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QUANTIFICATION OF SMITHING ACTIVITIES BASED ON THE INVESTIGATION OF SLAG AND OTHER MATERIAL REMAINS

SERNEELS Vincent, PERRET Sébastien
Mineralogy and Petrography, Department of Geosciences, University of Fribourg, Switzerland.

ABSTRACT :

Typical smithing slags are produced by an accumulation of fused materials at the bottom of the hearth. They have a characteristic plano-convex shape and variable dimensions. Between lighting and extinguishing, each corresponds to one unit of work in the hearth. Slag is made of different types of material in various proportions. It is possible to identify three main materials, characterized by aspect, mineralogical and chemical composition. Each type of material is related to a kind of work. The classification and quantification of a slag assembly allows to present a picture of the activity of a workshop.

KEYWORDS : iron, slag, smithing, classification, quantification.

THE PRODUCTION LINE OF IRON.

There are two main steps in the production line of iron. First, the metal has to be produced from the ore and then, the metal has to be shaped into an object (1).

During Antiquity, iron was produced in the solid state by reduction of iron oxides from an ore. This was achieved by the "bloomery process" or direct method of reduction by heating the ore with charcoal inside a furnace. At a temperature above 1000°c, the combustion gases, rich in carbon monoxide, reduce the iron oxide to the metallic state. The metal is far below its melting point and remains at the solid state. The other substances present in the load of the furnace, mainly silica, alumina and unreduced iron oxides, form a liquid phase - the slag - that separate and flow away from the metal. To melt the slag the temperature must rise above 1200°c. The chemical composition of the slag reflects that of the ore. The texture of the slag, vitreous or crystallized, is related both to the chemistry and the cooling conditions. The shape of the slag is linked to the type of the furnace. Typically, the shape corresponds to accumulation of cord-like flows or flat slabs when tapped and cooled outside of the furnace (2, 3). In other cases, slag is trapped at the base of the furnace in a pit previously excavated and forms a large cylindrical block (4, 5). The metallic product, the bloom, is an heterogeneous piece of metal, more or less consolidated, with a large number of pores and a variable amount of entrapped particles of slag and charcoal (6). In general, the carbon content of the bloom is limited and not homogeneous.

To produce an efficient object made of iron it is necessary to fashion the metal by plastic deformation in the solid state. Basically, this is done by heating the metal in an hearth and hammering it on an anvil (fig. 1). The smithing process not only affects the general shape of the piece, but also modifies the internal structure, the chemical composition and the physical properties of the metal. Hammering reduces the grain size, closes the pores and breaks the inclusions. Heating allows the grains to grow. At high temperatures, the material reacts with the atmosphere. By contact with oxygen during the heating phase, the carbon will burn and iron will oxidize. Another very important characteristic of metallic iron is its ability to be hot-welded. Two pieces of hot metallic iron are bound together by hammering. During the smithing process, different kinds of waste are produced. In the hearth, slag is formed by the melting of various materials that accumulate at its base. Hammerscales are formed during the hammering: under the hammer's blow, the oxidized crust formed at the surface of the hot metal by contact with the air is broken into small flat particles. Various metallic fragments can be lost or cut off by the smith during the fashioning of the object.

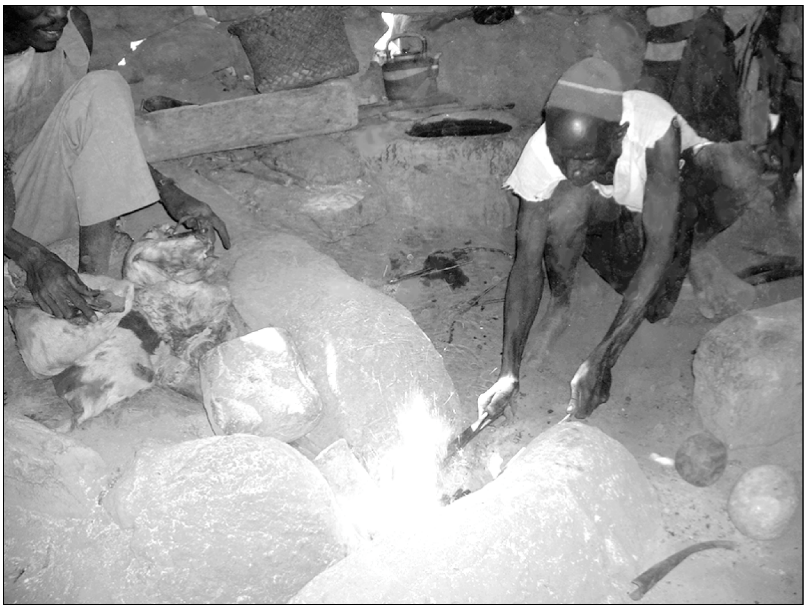


Fig. 1 : A traditional smithing workshop in the village of Sissongo (Mali).

The work at the forge is quite variable, depending on the physical nature of the metal worked, the complexity of the object and the skill of the craftsman. For this reason, the nature and the quantity of the waste is also highly variable.

THE STUDY OF THE METALLURGICAL WASTE.

The actual knowledge about the metallurgical processes applied in Antiquity allows, in most cases, to identify the different steps of the production line, especially to establish the difference between the material remains of a bloomery and of a smithing workshop.

In the case of the reduction step, our knowledge evolved considerably in the last decades. It is now possible to propose methodological answers (based on excavations of structures, quantification of residue, analyses in laboratories, anthracology, palynology, etc.) to the most frequently asked questions (kind of ore, pre-treatment of ore, type of furnace, use of flux, fuel, efficiency of the process, quantification of the production, quality of the product, etc.). As a general rule, the reduction of iron ore is a repetitive activity with a small range of variation at a given place during a given time. The nature of the waste provides indications about the process and the nature of the raw materials. Using this information, the amount of iron produced can be estimated based on the quantity of waste

The next challenge is related to use the archaeological evidence to describe smithing activity. In this case, knowledge at this stage is less developed and an improvement is necessary in the methodological approach. Contrary to reduction, smithing is a more varied activity and more complicated to describe. One can imagine blacksmiths performed always the same kind of work, for example, producing swords blades from bar of iron. Nevertheless, it is more likely that most were involved in different tasks. They probably changed frequently and used variable qualities of raw iron (uncompacted / compacted / recycled ; carbon-poor / -rich ; inclusions-poor / -rich ; phosphorus-poor / -rich), variable techniques (simple heating / hammering, welding, heath treatments, cementation) and produced different objects (simple / complex ; small / large). On the other hand, the volume of the activity can range from a single operation by an isolated smith to a full-time team of craftsmen working over several decades.

In this respect, there are two ways to try to arrive at the next step of understanding the work of the smith. The first one is to establish criteria to link one single piece of waste to a specific action. Detailed investigations of many specimens have been performed, proving great variability inside the smithing slags. In some cases, the authors propose linking specific morphologic (7, 8), chemical (9), petrographical (10) or metallographical (11) characteristics to a specific aspect of the work. Nonetheless, at present, there is no general consensus to validate the interpretations. The other approach is to consider the assembly of all waste from a given excavation to describe the volume and the range of the smithing activity. This is the point we are emphasizing in the following pages.

The material remains left by smithing activities are archaeological structures (workshops, hearths, working floors, anvil pits, storage pits etc.), tools (hammer, anvils, tongs, punches etc.) and residues (slag, hammerscales, metallic cuttings, etc.). In general, the archaeological structures are poorly preserved (12). Frequently, the blacksmith himself reorganized his workshop, destroying the hearth to rebuild a new one in the same place. Smithing tools are frequently found in hoards or graves (13, 14) but rather rarely in direct connection with a workshop. On the other hand, smithy debris is very common on archaeological sites. In particular, slag is very well preserved because it is difficult to recycle and little altered by burial. The study of the a slag assembly provides a reasonable, if not complete, idea of the activity of the smith.

The most common type of waste related to the smithing activities is the plano-convex slag (fig. 2). In many cases it is associated with iron cuttings, with hammerscales of various types (flat, irregular, spherical etc.), with nodular or irregularly shaped slag lumps, with fragments of hearth wall lining, etc. All this debris must be taken in account during the study. It provides ample supplementary or complementary information about the activity. Until now, only few efforts have been made to understand these remains and the field is still open for innovative research. They will not be discussed here in more detail.

THE FORMATION OF PLANO-CONVEX SMITHING SLAG.

Slag with a plano-convex shape ("plano-convex bottom" PCB) is a very common archaeological find all over Europe from the Hallstatt period to modern times. It has been recognized already in the 1960's as a type of waste related to the smithy (15). Further research based on archaeological, ethnographical and analytical arguments has confirmed this interpretation (16). This type of slag is formed by accumulation of fused materials in the lower part of the hearth (fig. 3). The material introduced in the hearth will fuse in the hottest zone of the fire, in front of the tuyere. The liquid slag will pour down and solidify when reaching a zone with lower temperature.

The most important process leading to the formation of slag is the oxidation of iron at high temperature. The oxidation process begins if there is free oxygen in contact with the iron. If the heating process continues, the oxides form a crust at the surface of the metal (17). Because the specific volume of the oxides is more important than that of the metal, the rigid crust will finally break due to this increase of volume. The particles fall down into the hearth contributing to the formation of the slag. At a low temperature and during a short time, the loss remains small. If on the other hand, the heath is long and intense, it becomes significant. This process is directly related to the size of the section of the bar of iron. To heat a small section bar up to the working temperature, only a few minutes are needed. A bar with a large section, on the contrary, can take hours. The dimensions of the bar are related both to the size of the object produced and to the size of the raw material available on the market. The hot oxidation is mainly responsible for the introduction of iron oxides into the slag.

The introduction of metallic fragments in the hearth is linked to the same general process. If the metal is not compact with numerous small cracks, the oxidation will occur also along the internal surfaces. Poorly connected parts of the metal can then be separated from the main piece. This process is then mainly linked to the quality of the metal. Working uncompact bloom-metal led to an important loss of metallic particles. This is also the case when the blacksmith recycled small bits of metal. On the other hand, the loss is negligible if the craftsman is forging a well compacted iron bar.

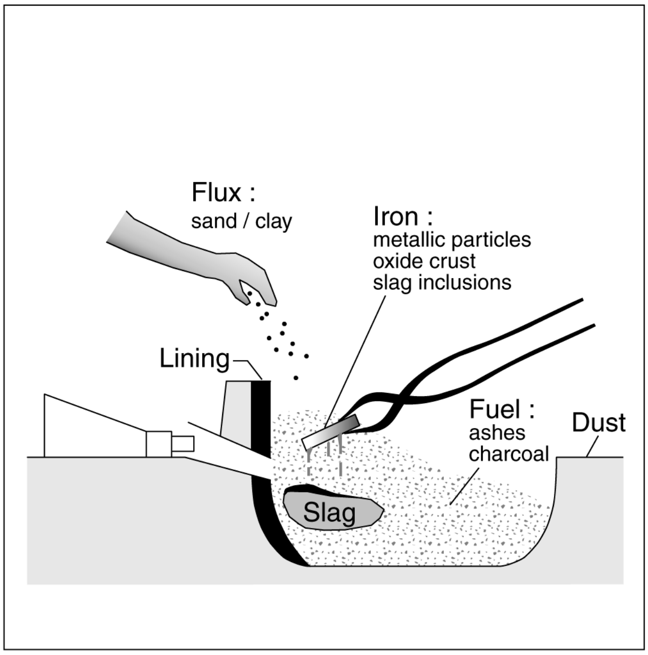


Fig. 2 : Typical plano-convex slags from the site of Châbles-Les Saux FR (19).

Fig. 3 : The formation of a plano-convex slag.

The silica, alumina and the other oxides derive from clay, sand or stones. They can be introduced in several ways. First, during smithing, the wall of the hearth is melted locally and a silica-rich liquid is introduced into the hearth. This is demonstrated by the observation of fused surfaces on lining fragments. It is also possible that dust and other particles from the working floor around the hearth fall accidentally in the hearth. Similar material can also be introduced with the fuel if it have been incorporated in the charcoal during its preparation or storage. Besides these accidents, it is common that the smith use sand or clay as a fluxing or protecting agent. To avoid hot oxidation, the craftsman covers the surface of the metal with another substance (sand, clay, ashes and so on). This material, in contact with iron oxides, forms a melt at low temperature. This liquid film protects the metal against oxidation and decarburation. To produce high quality welding, it is necessary to avoid the presence of oxides on the surfaces that have to be joined. The smith adds sand to the surface to produce a liquid that can be easily expelled by compression during hammering at high temperature.

Another important source of material is the fuel. The traditional fuel of the smith is charcoal. The mineral content of charcoal is highly variable (essence, age, part of the tree, location of the population, etc.) but always limited (between 0.5 to 5 % weight). Ashes contain mainly lime (CaO) and potash (K_2O) with small amounts of other substances (SiO_2, MgO, P_2O_5 etc.) (18).

Many other possibilities to introduce varied materials can be considered. For example, if the smith is also using copper-based alloys or precious metals to decorate an iron object, there is a possible loss that joins the slag. Another specific case is related to the presence of slag inclusions in the metal, especially when bloom iron is worked. If melted a second time, this reduction slag will contribute to the formation of the smithing slag, introducing iron oxides and silica as well as other substances typical of the original ore like Al_2O_3, MnO, TiO_2, V or Cr (3, 9).
An important observation is the solidification structure of the slag. In most cases, the aspect of the surface, the internal structure and the orientation of the porosity indicate that the slag solidifies during one single event. This indicates that the formation of a normal PCB occurs between the lighting and the extinguishing of the fire. They are produced during one unit of work. It is not possible to demonstrate the length of this unit of work. Logically, it could be a one-day session (8 to 10 hours) but it is also possible that it could be made in a shorter time and that several PCBs can be produced during one day in a single hearth. The hypothesis of the one-day work is supported by ethnographic evidence.

In a few cases, one piece of slag can be made of two (even tree or more) adhering parts with clear limits between the events of solidification. These “double slags” are evidence that the smith may avoid cleaning the hearth between two work sessions. Finally, it is possible to find PCBs with an internal multilayered structure that can be interpreted as the result of repeated phases of heating and cooling during one work session.

Since each PCB is one unit of work, the number of the PCB from an excavation provides a picture of the volume of the activity. It gives a minimal duration of the activity, considering the fact that the smith is also involved in other tasks unrelated to hot forging.

THE VARIABILITY OF THE PLANO-CONVEX SMITHING SLAG.

The general plano-convex shape is a common characteristic of slag from smithies. In spite of the similar shape, many variations are observed. The basic idea is that two identical PCBs must be the result of identical activities (same work, same conditions, same raw materials). Therefore, a classification of the PCBs is a necessary step to understand the nature and range of the smithing activities. Different quantitative and qualitative paramaters can be used to describe the morphologic, metric and physical characteristics. Whenever possible, these observations should be done on cleaned and complete pieces, but, even if the slag is broken, it is possible to estimate several characters (fig. 4).

Shape, dimensions and physical properties.

Several morphological characteristics are listed and discussed regarding the conditions of formation. A slag that solidifies at the bottom of the hearth must show small inclusions of sand or burnt clay on its inferior surface. If the solidification occurs inside the charcoal bed, the surface will be marked with prints of charcoal pieces. When the blast of the air through the tuyere is strong, the air penetrates into the charcoal and the hotter zone is located at a distance from the wall of the hearth. With a weaker air-flow, the hotter zone is closer to the wall. In this case, wall lining will adhere on the side of the slag. Often the slag is not circular in the horizontal plane, but elliptic. This elongation is frequently parallel to the air-flow or can be perpendicular. Generally, the lower surface is convex and the upper horizontal, but other kinds of profiles are observed and can be classified. These morphologic characteristics are related to the design of the hearth (position of the tuyere in relation to the bottom floor) and the air-flow rate (stronger / hotter ; weaker / cooler).

The aspect of the piece is very difficult to characterize. One can propose distinctions based on the aspect of the surface (relief, rugosity), the color, the fracture, the quantity and morphology of the pores, the presence of alteration products (rust), the presence of prints of charcoal or unmelted inclusions and so on. From our experience, most of those characters are linked to the nature of the material.

Nature of materials.

The nature of the slag (mineralogical and chemical composition) is quite varied and frequently very heterogeneous. Slag can be glassy (one or more different glasses) or crystallized. The minerals can be residual, crystallized from the melt or produced by alteration during burial. The most common species is fayalite (Fe_2SiO_4), frequently impure (small amounts of Mg, Mn, Ca) and zoned (Ca-rich external rim). It can be associated with oxide minerals (hercynite (Al_2FeO_4), ferro-hercynite ($AlFe_2O4$), magnetite (Fe_3O_4), hematite (α-Fe_2O_3), maghemite (γ-Fe_2O_3), wüstite (FeO) and iron oxy-hydroxides) and silicates (quartz (SiO_2), pyroxenes, mellilite etc.). Particles of iron alloys (from pure iron to steel or even cast iron) are frequently present. The presence of unfused pieces of rock or ceramic is observed. The chemical composition is basically dominated by iron and silicon oxides, ranging from material poor in iron oxides (5 % FeO_{tot}) to material very rich ones (95 % FeO_{tot}). Silica varies in the opposite direction. The other major elements are, in general, present at low grades.

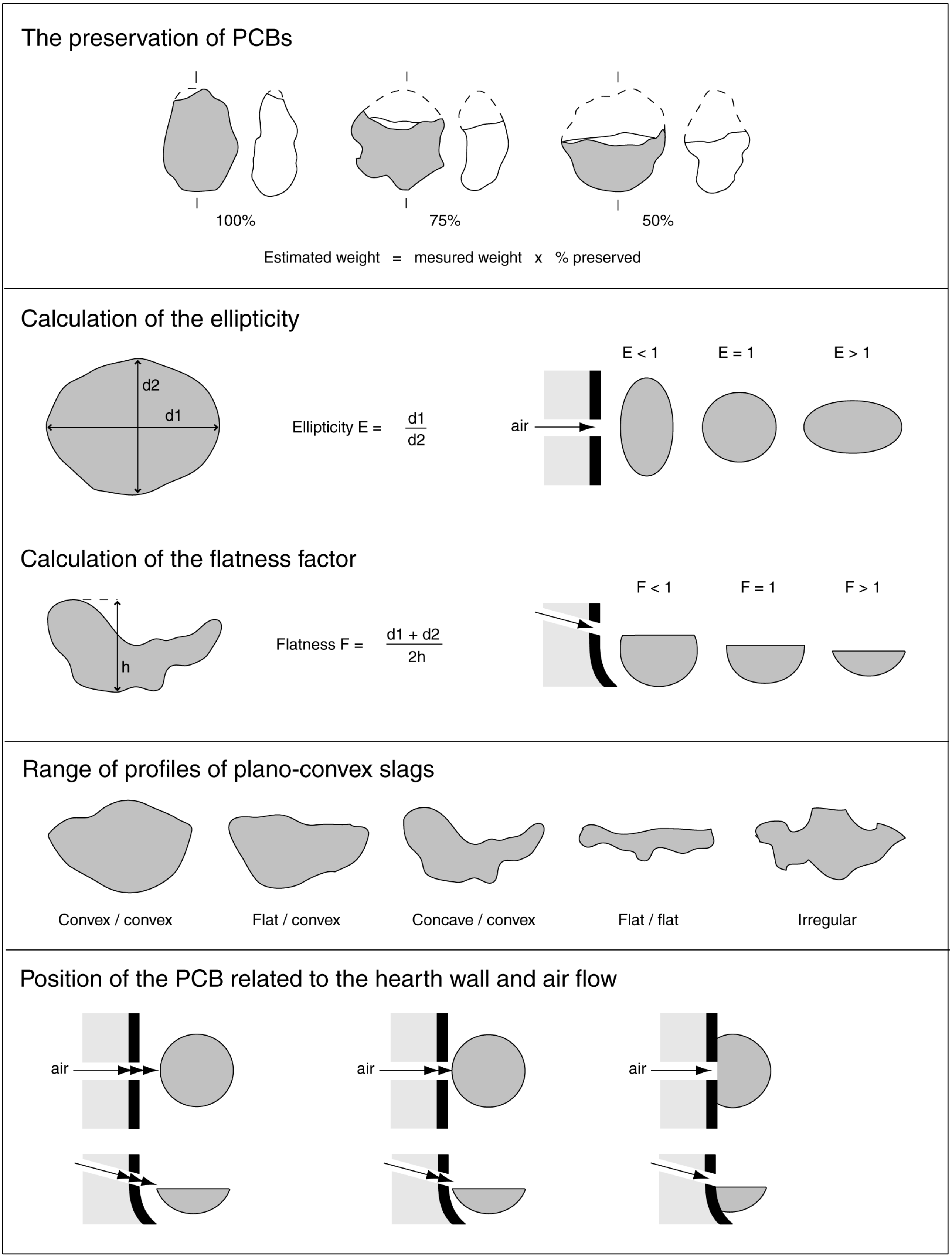


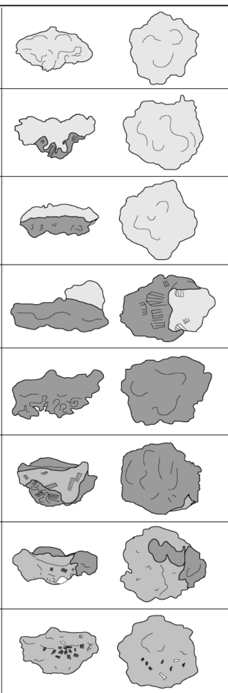
Fig. 4 : The morphological study of plano-convex smithing slag.

In facts, it is possible to characterize three important types of material present in the PCBs (10, 19). The first one is dominated by the assembly of fayalite with a variable amount of iron oxide (mainly wüstite) and with a small amount of interstitial glass. We call it SGD for "scorie grise dense" (dense grey slag). It is a grey or greenish-grey mass, very similar to the slag produced by the bloomery process. The composition is in the range of the low temperature melts of the SiO_2-FeO_x system. Sometimes it is possible to identify rounded or elongated ghost structures formed by iron oxide minerals that are probably not completely dissolved fragments of oxidized crust.

The second type of material is richer in silica and the other elements found in common rocks of granitic composition (granites, sandstones, clays). We call it SAS for "scorie argilo-sableuse (sandy-clayey slag). The iron content is always low. In general, sodium is depleted in relation with the potassium and the calcium content. Magnesium is very low. The material is frequently vitreous and contains many relictic grains of quartz. The color range is very large: black, brown, beige or even bright colors like blue and green. In some case, it is still possible to identify unfused particles of rock and ceramic or ghost structures of similar fragments.

The third material is richer in iron. This iron is present as metal, oxide or oxy-hydroxide particles. The metallic particles are relictic or crystallized from the melt. In this material there are also frequent inclusions of charcoal. Fayalite is also present. We call it SFR for "scorie ferreuse rouillée" (iron-rich rusty slag). The metallic iron is in general partly transformed into oxy-hydroxide during burial.

One PCB can be constituted from one kind of material but, in numerous cases, there are several zones or layers of different materials in one single piece. We propose to base the classification of the PCBs on the proportions between the materials (fig. 5). The more frequently observed cases can be distinguished into 8 major groups.



	Type	% SAS sandy-clayey material	% SGD grey dense material	% SFR iron-rich rusty material
1	SAS	100		
2	SAS-M	80 to 90	10 to 20	10 to 20
3	SAS-SGD	50	50	
4	SGD-B	10 to 20	80 to 90	
5	SGD		100	
6	SGD-SFR	0 to 10	70 to 90	10 to 20
7	SFR-M		50	50
8	SFR			100

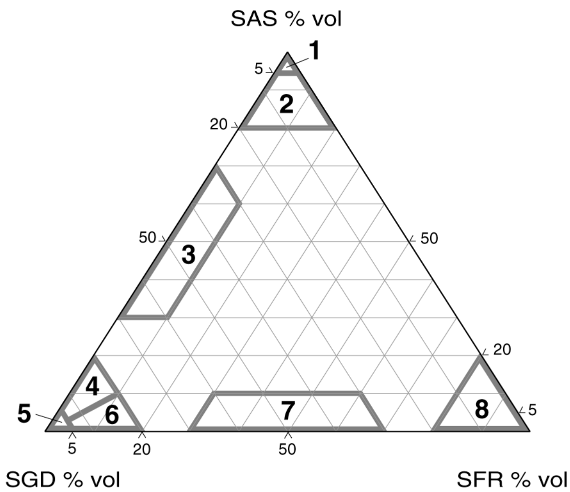


Fig. 5 : Classification of the plano-convex smithing slag based on the nature of the materials.

Relations between the characters.

From our experience, the shape (ellipticity, flatness, profile), the aspect (color, porosity), the physical properties (magnetism, apparent specific gravity) and the nature (mineralogical and chemical compositions) are linked to a certain extent. For example, a typical PCB made exclusively of SFR material will be dense, covered by rust and magnetic. The shape will frequently be rounded. A typical piece made of SAS will be variable in color, including light-colored areas. The shape will be irregular and not compact and the apparent density will be low. A typical SGD slag will be plano-convex with a regular shape. The fracture will be metallic-grey with few pores. The upper surface will be smooth and dark-grey, eventually wine-colored. The inferior surface will be vermicular with a grey-rusty color. In our opinion, the nature of the material is mainly the result of the way the work is done in the fire. The proposed classification, based on the proportions of the different materials (SAS / SGD / SFR), reflects the type of work done by the smith. On the other hand, the dimensions (size, weight) seem to be independent of the other characteristics. A PCB made of SFR material (respectively SGD, SAS or a given combination of these materials) can be either small (light) or large (heavy). In our opinion, the weight of the piece is not related to the type of work, but to the amount of work of a given type.

Using the classification based on materials combined with the distribution of weight, it is possible to characterize the activity of a given workshop through the slag assemblage. This is a tool to compare different workshops. We show some examples to demonstrate this approach (fig. 6). The two roman smithies from rural settlements are very similar (A and B / E and F), while the others show strong differences. The medieval workshop of Liestal is characterized by the domination of the types rich in metallic iron and by the presence of very heavy pieces. Following other archaeological and analytical arguments, it has been demonstated that the activity was mainly based on the fashoning of raw blooms into bars. At the La Tène site of Sevaz, the low weight of the PCBs and the small number of SAS are the most peculiar characters.

REFLECTIONS ON THE RELATION BETWEEN PCB TYPES AND SMITHY WORK.

At the moment, it is not possible to unambiguously relate one given type of PCBs to one specific action of the smith. In fact, it is probably not possible because the variation is not brusque but continuous, as is the variation in the activity of the smith. Some suggestions can, nonetheless, be made on the basis of the arguments developed above. Those are trails for thought and interpretation, but much scientific work is still needed to demonstrate these hypotheses.

The iron oxide-rich fayalitic material (SGD) is mainly produced by hot oxidation of the metal with a small input of silica from various sources (lining, ashes, dust and eventually flux). This is the dominant process during heating of the iron piece for hot forging. The quantity of iron oxide lost during this type of work must be related to the size of the bar and the length of the work. The metallic iron-rich material (SFR) is mainly produced by loss of metallic particles during the work of a poorly compacted metal. It can also occur when the smith is working at temperature near to the melting point of his metal, for example during welding operations. The silica-rich material (SAS) is produced when the smith adds a large quantity of flux to the surface of the metal. This action has several applications. For welding operations, the sand or clay plays the role of a flux. When working with steel, it will be important to cover the metal to minimize decarburization. Finally, after the fashioning of an object is completed, sand is used to minimize the oxidation of iron.

A PCB containing only one type of material is the result of work with few variations during the session. On the other hand, a piece made of two materials is the product of a sequence of activity, with a first phase producing a given material and a second step characterized by a second type. In this respect, the very common type of PCB, composed of a big lower SGD part (about 90 %) and a small bump of SAS on top, can be the result of a long session of hot forging to shape an object (SGD) followed by a shorter finishing phase where sand is applied to protect the metal (SAS). The reverse sequence is never observed.

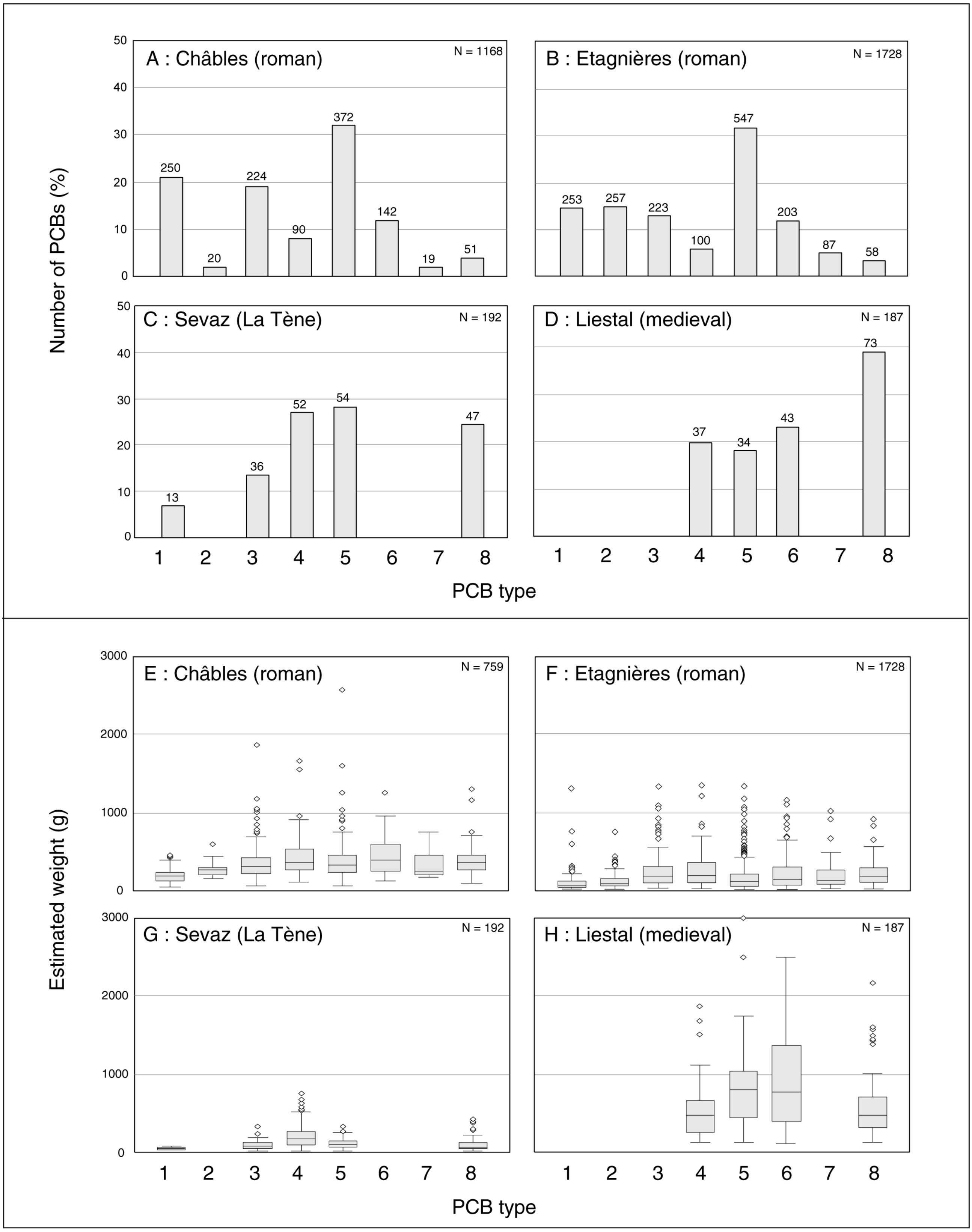


Fig. 6 : Comparison between four ancient workshops from Switzerland according to the plano-convex slag assemblages.
A-D : Frequence of the different types of plano-convex smithing slag.
E-H : Weight variations of the plano-convex smithing slags according to type.
Châbles-Les Saux FR: Roman rural smithy. Excavated by T. Anderson (19).
Etagnières-Les Ripes VD: Roman rural smithy. Excavated by F. Eschbach (20).
Liestal-Röserntal BL: Medieval iron-working village. Excavated by J. Tauber (21).
Sévaz-Tudinges 1 FR: Early La Tène metallurgical workshop. Excavated by M. Mauvilly (22).

CONCLUSIONS

The organization of the production of iron objects during ancient times is not yet understood. At this time it is only possible to differentiate the remains of a smithy from those of other metallurgical practices. There is still no general agreement to specifically characterize forges. This is an important question because there are workshops of very different socio-economic significance. For example, the socio-economic significance of a small workshop in a village for repair and maintenance of the iron tools is completely different from that of a large center specialized in the manufacture of sword blades. The approach, based on quantification and classification of slag, can be applied to a large collection of waste and can provide an accurate picture of the activities of the workshop. It therefore becomes a new tool for comparison of metal working sites. This is a new step in the direction of the understanding of the iron industry.

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