The multidisciplinary approach (archaeology and archaeometry) to bloomsmithing activities in France: examples of results from the last twenty years

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Over the last twenty years, archaeological and archaeometrical research implemented in France has made it possible to define the various stages of the chaîne opératoire *in iron and steelmaking (Mangin & Fluzin 2008) as well as the indicators that are linked to them (archaeological structures, wastes). These studies reveal that the* chaîne opératoire *may (or may not) split in space and time, but may also contain varying degrees of intensity (mini-maxi production). This implies that the production sites can be from different natures: they may include partial or complete* chaîne opératoire*, and are part of a social context (e.g., rural, urban, specialized, or domestic craft). The relationships within the* chaîne opératoire *create links between the sites and form a technological, economic, and social network through trade in semi-finished and manufactured products. The evolution of these networks must be studied by taking into account the cultural and political contexts of each period to draw up a coherent understanding of this organization. The determination of site activities (smelting, refining, elaboration, consumption, recycling), as well as intensity, allow a dynamic cartography of these activities, both synchronic and diachronic, to be realized. The physicochemical linkages between the ore, the smelting slag, the post-smelting slag, and the metal produced make possible an eventual understanding of the connection between sites that are part of the same exchange network. This in turn reflects the regional development of metallurgical organization and the trade in iron semi-products and manufactured goods.*

The typological attribution (morphology, level of impurities, iron/carbon composition, phosphorus contents, etc) of semi-products worked on the forging sites also makes it possible to refine the vision of what circulate and of what the sites acquire (Bauvais et al. *in press). Thus, an archaeological and historical study of these data can structure the relative image we have of these relations in the various periods (Mangin* et al.*, 2000a; Mangin* et al. *2000b).*

Bloom - Ferrous semi-products - Slag - Inclusion - Quality

Introduction

Working sequences in the bloomery process, as far as post-reduction is concerned, are more or less numerous and complex. The post-reduction work can begin in continuation of the smelting stage (compacting of the raw bloom) and strive towards final shaping of the artefacts, including the semi-product stage. The *chaîne opératoire* can thus be divided into space and time (Fluzin 2004a; Fluzin *et al.* 2004b) and presents different stages corresponding to several qualitative nuances of the material. Depending on periods and geographical areas, the technical system reflects a global organization that is more or less sophisticated and structured, varying with the context (rural, urban, etc.) and different interactive variables: environmental (raw material resources), social (hierarchy, economy, circulation, exchanges, intensity of production etc.) nature of the production (skills, specialization, etc). (Bauvais & Fluzin 2007; Mangin & Fluzin 2007).

Even though the physico-chemical and thermomechanical characteristics of the material transformation are so far better understood by rigorous crossing analytical methods and observation scales (Mangin *et al.* 2000b; Fluzin *et al.* 2000b), the restoration of the practical reality from archaeology, ethnoarchaeology, and experimentations (Fluzin *et al.* 2001) remains difficult and needs to take numerous methodological precautions.

Thus, to try to decipher and understand not only the activity of a given archaeological site, but also the characteristics of the ferrous materials that circulate, it is necessary at first to proceed to an exhaustive study of the remains (blooms, pieces of bloom, gromps, slag proportion, slag type, cake, shapelessness, lining, semi-products, worked metal fragment, forging scale, rejected fragments, artefacts, tools, etc). These studies must be performed on a significant number of archaeological sites in order to favour the most important corpus (in this case archaeological studies of 600 sites, 105 of them archaeometrically studied, i.e. 700 samples).

Moreover, in view of the heterogeneity caused by the smelting and forging in a solid state, if the morphological criteria can lead to a first typological classification this aspect is not intrinsically a sufficient discriminating factor (particularly for quality distinction). Our work has shown that there is no systematic link between the morphology and internal characteristics of wastes. This observation is true for blooms, semi-finished and manufactured products, and forging slag cakes.

A similarity of shape and aspect is not necessary linked to a similar texture, structure, or chemical composition (Dillmann *et al.* in press). Thus, an exclusively morphological approaches must be considered very carefully because a single artefact can present a substantial internal variability (composition or inclusion cleanliness gradients for metal, great or lesser degrees of stratifications for slag cakes). For this reason it is necessary to proceed to observation and study of the complete transverse section of artefacts whatever their nature or sizes (Pagès *et al.* 2009).

Our research over twenty years has studied a large number of sites and artefacts covering periods from the Early Iron Age to medieval times. Following the methodology of former work carried out in eastern France (Leroy 1997; Leroy *et al.* 1999; Fluzin *et al.* 2000), in the Swiss Jura (Serneels 1993; Eschenlohr 2001; Eschenlohr *et al.* 2007; Senn-Bischofberger 2005), and as part of several PhD theses (Pagès 2008; Desaulty 2008; Bauvais 2007; Orengo 2003; Berranger 2009), we have significantly completed our multidisciplinary and diachronic investigations on the French territory from the following areas: Nord du Bassin parisien, Narbonnaise (Languedoc-Roussillon, Provence-Alpes-Côte d'Azur), Grande Limagne d'Auvergne, Normandie, Pays de Bray, Pyrénées ariégeoises, and a large part of central Burgundy. More than 600 ironmaking sites and 700 artefacts have been studied.

This work has allowed us to define the internal characteristics of the materials precisely in order to evaluate on the one hand the real nature of the forging activities on given sites, and on the other hand the qualitative criteria that could help to identify some specificities and exchanges.

Reading archaeological wastes: some examples

Following the sequences of the *chaîne opératoire*, several short examples are given. The detailed procedure for metal analysis will not be presented here, since it can be found in the literature (Fluzin 1983; Fluzin 2004a; Fluzin *et al.* 2004).

For the last few years, our team has developed several analytical methodologies to analyse slag inclusions (major element and trace element[4]) embedded in the metallic matrix of the artefacts (in order to discriminate between two processes, direct and indirect: Dillmann *et al.* 2002). With regard to the bloomery process (direct reduction), all the elements that are mainly concentrated in the slag will be present in the slag inclusion of the metallic artefacts, preserving their respective ratios.

To identify inclusions coming from adding made during the forging

[4]Using μXRF analyses under synchrotron radiation, it may be possible in the near future to proceed to trace element analysis of a significant number of inclusions. However, adapted data-treatment programs have to be developed before the routine application of such a technique can be envisaged. A comparative study of all the trace-element analysis methods at the microscopic level has been made as part of the PhD thesis of Stephanie Leroy (2010 – CNRS/Synchrotron SOLEIL/CEA/UTBM).

stage, and also local enrichment effects mainly due to the small sizes of the inclusions, it is necessary to analyse a large number of inclusions for each artefact (at least 40) and then proceed to a filtering of the raw results (Desaulty *et al.* 2009).

Several parameters will influence the mechanical behaviour of ancient ferrous metals. The first one is the carbon content, which changes the hardness, elastic limit, etc. Nevertheless, as far as ancient artefacts are concerned it is necessary to take into account the eventual presence of phosphorus in the metal, but also the slag inclusions and porosities. Finally, it is also important to evaluate whether the artefact is made by welding different metal pieces and to evaluate the quality of the welding lines.

Several studies clearly demonstrate that the presence in the metal of relatively low quantities of phosphorus (more than 0.1%) can drastically change the mechanical behaviour of the metal and consequently its commercial or technical value. It seems, moreover, that specific technical gestures must be used in order to forge and weld it correctly (Vega *et al.* 2003a; Vega *et al.* 2003b), and so it appears that phosphoric iron must be considered as a specific material.

Depending on the smithing stage (cleansing) and on the slag quantity initially present in the raw bloom (but also on the final shape of the artefact), more or fewer slag inclusions remain embedded in the semi-finished and finished products. They have been shown to be a very useful mean of distinguishing smelting processes and provenances. However, as far as the mechanical behaviour of the metal is concerned, they can drastically modify the quality of the metal.

Because of their rarity in archaeological context, studies on raw blooms are not so numerous (Pleiner 2000). Most of the observations in our work (24 blooms morphologically studied including metallographic studies on seventeen blooms or fragment of 2–38kg: Fig. 99: a, b /Plate XXV/) confirm the intrinsic compositional heterogeneity of blooms (numerous slag inclusions and porosities, high variability in carbon distribution, from 0.02% to 0.9% and sometimes producing localized inclusions of cast iron). Cast iron may sometimes be considered to be a waste product, but this assertion is not consistent (Fluzin 1999; Fluzin 2000a; Fluzin 2003). Moreover, some blooms can be very homogeneous (ferritic or low carburised steel), showing an excellent mastery of the smelting stage. This kind of artefact is also easily forgeable (Fluzin 2006). Their presence in open urban areas and *oppida* shows (Berranger & Fluzin 2007) on the one hand that the raw materials (blooms) were exchanged as raw semi-product, probably over small distances (but not only: at the present time we are studying fifty blooms associated with fifty bipyramidal bars from the Byzantine period discovered in a wreck near Haifa), and on the other hand that these areas concentrated the supply and redistribution of it (Berranger 2009, Berranger & Fluzin, in press).

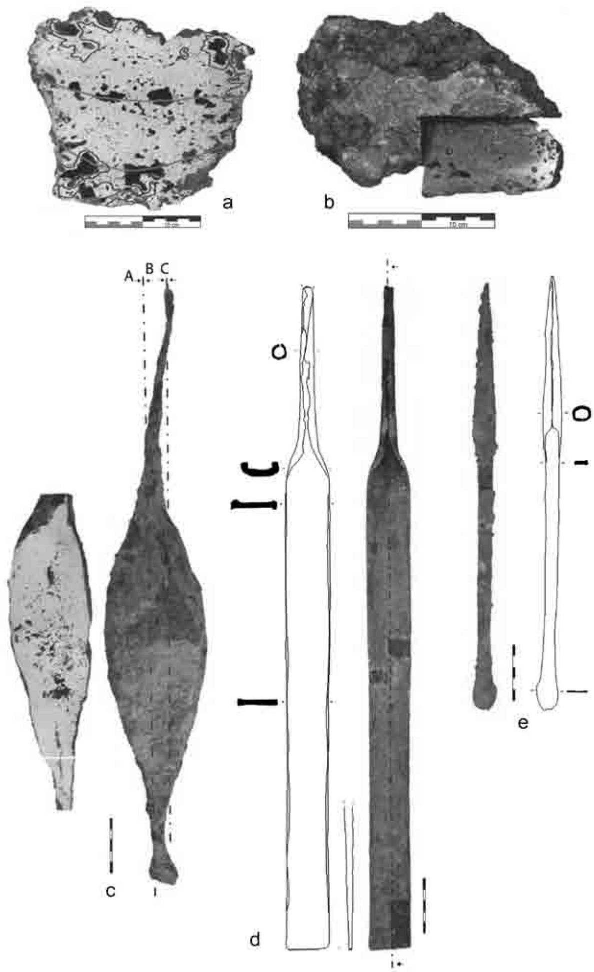

Figure 99: a: Raw bloom from Piani d'Erna (Italy); 2nd century BCE – 1st century AD; weight: 33kg and 38kg (Fluzin 2006); b: bloom from Selongey (Burgundy-France); Gallo-Roman; weight: 2.37kg.; c: iron bipyramidal bar from the hoard of Nottonville (Eure et Loir, France). 8th–5th century. BCE (14C date); NOT.94.14.07; weight 4950g; length 574mm, width 86mm, thickness 78mm.; d: iron 'currency bar' from the Saône river at Pouilly-sur-Saône (Burgundy, France) 3rd–1st century BCE; SAO.81.03.01; weight 650g; length 598mm; width 45mm; thickness 5mm.; e: iron 'socket bar' from the sanctuary of Saint-Maur (Picardie, France), 2nd century BCE; SM.5445; weight 69g; length 387mm; width 22mm; thickness 3mm. Photographs and sketches by P. Fluzin and M. Berranger.

As far as the typology and morphology of semi-products are concerned (Pleiner *et al.* 2004; Pleiner 2006), it appears that in most cases (730 artefacts archaeologically examined including about 200 archaeometric studies) bipyramidal or salmon-type ingots (80 artefacts analysed) correspond to a bloom or a bloom fragment that has been very summarily compacted (Fig. 99: c /Plate XXV/, Berranger 2009). We also confirm the hypothesis that the more or less strong elongation at their extremity was made in order to demonstrate the forgeability of the metal (qualitative test). In general terms, the thinner the semi product, the higher the cleanness (compacting rate, and forming work).

It is important to mention the exception of the bars from Saintes-Maries-de-la-Mer (Bouches-du-Rhône, France), dated from the 1st century BCE to the 1st century AD. These come from eleven Roman ships, each of which contains 20–150 tonnes of ferrous bars (Pagès *et al.* in press a; Pagès *et al.* in press b; Pagès *et al.* 2008; Pagès 2008, Pagès 2010). Indeed, despite their significant weights (between 1.5 and 33kg) and their cross-sections, which that can be as high as 10.4cm^2, the complete archaeometric study (54 bars) reveals high inclusion cleanness with some technological and morphological standardization. Moreover, the longer bars (1.5m) are made of two to four blooms (or fragments?) welded together by high-quality work (Fig. 100 /Plate XXVI/). These welding lines can be considered to be true technological feats.

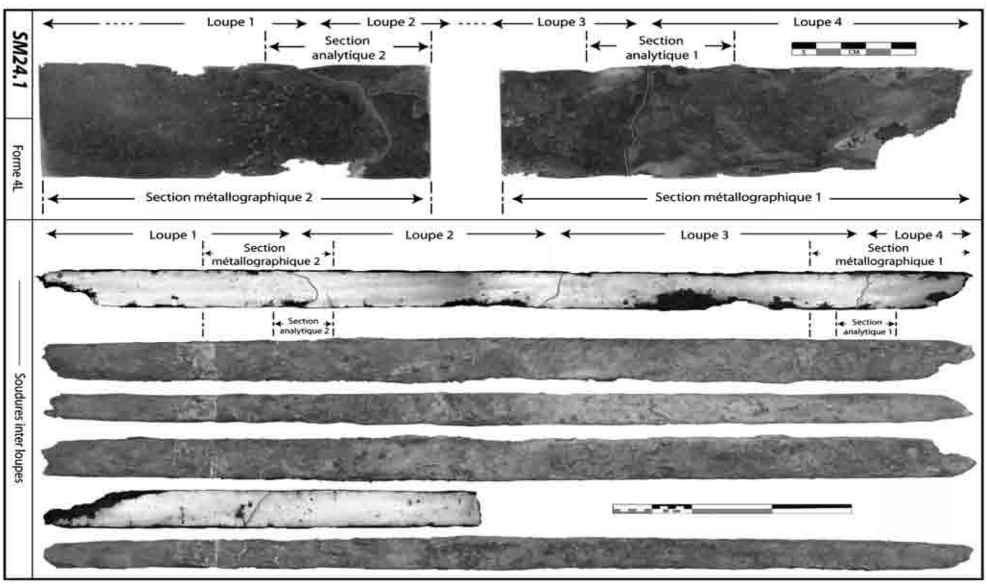

Figure 100: Bars (type 4L) discovered in the Roman wreck (SM24: 1st century BCE to 2nd century AD). Saintes-Maries-de-la-Mer (Bouches-du-Rhône, France). Weight 14kg, length 1160mm, width 58mm, thickness 40mm. Photographs and sketches by G. Pagès.

To sum up these results, metallographic analyses show that the semi-product morphology of the bars correlates with the metal quality. This means that the standard seems to be linked to the metal quality: each specific morphology is linked to a particular metal. There is no link between this aspect and the ship loading: it can be observed in all the studied ships.

Four groups can be distinguished according to the major chemical element:

1. Blooms with slag inclusions containing high phosphorus levels ($\%_{mass}$ $P_2 0_3$ from 8 to 10).
2. Bloom with inclusions with manganese average weighted content ($\%_{mass}MnO$ between 2 to 4).
3. Blooms with different $\%_{mass}MgO/ \%_{mass}Al_2O_3$ ratios.
4. All the other blooms with no special characteristics.

The fact that some bars are made up of blooms with different major chemical element signatures could indicate that semi-products are not systematically forged on the reduction site as often asserted for this period. They could also be made in different workshops more or less distant from the reduction workshop which import products from different workshops to manufacture the bars (Pagès 2008; Pagès *et al.* in press).

Another form of trade iron are 'currency bars' (Crew 1994). For the most part these exhibit a good to excellent quality of refining (depending on the heterogeneity of the initial bloom), and are made from a single bloom, sometimes hammered by repeated folding (75 objects were examined. Fig. 99: d /Plate XXV/, Berranger 2009).

A new type of semi-product (300 specimens already studied), with the same morphology as the currency bars, but with a lower mass, was also found, 'socket bars' (Fig. 99: e /Plate XXV/). These are small flat iron pieces with a socket (*c* 400 × 20 × 3 mm, average weight *c* 100g). These products seem to be mainly located in the French *Bassin Parisien* during the Iron Age. (Bauvais 2007, Berranger *et al.* 2007, Berranger 2009). Studies have revealed some qualitative particularities – excellent inclusion cleanness; intense hammering by successive folding, which could result in very good mechanical properties; quasi-systematic cementation treatment (probably in order to facilitate welding by lowering the weldability temperature). In the light of these aspects, it appears that these semi-products show specific qualities indicating an elaborated functional role.

Chemical analysis of slag inclusions contained in nineteen socket bars from eight different sites of this sector permitted a more precise understanding of their circulation. The socket bars, which were of local manufacturing and for local use, are composed of metals from various sources. This remark tends to confirm the massive importation of crude iron from distant sectors and local working up (Berranger *et al.* 2007).

The study of forging-slag cakes, and also of irregular slag (perhaps the result of a low-intensity activity that does not produce sufficiently high quantities to form slag cakes) is also fundamental (Fluzin 2004). Indeed, the forging cake bears witness to what happened inside the forging hearth. It contains all the compounds introduced in the hearth between two cleanings (Mangin *et al.* 2000b).

Our work takes into account more than 360 cakes fully analysed for a total number of about 4000 studied cakes. Their weights vary from 50 to 1000g with an average around 160g; without detailing all the aspects of such a study (Bauvais 2007), some points must be emphasized.

The morphological typology based on external aspects is not representative of the internal composition and can clearly cause erroneous interpretations. Thus, the three main cake families classically used (dense, sandy/clayey, magnetic) can be further divided after studying the complete transverse sections into more than ten categories. This is not surprising when one consider the variety of forging sequences, particularly in the case of polyvalent and versatile activities. Indeed, the precise examination of the outside and the inside of a given cake reveals numerous aspects:

– Dimensions reveal shape and size of the forging hearth and can sometime be correlated with the size of the forged objects. A careful examination often makes it possible to locate the ventilation axis (position of the tuyère).

– On the other hand, the cake weight is not a reliable qualitative criterion and is not representative of the nature of the work. In most cases, the cakes corresponding to cleansing are not heavier than those generated by other sequences.

– The forging cake is very often stratified. It reveals the different working sequences, making it possible to evaluate the nature of the activity, its relative importance and its duration, the intensity, the regularity and the degree of standardisation of the work, the working temperature, the importance of degassing, the degree of oxidation, the nature and the proportion of the material loss, the use of additions, and sometimes the quantities produced. It is then possible to follow in a same cake the work evolution during the forging. For example, the metal loss frequency is higher at the beginning than in the finishing stage.

– The relative evaluation of the metal loss into the cake provides important technical information. The abundance of metallic fragments shows a more or less complex work (forging of an heterogeneous metallic mass, cleansing, welding, work on small artefacts that are difficult to manipulate, etc). Metallographical studies of these fragments makes it possible to distinguish the quality of the material, the intensity of forming, the technical skill of the blacksmith, the high-temperature oxidation of the metal during forging, the thermochemical treatments (carburization or decarburization).

- The number and the morphology of the oxide scales generated during forging (flat, globular, prills) and the quantity of dissolved iron oxide (wüstite) give an idea of the metal loss by oxidation and the nature of the forging operation (more or less flat product, hammering intensity, welding, etc).
- The presence of sandy/clayey zones, depending on their position in the cake, can reveal the location of the furnace lining or the use of protective additions during the metal heating or of welding. The degree of melting gives an indication of the temperature levels and the duration of the heating sequences. In some cases it is possible to identify more complex additions and mixing of organic and mineral materials, and this can be correlated with specific thermochemical treatments (carbonitriding).
- The absence of metal loss is also important information which can be linked to a regular activity associated with finishing operations.
- The various crystalline phases (fayalite, wüstite, hercynite, etc.) can sometimes give information about oxidation intensity, melting phenomena, temperatures attained, and cooling conditions. In most cases, temperatures are not high enough to cause complete melting of the cake.

This non-exhaustive list illustrates part of the wealth of information that can be gathered from the interiors of forging cakes which can be compared in order to propose hypotheses about the forging operation. An important point is that these hypotheses must also be confirmed by experimental archaeological restitutions. Because of the lack of space, studies concerning gromps, amorphous slag, scraps, etc, will not be described here.

Lastly, all these observations on forging cakes, and also the one made on metallic artefacts detailed here, make it possible to understand more precisely the nature of the activities that were practised on a given site.

Conclusion

This detailed outline and the partial application of the *chaîne opératoire* approaches required to understand the regional organization (Bauvais & Fluzin 2009) of iron and steel making activities show the complexity of such an initiative. Moreover, this complexity lies in each discipline implemented, from engineering science to anthropology.

It is interesting to see that the individual comprehension of these activities is simplified and enlightened when they are approached in a dynamic and scalable way by confronting them with their context. Three parameters are important to keep in mind:

- The need to possess significant technological analytical tools (via archaeometry) as the basis of any interpretation.
- The requirement for wide knowledge of the socio-economical and socio-political systems underlying these activities, as they are the most crucial and most highly evolving elements.
- The importance of studying a large number of sites in order to be able to transcend the limits inherent to each individual site.

For this type of analysis to be truly fruitful, it is necessary to apply a constant back-and-forth approach between macrographic and micrographic scales, something that is possible with a multidisciplinary methodology.

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Plate XXV

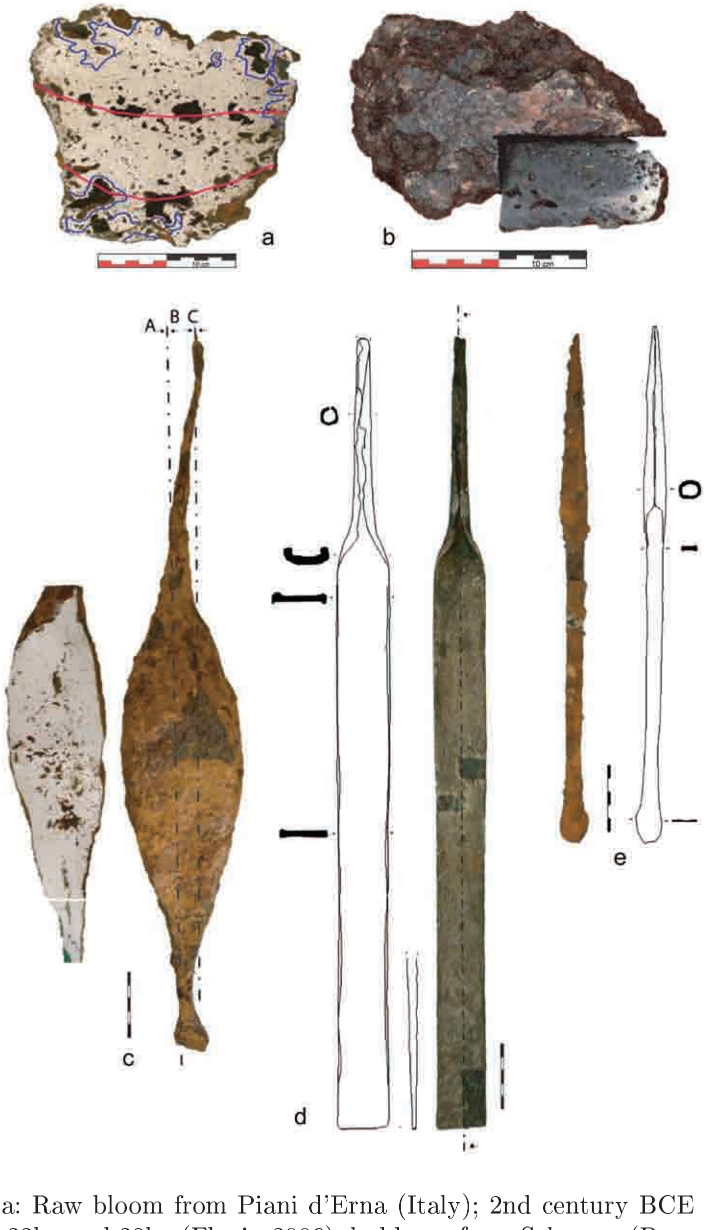

Figure 99: a: Raw bloom from Piani d'Erna (Italy); 2nd century BCE – 1st century AD; weight: 33kg and 38kg (Fluzin 2006); b: bloom from Selongey (Burgundy-France); Gallo-Roman; weight: 2.37kg.; c: iron bipyramidal bar from the hoard of Nottonville (Eure et Loir, France). 8th–5th century. BCE (14C date); NOT.94.14.07; weight 4950g; length 574mm, width 86mm, thickness 78mm.; d: iron 'currency bar' from the Saône river at Pouilly-sur-Saône (Burgundy, France) 3rd–1st century BCE; SAO.81.03.01; weight 650g; length 598mm; width 45mm; thickness 5mm.; e: iron 'socket bar' from the sanctuary of Saint-Maur (Picardie, France), 2nd century BCE; SM.5445; weight 69g; length 387mm; width 22mm; thickness 3mm. Photographs and sketches by P. Fluzin and M. Berranger.

Plate XXVI

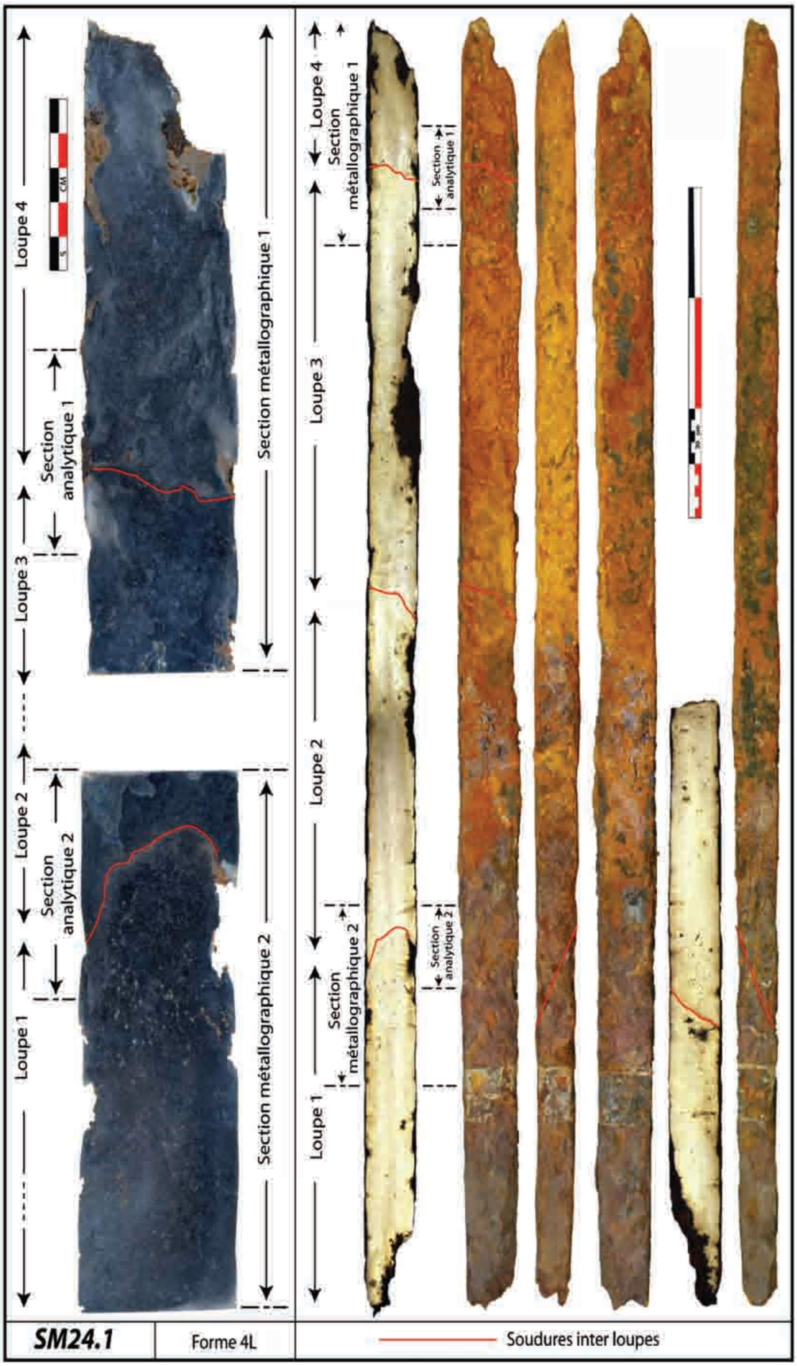

Figure 100: Bars (type 4L) discovered in the Roman wreck (SM24: 1st century BCE to 2nd century AD). Saintes-Maries-de-la-Mer (Bouches-du-Rhône, France). Weight 14kg, length 1160mm, width 58mm, thickness 40mm. Photographs and sketches by G. Pagès.

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Radomír Pleiner

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