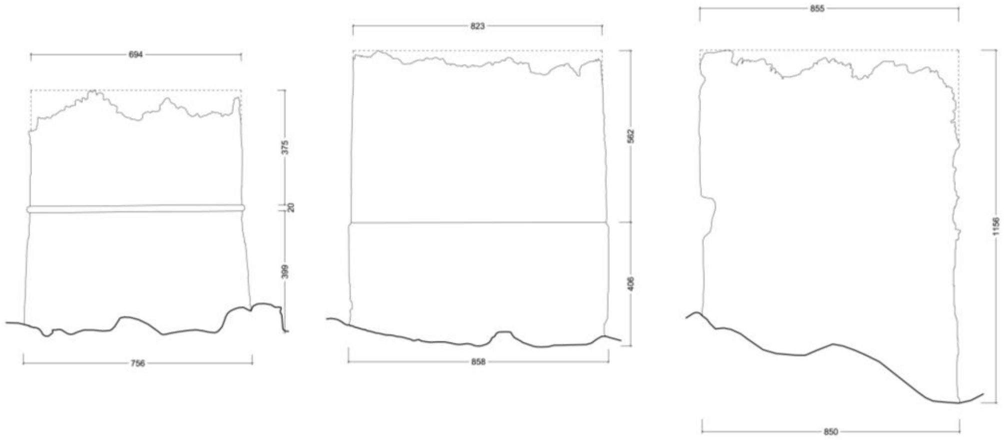
The layout on three levels is almost identical in the Sardinian towers. The base is full of earth and stones and the cistern is found here. At the second level usually a vaulted system covered the main room located at an altitude normally of about 5-6 m. The schedule of coverings in Sardinia is heterogeneous although the most common type of covering of the main room is the dome with different curvature. Finally on the third level the parade square is located, connected by stairs inside the wall or by a trap-door.

Building Techniques

The towers investigated had basically the role of a lookout point, therefore they were always located on rocky promontories. In other words, their position was imposed by the existence of obtaining a good visibility level towards the sea, as well as of the neighboring coastal area.

The dimensions of these towers are small, presenting a diameter usually included between 7 and 13 m and an height of 8-13 (Figure 3). The Bosa tower, as we will see, represents an exception by a dimensional point of view.

Figure 3. *Compositional Schemes Referring to the Three Types of Towers of the Investigated Area. Graphic Realization: S. Murru*



With reference to the investigated buildings, the study carried out is based on the use of an archaeological method, consisting in the sampling and the classification of the masonries, through a photographical, architectural, metrical and material survey, concerning the structures, the stones and the mortars used for their construction. Specifically, stones and mortars have been examined by a morphological, metrological, lithological and petrographical point of view, obtaining chronological series, referred to the $16^{th-}17^{th}$ centuries.

The sampling has been supported by the use of a database and a catalogue schedules, containing all the registered data, concerning the typology of each tower and the traditional construction techniques.

The drawing of each tower, with the annotation of their structural and material based conditions, was very useful for the understanding of the dimensional and technical characteristics (Brogiolo 1988; Ferrando, Mannoni and Pagella 1989).

The masonry technique used was ‘a cantieri’. This practice, deriving by the roman *opus incertum*, consisted in the preparation of two or three courses of rubbles, rough-hewed just in the external and support faces. The result was an irregular, coarse opus, with horizontal linings generally distanced 50-60 cm, characterized by thick joints between one another, with mortar of poor quality, sometimes signed by not slaked lime nodules. Very often the assembly of the rubble stony elements took place without paying attention to the stagger of vertical joints (Figures 4-5).

Notwithstanding the above mentioned characteristics, this typology was the outcome of an ingenious device, conditioned by economical reasons, i.e. by the aim of making the most of the available stones of different size, accurately dressing external angles and using horizontal elements with stabilizing function thus warranting structural solidity.

Figure 4. *Details of Masonry Referring to Some of the Towers Investigated. The Comparison Highlights the Different Masonry Textures that Characterize the Basis and the Upper Body of Each Tower and the Constructive Solution Adopted for the Connection between the Two Bodies. Graphic Realization: S. Murru*

As we will specify after, all the examples investigated used local material, using rubble pieces or regular ashlars of variable size and of various manufacturing processes. Numerous small rock pieces left over from hewing bigger blocks have been applied to fill empty spaces.

Between two courses one can find tiny squaring materials, together with a double mortar layer, highlighting the passing from one another, i.e. the closing of a module of the masonry and the following restarting of the new one.

Sometimes planking holes can be found, distanced both horizontally and vertically about 1.70 m. Generally it can be observed that for practical reasons, they are always aligned with the superior limit of the ‘cantiere’.

Interstices are filled with plentiful gross mortar, characterized by numerous components of unslaked lime nodules.

The fronts show a very simple drawing, devoid of any decoration element. The openings too are simple, with access doors situated some meters above the ground, accessible through a mobile wooden stair. Presently these structures are completely abandoned and they lost their function after the Unity of Italy.

With reference to our case-studies, the Argentina tower was built between 1580 and 1584, it was in contact with the Bosa and Columbargia towers. In 1784 it was restored, and after 1843 it was abandoned. It has a cylindrical shape on a trunked cone basis, with a diameter included between 9 and 11 m, and an height of 10.50 m. It is very similar to the Bosa tower, also in the interiors, having a ‘mushroom’ vault with central pilaster. In the middle of the cylindrical body there is an opening, allowing the entrance to the inner space, with a stair bringing to the upper terrace.

The masonry in the two bodies is different. In the cylindrical body it is realized with few courses of little rubble stones, never rough-hewed, that define a ‘*cantiere*’ of about 60 cm. The trunked cone basis has a more accurate masonry with more regular ashlar of bigger size, disposing in two courses, that define ‘*cantieri*’ high 80 cm. Currently its conditions are not so good.

The Iscra Ruia tower was built between 1580-84, interested by some restoration interventions in 1720, in 1784 and in 1838 (Rassu 2005, 98).

Its structure is a cylinder with a scarp frustum of cone basement, large 7.00-7.40 m, with a stony stringcourse in the middle of its height.

The rubble masonry has a thickness of about 140 cm; it is realized with medium and small-sized elements that define a ‘*cantiere*’ of about 60 cm.

Its current conditions are not good, because of a deep erosion phenomenon, interesting both the plasters and the masonry.

The Bosa tower was built during the first half of the 16th century. It was optically linked with Argentina and Columbargia towers. It is very similar to the Sperone, S. Giovanni and Porta Terra towers, situated in Alghero (Rassu 2005, 55).

Its shape is a cylinder wide 20 m of diameter, collocated on a circular frustum of cone basement of about 24 meters, and a total height of 13 m. The passage between the two circumferences is marked by a string-course frame, above which there is a series of seven splaying openings. The hatchway is positioned at 6 m from the ground, and it brings to an octagonal interior space. It is covered with a vault divided in eight gores marked by arcs, converging in a central massive pilaster. On the covering there was the drill ground.

The masonry has a thickness of about 3,50 m. It is heterogeneous and largely realized with medium-sized ashlars that define a texture with sub-regular courses. However the wall shows several areas characterized by the presence of smaller elements and a more irregular texture.

At the present its conditions are fairly good, even if large superficial areas have lost the original plaster, putting in evidence the masonry below.

The Columbargia tower was built about 1572, on a very suggestive promontory dominating the beach, and it was in contact with Iscra Ruia, Bosa and Argentina towers.

It consists in a cylindrc building, with a diameter of 8.5 m and about the same in height, with its access at 4 m from the ground. The interior space is vaulted with a ‘mushroom’ shape, i.e. with a pilaster in the center, usually used for bigger structures, has we saw for the Bosa tower.

The masonry is characterized by a rubble stones wall, with evident horizontal planes indicating the passage between two ‘*cantieri*’ high 55-60 cm. It is largely realized with medium-sized elements. The homogeneity of the masonry texture is interrupted by few rows of ‘*panchina tirreniana*’. They are characterized by a more regular size and shape.

Nowadays its conditions are very bad, because of the lost of the external face of the ‘a sacco’ masonry, putting in evidence the inner nucleus of it. Besides, the plaster is quite everywhere absent.

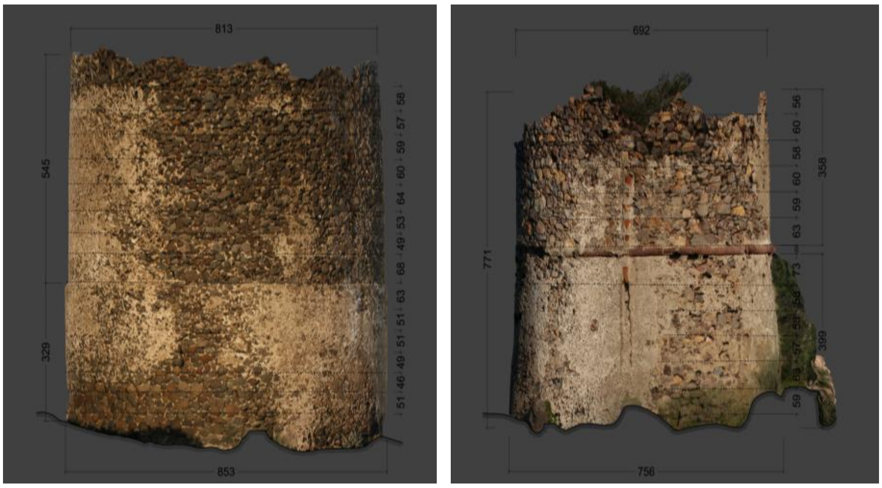
The Foghe tower is on the homonymous promontory, checking the mouth of the river called Riu Mannu and in contact with Iscra Ruia and Capo Nieddu towers. It was erected in 1580-84, later object of restoration projects in the second half of the 18th century and in the first half of the 19th century.

It is a cylinder with a basement lightly projecting, with a diameter of 8.60 m and an height of 9.60 m. An arched opening is situated at 4.00 m from the ground level, while a little internal stair built into the wall brings to the terrace.

The rubble masonry has a thickness of about 1,60 m. It is characterized by a medium-sized elements sometimes characterized by sub-rounded edges. The ‘*cantieri*’ are 55–60 cm high.

Presently it is in a bad state, showing very deteriorated masonries, with very corroded mortar joints.

Figure 5. *Foghe and Iscra Ruia Tower. Orthogonal Perspective View Highlighting the Dimensional Relations and the Size of the* ‘*Cantieri*’*. Graphic Realization: S. Murru*



The Capo Nieddu tower is situated in a isolated position. It was built after 1578, but very soon it was abandoned at the half of the 16th century, because of its position, to difficult to get to it and not practical to control the territory (Rassu 2005, 77). So, it went to ruin, and today remain only little parts. Originally its shape was similar to that one of Pittinurri, with a cylindrical body put on a frustum of cone basement, whose diameter is about 8.60 m. It doesn't show any architectural element, while its masonry is very easily readable, thanks to its bad repair. The masonry is characterized by a rubble stones wall; it is realized with medium and small-sized elements.

The Pittinurri tower was completed about 1580, in contact with the towers situated in the area of Sinis, as well as with the Su Puttu and Capo Nieddu tower. It worked until 1843, so it is in a good state, in spite of the diffused lack of plaster. It is a cylinder based on a trunked cone, with a diameter that varies between 11 and 13 m. The access to the interior is allowed by an opening positioned at the half of its height, while the entrance to the drill ground by a spiral staircase. Externally four little lunette openings mark the facades.

The cylindrical body is realized with small-sized elements, but the texture is not visible due to the presence of the plaster. Also in the trunked cone basis it is very difficult to define the original texture due to the numerous recent integrations. However some evident horizontal planes indicate the presence of '*cantieri*'.

The building seems to have be interested by a recent restoration intervention, as it is attested by the presence of plastered back draft masonry portions. The rest is without plaster.

The Su Puttu tower was built in 1580-84, but it was very early abandoned - about first half of the 17th century - because it was too much close to the Pittinurri tower.

Figure 6. *Foghe, Su Puttu and Iscra Ruia Towers. All These Examples Are in Bad Conditions, because Neglected. All the Images Put in Evidence the Various Questions of Degradations, i.e. Erosion, Alveolization, Anthropical Decay, Structural Instability. Photos: S.M Grillo*

It shows a circular frustum of cone shape, marked by a stringcourse and by the presence of an opening. Its diameter is 15 m, while its original eight - at the present of about 11 m - is not exactly appreciable, because of the state of ruin, having lost large parts of the walls as well as the roof.

The rubble masonry is realized with medium-sized elements. The '*cantieri*' have different height: 60 cm in the upper body and 70 cm in the basis.

Materials Characterization

Of the eight towers described before four of them are investigated for the material used for their building: Argentina, Foghe, Columbargia and Iscra Ruia towers. All the towers have been built with local stone materials; Oligo-Miocene cal-alkaline rhyolites; Plio-Pleistocene alkaline and subalkaline basalts and phonolites; and Quaternary costal to littoral conglomerates, sandstones and biocalcarenites ("Panchina Tirreniana").

Figure 7. *Different Kinds of Rocks Used of Construction of the Towers and their Specific Weathering Phenomena. The Original Mortar Very Often is Strongly Weathered. The Figure Shows the Fundamental Differences in the Weathering Characteristics of These Types of Rocks. Photos: S.M Grillo*

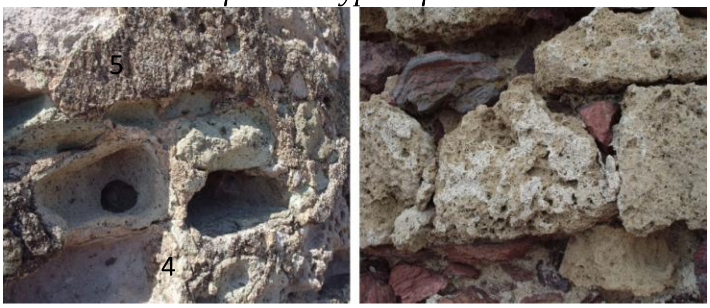
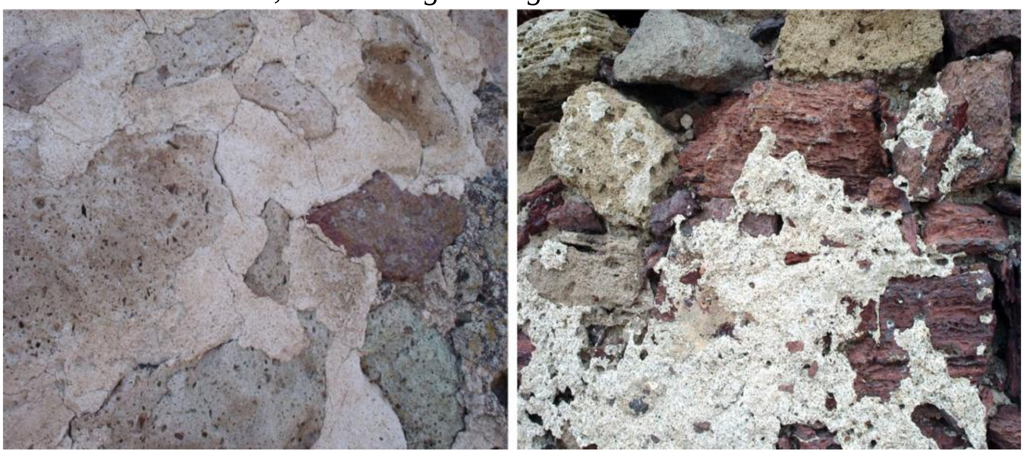


Figure 8. *The Original Plasters of the Towers are Conserved in Some Places, as for Example in the Columbargia Tower (Right Side). When the Original Plaster is Weathered, the Mortar Very Quickly is Washed Out, Seriously Damaging the Stability of the Wall. On the Left Side an Example of Recent Restoration is Shown, Concerning the Argentina Tower. Photos: S.M Grillo*



Acidic calkaline volcanic rocks are the most used building material found in the Argentina, Columbargia and Iscra Ruia towers. In the construction of the Columbargia tower also stones of the Panchina Tirreniana formation were used. Basalts and less phonolites were used for the Foghe tower (Figures 5-6).

Rhyolitic welded tuff ashlars have been used for the construction of the Argentina tower and usually show grey, cream and subordinate green colors. For the Columbargia and Iscra Ruia towers were used red calkaline ignimbritic rhyolities exhibiting eutaxitic texture with different degrees of welding.

The walls of the towers generally were all made of irregularly and partly regularly cut blocks of different kind of rhyolites and sandstones and only in the construction of the Foghe tower mainly rounded river stones of basalts and phonolites were (Figure 6).

In general stone used for the tower construction are highly resistant to weathering and only rhyolitic welded tuff ashlars show little signs of decay as alveolization and patina. In contrast to the above described volcanic rocks, the plaster and mortar show very serious signs of weathering as disaggregation, exfoliation etc. that are responsible of the sometimes serious damage of the towers (Figures 7-8). In fact, when the mortar weathers and is washed out from the interstices the ashlars lose their stability and fallout from the walls. So the first step of decay is the weathering and removal of the plaster which protects the mortar from weathering. The second stage is the wash-out of the masonry mortars between the stones and finally the whole wall breaks. This phenomena of weathering is very well developed on the walls exposed to the sea-side where wind and aerosols are heavily impairing the constructions. The main reason contributing to the erosion of mortar and plaster include a presence of salt crystallization, abrasive action of winds; and disintegrating effects of plant growing on the walls and water penetration leading to the concentrations of moisture and dampness.

The good knowledge of the chemical and mineralogical composition of the binder and aggregate in mortars and plaster is very important because it gives considerable information about the material used in the old, original mortar preparation. Thus, it represents a valid instrument for estimating the state of preservation of a building and provides useful information to help to reproduce the formulation of the original plasters and mortars.

Methods

Different ancient mortar samples from the towers have been analyzed to characterize their binder and aggregate fractions. The investigations which were carried out with mineralogical and petrographical (optical microscope and X-ray diffraction) analyses (Moropoulou, Bakolas and Bisbikou 2000; Hermann, Herz and Newman 2002; Elsen et al., 2004; Casadio, Chiari and Simon 2005).

The procedure for the mortar characterization was carried out by taking a part of the mortars using hammer and chisel. In order to obtain information on single components, their grain size and to estimate the proportions of binder/aggregate distribution the mortar samples were manually disaggregated and fractionated and sieved through UNI series of sieves (Figure 9).

The lowest fraction (<0,063 mm) is considered to represent the binder, although more of less significant quantities of finely grained aggregates can sometimes be found in this fraction. Accordingly it is also possible to find some binder in the coarser fraction (mainly aggregates) of the mortar sample. Grain sizes with diameters greater than 0,5 mm make up about 50 % of the total for almost all samples present. Only a few fragments are measured with diameters greater than 4 mm, above which the fractions tend to zero. Since very close to Argentina, Columbargia and Iscra Ruia towers there are sand beaches, it is very easy to assume that aggregates of mortars were taken from these beaches, as far as the ashlar were realized with local stones.

In fact, the Argentina tower, built along the coast where rhyolitc rocks crop out and where sand beach formed by disaggregation of this kind of rocks are present, shows aggregates formed mainly of single-crystal quartz grains and feldspar, rhyolitc fragments and only few carbonatic micro-fossil. Columbargia and Iscra Ruia towers, built on the ingnimbrite rhyolitic cliff locally covered with sedimentary rocks known as “Panchina Tirreniana”, show, more than Argentina tower, the presence of carbonatic microfossil and shell fragments. On the contrary, the aggregate of Foghe tower, built on the basaltic cliff where sand beaches are not present, is mainly formed of fragment of basalt and fonolite rocks, quartz grain and feldspar grain as the ahlars coming from the near Rio Mannu. These difference in the mineralogical composition of the mortars have been confirmed by the investigation with optical microscope and X-Ray diffraction (Figure 10).

The X ray diffraction analysis shows that the binder of the investigated mortars consist essentially of calcite and only in few cases it is possible to see very week indications of the presence of lumps observed also under the optical microscope. Finally the X-Ray analysis does not show any evidence for the presence of any phases typical of hydraulic mortar (Figure 10).

Figure 9. *Grain Size Distribution After Sieving of Mortar and Plaster in the Different Towers. A) Argentina Tower: A1, A4 Plasters; A2, A3 Mortars; C) Columbargia Tower: C3 Plaster, C4 Old Mortar; I) Iscra Ruia: I3 Mortar, I4 Plaster; F) Foghe Tower: F1, F2, F3, Mortars*

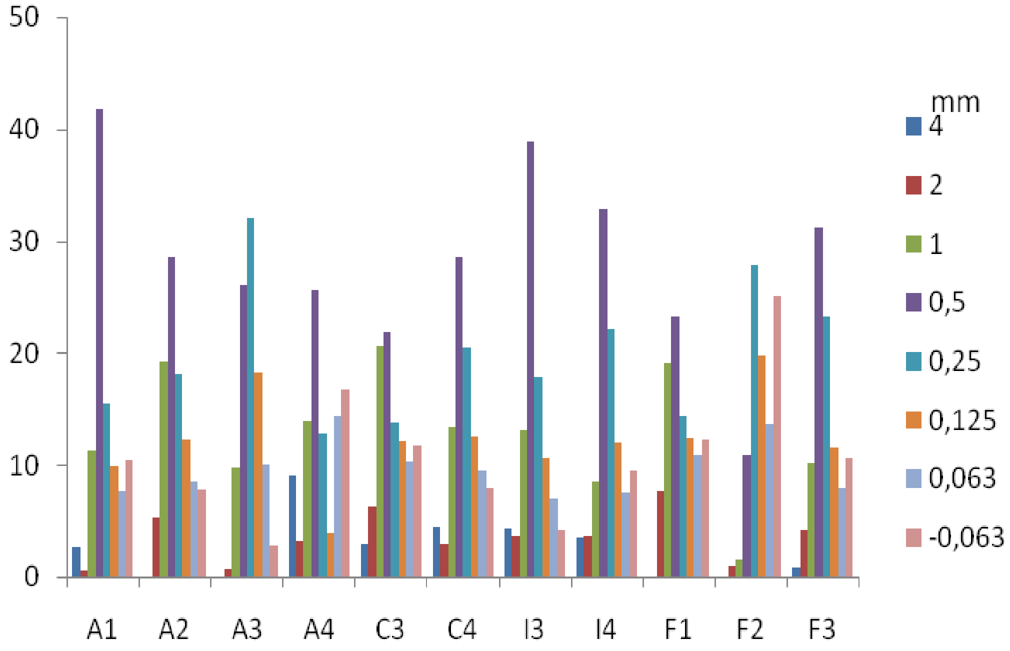
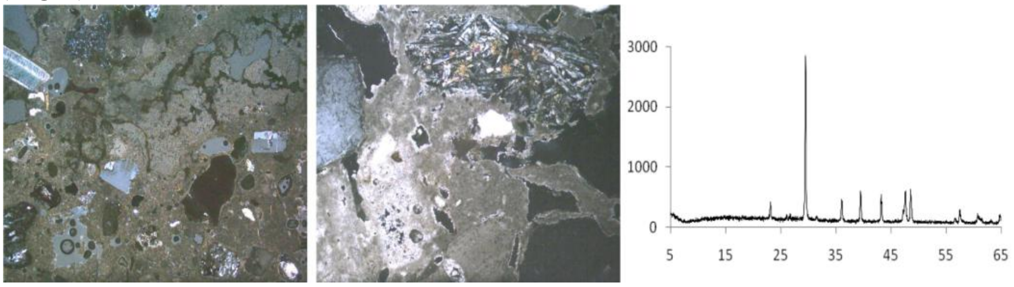


Figure 10. *Thin-Section Photomicrographs (Crossed Polarizer) of Mortars and X-Ray Diffraction Powder Pattern of Binder. The Aggregate Consists of Coarse Grained Quartz-Feldspar, Fossil and Fragment of Acid Volcanic Rocks (Left) and Fragment of Basaltic Rocks (Center). The Binder Shows a Non-Homogeneous Texture Due to the Presence of Lumps, Cracks (Left and Center) and Exhibits a Typical Microcrystalline Aggregate Texture of Pure Calcite (Right)*



Conclusions

Finally, the aim of this research is the understanding of the traditional building techniques used during the above mentioned centuries, combining dating strategies, with three different principal objectives:

1. to define the peculiarities of the traditional building techniques used during this period;
2. to increase the knowledge of the constructions and their degradation phenomena to warranty proper restoration;
3. to facilitate, on the basis of acquired data, the dating of other contemporary edifices, especially referring to the so-called 'minor' buildings, which are very often object of improper restoration.

The identification and characterization of the binders and aggregates of the original mortars and plasters used in these historical buildings is of appreciable importance in order to collect data that will be considered for the formulation of the restoration mortars which should match in a high degree the nature of the materials originally used in the construction of these towers. In fact, during the investigations presented in this paper, it was found that the majority of the mortars and plasters analyzed in this research are in a bad state of conservation.

The main reasons are the advanced age (most of the towers are approximately 500 years old) of the towers, and the fact that some of them are in a state of total abandonment.

The durability of the walls of the towers is depending on a number of different facts:

1. The exposure of the sea aerosol;
2. The quality of the mortar;
3. The existence of a protecting layer of plaster which was originally made of lime and clay brick dust as binder.

Notes and References

C. Giannattasio is the author of the paragraph: *Building techniques*, S. M. Grillo is the author of *Materials characterization* and *Methodology*. S. Murru is the author of *Historical profile and typologies of the Sardinian defensive system.* Together compiled the *Introduction* and the *Conclusions*.

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