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ORIGINAL ARTICLE

Iron Making in Fornovolasco (Italy) at the End of the Fifteenth Century, the *Canecchio* Furnace, and an Artifact Characterization

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Abstract This study investigates the rise of the Este family in Garfagnana (Tuscany, Italy) during the first half of the 15th century. The Este wanted to annex this region to improve their cast-iron production both for military and economic advantages. This article, thanks to a document found in the State Archives of Modena, encompasses an overview of the Fornovolasco settlement, a description of the furnace room, an analysis of the first casting campaign, and an attempt at furnace sizing. In the final section, a brief characterization of a cast-iron artifact found in that region and probably coming from this casting campaign is provided.

Resumen Este estudio investiga el surgimiento de la familia Este en Garfagnana (Toscana, Italia) durante la primera mitad del siglo XV. Los Este querían anexar esta región para mejorar su producción de hierro fundido por ventajas tanto militares como económicas. Este artículo, gracias a un documento que se encuentra en los archivos estatales de Módena, incluye una descripción general del asentamiento de Fornovolasco, una descripción de la sala del horno, un análisis de la primera campaña de fundición y un intento de dimensionamiento del horno. En la sección final, se proporciona una breve caracterización de un artefacto de hierro fundido encontrado en esa región y probablemente proveniente de esta campaña de fundición.

Résumé Cette recherche s'intéresse à l'ascension de la famille Este à Garfagnana (Toscane, Italie) au cours de la première moitié du 15ème siècle. Les Este souhaitaient annexer cette région pour améliorer leur production de fonte afin de bénéficier d'avantages militaires et économiques. Grâce à un document trouvé dans les archives d'état de Modène, cet article comprend une présentation de la population de Fornovolasco, une description de la salle du fourneau, une analyse de la première opération de fonte et une tentative d'évaluation de la taille du fourneau. Dans le chapitre final, une brève caractérisation est fournie portant sur un artéfact de fonte découvert dans cette région, probablement issu de cette opération de fonte.

Keywords 15th-century metallurgy - Fornovolasco settlements - *canecchio* furnace - cast-iron cannonball

Historical Background and Geological Settings

In the first half of the 15th century, 1430–1450, much of Garfagnana passed under the control of the Este family, who managed to annex most of this region to their domain. The Este were one of the most successful Italian families of Frankish lineage in the current Emilia Romagna region, mainly between Modena and Ferrara. Garfagnana is an historico-geographical area

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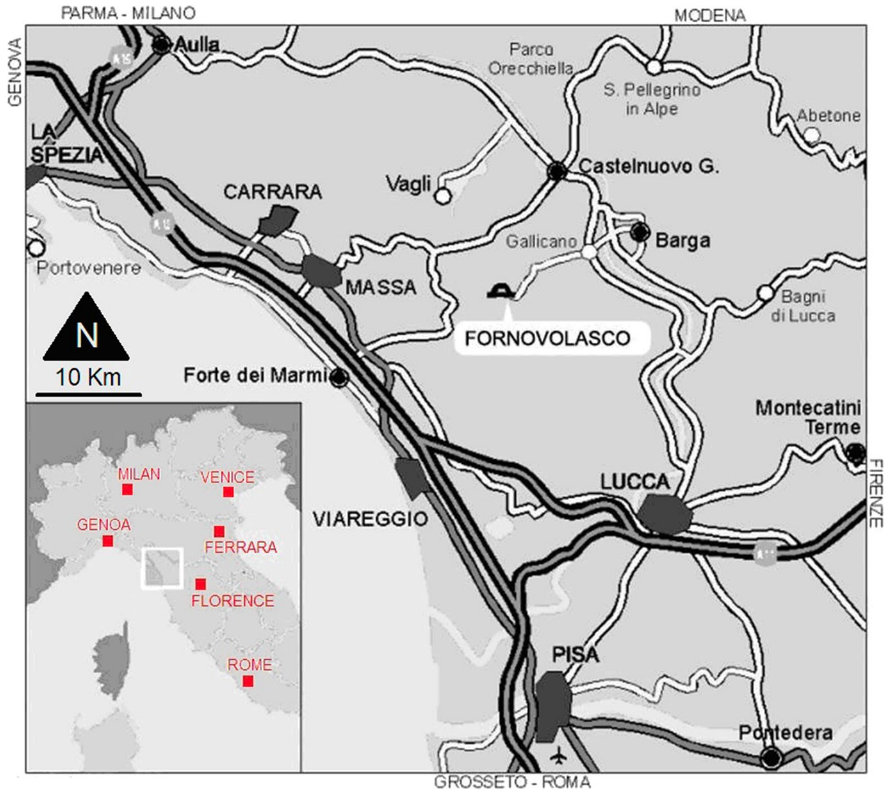

Fig. 1 Current map of the Garfagnana region. (Map by authors, 2019.)

of the province of Lucca, in Tuscany, between the Apuan Alps and the main chain of the Tuscan-Emilian Apennines (Fig. 1).

The Italian political situation between the 15th and 16th centuries is very complex to define. Italian territory was characterized by numerous states, duchies, and republics in continuous struggle for territorial and, above all, commercial supremacy. In this context, alliances, wars, victories, and treaties were constantly evolving, preventing an easy identification of the situation. Simply put, the states with the greatest power were the Republic of Venice, the Duchy of Milan, the Republic of Genoa, the Republic of Florence and that of Siena, the Papal States, and the Kingdom of Naples, which had considerable influence on a myriad of minor states, such as the duchies of Lucca, Mantua, and Ferrara. In the 14th century the Republic of Lucca failed in an attempt to annex Garfagnana to acquire more power against Pisa and Florence. With this failure of Lucca, the Garfagnana became loyal to the Este family of the Duchy of Ferrara in the 15th century. In 1482 Girolamo Riario, lord of Imola and Forlì, allied with Venice (in the interest of maintaining a monopoly of the salt trade), waged war against the Este family. This war ended with the Treaty of Bagnolo in 1484, and Ferrara maintained its territories, including Garfagnana. A new war broke out in 1508 that saw the League of Cambrai (France, Spain, and the Holy Roman Empire) against Venice for hegemony over Italian territory. The Duchy of Ferrara sided against the Republic of Venice by joining the League of Cambrai, which disbanded in 1510 at the behest of Pope Julius II, who was concerned about the supremacy that France might acquire with victory in the war. At the end of this conflict, the Este family remained allies of Louis XII of France. With the death of Alfonso II d'Este in 1597 and his lack of heirs, the territories under the control of the Duchy of Ferrara passed to the Papal States under Pope Clement VIII (Pieri 1970).

In Garfagnana, the iron and steel industry had begun before 1300, when iron was imported from Elba Island or extracted from local mines near the area called "Monticello-Le Pose." The southern

Apuan Alps are characterized by the occurrence of small baryte-pyrite-iron oxide deposits, exploited until the end of the 1980s. In the area of Fornovolasco, magnetite-pyrite ore bodies are embedded in either a metavolcanic and metasedimentary sequence (Fornovolasco's schists) or in dolomitic marbles of uncertain stratigraphic setting, known as "*grezzone metallifero*." Veins and lenticular bodies of magnetite-pyrite-sphalerite-pyrrhotite-iron hydroxides are scattered in the area of Fornovolasco. In addition to the ore minerals (magnetite, pyrite, and limonite), some common sulfides and sulfosalts and their alteration products were identified (Carmignani et al. 1976; Tanelli 1983; Tognarini 1984; Ciarapica et al. 1985; Assoggiu and Giannini 2004; Pandeli et al. 2004; Biagioni, Orlandi et al. 2008; Biagioni, Bonaccorsi et al. 2010).

Until that time, iron came to Modena from certain valleys in Lombardy. The rise of other iron and steel districts outside Venetian influence probably contributed to the encouragement of the Este family: settlements of the Duchy of Milan in Alpine valleys (Valtellina and Valsassina), the Apennines (Val di Nure, Piacenza), and Liguria (Masone, Republic of Genoa). In this way, the Este had to equip themselves with systems set up along the lines of those of Brescia to activate the important production of bombs and cannonballs. Moreover, since the resources of the subsoil were considered a patrimonial asset of the prince, these, from the exercise of the iron and steel industry aimed at armament and trade, would have obtained great prestige and significant advantages: Estensi saw the opportunity for acquiring equipment for the production of iron shot in order to obtain military and economic benefits from the trade in surplus iron-artifact production. Moreover, they decided to invest in the expansion of the existing steel production with the aim of developing weapons. Such effort represented a major commitment of resources that spanned three centuries, though not continuously, aimed at providing security throughout their vast territory (Baraldi and Calegari 2001; Giumlia-Mair and Maddin 2004; Nicodemi and Mapelli 2009).

In Fornovolasco, around 1450, at least three factories were in production, some of which also processed local minerals. Documentation dating back to 1480 shows that a ducal-owned steel center was already operating there; it consisted of a furnace for casting that used mineral ore dug nearby and a manufactory consisting of at least two forges. The masters were mainly from Brescia, and the furnace cycle was directed by Master Bartolomeo di Rampin from Gardone Val Trompia; however, the enterprise did not provide the expected results (Mucci 2000; Baraldi and Calegari 2001).

In the middle of the century, Borso d'Este (1413–1471) sent some mining experts to verify the quality of cast-iron and steel products coming from the production units operating in the area. The documentation retrieved communicates the prince's dissatisfaction concerning the inability to manufacture the desired ammunition for artillery. Such products were obtained from iron casting using the reduction-furnace ore with special molds that allowed them to replace outdated stone bombs with more reliable metallic material. His successor, Ercole I (1431–1505), went to the Pania mountains to inspect the existing factories personally and to verify the exact situation. Following the inspection, he decided to totally redo the Fornovolasco settlements.

From the beginning of his reign Ercole I was engaged by La Serenissima (Republic of Venice), which wanted to extend the territory under its control. During the ensuing clashes he lost the Este dominions in the Venetian Polesine, but strengthened his control in the lands south of the Po River.

From the correspondence sent to the duke, it is clear that in 1490 conspicuous hydraulic works to improve the flow of water to the buildings were in progress in Fornovolasco, but it has been ascertained that the attempts to produce metal cannonballs, which, in the duke's plans, had to replace stone balls, were not successful. It is important to say that the distinguishing characteristic of Fornovolasco is water. The town stands at the confluence of three streams, originating from karstic resurgences: the Turrite di Petrosciana, which comes from the source of the Chiesaccia; the Canale del Battiferro, from the spring with the same name; and the Canale dei Santi, which originates at the Risorgenza del Tinello. At the confluence the water course takes the name "Turrite di Gallicano."

After the initial failures, the duke probably considered a radical change in structures and techniques. Around the middle of 1496, the establishment at Fornovolasco was profoundly transformed, due to the involvement of Master Iacomo Tachetto, called Tachettino, from Gerola in Valtellina, the expert

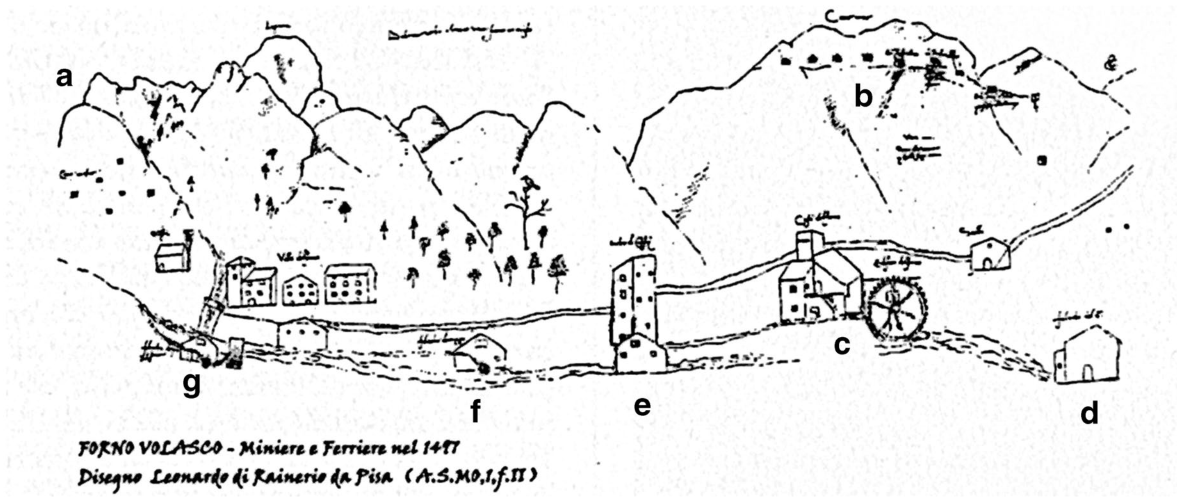

Fig. 2 Drawing by Leonardo di Rainerio di Pisa, 1497, with the indication of the old and new mines and the locations of different buildings: (*a*) *cave vecchie* (old quarry), (*b*) *cave nove* (new quarry), (*c*) *forno ducale* (ducal furnace), (*d*) *fabricha ducale* (ducal manufactory), (*e*) *fabricha de Cristoforo* (Cristoforo's manufactory), (*f*) *fabricha de Mezo* (Mezo's manufactory), and (*g*) *fabricha de più persone* (collective manufactory). (Image courtesy of the Archivio di Stato di Modena.)

designer and builder of similar plants in the Duchy of Milan. He hired workers from Valtellina to build the plants, importing competent manpower as well as the more advanced technique known as the "indirect method," which was used in many valleys of Lombardy, especially near Brescia (Mucci 2000; Baraldi and Calegari 2001; Giumlia-Mair and Maddin 2004; Nicodemi and Mapelli 2009).

Master Tacchetto employed a large number of specialists in various sectors: quarry workers, experts in the preparation and sizing of minerals, bricklayers, carpenters, charcoal burners, smiths of every specialty, experts in the transport of materials with pack animals, specialists in the construction of baskets (to measure the charges of charcoal and ore), and the *balote* masters, who were experts in cannonball casting. Together with these experts, the procedures, the criteria for evaluating work and remuneration also came from the Alps.

Fornovolasco's Plant and Buildings

The documents kept at the Archivio di Stato di Modena (State Archives of Modena) have remained unaltered to the present, and they are very accurate about both the location of the various production departments and about the production data of the various working campaigns. However, they do not specify the exact profile of the *canecchio* (a particular kind of blast furnace), which is obviously the main secret of the whole production process (Archivio di Stato di Modena 1909b).

From the drawing made in 1497 by Leonardo di Rainerio di Pisa (Fig. 2) and from the description of the buildings it is possible to assemble interesting information related to the location, layout, and dimensions of the various departments and the exact path of the water conduits for the propulsion system of the five hydraulic wheels. One of the wheels was used to operate the bellows of the *canecchio*, three were for the forge, and one for the mallet.

The various activities of the supply chain were carefully planned: large stocks of charcoal were accumulated, and close agreements with other jurisdictions were signed for the purchase of large batches of ore from Elba and for landing them at the port of Motrone and then transporting them through Pietrasanta and the Foce di Petrosciana. Finally, the systematic extraction of local minerals was developed. Also, the miners were recruited by Tachettino: from Valtellina came the master Ruscheto with his brother Matteo, while a separate contract was stipulated with Carlo de Simone de Villapiana. Previously, another master miner, Guarischo from Val di Sole, in Trentino, was also active in the area. However, the mineral

Fig. 3 Sketch and layout of the *stancia del forno* with the placement of the hydraulic wheel, the awning, the bellows, the *canecchio*, and the casting area. (Drawing by Walter Nicodemi, 2010.)

supply in 1497 was still insufficient. The aforementioned drawing of 1497 shows that the new buildings coexisted with the three older constructions that belonged to private individuals: the *fabricha de più persone*, *fabricha de Mezo*, and the *fabricha di Cristoforo*. Finally, the Fornovolasco plant was made more powerful by the acquisition of other, smaller factories in Isola Santa, Ceserana, and Sillico, to which successive stages of processing were delegated to counteract problems of emerging charcoal insufficiency (Biringuccio 1977; Cortese and Francovich 1995; Mucci 2000; Baraldi and Calegari 2001).

The sources on each building provide the fundamental measures for establishing volume: length, width, and height. Each construction is perfectly detailed. The complex therefore includes the *casa del forno* (furnace house), the *stancia del forno* (furnace room), the manufactory, and surrounding stables and warehouses. For example, the furnace room has a rectangular base; the side along the river measures about 13 m, the orthogonal side about 9.5 m, and the height 5 m. Inside, the bellows are on one side and the *canecchio* is on the other. In addition to these details, a drawing based on the sources (Fig. 3) shows the wheel used to operate the bellows, which is located outside, on the side along the canal, and which seems as tall as the building, about 5 m. The walls are quarried stones tied together with mud. The building is topped by an attic, from which the top of the mouth of the furnace extends 50 cm. Not far away, in the direction of the descent of the river, is the manufactory, which has a footprint of 11.5 × 10.5 m and a height of just under 4 m. It houses a mallet and three forges with their respective fires. Outside there are the channels that feed the four wheels, one for the mallet and the others for the bellows of the forges. Next to the manufactory is a warehouse for stocking the raw mineral (a bunker of 15 × 6 m and a little less than 4 m high). In an intermediate position between the oven and the manufactory, but slightly upstream, are two square-shaped stables of a little more than 7 m on each side and about 2.5 m high. The mallet visible opposite the furnace is called the "*pestaloppe*," and it was activated by the same wheel of the bellows. Its function was to break down the slag still rich in iron oxide. Thanks to this operation it was possible to obtain iron grit that could be reloaded into the furnace with no waste material.

The documents of the Modena archives also provided information about the team in charge of the process in the *stancia del forno*, which included a

Maestro di forno (furnace master): furnace and wind supervisor,

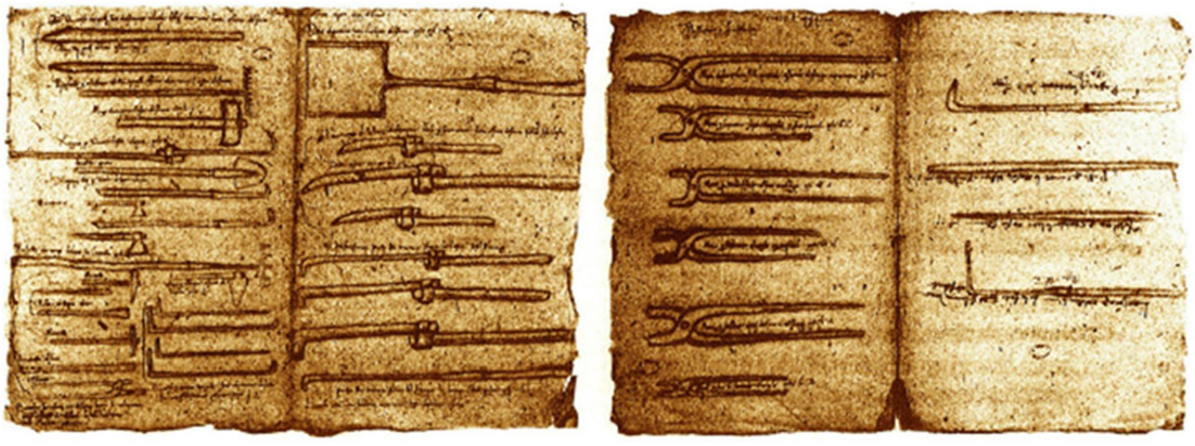

Fig. 4 Devices and accessories designed by Tacchetto for furnace operation. (Photo by authors, 2019; courtesy of the Archivio di Stato di Modena.)

Discente (first assistant): takes the place of the master in his absence,
Discentino (assistant): with the *discente*, in charge of supplying ore,
Pestaloppe, *pestsaloppe*: mallet operator,
2 *ministratori*: in charge of charcoal and ore loading, and
2 *braschini*: servants. (Archivio di Stato di Modena 1909a)

In Fig. 4, it is possible to see the sketches of some devices and accessories designed by Tacchetto for the furnace operation.

The Blast Furnace: The *Canecchio*

The reduction furnace deserves some special consideration because not many details have survived. This is more than understandable, both because this is the peculiar part of the system and because there can be no fixed rules, given that the dimensions are linked to the quality of the filler materials in general and to the characteristics of the mineral in particular.

Knowing both the daily production of iron and the daily amounts of materials charged on average, the useful internal volume of the *canecchio* can be estimated. The estimated profile has a rectangular cross section (Fig. 5), but it might be square as well, provided that a constant volume is maintained (Davis 1996; Brown 2000).

From the few details handed down, it is only known that the construction of the Fornovolasco *canecchio* was entrusted to the closest collaborator of Tacchetto, Master Donato, and that the oven was 5.5 m high and 3.3 m wide. It was made with refractory stones from the Cardoso quarries tied with a special mortar, the same that was also used to coat the crucible, to fix the wind nozzles on the side, and also to make the forms for the *balote* (cannonball) casting.

The front and back walls were full and the front was thinner, since it is subject to frequent rebuilding; in the lower part is the opening for the casting of the cast iron and the slag. The internal volume of the oven can be estimated at about 5 m^3, while the capacity of the crucible is about 100 dm^3. Feeding takes place through the mouth of the oven in the attic, placed about 2 m from the roof. Between the awning and the *canecchio* there was space for the casting and for the slag smelting, which are conveyed through special channels in the ground into water-cooled wells (Averlino 1972; Calegari 1989; Cima 1991).

The First Fornovolasco Casting Campaign

The production of the oven was guided by Tacchetto himself and lasted 64 days. Of this first campaign, conducted from 21 June to 29 August 1497, the initial heating period of the furnace and production of 21 days are known in detail, during which the consumption trend and daily production were recorded (Archivio di Stato di Modena 1909c). Master Tacchetto hoped for a supply of ore of satisfactory and relatively consistent quality, but, later, during the

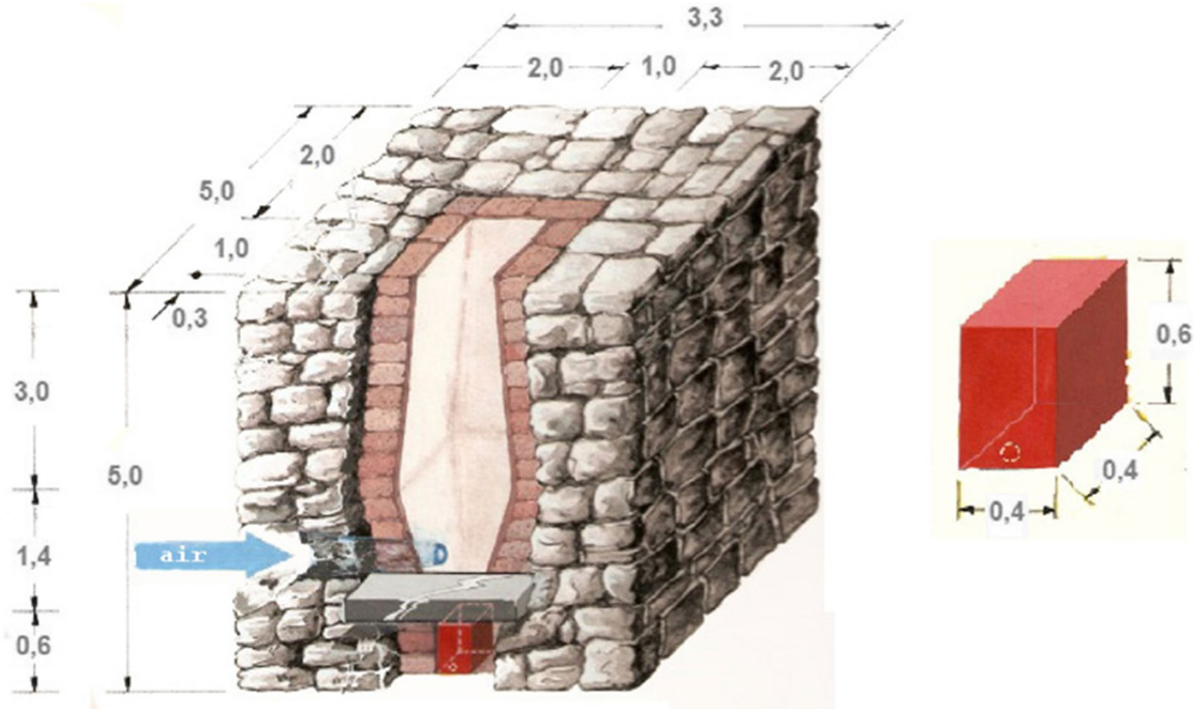

Fig. 5 Hypothetical profile of the *canecchio*; measurements are in meters. (Drawing by Walter Nicodemi, 2010.)

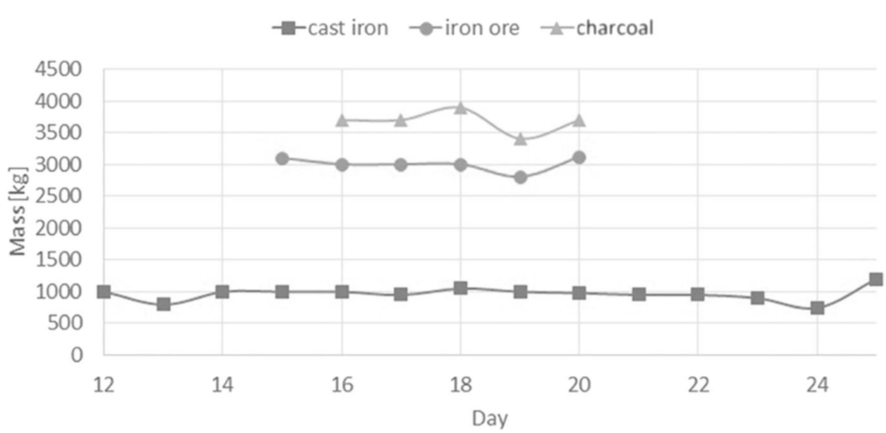

Fig. 6 Working data from 15 to 25 July 1497 (Archivio di Stato di Modena 1909c)

various campaigns, the situation progressively worsened. Initially, the furnace was heated with wood, then with charcoal. After eight days the bellows started, and then they introduced alternate layers of ore and charcoal. In the first 21 days of operation, between 5 and 25 July, production was about 20 t (60,201 lb.) of cast iron ("raw iron"), with a daily average, with small variations, of about a metric ton, but with great regularity of operation (Fig. 6).

During the same period the oven was fed daily with about 3.7 t of charcoal and 3 t of ore. The mineral/carbon ratio of 0.8 corresponds to the agreed ratio contracted. On day 19 the average daily quantity of charcoal dispensed was reduced; on the following day a regular trend of the castings is observed, followed by a sharp drop in the penultimate casting. It is probable that a mass had formed that altered the efficiency of the oven and that, necessarily, was somehow extracted without stopping the oven. On day 20, the quantity of ore was significantly increased to reestablish a correct driving trend. On day 25 strong differences were recorded between one casting and another: the latter is exceptional, perhaps marking a repetition of the decline observed a few days before, to which it is probable that Tacchetto reacted by increasing the quantity of charcoal, with consequent increase in production. Another campaign of the same oven, after significant reconstructions, is also worthy of note. It began on 23 July 1500 and ended on 10 September, for a total of 41 days. It was actually divided into two periods, with the suspension of a week between 4 and 12 August carried out to be able to modify the charges because the mineral was judged to be of lower quality than expected. It produced less than half the cast iron and production times tripled, a huge difference that recommended shutting off the furnace and abandoning the quarries.

In total, therefore, between 1497 and 1500, the ducal furnace produced 107 t of cast iron. Of that total, 38% was destined to the production of different caliber of *balote,* and the remainder was transformed by forging into semi-finished products, tools for the oven and the forges, anvils and hammers, etc.

It was not uncommon throughout the sixteenth century for the steel industry to have its ups and downs. Investments made did not always result in the expected success. The supremacy of Fornovolasco in the metallurgical industry of Garfagnana was undermined by the new Isola Santa plants built by a master from Gardone Valtrompia, who also brought in Brescian workers; at Isola Santa the production was constant because they used Elban hematite.

For Fornovolasco, there is no news of the operation of the furnace after 1500, where only the mining activity continued for a short time, while the reduction of the mineral was relocated to be not far from the aforementioned Isola Santa. From the documented experience of Fornovolasco it can be concluded that the campaign of that year lasted, on average, 3 months, producing about a metric ton of cast iron a day with 7–8 castings of 100–150 kg each and consuming, for each metric ton of cast iron produced, 3 t of ore and 3.6 t of charcoal. Among the reasons for the success or failure of so many attempts are, first of all, the greater or lesser availability of good ore and fuel, consisting of charcoal, which remains the real critical element of the steel industry.

In the 16th century, Tuscany was under the rule of the Medici family, but the Medici did not succeed in annexing Garfagnana, which remained under the rule of the Este family, the dukes of Ferrara. In 1542, Grand Duke Cosmo I de' Medici established the Magona del Ferro, a state office to manage the important and strategic iron industry as a monopoly. The Magona managed the smelting of iron ore (extracted mainly from Elba) in various blast furnaces as well as the refining and processing of crude iron. Therefore, the Magona secured exclusive rights to the production and sale of cast-iron products and byproducts for both civil and military use (Barlucchi 2006).

A Round Cast-Iron Find

During the research a round artifact was found that probably dates back to the period of the Fornovolasco *canecchio.* The artifact is a stray find that the Buffardello Team (a cultural association from Lucca) found during a hike in 2010. Since the production of the time in those places was mainly for military purposes, it suggests that the found object is a botched cannonball or casting remnant.

The item was found along a medieval mule track that led from the Garfagnana region to what was once the Florentine Republic. These roads were widely known by merchants that supplied cast iron produced in the vicinity. The artifact, lost or abandoned along the mountainous route, had not been shot and is in a good state of conservation.

The artifact shape is irregular: it is 11 cm in diameter and 2–4 cm in height; it weighs almost 1.2 kg (Fig. 7). The bottom part is flat and regular, which indicates solidification while in contact with a smooth surface. Conversely, the other parts are irregular, with many depressions and bulges, suggesting free solidification and consequent shrinkage modeling the

Fig. 7 Round artifact found on a mule track: a botched cannonball or casting remnant. (Photo by authors, 2019.)

Table 1 The chemical composition of the artifact (percentages by weight)

C	**Mn**	**Si**	**P**	**S**	**Cr**	**Mo**	**Ni**	**Al**	**Co**
4.3	0.04	0.30	0.027	0.11	0.016	0.003	0.008	0.002	0.007
Ti	**V**	**W**	**Pb**	**Sn**	**As**	**Bi**	**Ca**	**Sb**	**Cu**
0.004	0.003	0.04	0.003	0.025	0.06	0.001	0.005	0.015	0.09

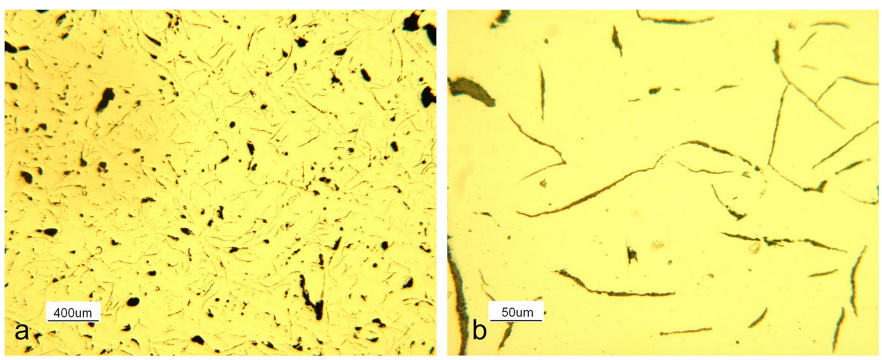

Fig. 8 Microstructural pattern after surface polishing. (Photos by authors, 2019.)

external surfaces. The metal appearance is reddish, due to rust on the surface.

Table 1 reports the chemical composition of the artifact detected by quantometer analysis, while the carbon content was estimated by LECO.[1] Quantometer analysis measures the chemical composition of an object by analyzing the emission spectrum of electromagnetic radiation that invests the sample; LECO analysis uses infrared absorption and thermal conductivity to measure the chemical composition of combustion gases after the combustion of a metallic sample.

The mean chemical composition conforms with the composition of a eutectic iron. This is coherent with the production process. This composition led to the lowest melting temperature. No alloying elements are detected; silicon content, good for castability, is low and comes from the ore. Most likely the iron ore came from magnetite embedded in a metavolcanic compound formed prevalently by a siliceous matrix. These kinds of rocks are typical of the Apuan Alps, confirming the local provenience of the iron ore and the artifact. The sulfur level is lower than in modern gray cast iron because charcoal was used instead of fossil coal that contains significant amounts of sulfur, and because the high-quality ore was low in sulfur compounds. Moreover, iron sulfides were not used in this period because of the difficulties of eliminating sulfur from the metal bath. Calcium probably came from the ore: hematite can be a component of metasedimentary rocks, such as oolites (Pipino 2016). These rocks are typical of the region and mainly composed of calcium carbonate. The other trace elements present are probably due to the ore, the pollution of the charcoal, or the environment inside the furnace (Carmignani et al. 1976; Ciarapica et al. 1985; Davis et al. 1996; Brown 2000; Biagioni, Bonaccorsi et al. 2010).

[1] Laboratory Equipment Corporation.

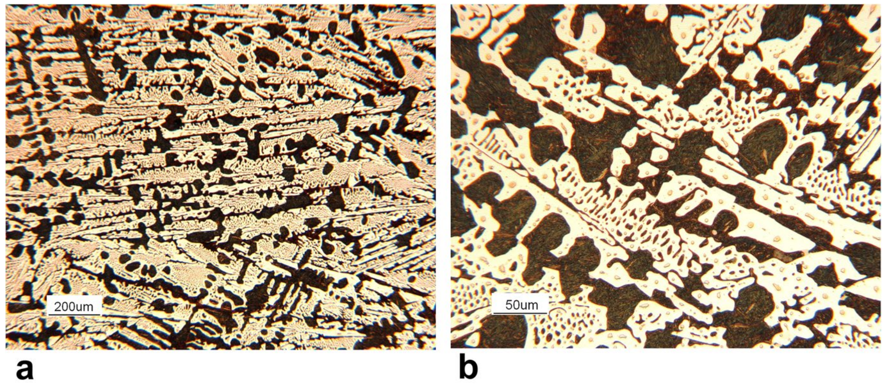

Fig. 9 Microstructure after chemical etching: pearlite (*brown*) and cementite (*white*). (Photos by authors, 2019.)

Figure 8 shows images of the polished surface of the component. It is possible to distinguish mainly graphite flakes and a minor presence of vermicular or spiky graphite. This corresponds to ASTM Type VII and Class 1, usually seen in gray cast iron (ASTM A247-19). No porosity or shrinkage was detected.

The microstructure was revealed by using nital 2% for 5 s.; it is shown in Fig. 9. The artifact features a dual-phase structure characterized by two structural constituents: the dark one is the eutectic constituent, pearlite, embedded in the white one, cementite I (iron carbide, Fe_3C). This structure is academically known as "ledeburite II." A cut through an original austenite dendrite that has turned to pearlite can be seen. In addition, there are small flecks of pearlite (Davis 1996). This led us to consider a slow cooling rate: maybe the component was a remnant inside the oven collected after the furnace renewal.

The sample drawn is rich in inclusions, and slag entrapment is evident. This sort of entrapment is typical of ancient artifacts due to the complexity of the production process.

By using a scanning electron microscope equipped with an energy-dispersive spectroscopy probe, it was possible to determine the local chemical composition in order to obtain information about nonmetallic compounds within the metal matrix that can be useful in defining the provenience of the mineral. Figure 10 shows the analyzed locations; the different grayscale areas underline the different chemical compositions.

The mean chemical composition of the slag is reported in Table 2.

The overall composition shows mainly the presence of calcium-magnesium and silicon, the main elements composing the rock that contains the iron ore and not easily eliminated by calcination. These rocks are metasedimentary (calcium-magnesium based) and metavolcanic (silicon based); the former are characteristic of Tuscany and the latter of Elba (Gill 2014).

The local energy-dispersive spectroscopy analysis on different phases visible in the slag itself shows the presence of iron oxide not completely reduced and also pure iron that was reduced but remained entrapped in the nonmetallic compound. Also, sodium, potassium, chlorine, and phosphorus were revealed and are symptomatic of the mineral. The high content of aluminum and titanium is interesting: these elements compose titanite and chloritoid, which are peculiar to mines in the Ligurian backcountry (between Genoa and La Spezia), and this implies the iron ores were extracted in that place. Moreover, it is important to remember that magnetite often comes with the presence of titanium, an element that is hard to remove from the metal bath (Pipino 2016). The simultaneous presence of hematite and magnetite suggest that the ore was a mixture of several minerals coming from the surrounding quarries (mainly Liguria, Elba, Tuscany).

In closing, the small amount of iron oxide detected (≈3%) in the nonmetallic inclusions confirms the iron was produced using a blast furnace, namely the *canecchio* (Carmignani et al. 1976; Ciarapica et al. 1985; Scott 1987; Brown 2000; Biagioni, Bonaccorsi et al. 2010; Mentovich et al. 2010; Cvikel et al. 2013; Gill 2014; Benvenuti et al. 2016).

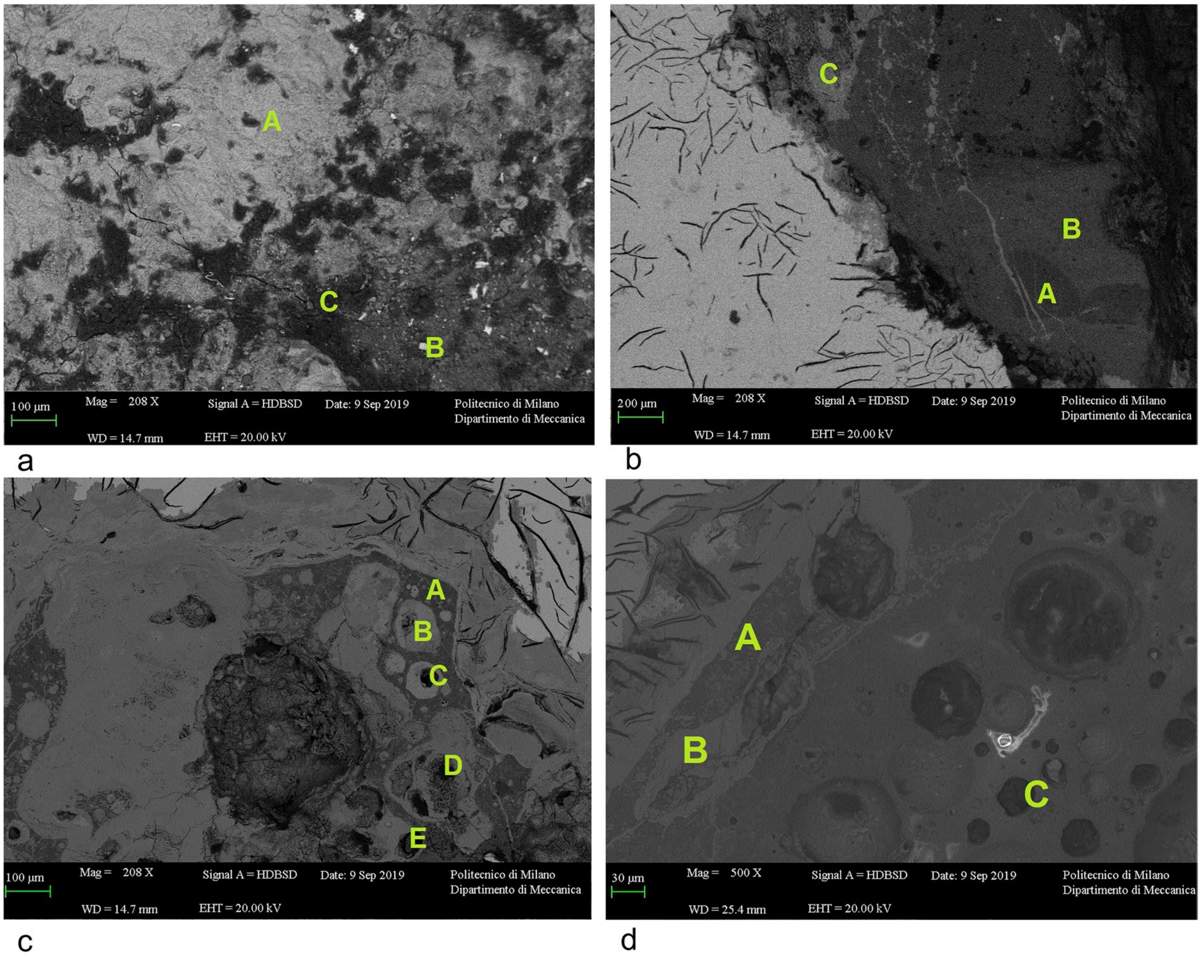

Fig. 10 Local chemical composition analysis of the slag: on the surface (*a*) and on polished surfaces (*b, c, d*). Capital letters (A, B, C, etc.) refer to Table 2. (Photos by authors, 2019.)

Conclusions

This article reports the historical context that brought the Este family to the annexation of the Garfagnana region in order to acquire equipment for the production of iron shot for both military and economic benefits. Thanks to the documents preserved by the Modena archives and thanks to the resourcefulness of the Buffardello Team (a cultural association of Lucca) it was possible to reconstruct the Fornovolasco settlement, i.e., the place chosen for the intense casting campaigns of the Este. Moreover, it was possible to sketch the *stancia del forno* (furnace room) with details and dimensions. The documents provided information about the first casting campaign undertaken by Master Tacchetto; this information was useful in understanding the blast-furnace process and for sizing the furnace itself.

During the research, a round artifact was found and analyzed. The artifact, perhaps a botched cannonball, is a eutectic, gray cast iron characterized by low porosity and good microstructural features in terms of dendrite development and structural constituents. The traces of calcium, silicon, titanium, and aluminum in the slag confirm that the iron ore was a mixture of hematite and magnetite coming from the surrounding quarries.

Table 2 Results of the scanning electron microscope energy-dispersive spectroscopy analysis of the slag (percentages by weight)

		C	O	Na	Mg	Ti	Al	Si	S	P	Cl	K	Ca	Fe
Figure 10	Overall [a]	21	26	—	2.2	—	2	4.2	2	—	1	1	7	33
Figure 10*a*	A	—	28	—	—	—	—	1	—	1.4	—	—	1	68
	B	—	23	—	—	—	—	—	—	—	—	—	—	77
	C	31	20	—	5.3	—	5	11	—	—	2	6	—	20
Figure 10*b*	A	—	37	—	28	—	2	27	—	—	—	2	—	4.7
	B	—	38	2	—	—	8	28	—	—	—	5	8.1	11
	C	—	21	—	—	—	—	1.1	—	—	—	—	—	78
Figure 10*c*	A	6.4	40	1	1.2	1	6	25	—	—	—	2	16	1.7
	B	6.2	35	—	—	—	—	1.7	0.1	—	0.1	—	0.1	57
	C	3.5	2.5	—	—	—	—	0.4	—	—	—	—	0.3	93
	D	—	21	—	—	—	—	4.4	—	—	—	—	—	75
	E	—	—	—	—	—	—	1.7	—	—	—	—	—	98
Figure 10*d*	A	15	46	1	0.7	0.3	7	20	—	—	—	4	5	1.2
	B	14	41	—	—	—	0.3	3.8	—	—	—	—	0.2	41
	C	—	16	—	—	—	—	3.9	3	—	—	—	5.1	73

[a] Capital letters (A, B, C, etc.) refer to indicated locations in Fig. 10

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