From the bloomery furnace to the blast furnace: The iron working complex of Valle delle Forme at Bienno, Brescia, northern Italy (mid 13th to mid 15th century)

C Cucini, M P Riccardi and M Tizzoni

ABSTRACT: The Lombard Iron District lies in the Alpine valleys of the provinces of Bergamo and Brescia in northern Italy. Its iron ore is high in manganese, low in sulphur and without phosphorus. This area played a key role in the development of the Alpine/Lombard blast furnace. Valcamonica, in the province of Brescia, is part of this district. Some years ago, four iron smelting and forging sites were excavated in this valley in the territory of the village of Bienno. One site belonging to the late medieval times was explored where there was a blast furnace with its forge and its annexes. This paper aims to discuss the spatial organization of this site, its parts and its waste with reference to the Lombard literary and archival sources. The other three sites were earlier; one belongs to the late Roman Imperial period (early 5th century) and shows the intentional production and decarburization of cast iron while two sites belonging to the Lombard period (7th century) had bloomeries.

Introduction

The Lombard Alpine valleys had an important role in the transition from the direct to the indirect process in iron metallurgy. During the Middle Ages, the technique of the so-called Bergamasque (or Brescian) blast furnace was mastered in this area. This blast furnace is different from the Walloon types known in central and northern Europe.

At the site of Valle delle Forme there was an archaic blast furnace and a forge with a water-powered trip hammer used for the decarburization of cast iron for the production of semi-finished wrought iron. Bergamo University under the direction of M Tizzoni partially excavated this site in 1997 and in 2006 (Cucini Tizzoni and Tizzoni 1999a, 201-213; Cucini Tizzoni 2008), while the iron scraps and the slags from the site were the subject of a PhD thesis at Pavia University and at the CEA at Saclay in France (Uda 2015-16).

The geological and technological context

The site of Valle delle Forme lies in the territory of the village of Bienno in the Camonica valley in the province of Brescia (Lombardy, northern Italy). The Camonica valley (Valcamonica), well known for its prehistoric rock-carvings, lies within the area of the so-called Lombard Iron District stretching from Lake Como to Lake Garda (Stella 1921). This area is rich in haematite, siderite and goethite deposits, which were of the highest importance for the economic history of these valleys for two millennia. The iron from the reduction of these ores is of high quality because of their high manganese content, low sulphur and lack of phosphorus (Curioni 1877; Stella 1921; Cucini Tizzoni and Tizzoni 1999a, 114; Leroy 2010).

These ores can be reduced at relatively low temperatures forming white cast iron. Their historical and economic importance, their production and the quality of their iron allows us to compare the Lombard iron deposits to those of the far better-known regions of Noricum and

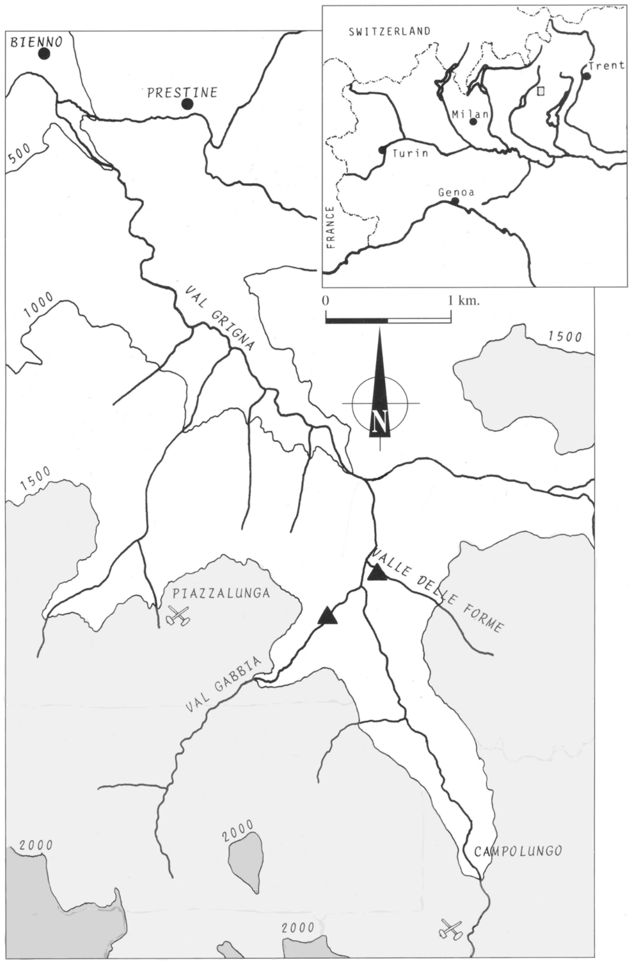

Figure 1: Places mentioned in the text. The black triangles mark the smelting sites in Val Gabbia and Valle delle Forme; the crossed hammers indicate iron ore mines.

the Pyrenees (Tizzoni 1997; 1998; Cucini 2012, 47-48). Intense mining activities are known in this area since the Roman Imperial (Flavian) period (Cucini 2012, 50-51). There were widespread mining areas often in remote and steep valleys covered by thick coniferous woods, which provided the wood necessary for both the mines and for charcoal making. During the transition from the late Roman period to the early Middle Ages, iron production in these remote mining districts was undisturbed. The collapse of the Roman centralized economy did not upset their metallurgical output, which instead developed important technological innovations until the late Middle Ages (15th century) (Cucini Tizzoni and Tizzoni 1999b; Giannichedda 2006; Cucini and Tizzoni 2014).

The key sites showing the passage from the direct to the indirect process in iron metallurgy are in the territory of Bienno (Fig 1). At about 500m as the crow flies from the site of Valle delle Forme, there are the iron smelting sites of the tiny Val Gabbia, and together these sites provide a clear example of the century's old exploitation of the Lombard Iron Basin. During an early mining and metallurgy research project from 1994 until 2006 (Cucini Tizzoni and Tizzoni 1999b; 2000; 2006), three iron smelting sites were archaeologically explored in Val Gabbia (at 1375m above sea level) and they have radiocarbon dates spanning from the beginning of the 5th until the middle of the 8th century CE. The ores used at these sites are from the large haematite and goethite mine of Piazzalunga (at 1330-1635m above sea level) (Morin 1999), though the exploitation of closer and yet undiscovered but much smaller iron ores bodies cannot be ruled out (Curioni 1877). The Piazzalunga mine is 3km as the crow flies from these sites and its last exploitation has been dated within the years 1390 and 1640 CE (Morin 1999).

At site 3 of Val Gabbia (radiocarbon dating 410-600 CE) the product of the reduction furnaces was worked in a semi subterranean forge-hut, where the smiths decarburized lumps of white cast iron in order to make finished products (Cucini Tizzoni and Tizzoni 2003; Fluzin 1999; 2000; 2003). This site is very important for the origin of the blast furnace because here we have the earliest known intentional cast iron production and the mastering of the decarburization technique.

The nearby sites 1 and 2 are later, belonging to the Lombard period (radiocarbon dating 590-680 CE and 560-760 CE) and they seem to continue the direct process tradition of bloomery smelting.

Palaeo-botanical investigations in this area have shown that there was a first period of deforestation beginning around the year 500 CE with peaks in the period 800-880 CE and above all in 1150-1250 CE (Mighall *et al* 2003).

There are nine radiocarbon dates from the site of Valle delle Forme, all of them within the years 1223 and 1440 CE. This is the exact prototype of the metallurgical structure known from the following centuries as the Bergamasque blast furnace with an attached forge for cast iron decarburization (Cucini Tizzoni and Tizzoni 2006).

The earliest record of a water-powered furnace with all its equipment (*furnus* with *aquaducti* and *scherpa*) is in a 1212 Bergamasque document referring to the rent of such a furnace located in a valley near Bergamo (Cucini Tizzoni 1994). This metallurgical plant was divided into forty parts, similar to division used with ships and mines, of which half belonged to the bishopric of Milan. In the 1212 document Alberto son of Ottebono Bruzzoni rents to Domenico Negrelli half of his seven parts of the furnace with its water ducts and equipment. From later documents, we know that the number of parts held by each owner corresponded to a certain amount of time during which he had the right to run the furnace to reduce his own ore.

Slightly later, in 1227 and 1236, it is recorded that rents were paid in cooked iron (*ferrum coctum*) to the Abbey of Astino near Bergamo (Cucini Tizzoni 1994). At the end of the 13th century large amounts of raw (*ferrum crudum*) and cooked iron (*ferrum coctum*) were delivered to the town of Bergamo (Mainoni 1997, 68-79). Since the 15th century archival documents show the Bergamasque blast furnace had spread to the other Italian states, as far as Sicily and Corsica and to the north of the Alps in Dauphiné (France), Switzerland, Austria, Slovenia and Poland (Cucini Tizzoni and Tizzoni 1993).

The iron-making site of Valle delle Forme

The archaeological data

The site lies in a very small side valley off the main Val Grigna (Fig 2). Its unusual name (Valley of the Moulds) is connected to liquid iron casting into sand moulds. It is located at 1200m above sea level on a river terrace slightly sloping to NNE. It was necessary to cross this site when going to the medieval village of Bienno from the Piazzalunga iron mine.

An archaic blast furnace formed the metallurgical plant. It had a slag-crushing device upstream near the ford of the river and a forge with its hammer at about 80m downstream. A long water channel fed by the waters of the Grigna River (6 to 3 on Fig 2) connected them all. This channel had a regular slope and at least one branch to the water wheels. Near the forge there was a small hut used by the iron masters. The site was damaged by landslides and rocks falls from the overhanging mountain. The presence of some huge boulders limited the extent our excavation.

The location of the forge and its hammer were the result of rational and accurate planning. They were built in a flat area cleared of rocks, levelled by heavy work and by a retaining wall (Fig 3, F). To the south, toward the mountainside, where the landslide was more extensive, a huge wall was built using large boulders, which meets the water channel at a right angle. There were other smaller retaining walls, but they collapsed as a result of the landslide that caused the final abandonment of the site. Other structures connected to those previously mentioned and built in a similar technique are the masters' hut (Fig 3, H) and a sort of narrow passage (0.70-0.80m wide) running along the edge of the branch of the water channel (Fig 3, P). The natural depression existing almost at the centre of the site was filled in using large stones for its bottom and thin flakes of stones and soil at its top in order to create room for the trip hammer.

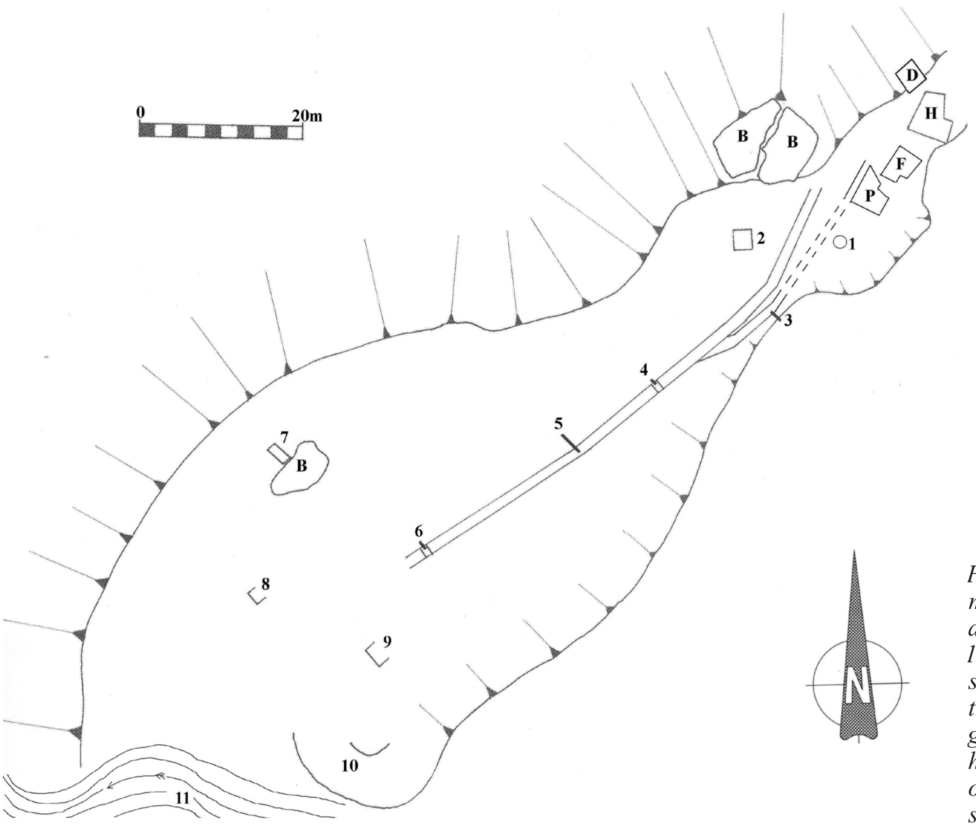

Figure 2: The Valle delle Forme metallurgical area. D, H, F and P, archaeological trenches; B, boulders; 1, circular structure; 2, rectangular structure; 3–6, trial trenches across the water channel; 7, trial trench in the glassy slag deposit; 8, corrugated iron hut; 9, old stone house (built on the site of the blast furnace); 10, track to the site; 11, ford of the river Grigna..

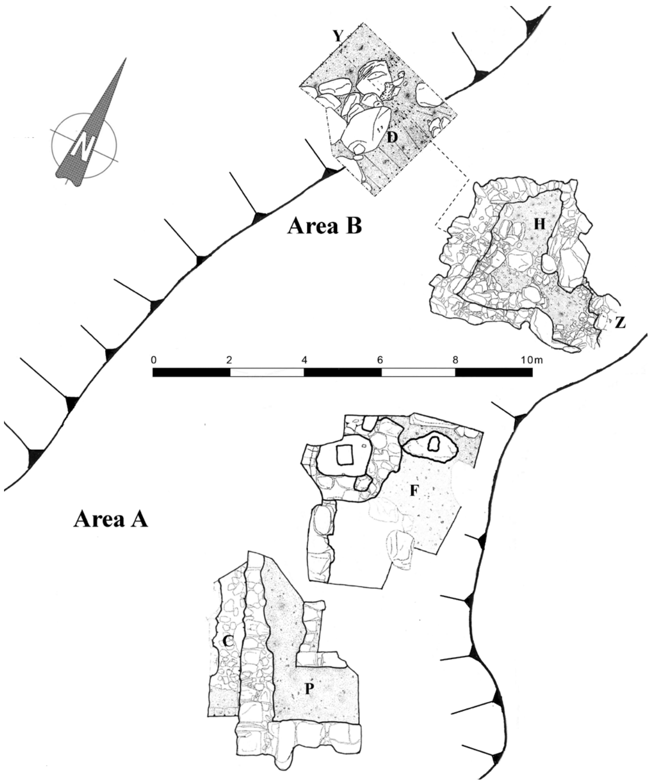

Figure 3: Plan of trenches D, H, F and P in areas A and B.

The water-powered trip hammer was set at a short distance from the water channel and the passage running along it. The water flowing in the channel turned the water wheel and its cam axle. This axle was connected to the hammer by a hole in the forge (Fig 3, F) outside wall. Activated by the cam axle the hammerhead struck an anvil, possibly made of steel. The ground around the hammerhead was paved with slabs of stone set into a reddish clay. This flooring was roughly square in plan (2.30 x 2.30m) and it possibly had the function of easing the movements of the workers around the hammerhead. Above it there was a large and thick rectangular stone, perfectly flat and horizontal with rounded edges (1.30 x 1.05m). At its centre it had a carefully chiselled rectangular recess (0.50 x 0.38m, 20-30mm deep). This was the setting for the wooden log (Bergamasque dialect: *soc*) of the anvil for the trip hammer. Close to its longer sides, two holes (0.40 x 0.36m, 0.24m deep and 0.50 x 0.35m, 0.21m deep) are cut into the floor. In front of the anvil base a large and tall rhomboid stone (1.45 x 0.80m, 0.20m high) was the base for the wooden log of the smaller anvil (Bergamsque dialect: *incösineta*) used for hand hammering. Its flat upper face had an irregular rectangular recess chiselled out (0.39 x 0.25m) and was the setting for its log. The trip hammer's helve must have been about 3m long. It was a big trip hammer of the sort used for cast iron decarburization in order to make semi-finished products.

Along the river terrace where the smithy was situated, a branch of the water channel ran from SW to NE (Fig 3, C). Its masonry was rather regular, square in section and paved with stone slabs. It was 0.60-0.80m wide and sloping regularly with a gradient of 4%. The iron masters must have used the passage (Fig 3, P) running along it in order to check the operation of their machinery.

The forge

During the forging operations thick layers of debris formed around the bases of the anvils. Around the larger anvil there were mainly oxidized fragments of iron giving the layer a brilliant rust-red colour, while around the base of the smaller anvil there were many lenses of hammer scale, charcoal and lumps of oxidized iron. A sub-circular layer formed by hammer scale with many iron lumps covered the small anvil base up to 150mm thick. The forging activity must have been intense as demonstrated by the deposit of layers of hammer scale and by areas of trodden soil formed by iron lumps, charcoal and hammer scale (*sols d'atelier de forge*, Leblanc 2004). Both the anvils bases were completely covered by metallurgical debris. No forge hearths were found, they must have been outside the excavated area.

The end of the metallurgical site

The metallurgical plant was abandoned around the middle of the 15th century. All its iron parts, the anvils, every tool, also the main and more prized wooden parts such as the water wheel and the axles were recovered with outmost care. The site was also stripped of the valuable stone struts of the hammer. A landslide more than 1m thick covered the whole area and the branch of the channel. Possibly the site was transferred somewhere else closer to the village of Bienno, where an ancient blast furnace existed until a few years ago (Forno de La Parada). At Bienno itself traditional water powered forges were active until about 30 years ago.

The metallurgical waste disposal

The waste produced by the forge and the trip hammer was huge. Most of it was simply thrown down the river terrace edge along the steep mountainside. A trial trench at the northern edge of the metallurgical area showed a thick layer (over 1m thick) of black soil rich in charcoal, slags, slag cakes, hammer scales and iron fragments (Figs 3(D) and 4). Notwithstanding the steep mountainside, the dumping of waste was such that it enlarged the river terrace itself. Because of this, the iron masters were compelled to set up a small gangway made of nailed planks overhanging the mountain slope. In this way, they could dispose of the larger slags, such as the slag cakes and the large slag lumps, which could form

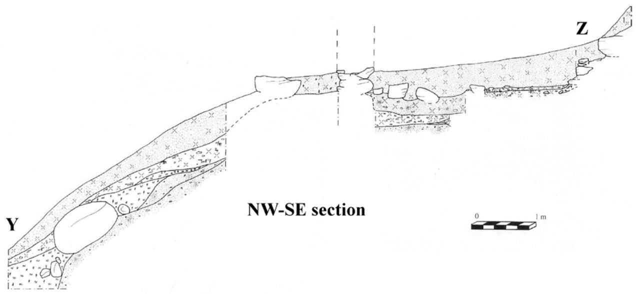

Figure 4: Archaeological section Y-Z across Area B.

and remain trapped inside the blast furnace.

The iron masters' hut

The iron masters' lodging was a small stone hut at the northern edge of the metallurgical plant (Figs 3(H) and 4). It was formed of two contiguous rooms with an irregular plan and a compacted earth floor.

The archaic blast furnace

A dispersal of many glassy slags (*laitiers*) near the ford of the Grigna River at about 80m uphill from the trip hammer and the smithy pointed to the existence of a blast furnace. Today in its place there is an old semi-subterranean stone house (Fig 2, 9). Stones from the blast furnace were used in its construction. They are carefully squared, slagged stones showing traces of molten iron. The abandoned blast furnace was used as a quarry for this building.

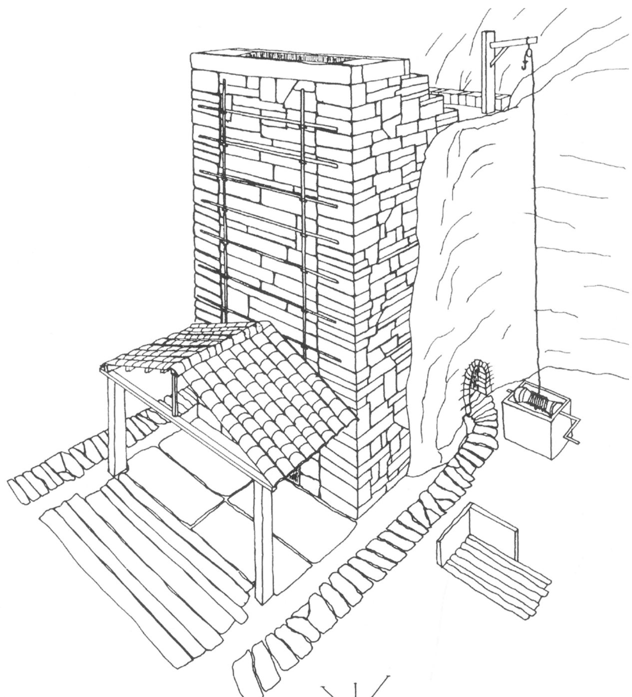

Figure 5: Reconstruction of the Bergamasque blast furnace at Locarno Valsesia (Piedmont) according to a description of the end of the 17th century.

The typical Bergamasque blast furnace is a heavy tower-like structure (Fig 5). It is square in plan, about 8m tall and built with large, square fire-resistant stones reinforced with iron tie rods. Its bottom could be slightly lower than the surrounding ground. It was built against a rising slope in order to provide better insulation, but it was separated from it by a vaulted low and narrow stone passage in order to avoid water infiltration. The furnace is hollow inside and its section has the form of two truncated pyramids joined at their bases (Fig 6). Its inner surface is covered with fire resistant clay. The ore and the charcoal are poured in from its top, while the molten slag and the cast iron come out of the opening at its base. In order to reach the necessary temperatures for cast iron formation it had a forced ventilation system provided by a couple of huge bellows moved by a cam axle connected to a waterwheel (the hydro-aeolian trompe was introduced after the 17th century). Since the interior was square this blast furnace had the problem of having four cooler corners where large lumps of slag, iron and partially reduced ore could accumulate, which had to be removed when the furnace was blown out. In order to avoid this problem, the so-called Norwegian blast furnace was introduced from the beginning of the 19th century and its round internal plan allowed much more uniform temperatures.

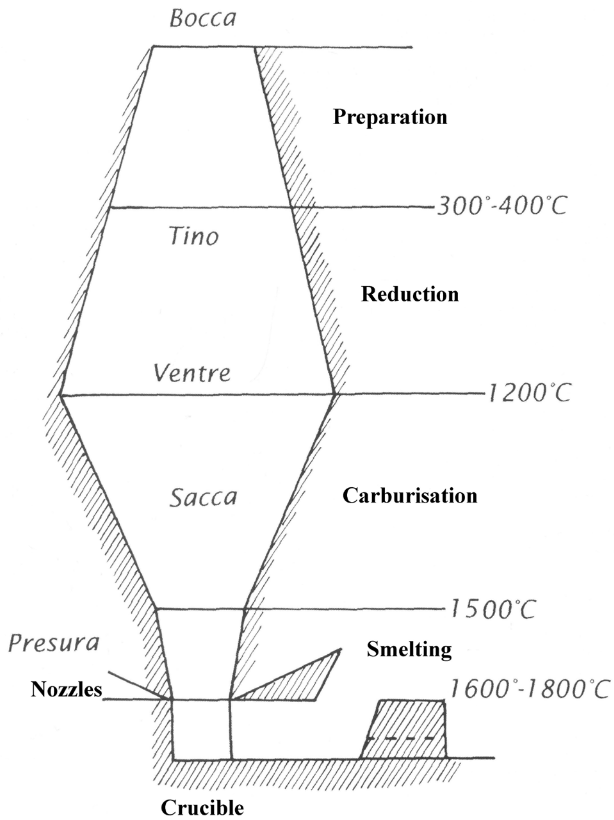

Figure 6: Cross section of the interior of a Bergamasque blast furnace with the Italian names for its parts (after Zoppetti 1894) with English descriptions of what is happening at each level.

The fuel used in all these furnaces and forges was always charcoal since coal is exceedingly rare in the Alps and quite scarce in Italy itself. This explains why this technology spread in the Alpine area, across the Italian peninsula and in Poland whose coal deposits were only discovered in the 18th century. The small and poor-quality Lombard brown coal and peat deposits were not exploited until the late 19th century. The idea of 'a stone' which burns sounded such a nonsense that when in 1585 a Girolamo Rinaldi informed the Secret Council of the State of Milan about his discovery of a 'stone' which could make a very hot fire useful for domestic purposes, it did not deserve an answer. It is interesting to observe that Rinaldi himself did not even consider the possible uses of this 'stone' in metallurgy (Vianello 1936, 512).

The slag-crushing device

This machine (It *pestaloppe*) was set up at about 25m from the blast furnace, not far from the water channel (Fig 2, 6). Here only glassy slags were found, broken up and crushed almost to dust. The glassy slags (It *loppe*) had to be broken in order to recover the iron prills, nodules and filaments (It *ferrino*) trapped inside. This happened in all the Bergamasque blast furnaces. The 19th century metallurgist V Zoppetti correctly wrote that the recovery of *ferrino,* while very rare abroad, was quite important in Lombardy. This was due to the 'higher degree of basicity of our vitreous slags, which do not separate easily from the metal if it is not from very manganiferous ores' (*maggiore basicità delle nostre loppe, le quali meno facilmente si separano dal metallo se non provengono da minerali molto manganiferi*) (Zoppetti 1873, 113). These slags belong to the type called in French *laitiers à grenaille*.

These tiny iron nodules recovered by crushing the slags could be an important part of metal production. In certain instances, they could amount to the half of the metal produced (Cucini Tizzoni and Tizzoni 2001, 169). When molten, the iron content of the *ferrino* was 80%.

We have a lot of information about this crushing device in archival documents, but not a single illustration has been discovered so far. There is also no trace of this machine in Renaissance and modern metallurgical treaties, maybe because they are not dealing with Lombard iron metallurgy specifically. Possibly it was a similar machine to the one used for crushing ores illustrated by Della Fratta Montalbano (1687, 61). This was powered by a waterwheel with an axle and cams; at Valle delle Forme it was set up close to the water channel so could have been water-powered.

The metallurgical waste and its distribution

There was a large amount of waste at the site and it belonged to different categories. Some heavy and dense bloomery slags were from the landslide layers in Area A (Fig 3), immediately below the southern slope of the river terrace, but not a single piece of bloomery furnace was found anywhere at the site. We can suppose that these slags came from the bloomeries of the nearby Val Gabbia sites 1 and 2 and that they were brought here for recycling. They were heaped against the retaining wall and were the first to be covered by the landslide. We know from archival documents that slags from bloomery furnaces were usually recycled in blast furnaces (Cucini Tizzoni and Tizzoni 1992). When Val Gabbia sites 1 and 2 were discovered the archaeologists were surprised that there were no significant slag heaps at these sites but rather a scatter of slags on the soil surface. This gave the impression that something had already been removed from the sites whose surface appeared disturbed.

The hammer scale and the strongly magnetic iron lumps are only from Area A, close to the hammer's anvil. The glassy slags were found only in the area where the archaic blast furnace and the slag-crushing device were (Fig 2, 7 and 9). In the dump below the terrace – Area B (Fig 3) – there were all kinds of slags, mainly the large slag cakes formed during the pig iron fining.

Cast iron decarburization as described by 18th- and 19th-century Lombard metallurgists

In the Lombard and Eastern Piedmontese Alps, the numerous Bergamasque furnaces known from documents since the 13th century were connected with forges for cast iron decarburization. They are called 'big forges' (Bergamasque dialect: *füsina grossa*). The word 'big' is a technical and not a generic description. Here ingots of cast iron were reheated on the forge hearth and beaten with a trip hammer to be transformed into semi-finished products.

Archival documents distinguish the 'big forge' from the thinning or flattening forge (Bergamasque dialect: *sutiladora*) (Figs 7 and 8) and from the forge for nails (Bergamasque dialect: *ciodéra* or *ciodaröla*). These smaller forges were dealing with later phases in the *chaine operatoire*, the transformation of the semi-finished products (for example round or square sectioned iron bars) into smaller finished objects: from any sort of large tools and buckets down to needles.

The remains of a trip hammer belonging to a 'big forge'

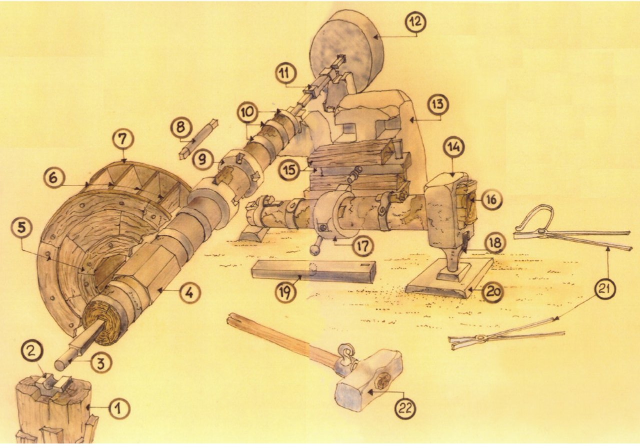

Figure 7: The trip hammer of a thinning or flattening forge at Bienno. This type of hammerhead and tongs is for forging buckets. At the far end of the axle, which is driven by the water wheel, there is a grindstone. Each component of the plant had its own technical name. In the local dialect they are: 1, la cavra; 2, öl runì; 3, la guei; 4, l'erbor; 5, i gaei; 6, i cop; 7, la röda; 8, la pálmola; 9, i garciocc; 10, le ere; 11, la bühola; 12, la mola; 13, la hoca; 14, öl cö del mai; 15, i primahöi; 16, öl manech del mai; 17, la boga; 18, la boca; 19, öl pal de fer; 20, la mahèta; 21, le tanae; 22, la maha del rampì.

were discovered at Valle delle Forme and its radiocarbon dates show that it was active between 1250 and 1431.

Unfortunately, while we have many reliable representations and photos of thinning or flattening forges, there is not such a rich iconography for the 'big forge'. When the last Norwegian blast furnace at Fiumenero in Bergamo province (Fig 9) closed at the end of the Second World War, its 'big forge' was razed to allow the building of a garage. If we look at the iconography of decarburization forges to the north of the Alps, it is rather unreliable. There are barehanded iron masters holding iron bars with an incandescent extremity under the hammer, or there is a single master holding large bars with huge tongs. These are two feats impossible for a human being. The masters must have

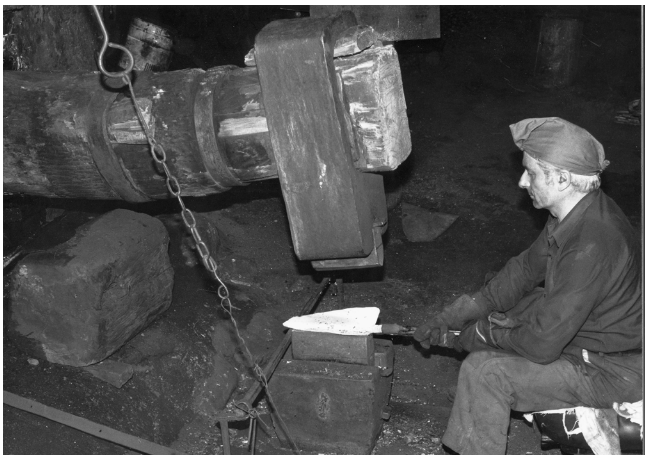

Figure 8: One of the last iron masters of Bienno at work in his forge in 1989.

Figure 9: The Norwegian blast furnace at Fiumenero was rebuilt in the 19th century in the Bergamasque furnace style, although its crucible was circular rather than square.

had some help to move and keep the iron bar under the hammerhead. The combined effects of the weights of the bar, of the tongs and the vibrations due to the strokes of the hammer would have been impossible to withstand. Some kind of support for the handles of the tongs must have been necessary. We suggest that the two symmetrical holes close to the large anvil base were the settings for two wooden stumps as high as the anvil where the master could lay his tongs handles for support during forging.

In the19th century Lombard metallurgical literature there are descriptions of how these plants worked, the most accurate and detailed is by the engineer V Zoppetti (1873, 134-37). He wrote that once upon a time 'the properly called Bergamasque Method' (*Metodo bergamasco propriamente detto*) was in use in every Lombard valley. He divides it into three phases described as follows:

- Smelting. The iron master (Bergamasque dialect: *maister* or *maistr*) fills the forge hearth with charcoal, flat ingots of pig iron are loaded above it and close to the nozzle. The forced air blow is started, but it must be kept low since this is a slow process. Charcoal is then added gradually. The smelting is complete after two and half hours. Then the fire is cooled by sprinkling water on it, the coal and slags on the surface are taken away. Many hammer scales are then thrown on the molten metal, which is then stirred until it becomes doughy and begins to set in lumps. Then the master takes this metal to the working bench where he cools it with water. The slag formed during this phase is either thrown away, or recycled in the blast furnace.

- Formation of the 'overdone' (Bergamasque dialect: *cottìsc*). After the cleaning of the nozzle and hearth, it is filled again with charcoal leaving an empty space in front of the nozzle where one sixth of the smelted metal is put. This is covered with charcoal and the air blow is started while gradually adding small chips of charcoal. Thus partially decarburized, this lump of metal forms a porous mass. The small amount of slag still trapped in the metal becomes doughy. As the decarburization processes the metal becomes more coherent. After about 45 minutes it coagulates forming a globular 'overdone'. Then the master follows the same process for all the remaining smelted metal.
- Formation of the 'masses' (Bergamasque dialect: *massèl*). The hearth is cleaned again and loaded with burning charcoal; the iron master places the 'overdone' on it close to the nozzle. The air blow is started, but this time with constantly increasing strength. Charcoal, iron rich slags and hammer scales are gradually added to the sides of the nozzle. In this oxidizing atmosphere the metal of the 'overdone' begins to form metal droplets that fall to the bottom of the hearth where they coalesce forming an amorphous mass. While falling these drops cross the pool of molten slags under the fire and decarburize. The master takes this 'mass' to the working bench where it is cleaned of the charcoal and adhering slags. Then, using a special pair of tongs he puts this metal under the trip hammer's head in order to give it a roughly parallelepiped form. After this, he reheats the 'mass' on the forge hearth, when it is hot he puts it again under the trip hammer's head to split it into three parts. Each part (Bergamasque dialect: *tajù*) is then elongated with the trip hammer forming a 12-13kg heavy iron bar.

It takes eighteen and a half hours to complete the whole process. This metallurgical process seems to be the same described by Brembato in the short part of his book of 1663 devoted to iron metallurgy (Tizzoni 1991).

In1784 the metallurgist E Pini compared this method to the one used in Styrian forges. He discovered that the Bergamasque method was not efficient at all since it used twice the amount of charcoal, and that the Styrian preparation of the 'overdone' took only 18 minutes (Frumento 1963).

Characteristic of the Bergamasque finery method was the use of a large amount of hammer scale in the first and in the last phases of the decarburization process. The metallographic analyses of the finery slags (slag cakes and smithy slags) have shown the presence of metal chips and hammer scales (Uda 2015-16, 91, 93). This reveals that at Valle delle Forme this method for cast iron decarburization was already in use by the end of the 13th century.

Conclusions

The iron-working site of Valle delle Forme formed an organized and functional production plant provided with all the machines and equipment for the production of iron and steel by the indirect process. An archaic blast furnace close to the river had a trip-hammer forge for cast iron refining and a slag-crushing device for the recovery of the iron left trapped in the too viscous basic slag. Each machine was water powered, fed by a long artificial channel. This metallurgical plant was well-planned and built all in a single phase. There were spaces and corridors allowing the control and the correct working of all the machines. A stone hut was provided for the workers. All the walls of the constructions were built with care. The usage of large stones in the structures shows that they were meant to last for a long time.

Acknowledgements

Figure 7 is by A Bettoni, Figures 5, 8 and 9 by M Tizzoni.

References

Cucini C 2012, 'Venti anni di ricerche archeometallurgiche in Italia del nord', in C Cucini (ed), *Acta mineraria et metallurgica. Studi in onore di Marco Tizzoni* [=*Notizie Archeologiche Bergomensi* 20], 39-56.

Cucini Tizzoni C 1994, 'Miniere e metallurgia in alta Val Brembana – Bergamo (secoli XII-XVI)' , *Bergomum* 2, 47-98.

Cucini Tizzoni C 2008, 'Il maglio, la fucina, i forni e il pestaloppe della Valle delle Forme (Bienno, Brescia)', *Notizie Archeologiche Bergomensi* 16, 227-248.

Cucini C and Tizzoni M 2014, 'Iron production in Lombardy from the 2nd century BC until the 6th century AD', in B Cech and T Rehen (eds), *Early Iron in Europe* (Montagnac: Monographies Instrumentum 50), 173-180.

Cucini Tizzoni C and Tizzoni M 1992, *Le antiche scorie del golfo di Follonica (Toscana)* (Milano).

Cucini Tizzoni C and Tizzoni M 1993, '"Li Peritj Maestri". L'emigrazione di maestranze siderurgiche bergamasche della Val Brembana in Italia e in Europa (secoli XVI-XVII)', *Bergomum* 3, 79-178.

Cucini Tizzoni C and Tizzoni M 1999a, *La miniera perduta. Cinque anni di ricerche archeometallurgiche nel territorio di Bienno* (Breno).

Cucini Tizzoni C and Tizzoni M 1999b, 'The Late Roman ironworking site of Ponte di Val Gabbia III, Bienno (Brescia, Italy)', in L C Norbach (ed), *Prehistoric and medieval direct iron smelting in Scandinavia and Europe: Aspects of technology and society*. Proceedings of the Sandbjerg Conference 16th to 20th September 1999, [=*Acta Jutlandica* 76], 49-53.

Cucini Tizzoni C and Tizzoni M (eds) 2000, *Il ferro nelle Alpi. Giacimenti, miniere e metallurgia dall'antichità al XVI secolo - Iron in the Alps. Deposits, mines and metallurgy from antiquity to the XVI century.* Proceedings of the conference, Bienno, Italy, 2-4 ottobre 1998 (Breno).

Cucini Tizzoni C and Tizzoni M 2001, 'Il riciclaggio delle scorie negli altoforni preindustriali', in M-C Bailly-Maître, A Ploquin and N Garioud (eds), *Le fer dans les Alpes du Moyen Âge au XIXe siècle*, Actes du Colloque International, Saint-Georges-d'Hurtières 22-25 Octobre 1998 (Montagnac), 167-170.

Cucini Tizzoni C and Tizzoni M 2006, 'Alle origini dell'altoforno: i siti della Val Gabbia e della Val Grigna a Bienno in Valcamonica', in P Poggio and C Simoni (eds), *Musei del Ferro in Europa e in Italia. La ricerca storica e le esperienze di conservazione e valorizzazione*, Atti del Convegno di Brescia, 24-25 settembre 2004 (Brescia), 21-42.

Curioni G 1877, *Geologia applicata delle provincie lombarde*, 2 vols (Milano).

Della Fratta Montalbano M A 1687, *Pratica Minerale* (Bologna).

Fluzin P 1999, 'Ponte di Val Gabbia III: i reperti metallici della forgia. Primi risultati dello studio metallografico' in C Cucini Tizzoni and M Tizzoni (eds), *La miniera perduta. Cinque anni di ricerche archeometallurgiche nel territorio di Bienno* (Breno), 189-194.

Fluzin P 2000, 'Ponte di Val Gabbia III (Bienno). Les premiers résultats des études métallographiques', in C Cucini Tizzoni and M Tizzoni (eds), *Il ferro nelle Alpi. Giacimenti, miniere e metallurgia dall'antichità al XVI secolo - Iron in the Alps. Deposits, mines and metallurgy from antiquity to the XVI century*, Proceedings of the conference, Bienno, Italy, 2-4 ottobre 1998 (Breno), 24-31.

Fluzin P 2003, 'Synthèse des études métallographiques d'échantillons de la forge de Ponte di Val Gabbia III (bienno V-VI century AD). Mise en évidence de la décarburation de la fonte', in L C Norbach (ed), *Prehistoric and medieval direct iron smelting in Scandinavia and Europe. Aspects of technology and society,* Proceedings of the Sandbjerg Conference 16th to 20th September 1999, [=*Acta Jutlandica* 76], 139-145.

Frumento A 1963, *Imprese lombarde nella storia della siderurgia italiana, vol II: Il ferro Milanese tra il 1450 e il 1796* (Milano).

Giannichedda E 2006, 'Metal production in late Antiquity: from continuity of knowledge to changes in consuption', in D Lavan, E Zanini and A C Sarantis (eds), *Technology in transition: AD 300-650* (Leiden: Late Antiquity Archaeology 4), 187-209.

Leblanc J-C 2004, 'Nouveaux apports pour une archéométrie des sols d'atelier de forge', in M Mangin (ed), *Le Fer* (Paris), 103-105.

Leroy S 2010, Circulation au Moyen Âge des matériaux ferreux issus des Pyrénées ariégeoises et de la Lombardie. Apport du couplage des analyses en éléments traces et multivariées. Unpublished doctoral thesis, l'Université de Technologie de Belfort-Montbéliard.

Mainoni P 1997, *Le radici della discordia. Ricerche sulla fiscalità a Bergamo tra XIII e XV secolo* (Milano).

Mighall T M, Tizzoni M, Cucini Tizzoni C, O'Brien C 2003, 'The impact of Iron Age copper mining on vegetation: palaeocological evidence from Campolungo, Bienno, Lombard Alps, Northern Italy', *Notizie Archeologiche Bergomensi* 11, 253-271.

Morin D 1999, 'La miniera di ferro di Piazzalunga', in C Cucini Tizzoni and M Tizzoni (ed), *La miniera perduta. Cinque anni di ricerche archeometallurgiche nel territorio di Bienno* (Breno), 49-60.

Stella A 1921, *Le Miniere di Ferro dell'Italia* (Torino).

Tizzoni M (ed) 1991, *Brembato's La Mineralogia (1663)* (Firenze).

Tizzoni M 1997, *Il comprensorio minerario e metallurgico delle valli Brembana, Torta e Averara dal XV al XVII secolo* (Bergamo).

Tizzoni M 1998, *Il comprensorio minerario e metallurgico valsassinese*' (Lipomo: Monografie Periodiche dei Musei Civici di Lecco).

Uda I 2015–16, *The archaeological site of Valle delle Forme: archaeometric study of the iron making process between Middle Ages and modern period in northern Italy*. Unpublished PhD thesis, Pavia University.

Vianello C A 1936, 'Cave di lignite in Lombardia nel XVI secolo', *Archivio Storico Lombardo*, 512.

Zoppetti V 1873, *Stato attuale dell'industria del ferro in Lombardia e cenno sul possibile sviluppo della siderurgia in Italia* (Milano).

Zoppetti V 1894, *Manuale di siderurgia* (Milano).

The authors

Costanza Cucini, PhD in Archaeology at Pisa University, has surveyed and explored many metallurgical sites both in Tuscany and in the Alps over the years. She specialises in iron and copper metallurgy. She collaborates with CNRS (Laboratoire 'Métallurgies et Cultures' UMR 5060, CNRS IRAMAT Université de Technologie Belfort-Montbéliard).
Address: Via Pria Forà, 4, 20127 Milan, Italy
E-mail: costanza.cucini@libero.it

Maria Pia Riccardi is associate professor in Applied Mineralogy and Petrography (GEO/09), Earth and Environmental Department, University of Pavia. Her scientific activity concerns mainly mineralogical and petrographic studies of metal alloys and metallurgical slags.
Address: Dip. di Scienze della Terra e dell'Ambiente, Università degli Studi di Pavia
Via Ferrata, 9, 27100 Pavia, Italy
E-mail: mariapia.riccardi@unipv.it

Marco Tizzoni was formerly professor of European Prehistory at Bergamo University and has been researching ancient and early mining and metallurgy in the central area of the Southern Alps for over twenty years.
Address: Ra brüsadèla, 1, 6992 Cimo, Switzerland
E-mail: marco.t@bluewin.ch