Journal of Archaeological Science: Reports 67 (2025) 105374

Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

journal homepage: www.elsevier.com/locate/jasrep

A 17th century bell foundry in the belfry (UNESCO's world Heritage site) of Gembloux (Belgium): an archaeometric study

Eric Goemaere [a,*], Michel Siebrand [b], Souad Ech-Chakrouni [c], Alexandre Chevalier [d], Quentin Goffette [d], Thomas Goovaerts [a], Thierry Leduc [a], Sidonie Preiss [d]

[a] Geological Survey of Belgium, Earth and History of Life, Royal Belgian Institute of Natural Sciences, Rue Jenner 13, 1000 Brussels, Belgium
[b] Agence wallonne du Patrimoine, zone Centre-Wavre, Public Service of Wallonie, avenue Vésale 15, 1300 Wavre, Belgium
[c] Centre de Physique du Globe de l'IRM, Rue du Centre Physique 1, 5670 Dourbes (Viroinval), Belgium
[d] Quaternary Environments & Humans, Earth and History of Life, Royal Belgian Institute of Natural Sciences, Rue Vautier, 29, 1000 Brussels, Belgium

ARTICLE INFO

Keywords:
Bell bronze foundry
Moulds and bricks
Crucibles
Clay supply and recipes
Archaeomagnetic dating

ABSTRACT

This study presents the first comprehensive analysis of a late 17th-century bell foundry workshop excavated within the UNESCO-listed belfry of Saint-Sauveur church in Gembloux (Belgium). Archaeological investigations revealed exceptionally well-preserved structures, including a casting pit, the kiln floor of a smelting furnace, and ash pits, alongside a significant assemblage of artifacts: 29,000 clay mold fragments (core, false-bell and cope moulds), bricks, crucibles, slag, and copper alloy residues. Archaeomagnetic dating places the foundry's activity between 1669 and 1689 CE, likely following a devastating fire in 1678. At this time, the bell founders from eastern France established temporary workshops near the bell installation sites. Thin-section petrography and EDS (Energy-dispersive X-ray spectroscopy) analyses identified local loess as the primary raw material for moulds and bricks, with lime and sand as well as vegetal, and animal fibres added to the clay moulds for structural enhancement. Preliminary botanical analysis suggests the use of flax, hemp, or nettle fibres in the moulds. Crucibles, however, were crafted from refractory clays imported from the Meuse Valley, indicating external specialized production. This multidisciplinary research provides valuable insights into historical bell-making techniques, raw material sourcing, and the regional network of itinerant artisans, contributing to the conservation and cultural development of this unique heritage site.

1. Introduction

Since 2005, the belfry of Gembloux (Belgium, province of Namur) has been inscribed on UNESCO's World Heritage list, along with other belfries in Belgium and Northern France. The tower originally the bell tower of the Saint-Sauveur parish church (16th-early to 19th centuries) is nearly 35 m high, and houses 54 bells and 4 clocks. It dominates the Orneau river and the city centre of Gembloux (Fig. 1).

Between 1992 and 2023, archaeological research by the Walloon Heritage Agency (AWaP) revealed traces of medieval occupation predating the 12th century, along with remains of two successive churches (12th-16th centuries and 16th-early to 19th centuries (Siebrand & Parmentier, 2016, 2018; Siebrand and Goemaere, 2023; Fig. 1/3). Excavations uncovered a well-preserved late 17th-century bell foundry in the bell tower's ground floor and part of the church's main nave (Siebrand et al., 2022, 2023, 2024). The foundry included a casting pit, three fuel furnace pits or ashtrays and a melting furnace base (Fig. 2). Another furnace was in the church nave, east of the casting pit. It is not uncommon to discover elements of temporary workshops of bell foundries as attested by the censuses for Wallonia and France (Berthelé, 1908; Fauq, 2002; Schweitz & Rossillo, 1982; Slégers, 2019; Thomas, 2017, 2019). But these findings are usually incomplete, unlike the extensive remains at Gembloux. This discovery makes Gembloux's site exceptional in Europe for its structural integrity, abundance of archaeological material, and conservation quality.

The casting pit on the ground floor of the belfry contained 13 mould bases, 1 intact core, and a lot of archaeological material. North of this pit, in the centre of the room, was a circular melting furnace (diameter: 1.20 m) built on a thick clay plate. Further north, was an adjacent vast ashtray pit, nearly 2.20 m deep, arranged to accommodate the oven fuel. A thick layer of charcoal and coal was found at the bottom. Westward from the casting pit, a small oven-ashtray 0.80 m deep, was discovered

* Corresponding author.
E-mail address: egoemaere@naturalsciences.be (E. Goemaere).

https://doi.org/10.1016/j.jasrep.2025.105374
Received 16 March 2025; Received in revised form 21 June 2025; Accepted 25 August 2025
Available online 3 September 2025

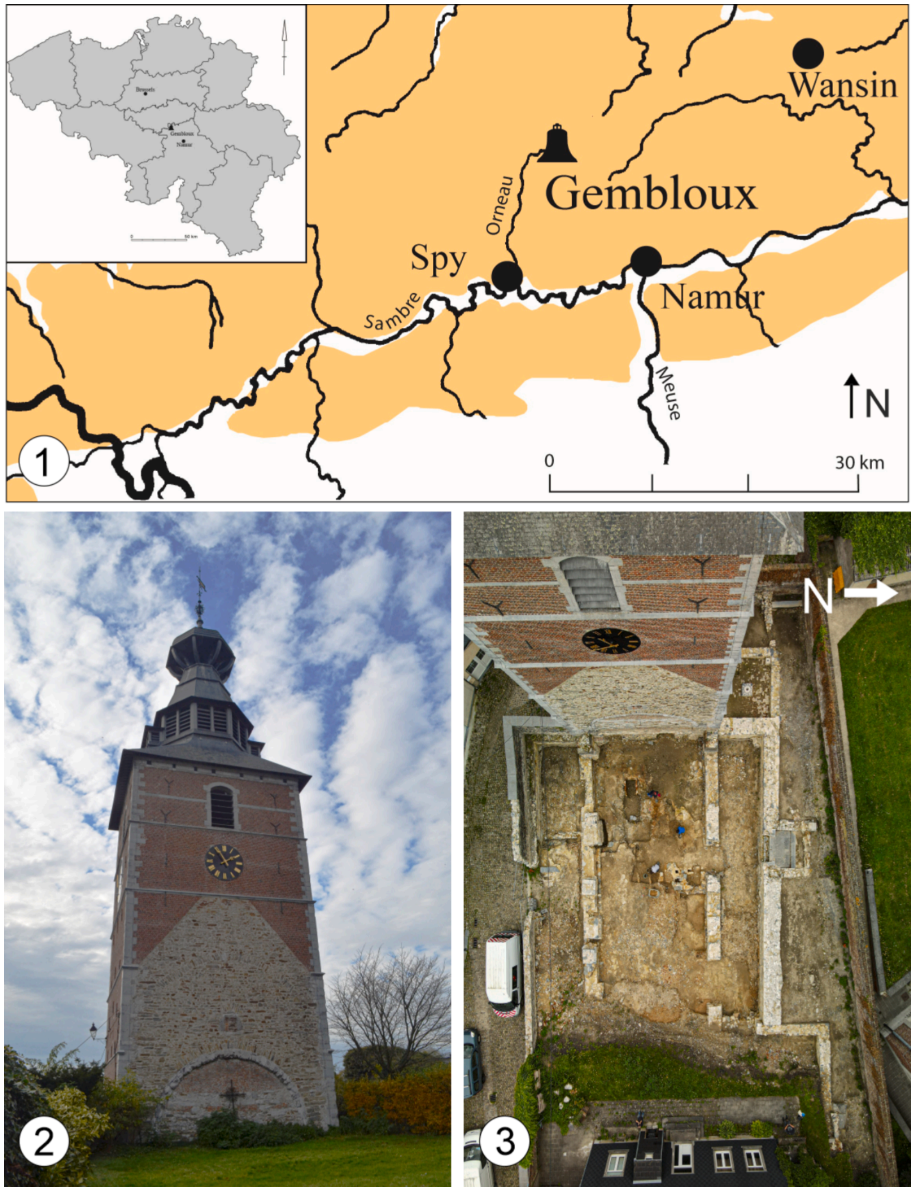

Fig. 1. The belfry of Gembloux. 1. Location map of Gembloux (province of Namur, Belgium). Light, orange-coloured area represents the loess cover; 2. Belfry of Gembloux, former bell tower of the Saint-Sauveur church (16th century) whose nave was destroyed between 1810 and 1825 (picture taken before AWaP excavations); 3. Aerial view of the excavated naves of medieval (12th century) and modern (16th century) churches, east of the belfry. Infography by M. Siebrand.

against the west wall of the tower containing layers of charcoal and coal. Finally, a third combustion oven-ashtray, more than 2 m deep, was excavated in the old central nave of the Saint-Sauveur church. It had to be connected to a melting furnace which had to be located between it and the casting pit.

The excavation uncovered nearly 28,000 mould fragments (over 650 kg), copper alloy waste (study in progress), charcoal, raw clay, bricks (whole or fragmented), casting channels, and furnace dome fragments. Four melting crucibles were also found (Fig. 5/5). Fragile structures, like the mould bases and intact core, were reburied for protection. Collected artifacts are preserved in the AWaP archaeological reserves.

Why a bell foundry workshop in the tower of a church? The workshop followed the city's 1678 fire, which destroyed much of Gembloux, including the Saint-Sauveur church and part of the Benedictine abbey, founded at the end of the 10th century (Toussaint, 1977). The sturdy 40 m^2 bell tower, built entirely of local quartzophyllades, schist and limestones, with 2-meter-thick walls, was ideal for housing the foundry. The vaulted ceiling, 6 m high, and a wide arched opening facilitated fume evacuation from the workshop through the central nave. At the time, the church's western part had yet to be restored.

The foundry reflects a long tradition of itinerant workshops before the development of railway networks and the rise of fixed foundries in the 19th century (Napoleon's 1810 imperial decree, Bouvet, 2009, p. 117). These workshops moved where demand arose, often setting up in churches or nearby spaces (cemetery adjacent to the sanctuary, neighbouring parcel…). Craftsmen set up their foundry for several months or several seasons to supply the surrounding villages (Berthelé, 1908; Bouvet, 2009). In cities, bells were most often cast by foundries

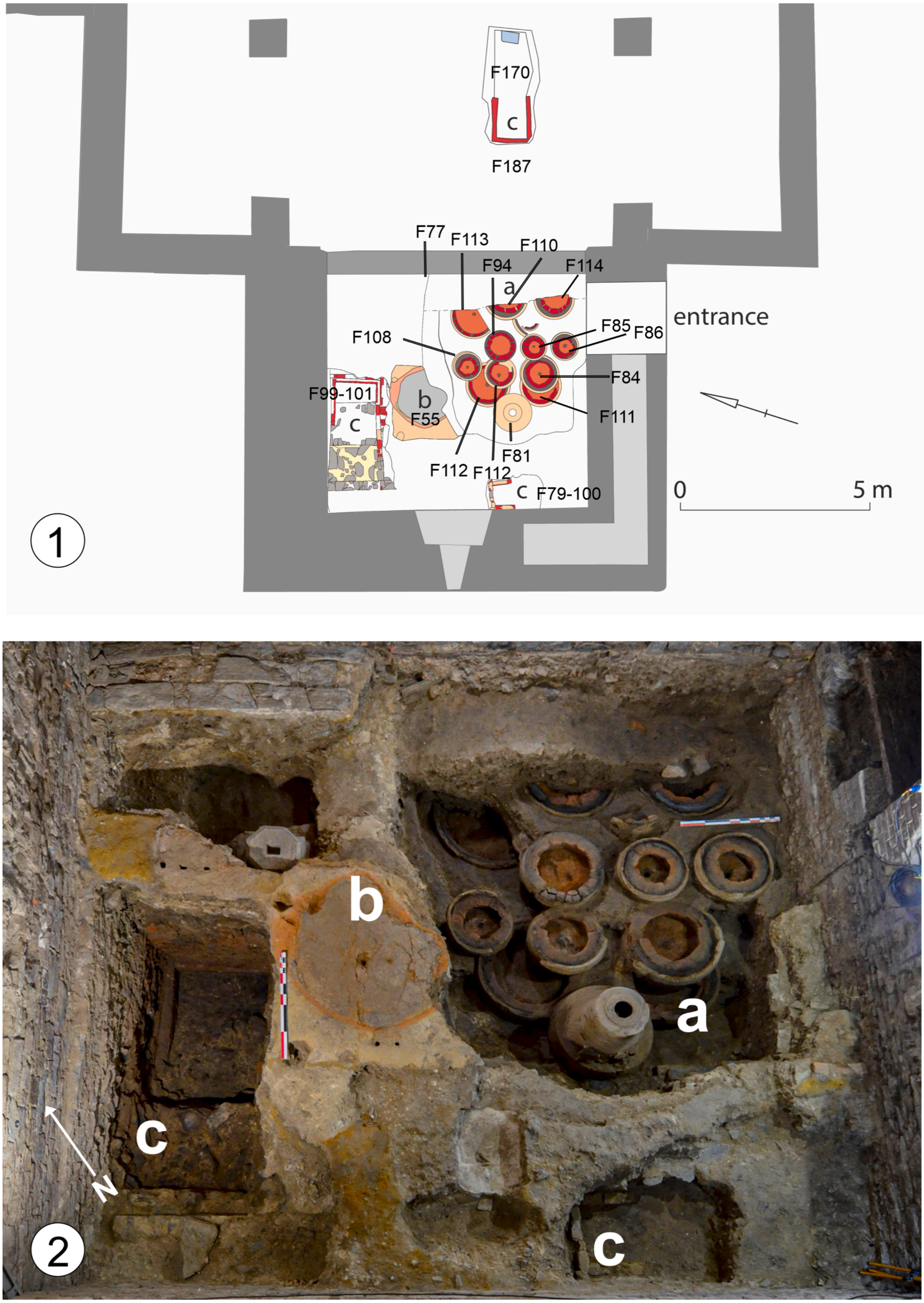

Fig. 2. 1. Location of the remains on the ground floor of the tower and in the central nave of the modern church linked to the bell foundry; 2. Zenithal view of the foundry, on the ground floor of the tower: a) casting pit (17 m^2) of the bells (13 bases and 1 core), b) burned floor of the melting furnace (cfr. Fig. 4/1), c) ashtrays. Picture and infography by M. Siebrand.

specialized in other objects. For example, in Valenciennes (Hauts-de-France, France), in the 17th century, bells were cast by the Perdry foundry, which specialized in the manufacture of bronze armor and cannons (Korpium, 2010, p. 70-71). Itinerant cross-country craftmen left their villages in the spring after Ash Wednesday and returned home for November 1 (Slégers, 2019). Many bell founders[1] in southern Belgium came from Bassigny (Grand-Est, France), over 400 km away (Ronot, 2001). In Gembloux, two foundry coat fragments were linked to Edmé Delapaix (d. 1694; Ronot, 2001, p. 139), a bell-founder from this region. He produced two bells, dated 1682, preserved in the church of Wansin (Hannut, Liège province), 30 km east of Gembloux (Association Campanaire Wallonne, 2022).[1]

This study aims to understand 17th-century bell-moulding techniques, characterize artifacts (moulds, bricks, crucibles), and analyse manufacturing recipes and raw materials. Alloy waste studies are ongoing.

2. Dating of the bell foundry workshop

The foundry's absolute dating remains uncertain, but evidence places it post-1678 fire. Edmée Delapaix's moulds confirm bell production before 1694, the year of the bell-founder's death (Ronot, 2001). The foundry likely operated for months, evidenced by five phases of use and plant growth within moulds. Parallel operations such as the manufacture of melting furnaces, the digging of pits to accommodate moulds and fuels make it physically impossible to manufacture about fifteen moulds in one season. Archaeomagnetic dating suggests use between 1669 and 1689. A.D. (cfr. chapter 5.7).

3. Description of the bell foundry remains

The study reconstructed much of the 17th-century bell-moulding process. The craftsmen first dug a casting pit with a 17 m^2 maximum extension and a depth of 1.60 m. It contained a nearly intact conical core and 13 circular mould bases (*meules* – French words are in italic) (Fig. 2). The core, intended to shape the internal profile of the bell, was hollow and measured 1.20 m high (base included) for a maximum diameter of 0.965 m, while the 13 bases, also hollow, had a diameter, in their upper part, which ranged from 0.40 m to 1.25 to 1.30 m. These dimensions corresponded to the maximum inner diameter of the bells to be supplied.

The manufacture of a bell mould is carried out in several stages (Fig. 2, Fig. 3, Fig. 4, Siebrand et al., 2024). Each mould base had been manufactured using the same process. These bases, hollow and made of brick layers of the same thickness, were set around a central wooden stake, that served as the central axis for manufacturing (Fig. 4/2). The base or grinding wheel was on average thirty centimetres high and pierced with four vent holes. The bricks were specially made for this purpose (23.5/24 × 11 × 5.5/6 cm module). Their corners were cut to form a trapezoid to build the circular shape. The bricks were cemented and caulked by clays. On this base, a hollow cone of bricks was mounted, the inner walls of which were also covered with clay (or lut) to consolidate the structure. The outer face of the cone was covered with prepared clay which was smoothed with a template or strickle board (*planche à trousser*). This one drew the internal profile of the bell or core (*noyau*) whose thickness of the layer of earth varied between 3 cm to 6.5 cm, up to 9.8 cm for the large bells. On the core, layers of clay were deposited and smoothed with the template to form the false bell (Fig. 5/3) or earthen replica of the bell, provided with its decor of horizontal cords. The decorations and wax letters of the phrases and names of people were added on the bell. The thickness of the clay false bell (*fausse-cloche* or *modèle de la cloche*) varied according to the size and diameter of the bell as well as the part of the bell considered (clamp, dress, shoulder or brain). Thus, the upper part of the bell was less thick than the lower part which received the strike of the flapper. The thicknesses recorded ranged from 1.5 cm to 8.8 cm. The false bell was then covered with a succession of layers of clay to form the cope (*chape, chappe* or *manteau*) which forms with its internal surface the external profile of the bell provided with decorations and lettering (Fig. 5/4). The successive layers of the cope were smoothed by the strickle board. Their thickness varied according to the bell size, between 2.1 cm and 6.8 cm. The thickness of the stratified layers varied between 0.5 cm and 1.5 cm. To avoid sticking between successive moulds, the contact surfaces had to be coated with a coating (not recovered in Gembloux) that could be bees wax, charcoal, tallow, ash, graphite or soap (Nicourt, 1971). The built-up clay false bell is used only once.

To speed up the drying of the mould and solidify the brick structure bound to the clay, a fire was lit within the hollow core and fed with wood. Its draw was augmented due to the four holes of vents. Once the three parts of the mould were dry, heat was applied to melt out the wax and the cope may be lifted off and the false bell removed. The latter was then repositioned on the core to prepare the casting, enclosing an empty space between the core and the cope into which the metal is poured to form the bell. The mould making operation was completed with the making of the crown (*chapeau* or *couronne avec anses*) and the casting cone shaped independently. Once the mould was ready in the pit, it was covered with sand which is compacted to constrain it to prevent it from exploding when it received the molten metal. The various observations made using Gembloux's structures and materials confirm the descriptions made in the Encyclopédie of Diderot et d'Alembert (1767) and the observations made in this regard by anthropologists and archaeologists (Thomas, 2017).

Bell moulds in Gembloux were produced in five series, ranging from large (1.10–1.30 m diameter) to small (<30 cm diameter). Several bells were likely cast in one season. The first series, the deepest buried, corresponds to the manufacture of four large bells (1.10–1.30 m diameter). The bell-founders then made the intact core (second series). The third series has three bells whose diameter varied between 0.635 m and 0.863 m. Then four bells were born and whose diameter varied between 0.40 m and 0.82 m (series 4). Finally, the last series gave birth to two bells (diameter: 0.98 m and 1.05 m). Based on fragments found in the excavation, it is likely that two small bells of less than 30 cm in diameter were also made that did not leave a brick core.

4. Material and methods

4.1. The study material

Archaeological material studied is composed of 22 artefacts (Table 1). Sixteen samples of loess were used as comparative material [12 samples from various loessic horizons (B2, BT, B, Kessel soil horizon, cultivated soil) analysed with LA-ICP-MS (Laser Ablation Inductively Coupled Plasma Mass Spectrometry) by Golitko (2015), three from the south of Brussels and one from a cultivated soil from Villers-le-Bouillet (Province of Liège), all analysed by EDS].

4.2. Analytical methods

Archaeological materials were analysed through macroscopical and mesoscopic descriptions, microscopy (optical, SEM), Energy Dispersive X-ray Spectroscopy, X-ray diffractometry, and archaeomagnetic dating (Supporting Information SI-1 for more information).

4.3. Fibers and seeds

Fibers in moulds were studied to determine their plant or animal nature and origin. Plant fibers from selected samples (GBX18BEF 03.113/2288-2291, 03.166/13805-1380, 03-183, 03.219, and 02.239;

[1] Bell-founders are called seinter, ceinter ou seynter in the past, translation of the French word *saintier*.

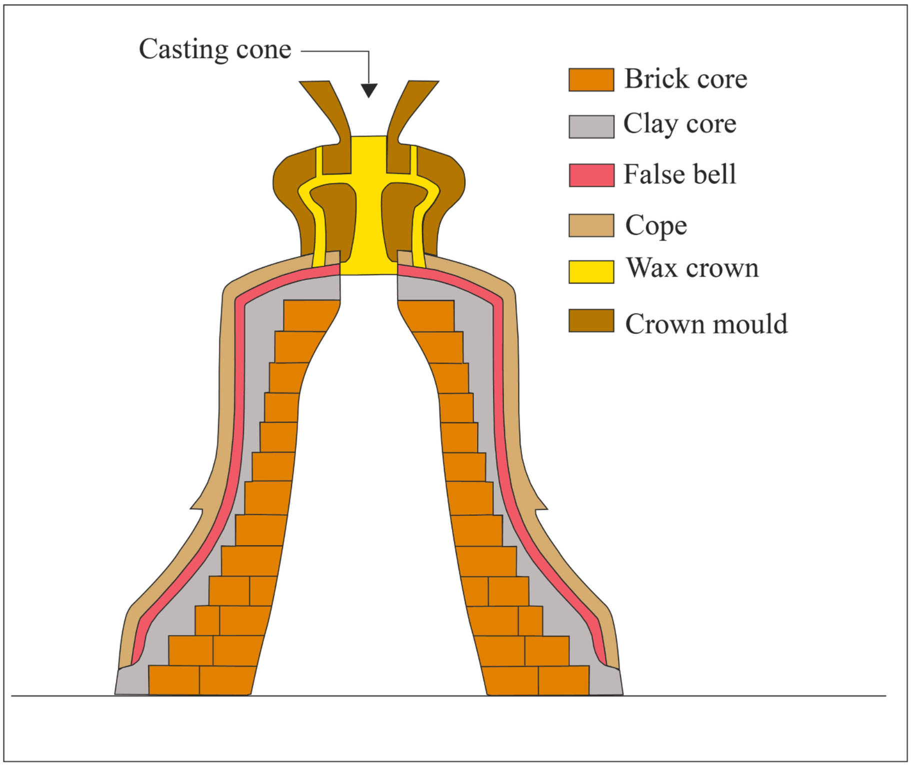

Fig. 3. Schematic description of the bell-casting mould. Infography by M. Siebrand.

BEF 03.295.003, GBX-9 LM, and GBX-12 LM; Table 1) were observed under low-magnification stereomicroscope (10-50x) as well as under transmitted and reflected light microscope (50-500x). Seed samples from two types of contexts were also studied. The first batch of seven samples came from ash pits F100 and F99-101. A second batch of nine samples came from backfill directly linked to the manufacture of the bells, attached to the different mould types (F77, F84, F86, F90-91, F94, F107 and/or F108 and F113, Table 1, Fig. 2/1). All samples were taken from sediment samplings of around 6.5 L. They were sieved under two sieves with mesh sizes of 4 mm and 0.2 mm. All remains of fruit and seed are preserved by carbonization. They have been observed using a low-magnification stereomicroscope. Identification was carried out with the help of atlases and the reference collection of the RBINS archaeosciences laboratory.

5. Results and discussion

5.1. The clay moulds

Macroscopic examination of both clay cores and copes reveals they are made of successive layers made of brown (core) to beige/light brown (cope) clay-sandy silts, with few small mica-flakes, regardless of chronology (Fig. 2/2, Fig. 4/2, Fig. 5/1-2-3). The sand fraction consists of fine-grained rounded quartz, and granulometry shows continuity between clay, silt and sand. Macroporosity is low. Small black charred vegetal fragments and cm-long animal fibres are present in the silty paste, examined under SEM. White millimetre-sized calcite spots are rarely observed. The material is weakly coherent, with internal zonation reflecting successive layering. Inner and outer surfaces are smoothed, finely striated due to strickle board use, and show no significant thermal effects. Pluricentimetric charred plant fragments appear on the outer core and inner cope surfaces. No graphite, ashes, wax, or tallow were found, but white gypsum crusts (1–20 μm platy crystals) and grey mineral powdery crusts were identified via SEM.

False bells share the same sediment and tempers (plant remains, animal fibres, carbonate lime spots, rare lithic grains) but appear looser and lighter than cores and copes. A single observed crown fragment, of similar material, displays colorimetric zonation (red to deep grey). The silty paste contains small metallic fragments, rare lithic pieces, and one loessic calcitic concretion (*poupée de loess* occurring in loess horizons located below the decarbonated zone). Possible moulding sands appear on the crown surface.

Petrographic observations (Fig. 6) confirm that all moulds (cores, false bells, copes, crown) and the melting furnace floor derive from the same raw material, showing no recipe changes across periods and the moulds of different diameters. This suggests continuity in the bell foundry workshop over one or multiple seasons. The paste consists of weakly micaceous clay-sandy silts, with rare larger quartz grains interpreted as accidental impurities. No intentional sand addition was detected. Iron-rich spots and pedogenetic features (orange argilanes/cutanes from infiltrated colloidal clay, root traces, gleyfication) are present. Heavy detrital minerals (zircon, rutile, leucoxenes) are rare and small. The features align with loessic sediment deposits of local to regional origin. Vegetal fragments (mm-cm) are present in all pastes but concentrated in the inner cope wall. Centimetric animal fibres (50–80 μm, SEM observed) reinforce clay cores, false bells, and copes. Accumulations of vegetal remains appear on inner cope surfaces. Small calcite spots with coarse quartz grains suggest minimal unsifted fine-grained lime addition, improving workability by aggregating clay particles.

Scanning electron microscopy (Fig. 7) and EDS analysis ($n = 59$) confirm optical microscopy results (Fig. 6, Fig. 8/1–2; Table 2). The clay moulds share raw materials with core bricks and interstitial clays. The bell-founder utilized local resources from quaternary loess in the *Hesbaye namuroise* region, likely sourcing animal and vegetal fibres locally. Chemically, the composition is dominated by silica (76.8 wt% SiO_2), alumina (12.2 wt% Al_2O_3), iron (4.2 wt% Fe_2O_3), potassium (2.8 wt% K_2O), and magnesium (1.2 wt% MgO), with phosphorus, soda, and titanium occurring in minor amounts (<1 wt% oxides) (Table 2). Calcium and iron in whole loess are underestimated due to surface choices

Fig. 4. 1. Burned floor of a reverberatory melting furnace (sampled for archaeomagnetic study), on the ground floor of the tower; 2. Casting pit with an almost intact core in the foreground and base of successive moulds of variable diameters. The brick structure indicated by the yellow arrow was selected for archaeomagnetic measurements. Pictures by M. Siebrand.

selected for EDS measurements, excluding calcite and Fe-rich spots. The chemical composition aligns with XRD findings, showing quartz, feldspars (K-feldspar, plagioclase), kaolinite, and irregular swelling mixed layers.

XRD analysis confirms that the clay core, false-bell, and crown moulds share an identical composition of quartz, feldspar, muscovite/illite, and kaolinite, indicating a firing temperature below 500 °C (kaolinite dehydroxylation threshold). A nearby loess sample closely matches GBX-4 to GBX-19.

The outer striated surface of some core moulds features white gypsum crystallizations or a rough grey crust (GBX-20). The latter, composed of quartz, calcite, and an unidentified artificial calcium silicate, was analysed via SEM-EDS. These phases suggest that mould makers used coal/wood cinders (rich in Ca, K, Mg, P, S, Si, and Al) mixed with organic compounds to facilitate cope removal before bronze casting.

Embossed agglomerations of small grains of Cu-Sn alloys with Zn traces, likely from casting defects, were observed on the grey crust. Additionally, deep green rosettes (10–80 μm) of atacamite [$Cu_2Cl(OH)_3$] were found, consisting of prismatic crystals (1–10 μm). Atacamite is a common oxidation product of ancient bronze, copper artefacts and even constituting the patina of the Statue of Liberty but also found naturally on oxide copper deposits (Monari et al., 2023; Robbiola et al., 1998). Atacamite forms through Cu-alloy corrosion in acidic pore fluids. The chlorine source remains unknown.

Weathering and elemental mobility in the casting pit deposits are evidenced by black manganese oxide spots (multi-millimetre in size) on the outer and inner surfaces of a cope mould (GBX-21).

5.2. The core bricks

Well-fired core bricks exhibit a cadmium red variegated colour with a silty matrix, identical to cores, copes, and false clays. They contain dark red-brown rounded semi-plastic clay inclusions, rare grog fragments, and display folded stratification with colour variation, indicating moderate raw material uniformization by the brick-makers. Linear pores suggest added vegetal fragments or naturally occurring roots. Gravels (quartzite, rare flint) and medium-sized rounded moulding sands (quartz, flint, no glauconite) primarily appear at the brick's outer border and are partly embedded in the matrix. Red bricks are joined by a silty orange-brown paste by luting, which also coats their inner walls. The clay cement and coating share the same composition as cores, copes, and false bells. Core base bricks exhibit the same petrographic features as clay moulds but lack plant fragments, animal fibres, and calcite spots. Small pockets of moulding sands appear inside the paste due to preparation. Brick firing induces iron-rich red to black spots and porosity. XRD analyses reveal detrital quartz, feldspars (K-feldspars, plagioclase), and illite/muscovite. Hematite is detected in one of three studied bricks, indicating heating between 700–900 °C.

5.3. The melting furnace ground

Macroscopically and microscopically (OM and SEM-EDS), the kiln floor consists of the same material as the moulds, displaying a red to dark red colour (Fig. 2). Its coherence is higher due to heating over 350 °C, exceeding that of the clay moulds. XRD analysis of the furnace ground base places its composition between clay cores, false bells, copes, and bricks, with temperatures below 500 °C.

5.4. The raw crude clays

Crude beige clayey sands (ashtray filling material from excess raw clay) are unsorted, mixing coarse quartz sand and silts used for mould-making. They contain mm- to cm-sized granules of carbonated impure lime (with detrital quartz grains), lithic fragments, fired clay pieces, and clay patches (illuviation clays). No animal or vegetal fibres were observed. Settling clays (GBX-17 & 18) are enriched in colloidal clays via infiltration (illuviation). EDS analysis of the silty matrix confirms the same loessic material constitutes the moulds and the furnace base near the casting pit.

The clay fraction (<2 μm) from eight samples (GBX-3, 4, 5, 6, 14, 15, 16 & 18, Table 3) covers various artefacts. The brick contains only traces of micas, lacks other clay minerals, is rich in amorphous compounds, and primarily consists of quartz and neoformed minerals. The clay binding the bricks is richer in micas, contains low mixed-layers with minimal swelling capacity, and lacks kaolinite, indicating heating between 500 and 700 °C. The crude clay, the richest in swelling irregular mixed layers, contains degraded illite and kaolinite but lacks vermiculite and chlorite. Core and cope clay exhibit similar content with illite, muscovite, kaolinite, irregular illite–smectite mixed layers, and no vermiculite or chlorite. Compared to crude clay, lower swelling clay content suggests heating at 200–250 °C. The false bell contains the same clay as crude clay, retaining unheated smectite.

5.5. The melting crucibles

Crucibles form a single paste group. Two distinct crucibles (Fig. 5/5; Table 1) are represented by thick walls (20–25 mm), showing a red oxidized outer surface and a glazed, vitrified inner surface (green/red hues). One sample comes from the upper border, the other from the lower half. The dark red-brown vitrified paste, rich in grog (<1 mm to 1

Fig. 5. 1. Hollow core mould base (bricks and lut) with ash and calcined central stake; 2. Fragment of core mould lying on the brick base; 3. Fragment of clay false bell wall stuck to the base of an intact hollow core mould (F81); 4. Piece of the cope inner wall with decorations and inscriptions, note the black colouration of the inner surface; 5. Half-crucible (height: 29 cm; maximum external diameter: 20 cm). Pictures by M. Siebrand.

cm) from crushed used crucibles, has large alveolar pores. The inner surface, vesicular and bluish, contains cuprous alloy traces.

Petrographic analysis reveals a porous (connected bloating pores), dark vitrified matrix (~40 %) with minor detrital quartz (<2%) and abundant angular grog (~40 %), contaminated with metal oxides. No vegetal remains, heavy minerals, or mica flakes are present. The border is gas-bubble-rich, with mullite and cristobalite crystals, and copper-rich globules (some with micrometric Pb inclusions). Some bubbles contain blue/green Cu chlorides or oxides.

The clay matrix of the crucibles and the grogs were chemically analysed separately, then compared with the moulds from the foundry workshop. The analysis distinguishes crucibles (Tables 2, 4, 6) by their refractory nature: higher alumina (31.9–35.4 wt% Al_2O_3) and lower fluxes (1.1–2.3 wt% Na, Ca, K). The K_2O/Al_2O_3 (0.03–0.07 wt%) show that the paste is kaolinitic, with detrital quartz (100–200 µm). XRD of GBX-1 and GBX-2 reveals high-temperature phases (mullite, cristobalite, tridymite, hercynite, leucite), indicating > 1100 °C firing, with incompletely molten detrital quartz (Table 5). Due to high temperatures, feldspar grains and mica flakes cannot be observed but their proportions had to be low regarding the low concentrations in K, Na and Ca and high alumina and titanium values (enrichment deriving after chemical weathering processes) (Saussus et al., 2022). The paste is mixed with 30–40 % of unsorted infra- to plurimillimetric grogs. Comparatively to the clay paste, the clay of the grogs has a distinct composition (percentages recalculated by subtraction of the Zn, Cu and Sn contamination), underlined by mean alumina values (18.2–30.4 wt% Al_2O_3) and lowest content in K (0.4–1.4 wt% K_2O) and Mg, giving a refractory nature (K_2O/Al_2O_3 between 0.01 and 0.06) to the clay used (Fig. 8, Table 2). Despite the differences in composition of the two main components of the crucibles, they can share the same origin with differences being due to variation inside the kaolinitic clay deposits. Crucibles from Gembloux resemble early 15th-century Brussels brass foundry crucibles which were made from non-local refractory clays (Saussus et al., 2021, 2022). Northward of the Sambre-Meuse axis, marine tertiary sand and clays from the northern half of Belgium are dominated by illite, glauconite, illite–smectite irregular mixed layers with a small contribution in kaolinite. Alumina rich clays don't occur in Gembloux area, so crucibles were produced from non-local refractory clays. The nearest source of kaolinitic clays is represented by the cryptokarstic Tertiary clays from the Entre-Sambre-et-Meuse area, south of Gembloux and well-known as Andenne clays or white *derle* in the Belgian literature (Goemaere, 2017; Goemaere et al., 2012; Saussus et al., 2022). Grog-rich paste suggests

Table 1
Analytical dataset of material selected from the bell-casting foundry of Gembloux. 03.205: backfill of the ashtray F101, located north of the furnace floor (Fig. 4/1); after phase 2, or even after phase 3; 03.212: crucible found in ashtray F101, after phase 2; 03.150: backfill in space between the pit boundary and the manufacture of the intact F81 mould, post-phase 2. XRD: X-Ray diffraction; SEM/EDS: Scanning Electron Microscopy/Energy Dispersive X-ray Spectroscopy; OM: Optical Microscopy; AF: Animal Fibres; PF: Plant Fibres, S: Seed; B-site abandoned phase.

AWaP Id. (GBX 18)	Lab Id.	Chronology structure	Object	Analyses
BEF 03.242.002	GBX-1	F101 > phase 1	Crucible wall	XRD, SEM/EDS, OM, AF
BEF 03.242.003	GBX-2	F101 > phase 1	Crucible wall	XRD, SEM/EDS, OM, AF
BEF 03.295.001	GBX-3	F111 (phase < 4)	Brick (core mould base)	XRD, SEM/EDS, OM, AF
BEF 03.295.002	GBX-4	F111 (phase < 4)	Coating clay on bricks	XRD, SEM/EDS, OM, AF
BEF 03.295.003	GBX-5	F111 (phase < 4)	Core clay mould	XRD, SEM/EDS, OM, AF
BEF 03.295.004	GBX-6	F111 (phase < 4)	Cope clay mould	XRD, SEM/EDS, OM, AF
BEF 03.183.001	GBX-7	F94 (phase 4)	Brick (core mould base)	XRD, SEM/EDS, OM, AF, PF
BEF 03.126.001	GBX-8	F85 (phase 4)	Coating clay on bricks	XRD, SEM/EDS, OM, AF
BEF 03.295.003	GBX-9	F85 (phase 4)	Core clay mould	XRD, SEM/EDS, OM, AF, PF
BEF 03.295.004	GBX-10	F111 (phase 1)	Cope clay mould	XRD, SEM/EDS, OM, AF
BEF 03.281.001	GBX-11	F110 (phase 5)	Brick (core mould base)	XRD, SEM/EDS, OM, AF
BEF 03.281.002	GBX-12	F110 (phase 5)	Core clay mould	XRD, SEM/EDS, OM, AF, PF
BEF 03.280.001	GBX-13	F110 (phase 5)	Cope clay mould	XRD, SEM/EDS, OM, AF
BEF 03.109.001	GBX-14	F81 (phase 2)	False-bell	XRD, SEM/EDS, OM, AF
BEF 03.280.001	GBX-15	F55 (phase 1 or 3?)	Furnace clayey floor	XRD, SEM/EDS, OM, AF
BEF 03.205.001	GBX-16	F99-101 > phase 2 or > 3	Clay crown	XRD, SEM/EDS, OM, AF
BEF 03.205.002	GBX-17	F99-101 > phase 2 or > 3	Crude clay from ashtray	XRD, SEM/EDS, OM, AF
BEF 03.212.001	GBX-18	F100 > phase 2	Crude clay from ashtray	XRD, SEM/EDS, OM, AF
BEF 03.150.001	GBX-19	F77 > phase 2	False-bell	XRD, SEM/EDS, OM, AF
BEF 03.148 5938	GBX-20	F77 (phase 4B)	Grey surface – false-bell	SEM/EDS, AF
BEF 03.150 6135/6137	GBX-21	F77 > phase 2	Black points – false-bell	SEM/EDS
BEF 03.210	GBX-22	F100 (phase 1-phase5B)	Casting channel	SEM/EDS, S
BEF 03.113/2288–2291		F77 (phase4B)	Cope	S + PF
BEF 03.166/13805–13806		F90-F91 (phase2B)	Cope	S + PF
BEF 03.219		F99-101 > phase 2 or > 3		PF
BEF 03.239		F99-101 > phase 2 or > 3		PF
BEF 03.066		F77 (phase 5B)		S
BEF 03.079		F99-101 > phase 2 or > 3		S
BEF 03.115		F107-108 (phase1B-phase3)		S
BEF 03.136		F86 (phase 4B)		S
BEF 03.159		F81(phase 2B)		S
BEF 03.185		F94 (phase4)		S
BEF 03.205		F99-101 > phase 2 or > 3		S + PF?
BEF 03.208		F100 (phase1-phase5B)		S + PF?
BEF 03.253		F101 > phase 2 or > 3		S
BEF 03.261		F107 (phase3)		S
BEF 03.312		F113 (phase1B)		S

crushed used crucibles were added, with quartz coarse sands. Quartz sands also occur mixed with kaolinite in the Andenne clay deposits. A wide variety of clays of different colours occur and were selected for specific artisanal to industrial uses (refractories, porcelain, earthenware and stoneware) in function of their alumina, fluxes, quartz and iron contents. Regional names in French (italics)are given to the different types of clays (lean clay – *maigres* –, semi-lean clay – *demi-maigres* – or semi greasy clay – *demi-grasses* –, greasy clay – *grasses* – alias soapy clays (*savon*) and hyperaluminous clays) (Table 4). EDS shows zinc-rich grogs with minor Cu, no Sn (Table 6), confirming their use in brass production. SEM-EDS of the inner surface identifies recrystallized glass (mullite/cristobalite), Cu-Sn alloy inclusions (sometimes with micrometric rounded inclusions of Pb due to the non-miscibility between Cu and Pb), and metallic Cu. Copper chlorides and oxides crystallized in pores (Fig. 7/8). Cu/Sn ratios match the bronze alloys used for bells, suggesting the crucibles cast small bells or clappers. Zinc in the scoriaceous surface indicates contamination from grogs.

5.6. Casting channel

A few casting channel fragments from the casting pit infill were examined under a binocular microscope. Made of the same silty material as other artifacts, their scoriaceous inner surface (GBX-22) displays diverse mineral phases, various hues (black, green, red), lustre (metallic to earthy), and Cu-Sn alloys. Identified compounds include Cu oxides (CuO, Cu_2O), Cu chlorides, probable Cu carbonates, Sn oxides, Fe oxy-hydroxides, Zn traces, and Pb-containing phases.

5.7. Archaeomagnetism

Clay or other ferromagnetic materials heated to high temperatures, acquire during cooling, a remanent magnetization with a direction parallel to, and an intensity proportional to, the ambient Earth magnetic field. Analysis of this remanence permits the determination of this direction and intensity of the Earth's magnetic field at the time and place where the cooling process occurred. By comparing these recorded magnetic signatures with established geomagnetic reference curves, scientists can determine when the material was last heated. Characteristic remanent magnetization (ChRM) directions were calculated using the principal component analysis (Kirschvink, 1980) (SI-2).

Magnetic directions from the kiln floor (GEMa02) are tightly grouped in an equal-area projection, indicating that the magnetic fabric is well-aligned in these specimens (Fig. 9D). The fact that only a few outliers exist (maximum three directions) further strengthens the idea of a stable, primary remanent magnetization. In contrast, the bell mould bricks (GEMa03) show scattered directions (Fig. 9E), suggesting a less stable or more complex magnetic history (Fig. 9E). There is no visible physical reason for it during the fieldwork (e.g., the bricks do not appear cracked or shifted). This suggests that the dispersion of magnetic directions is not related to physical movement or arrangement of the bricks in the mould during firing. Potential causes are explored in Supporting Information (SI-2).

Magnetization analysis followed three steps: a) Filtering specimen directions exceeding 12° angular deviation; b) Calculating mean magnetization using Fisher statistics (Fisher et al., 1987); this method averages the directions of individual specimens and c) Determining

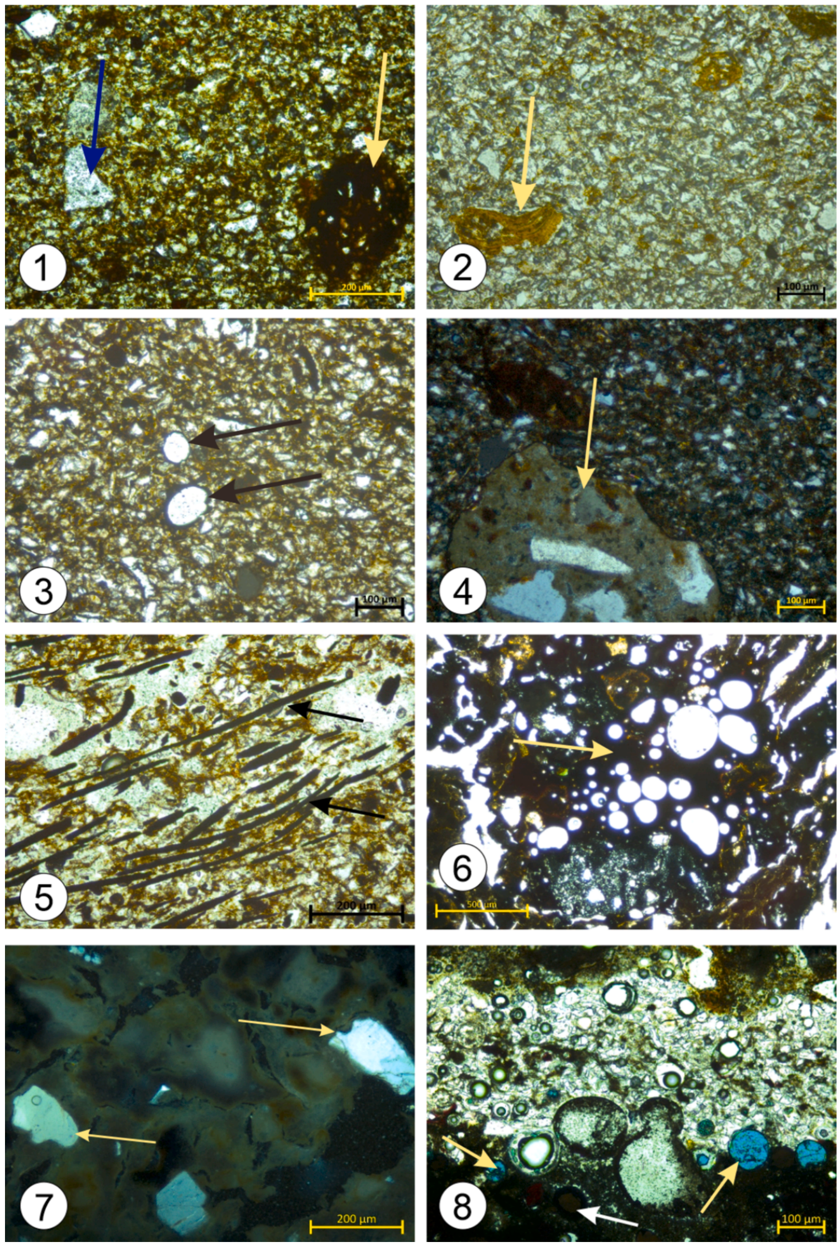

Fig. 6. Polished thin-section photomicrographs under the petrographic microscope. PPL: Planed polarized light, XPL: crossed polarized light. 1. Paste of brick made in a silty paste including a clay fraction and a fine-grained sand (quartz) fraction (blue arrow). Gley spot rich in iron (yellow arrow). Brick, Id: Gbx-11, PPL; 2. Silty matrix similar to the Fig. 1/1–3-4–5 showing (yellow arrow) a papule (illuviation clay paedogenic feature). Cope mould, Id: Gbx-10, PPL; 3. Two rounded to elliptic sections through animal fibres. The organic matter has been partly removed during the thin section preparation (black arrows). Silty clay matrix. Core mould, Id: Gbx-05, PPL; 4. Coarse inclusion of impure (quartzose) carbonated lime inside a silty clay matrix. Core mould, Id: Gbx-05, XPL; 5. Alignment of vegetal fibres (black arrows) in the silty clay matrix. Core mould, Id: Gbx-12, PPL; 6. Vitrified temper (yellow arrow) rich in bloating pores inside a porous glassy vitrified matrix. Crucible, Id: Gbx-01, PPL; 7. Vitrified matrix with unmelted quartz grains (yellow arrows). Crucible, Id: Gbx-01, XPL; 8. Inner wall of a crucible showing rounded gas bubbles with one filled by copper oxide (yellow arrows) and one metallic copper inclusion (white arrow). Id: Gbx-02, PPL. Pictures by É. Goemaere.

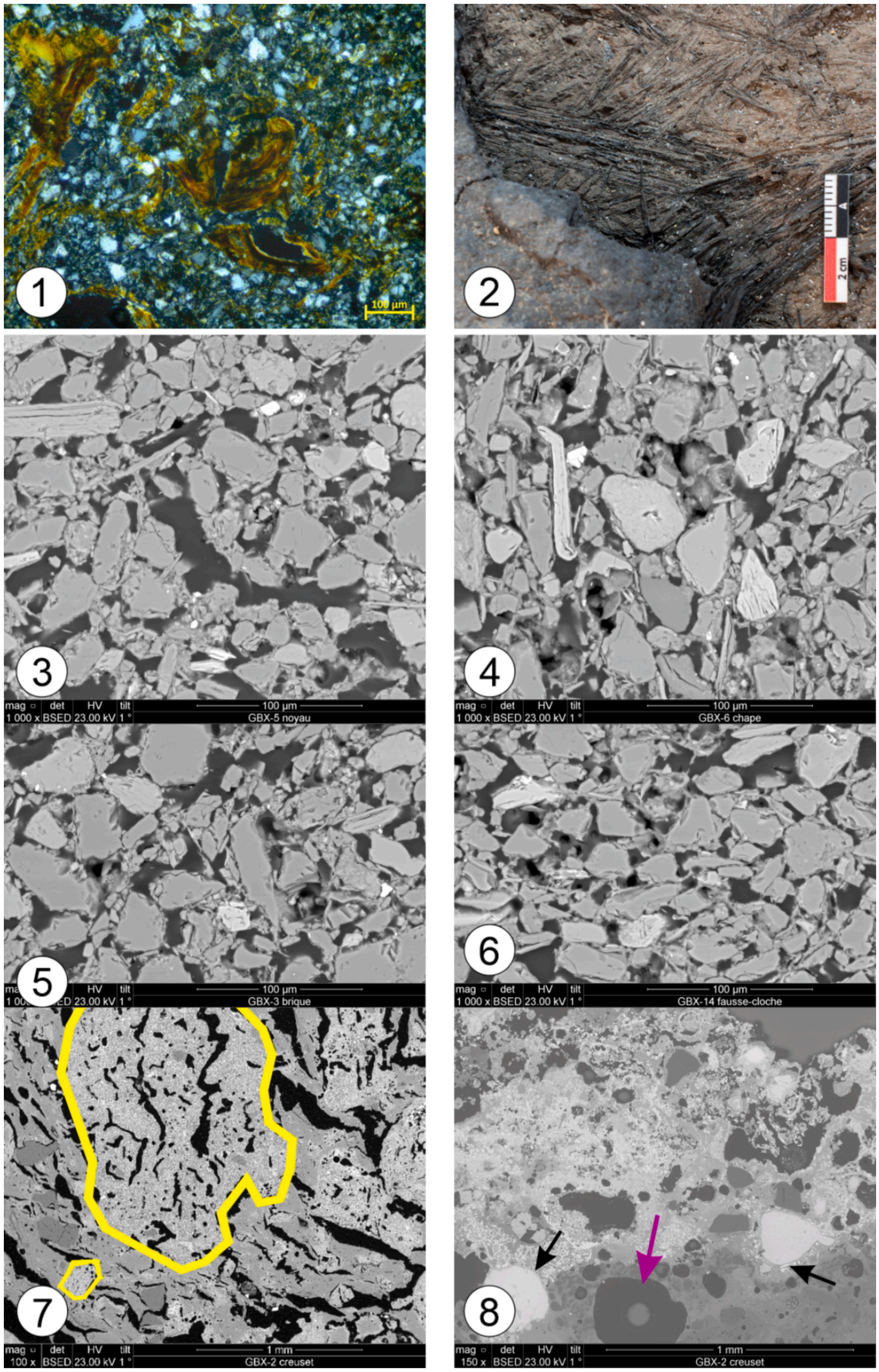

Fig. 7. 1. Silt raw material from the settlement tank showing infiltrated colloidal clay (orange yellow hues), Id: Gbx-17, XPL; 2. Macroscopical picture of the inner side of a cope mould showing a concentration of blacked (thermally affected) vegetal fibres; 3. Petrofacies general overview of the core mould with detrital quartz grains, phyllosilicate flakes (muscovite, chlorite, phengite), feldspars and heavy minerals, Id: Gbx-5; 4. Petrofacies general overview of the Cope mould, Id: Gbx-6; 5. Petrofacies partial (cut) view of the brick matrix. Brick from the core mould, Id: Gbx-3; 6. Petrofacies partial (cut) view of the matrix of the false bell, Id: Gbx-14; 7. Two fragments of crucibles used as temper are highlighted by a yellow line, occurring inside the wall of a crucible. Tempers are light grey due to zinc contamination. Unmelted quartz grains show medium grey colours. Crucible, Id: Gbx-2; 8. Inner wall of a crucible showing a recrystallised matrix (mullite, cristobalite) with Zn, Pb and Sn zones of concentration, pores, metallic Cu rounded inclusions (black arrows) and a bloating pore filled by copper oxide. Crucible, Id: Gbx-2. Pictures: 1 (É. Goemaere), 2 (M. Siebrand), 3–8 (T. Leduc).

mean structure magnetization with Scrolplot software. Magnetization quality was assessed using 1) concentration factor k, where higher values indicate that the individual directions are closely grouped around the mean, reflecting minimal dispersion and 2) factor α_{95}, which provides a 95 % confidence interval. Lower α_{95} values indicate more reliable data. Archaeomagnetic dating requires $k \geq 100$ and $\alpha_{95} \leq 5°$. The kiln floor yielded excellent results ($k = 3008$, $\alpha_{95} = 0.6°$), making it suitable for dating, while the bell mould bricks ($k = 2$, $\alpha_{95} = 30.5°$) were too scattered for reliable dating (Table 7). Kiln floor dating used French reference curves of secular magnetic variation (Gallet et al., 2002) and

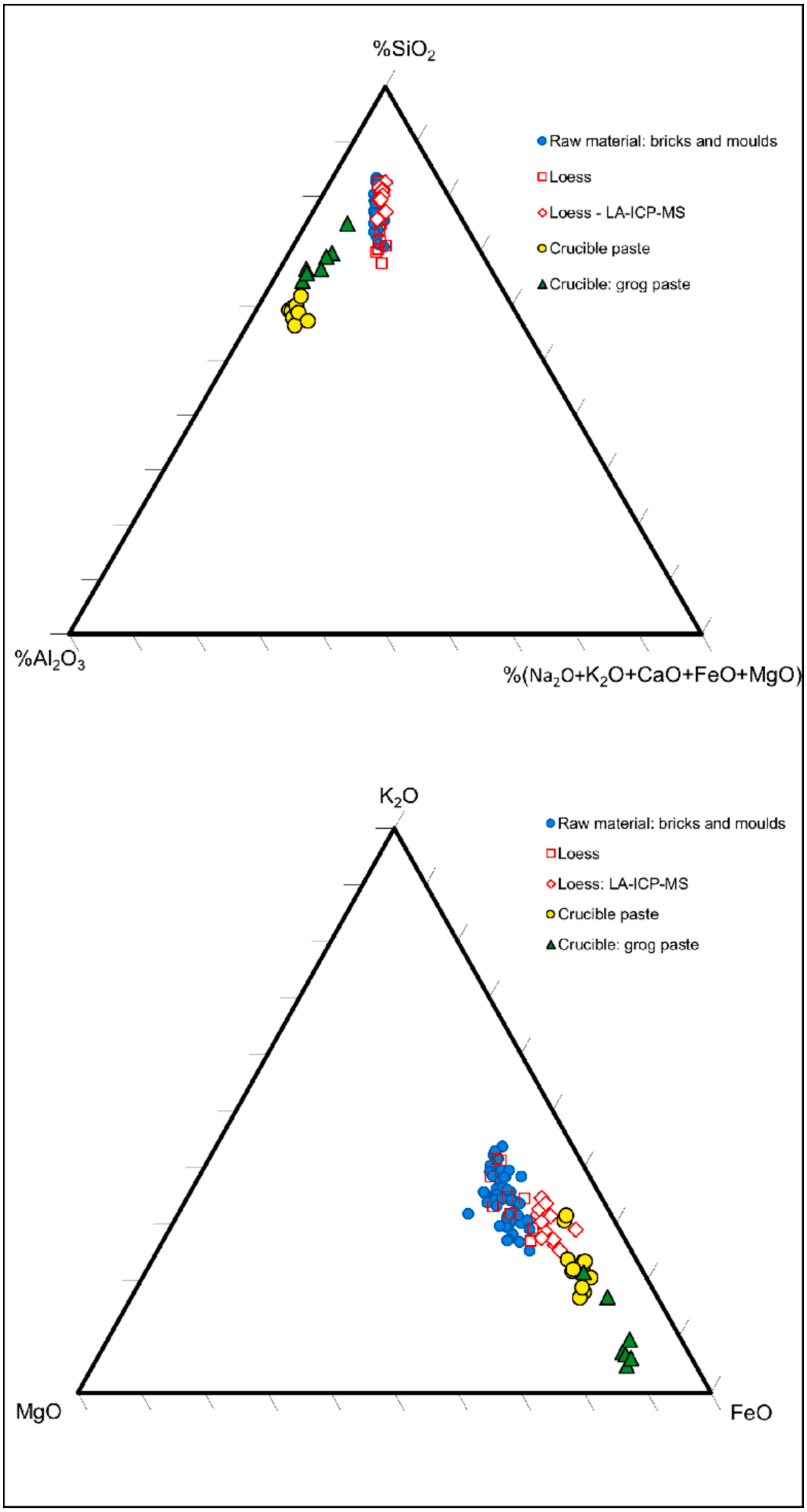

Fig. 8. Chemical composition of the material. 1. Bulk elemental compositions (wt%) of studied material (artefacts from the Gembloux bell bronze foundry and loessic regional soils), plotted on a ternary diagram [SiO_2 – (Na_2O + K_2O + CaO + FeO + MgO) – Al_2O_3]. Empty red squares: loess analyses by EDS. Red empty diamonds: loess analysed by LA-ICP-Ms by M. Golitko (2015); 2. Ternary diagram (K_2O – FeO – MgO) illustrating the chemical composition (wt%) measured by EDS of the paste of artefacts compared with regional loess sediments (empty red square by EDS and yellow crosses by LA-ICP-MS. Infography by É. Goemaere.

Table 2
Chemical composition determined by EDS on artefacts from Gembloux bronze bell foundry.

EDS surface analyses	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	FeO	TiO_2	K_2O/Al_2O_3
Mean bricks (n = 9)	0.93	0.93	10.55	80.89	0.20	2.30	0.51	3.10	0.50	0.22
Mean lut (n = 7)	0.97	1.32	12.07	77.65	0.14	2.59	0.59	3.94	0.58	0.21
Mean “clays” (core, false-clock, cope, crown) n = 28	1.01	1.27	12.24	76.60	0.30	2.80	0.67	4.22	0.75	0.23
Mean “fire place” (n = 3)	0.85	1.20	12.09	76.42	0.11	3.44	0.88	4.08	0.73	0.28
Mean “crude clays” (n = 6)	0.99	1.18	12.02	77.78	0.16	2.57	0.57	4.07	0.50	0.21
Mean loess (n = 6)	0.88	1.43	15.15	69.45	0.39	3.60	1.12	6.53	1.30	0.24
Mean totale (n = 59)	0.97	1.23	12.23	76.76	0.25	2.79	0.68	4.23	0.72	0.23
Mean crucible paste (n = 12)	0.38	0.64	33.97	57.64	0.15	1.51	1.00	2.92	1.79	0.04
Mean crucible grog (n = 7)	0.00	0.53	25.78	66.91	0.09	0.61	1.07	3.33	1.69	0.02
	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	FeO	TiO_2	
STD bricks	0.19	0.15	0.88	1.55	0.16	0.36	0.09	0.40	0.15	
STD lut	0.29	0.20	1.63	3.22	0.11	0.56	0.36	0.68	0.21	
STD terres (core, false-clock, cope, crown)	0.39	0.25	1.54	2.95	0.16	0.47	0.25	0.91	0.42	
STD “fire place”	0.17	0.23	2.37	3.25	0.09	0.34	0.41	0.64	0.07	
STD “crude clays”	0.43	0.32	1.39	2.88	0.08	0.54	0.18	0.61	0.12	
STD loess	0.46	0.11	1.06	2.35	0.12	0.69	0.49	1.00	0.66	
STD totale	0.35	0.26	1.81	3.93	0.16	0.60	0.32	1.16	0.42	
STD crucible paste	0.09	1.00	1.42	0.11	0.38	0.10	0.68	0.14	0.07	
STD crucible grog	0.06	4.23	3.35	0.12	0.42	0.43	0.82	0.30	0.12	

Table 3
Mineralogical composition of the < 2 μm fractions of bell bronze foundry workshop material acquired by XRD (oriented aggregates).

Id	Artefacts	Illite	Muscovite	Swelling mixed-layers	Smectites	Kaolinite	Amorphs	Quartz	Feldspars
3	**Brick**		(+)				+++	+++	++
4	**Caulking clays/lut**		+	+			+	+++	++
15	**Fireplace**	++	+	(+)		+	+	+++	+
5	**Core mould**	++	+	++		++		+++	+
6	**Cope mould**	++	+	++		++		+++	+
16	**Crown mould**	++	+	++		++		+++	+
14	**False bell**	++	+	+	++	++		+++	+
18	**Crude clay**	++	+	+	+++	++		+++	+

Table 4
Chemical composition (major and minor elements) determined by EDS of grog-tempered crucibles. The values of the chosen chemical elements were recalculated to be 100%.

Wt% Crucible Id.	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	FeO	TiO_2	MnO_2
Grog occurring in crucibles (excluding Zn, Cu, Pb, Sn, Sb, Ni)										
1	0.0	0.4	18.2	73.8	0.0	0.5	1.7	3.7	1.5	0.0
1	0.0	0.5	28.7	65.7	0.0	1.0	0.6	2.0	1.5	0.0
1	0.0	0.6	30.4	63.6	0.0	0.4	0.7	2.9	1.3	0.0
2	0.0	0.6	28.9	64.9	0.1	0.3	0.7	3.0	1.6	0.0
2	0.0	0.6	23.0	67.7	0.3	1.4	1.5	3.1	2.2	0.2
2	0.0	0.5	24.2	67.3	0.1	0.4	1.1	4.1	2.0	0.2
2	0.0	0.5	26.3	65.3	0.1	0.3	1.1	4.4	1.7	0.2
Crucible paste										
1	0.0	0.7	34.2	58.0	0.0	1.1	0.9	3.2	2.0	0.0
1	0.0	0.6	34.5	58.1	0.0	1.4	0.9	2.9	1.6	0.0
2	0.0	0.6	35.0	58.1	0.0	1.3	1.0	2.4	1.7	0.0
2	0.0	0.6	34.0	58.4	0.2	1.5	1.0	2.4	1.8	0.1
2	0.0	0.5	34.5	57.6	0.2	1.5	1.0	2.5	1.9	0.2
2	0.0	0.6	33.5	59.0	0.1	2.2	0.9	2.1	1.6	0.0
2	0.0	0.5	31.9	60.6	0.2	2.3	1.0	1.9	1.6	0.1
1	0.0	0.7	34.5	57.0	0.2	1.6	0.9	3.3	1.8	0.0
1	0.0	0.7	34.9	56.5	0.3	1.4	1.2	3.1	1.9	0.0
1	0.1	0.7	35.4	55.2	0.1	1.5	1.1	4.1	1.9	0.0
2	0.0	0.8	33.6	57.4	0.3	1.1	1.1	3.8	1.8	0.1
2	2.6	0.7	32.8	55.9	0.2	1.2	1.1	3.4	1.9	0.2
	wt % alumina									
	10/18		*“maigres”* (lean clays)							
	18/28		*“demi-maigres” or “demi-grasses”* (half lean or half fat clays)							
	28/33		*“grasses”* (fat clays)							
	>33		*“alumineuses”* (aluminous)							

Table 5
Results of X-ray diffraction analysis of bulk matrix sample taken from the Gembloux workshop.

		Crucibles		Bricks			Caulking clays/lut		Core mould		
	id.	GBX-1	GBX-2	GBX-3	GBX-7	GBX-11	GBX-4	GBX-8	GBX-5	GBX-9	GBX-12
Primary phases	Quartz	14.3	9.4	++++	++++	++++	++++	++++	++++	++++	++++
	Feldspars			++	++	++	++	++	++	++	++
	Illite/muscovite			<LD	+	+	+	+	+	+	+
	Chlorite+kaolinite								<LD	<LD	<LD
	Hematite			+	<LD	<LD					
Secundary phase	Calcite										
High temperature phases	Cristobalite	20.2	18.6								
	Tridymite	16.2	19.7								
	Mullite	9.0	8.9								
	Hercynite	38.7	43.5								
	Leucite	1.7									

		False bell mould		Cape mould			Crown	Furnace	Raw clays		Loess
	id.	GBX-14	GBX-19	GBX-6	GBX-10	GBX-13	GBX-16	GBX-15	GBX-17	GBX-18	Loess
Primary phases	Quartz	++++	++++	++++	++++	++++	++++	++++	++++	++++	++++
	Feldspars	++	++	++	++	++	++	++	++	++	++
	Illite/muscovite	++	++	++	++	++	++	++	++	++	++
	Chlorite+kaolinite	+			+	+	+	+	++	<LD	<LD
	Hematite										
Secundary phase	Calcite							+			

Table 6
Chemical composition of selected chemical elements of grog-tempered crucibles and determined by EDS to put in evidence the grog Zn contamination and the partial diffusion of Zn in the paste. < LD: concentration below the detection limit.

Wt%							
Crucible Id.	FeO	PbO	TiO_2	MnO_2	SnO_2	CuO	ZnO
Grog occurring in crucibles							
1	3.26	<LD	1.34	<LD	<LD	0.24	12.35
1	1.70	<LD	1.28	<LD	<LD	0.08	15.13
1	2.52	<LD	1.13	<LD	<LD	0.20	14.18
2	2.58	0.53	1.35	<LD	<LD	<LD	13.77
2	2.80	<LD	1.97	0.20	<LD	0.28	8.34
2	3.50	0.68	1.73	0.20	0.81	0.19	13.51
2	3.78	0.78	1.46	0.19	<LD	0.10	13.56
mean (grog)	2.88	0.66	1.46	0.20	0.81	0.18	13.0
std (grog)	0.70	0.13	0.29	0.004	–	0.08	2.21
Crucible paste							
1	2.99	<LD	1.85	<LD	<LD	0.28	5.52
1	2.87	<LD	1.61	<LD	<LD	0.23	1.25
2	2.32	0.43	1.71	<LD	<LD	0.26	1.19
2	2.34	0.51	1.76	0.13	<LD	0.16	1.40
2	2.42	0.66	1.86	0.15	<LD	0.13	1.48
2	2.10	0.44	1.54	0.03	<LD	0.07	1.32
2	1.89	0.60	1.53	0.06	<LD	0.10	1.32
1	3.12	<LD	1.72	<LD	<LD	<LD	4.46
1	2.89	<LD	1.81	<LD	<LD	<LD	5.24
1	3.97	<LD	1.82	<LD	<LD	<LD	3.23
2	3.58	<LD	1.64	0.11	<LD	0.86	5.96
2	3.41	<LD	1.91	0.18	<LD	<LD	<LD
mean paste	2.82	0.53	1.73	0.11	–	0.26	2.94
std (paste)	0.63	0.10	0.13	0.06	–	0.25	1.98

<LD: concentration below the detection limit; std: standard deviation

Rendate software (Lanos et al., 2004), providing three possible age intervals at a 95 % confidence level: [-466; −266] A.D., [686; 837] A.D., and [1663; 1689] A.D. The last interval aligns with the 1678 fire and subsequent smelter construction, placing kiln use between 1678 and 1689 (Fig. 10).

5.8. *Fibers and seeds*

5.8.1. *Moulds*

The vegetal fibres within the clay casts are very thin, long, and somewhat flexible. Due to burning, their internal structure, cell shapes, specific dislocation patterns and potential crystal or silica content could not be observed under transmitted or polarized light. However, reflected light shows unarticulated smooth elements with very fine longitudinal furrows and patterns, but no incremental scale whatsoever. SEM analysis revealed the fibres are hollow. Despite the presence of numerous cereal and grass seeds, straw use is unlikely. Instead, the fibre characteristics better suggest the use of other vegetal fibres, such as flax (*Linum usitatissimum*), hemp (*Cannabis sativa*), or nettle (*Urtica dioica*) as possible sources (Bergfjord et al., 2010; Catling & Grayson, 2004; Kvavadze et al., 2009; Lukesova & Holst, 2024). Again, because we couldn't observe their inner characteristics, we cannot be more precise than these three suggestions (Bergfjord & al., 2010; Catling & Grayson, 2004; Kvavadze & al., 2009; Lukesova & Holst, 2024).

Animal hair was identified based on its surface lacking fine longitudinal furrows typical of plant fibers (Appleyard, 1960; Teerink, 1991). Polygonal scale structures were occasionally observed, but most surfaces were altered by combustion. Animal hairs were found in only two samples: one cope clay mould (GBX-10 LM) and one core clay mould (GBX-12 LM). They are plurimillimetric or centimetric in length. The best-preserved specimen (GBX-10 LM) measures 58 μm in diameter, with scales forming a mosaic pattern resembling cattle hair (Appleyard, 1960, Fig. 16d). Due to fibre fragility, cross-sectioning and transmitted light observation were not attempted.

5.8.2. *Other contexts*

Seeds in the samples, mainly from ash pits and bell-making contexts, were predominantly cereal grains (cfr. SI-2). Identified species include oats (*Avena* sp., likely cultivated based on size), barley (*Hordeum vulgare*), rye (*Secale cereale*), naked wheat (*Triticum aestivum/durum/turgidum*), and occasional spelt grains (*Triticum spelta*). Legume remains include peas (*Pisum sativum*) and faba beans (*Vicia faba* subspec. *minor*). Straw and wild plants, such as brome grass (*Bromus* sp.), were found in samples 03.079 and 03.253 (F101). Ash pit F101 also contained hemp (*Cannabis sativa*) fragments and hazelnut epicarp (*Corylus avellana*).

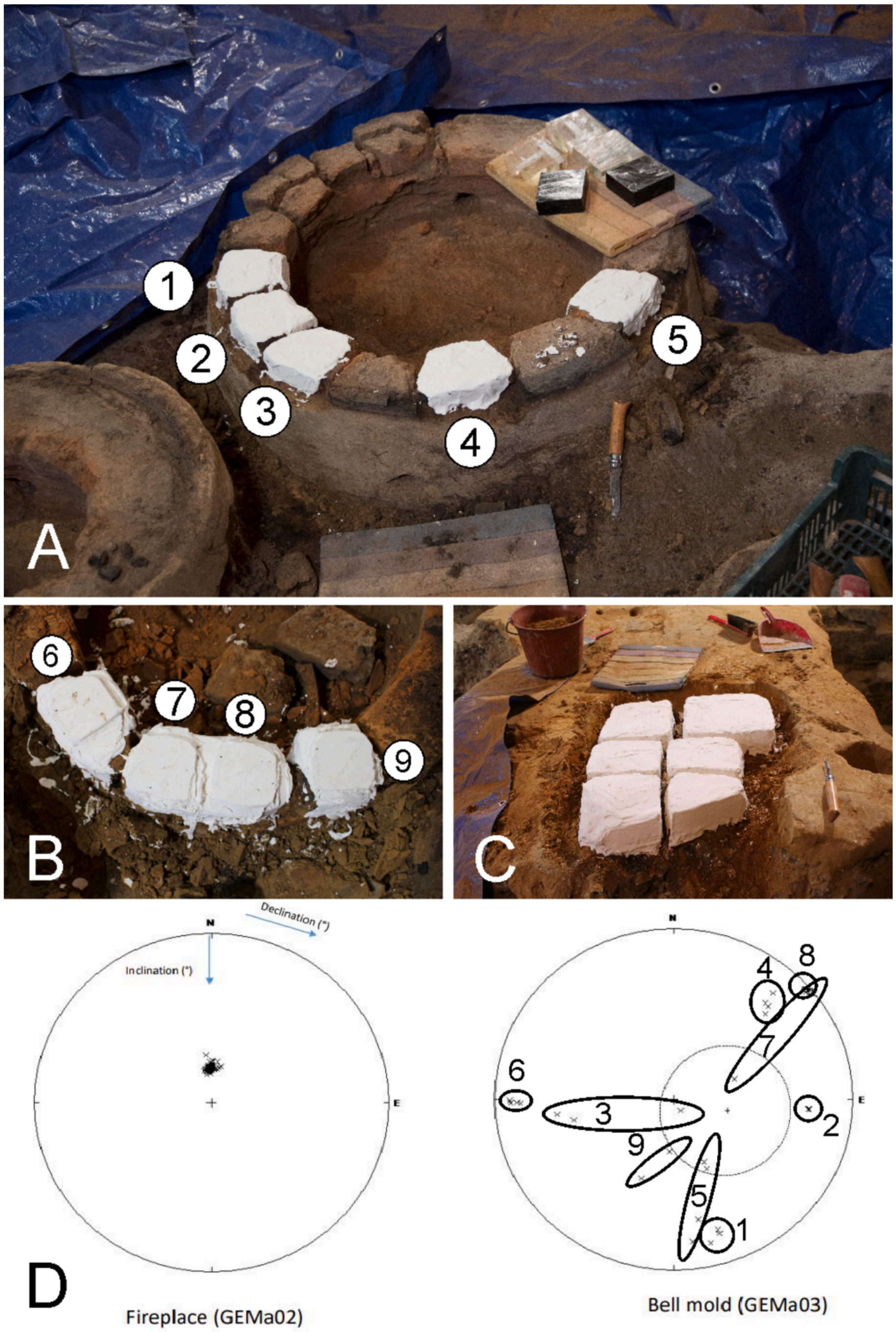

Fig. 9. Archaeomagnetic sampling and results. A. The bell mould with 1 to 5 numbered bricks sampled (upper layer); B. The bell mould with 6 to 9 numbered bricks sampled (lower layer). It is important to note that bricks 6, 7, 8, and 9 are positioned respectively below bricks 1, 2, 3, and 4, indicating a two-row stacking pattern; C. Sampling of the reddened material from the base of the kiln (fireplace); D and E. Equal area projection of the individual characteristic remanent magnetisation directions of all specimens of the melting furnace floor (D) and of the bricks (highly scattered values; E). The circle in the projection of the directions (bell mould and non-bell mould) represents the average of the individual directions of the recorded magnetisation grouped together in this circle (E). Pictures and infography by S. Ech-Chakrouni.

6. Conclusion

The bell foundry workshop discovered in Gembloux during excavations in the belfry of the Saint-Sauveur church is remarkable for the quantity and quality of preservation of artefacts illustrating all stages of manufacture. Archaeomagnetic dating of the surviving first kiln places it between 1669 and 1689. Archaeologically, we can place its use after the fire of 1678 (total destruction of the city) and before the death of founder Edmée Delapaix in 1694, who had cast at least two bells in this workshop. However, we cannot determine exactly when the workshop ceased operations, as there are no traces (coat-of-arms and decorations) of other foundrymen, and we are unable to date the second furnace, which has now disappeared. The multidisciplinary archaeometric study allowed us to determine the recipes used at the end of the 17th century by itinerant bell-makers and in particular the use of local to regional natural mineral resources (quaternary loess, lime, sand, coal) and organic resources (animal and vegetal fibres). Analyses and observations demonstrate the similarity of the clays used for the moulds (including

Table 7
Fisherian mean directions (Dm and Im) of the ChRM of the baked structures, with the number of samples and specimens (NSamples/NSpecimens), the concentration parameter (*K*) and the angle of confidence α_{95}.

Site	Code	N Samples/ N Specimens	Dm (°)	Im (°)	*k*	α_{95} (°)
Belfry of Gembloux	GEMa02	23/46	358.1	73.8	3008	0.6
	GEMa03	9/29	102.7	65	2	30.5

bricks), the furnace, the cast channels, all made with local loess. Naturally decarbonated upper horizons called *lehm* (thickness between 0.6 and 2 m) occurred on the territory of the commune of Gembloux but we did not find any information related to the brick making at the end of the 17th century. Lime was produced by heating of Dinantian limestones (Lives Formation, Livian) occurring 8 to 10 km south of Gembloux and mined in the Orneau valley and the *ruisseau des Chaufours* (stream named after lime kilns, in Delcambre & Pingot, 2008; Delcambre & Pingot, 2002). Coarse sands added to the lime are attributed to the Brussels Formation (Lutetian, Eocene) available around Gembloux. Animal fibres (their identification is obscured by combustion, although several characteristics of one hair are consistent with cattle hair) and vegetal fibres (from flax, hemp or nettle rather than from straw, but non-exclusive) were used as part of the recipe to produce clay moulds, likely to strengthen their mechanical resistance to firing and to avoid cracking. Preliminary findings concerning seeds could highlight the use of cereal straws, or even grains in the different moulds corresponding to the various stages of making bells. The results of the analysis of the seeds and fruits present in the sediment linked to the manufacture of the bells provide no evidence to support the hypothesis that horse manure was used in the recipe for the moulds used to make the bells (cf. Encyclopédie of Diderot et d'Alembert, 1767). In fact, no small seeds of wild plants (0.3 to 2 mm) associated with meadows and pastures frequented

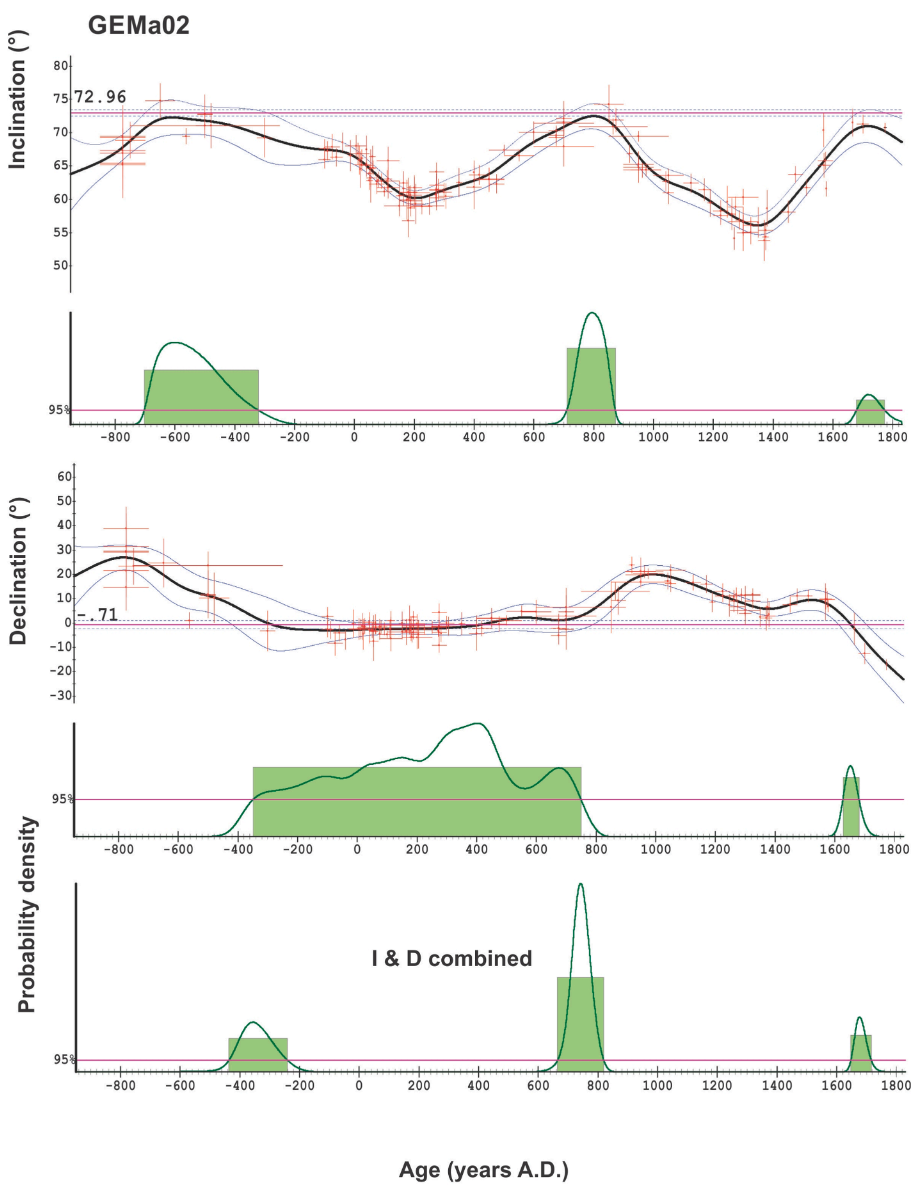

Fig. 10. Archaeomagnetic dating of the melting furnace floor (GEMa02) by referring to the secular variation of the field inclination and declination for the last three millennia for France by Gallet et al. (2002) with the error envelopes using the software Rendate (Lanos, 2004). The values of the average inclination and the average declination of the oven (bold dashed lines), with the errors after relocation to the geographical coordinates of Paris are compared with the French secular variation master curves. The distributions of the density of probability of the possible ages are given for inclination and declination separately and combined. Green rectangles represent the intervals of possible ages at a 95% confidence level. Infography by S. Ech-Chakrouni.

by horses and which could attest to the presence of horse manure were identified. The nature of the medium respectively used between core and false-bell and between false-bell and cope stay poorly understood but we found indications on the use of cinders.

The founders came to the sites with their know-how. The workshop of Gembloux shows many similarities to the one described by Diderot and d'Alembert in their Encyclopédie. The addition of lime to the clay used seems to have no equivalent in literature.

Crucibles were used to cast bronze objects (small bells?) as attested by the specific composition of alloys occurring as inclusions inside the inner wall of the crucibles. Crucibles are made with a refractory clay and tempered by grogs coming exclusively from crushed disused crucibles, first used to produce brass. Clays are associated to cryptokarstic white kaolinic clay matrix from the Entre-Sambre-et-Meuse area but the location of workshops producing this type of crucible is unknown. However, the recipe is close to that described by Saussus et al. (2022) for a late medieval brass foundry 15th century in Brussels. These occurrences show the importance of recycling in the production of refractories. We propose that melting crucibles were traded by bronze founders because their fabrication required specialised skills, to be found outside the bell founders' sphere; hypothesis which could be confirmed by further research.

The archaeological site is currently undergoing cultural and tourist development, and the remains have had to be reburied to protect them from degradation (November 2024). Many fragments have been preserved for further studies. Two studies on metal alloys and charcoal are currently underway.

Funding

The work of Sidonie Preiss, Alexandre Chevalier and Quentin Goffette took place within the framework of a partnership between the *Agence wallonne du Patrimoine* and the Royal Belgian Institute of Natural Sciences (Brussels).

Availability of data and materials

In addition to the detailed data (text and tables) presented in the SI, SEM images, point and surfaces analyses as well as OP images are available from the corresponding author on request. The analysed materials are available at the AWaP (Public Services of Wallonia).

CRediT authorship contribution statement

Eric Goemaere: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Michel Siebrand:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Souad Ech-Chakrouni:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Alexandre Chevalier:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis. **Quentin Goffette:** Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis. **Thomas Goovaerts:** Writing – original draft, Methodology, Investigation, Formal analysis. **Thierry Leduc:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Sidonie Preiss:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis.

Funding

The work of Sidonie Preiss, Alexandre Chevalier and Quentin Goffette took place within the framework of a partnership between the *Agence Wallonne du Patrimoine* (AWaP) and the Royal Belgian Institute of Natural Sciences (RBINS, Brussels).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors sincerely thank Jérôme Parmentier (CRAHG) and Manu Delsaute (Gembloux City – CRAHG) for their expertise and invaluable assistance in conducting the excavation and cataloging the archaeological material. They also extend their gratitude to Pierluigi Canepa for the preparation of thin sections, É. Van de Gehuchte (RBINS) for photography, and Damien Hanet (Société Archéologique de Namur) for editing.

The authors further acknowledge the constructive feedback and insightful comments provided by the two anonymous reviewers and the editors, which significantly contributed to improving this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2025.105374.

Data availability

Data will be made available on request.

References

Appleyard, H.M., 1960. Guide to the Identification of Animal Fibres. Wool Industries Research Association, Torridon, 118 p.

Association Campanaire Wallonne asbl, 2022. Fiche Inventaire Cloche, Eglise Sainte-Apolline, Wansin, 2 files. (Unique inventory) Unpublished data.

Bergfjord, C., Karg, S., Rast-Eicher, A., Nosch, M.-L., Mannering, U., Allaby, R., Murphy, B.M., Holst, B., 2010. Comment on "30,000-Year-Old Wild Flax Fibers". Science 328 (5986), 1634. https://doi.org/10.1126/science.1186345.

Berthelé, J., 1908. Les fontes de cloches à l'intérieur des églises, à propos d'un four découvert en 1892 dans l'Eglise Saint-Crépin à Château-Thierry. Annales de la Société historique et archéologique de Château-Thierry, 36 p.

Bouvet, M.-B., 2009. L'art campanaire en Lorraine au XIXe siècle, ou l'alliance inavouée de la tradition et de l'innovation, dans Les arts en feu. Actes du 127e Congrès national des sociétés historiques et scientifiques, Le travail et les hommes, Nancy, 2002. Paris, édition du CTHS, 111-125. Actes des congrès nationaux des sociétés historiques et scientifiques, 127-10. https://www.persee.fr/doc/acths_1764-7355_2009_act_127_5_1511.

Catling, D., Grayson, J., 2004. Identification of Vegetable Fibres. Archetype Publications, London, 106 p.

Delcambre, B., Pingot, J.-L., 2002. Chastre-Gembloux 40/5-6. Carte géologique de Wallonie (échelle 1/25 000) et notice explicative. MRW-DGRNE Ed., Namur, 72 p.

Delcambre, B., Pingot, J.-L., 2008. Fleurus-Spy 47/1-2. Carte géologique de Wallonie (échelle 1/25 000) et notice explicative. MRW-DGRNE Ed., Namur, 96 p.

Diderot, D., d'Alembert, J.L.R., 1751-1772. Encyclopédie ou dictionnaire raisonné des Sciences, des Arts et des Métiers, par une Société de gens de Lettres. Suivi du Recueil de planches sur les Sciences, les Arts libéraux et les Arts mécaniques avec leur explication, Paris, 28 vol.

Fauq, B., 2002. Les fours à cloches en Basse-Normandie, Séminaire de Jean Chapelot. Année universitaire 2002-2003. Mercredi 4 décembre 2002. Archéologie du chantier de construction (Atelier de taille de la pierre, four à chaux, forges, fours à cloches, etc.). Résumé de l'intervention par Jean Chapelot. 2 p.

Fisher, N.I, Lewis, T., Embleton, B.J.J., 1987. Statistical analysis of spherical data, Cambridge University Press, 329 p. DOI: 10.1017/CBO9780511623059.

Gallet, Y., Genevey, A., Le Goff, M., 2002. Three millennia of directional variations of the Earth's magnetic field in western Europe as revealed by archeological artefacts. Phys. Earth Planet. In. 131, 81–89. https://doi.org/10.1016/S0031-9201(02)00030-4.

Goemaere, É., 2017. "Terre à terres" : quelques mots sur la formation de la derle à Andenne et les communes voisines, in: Piechowski C. (ed.), La Derle – Li Dièle. L'habile Argile Du Condroz. Vingt Siècles de Céramiques En Terres d'Andenne, Les Dossiers de l'IPW. Institut du patrimoine wallon, Namur: 19-33.

Goemaere, É., Declercq, P.-Y., Quinif, Y., 2012. Vingt siècles d'exploitation des argiles plastiques d'Andenne (Belgique) : du gisement au musée de la céramiqu. Annales De La Société Géologique Du Nord 19, 87–97.

Golitko, M., 2015. LBK realpolitik: an archaeometric study of conflict and social structure in the Belgian Early Neolithic. Archaeopress Archaeology Series. Archaeopress, Oxford, 188 p. DOI: 10.2307/j.ctvqmp16x.

Kirschvink, J.L., 1980. The least-squares line and plane and the analysis of palaeomagnetic data. Geophys. J. R. Astron. Soc. 62 (3), 699–718. https://doi.org/10.1111/j.1365-246X.1980.tb02601.x.

Korpium, P., 2010. Dans l'atelier des Perdry. Maîtres fondeurs du roi d'Espagne à Valenciennes au XVIIe siècle. Fouilles archéologiques préventives de la rue d'En-Bas-l'Eau, Service archéologique de Valenciennes, Valenciennes, 166 p.

Kvavadze, E., Bar-Yosef, O., Belfer-Cohen, A., Boaretto, E., Jakeli, N., Matskevitch, Z., Meshveliani, T., 2009. 30,000-Year-Old Wild Flax Fibers. Science 325 (5946), 1359. https://doi.org/10.1126/science.1175404.

Lanos, Ph., 2004. Bayesian inference of calibration curves: application to archaeomagnetism, in Tools for Constructing Chronologies: Crossing Disciplinary Boundaries, in: Buck C. & Millard A. (eds), Lecture Notes in Statistics, Springer-Verlag, London, 177: 43-82.

Lukesova, H., Holst, B., 2024. Identifying plant fibres in cultural heritage with optical and electron microscopy: how to present results and avoid pitfalls. Heritage Science 12 (12). https://doi.org/10.1186/s40494-023-01122-z.

Monari, G., Galeotti, M., Matteini, M., Salvadori, B., Stifanese, R., Traverso, P., Vettori, S., Letardi, P., 2023. Protective treatments for copper alloy artworks: preliminary studies of sodium oxalate and limewater effectiveness against bronze disease. Environ. Sci. Pollut. Res. Int. 30 (10), 27441–27457. https://doi.org/10.1007/s11356-022-24107-0.

Nicourt, J., 1971. Fabrication des cloches fondues. Permanence des techniques. Ethnologie française, 1(3-4): 55-82. https://www.jstor.org/stable/40988168 (last access 09/2024).

Robbiola, L., Blengino, J.-M., Fiaud, C., 1998. Morphology and mechanisms of formation of natural patinas on archaeological Cu–Sn alloys. Corros. Sci. 40 (12), 2083–2111. https://doi.org/10.1016/S0010-938X(98)00096-1.

Ronot, H., 2001. Dictionnaire des fondeurs de cloches du Bassigny. Un rayonnement sur l'Europe, Dijon, p. 139.

Saussus, L., Goemaere, É., Thomas, N., Leduc, T., Goovaerts, T., Fourny, M., 2021. L'atelier d'un fondeur de laiton à Bruxelles au début du XVe siècle: production, matériaux et approvisionnements (RBC). Archaeologia Mediaevalis, Chronique 44, 106–108.

Saussus, L., Goemaere, É., Thomas, N., Leduc, T., Goovaerts, T., Fourny, M., 2022. Practices, recipes and supply of a late medieval brass foundry: the refractory ceramics and the metals of an early 15th century AD metallurgical workshop in Brussels. J. Archaeol. Sci. Rep. 42, 103358. https://doi.org/10.1016/j.jasrep.2022.103358.

Schweitz, D., Rossillo, A., 1982. Un atelier médiéval pour la fonte des cloches à Issoudun (Indre). Compte-rendu de fouilles. Revue Archéologique Du Centre De La France 21 (1), 47–62. https://doi.org/10.3406/racf.1982.2328.

Siebrand, M., Goemaere, É., 2023. La fonderie de cloches du beffroi de Gembloux (fin du XVIIe siècle). Structure et matériel archéologique en terre. Premiers résultats. Pré-actes des Journées d'Archéologie en Wallonie, Andenne, 23-24 novembre 2023, Rapports d'Archéologie n°2, AWaP Ed., 52 p.: 16-18.

Siebrand, M., Parmentier, J., 2016. Gembloux/Gembloux : nouvelles données concernant l'église Saint-Sauveur et le beffroi. Chronique De L'archéologie Wallonne 24, 280–282.

Siebrand, M., Parmentier, J., 2018. Gembloux/Gembloux : nouveaux sondages au beffroi. Chronique De L'archéologie Wallonne 26, 206–208.

Siebrand, M., Parmentier, J., Delsaute, E., 2022. Gembloux/Gembloux : découverte de deux églises et d'une fonderie de cloches au beffroi. Chronique De L'archéologie Wallonne 30, 239–242.

Siebrand, M., Parmentier, J., Delsaute, E., 2023. Gembloux/Gembloux : découverte de deux églises et d'une fonderie de cloches au beffroi. Chronique De L'archéologie Wallonne 31, 209–211.

Siebrand, M., Parmentier, J., Delsaute E., 2024. Beffroi de Gembloux : découverte de deux églises et d'une fonderie de cloches du XVIIIe siècle, dans 11e Congrès de l'Association des cercles francophones d'histoire et d'archéologie de Belgique et 58e Congrès de la Fédération des cercles d'archéologie et d'histoire de Belgique. Congrès de Wallonie picarde, Tournai, organisé par les sociétés d'histoire et d'archéologie d'Ath, Mouscron et Tournai, avec la collaboration du Centre Hannonia, 19-22 août 2021. Actes, tome 2 (Tournai): 117-126.

Slégers, P., 2019. Vestiges d'anciennes fosses de moulage et de coulée de cloches en Wallonie. Le Bulletin Campanaire. Association Campanaire Wallonne, 98(2019/03): 4-12.

Teerink, B.J., 1991. Hair of West European Mammals: Atlas and Identification Key. Cambridge University Press, UK, 224 p.

Thomas, N., 2017. Un atelier de fondeur de cloche dans l'enceinte du château de Montbrison, in: Mathevot C. & Poisson J.-M. (eds), Montbrison médiéval, Actes du colloque de Montbrison du 6 février 2016, Montbrison, La Diane: 181-211.

Thomas, N., 2019. Une fonderie de cloche installée dans la nef au XVIe siècle ? (sondage 4), in: Piré A. (dir.), Ile-de-France, Seine-et-Marne (77), Chenou. Eglise Saint-Sulpice et Saint-Antoine, Pantin: 62-91. (INRAP Rapport diagnostic).

Toussaint, J., 1977. Gembloux. La ville et l'abbaye. Aperçu géographique, historique et artistique. Gembloux. Editions De L'orneau 654 p.