Reviewed Article:

(Re)constructing an Early Medieval Irish Ard

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This article outlines the results of an EXARC funded 2019 Twinning project exploring the production and use of an Irish early medieval ard. In this, the project partners researched the evidence for early ploughs and ards, made bloomery iron, produced an ard share, and worked wood to form the frame of the ard. This paper also includes the results of scientific analysis and reflections on ploughing using specially trained draft animals. Ultimately, this

provided details about this crucial agricultural technology and its place within early medieval society. This project is also a case-study, showcasing collaborative, practical research strengths between leading centers for experimental archaeology.

> What we now know is that even a light ard, like the one reconstructed for this project, represents a huge number of skills. Iron must be made by a community of people, transforming ores, charcoal, and clay into ingots of hard metal.

Introduction

The early medieval period in Ireland (AD 400-1100) was a time of far-reaching social, religious, and technological developments across the island (O'Sullivan and McCormick, 2017). The people were mainly pastoralists, devoted to raising cattle, but were also increasingly engaged in arable farming. Somewhat unusually, there is excellent and abundant evidence for the kinds of crops people were growing and how they were processing these to make bread, pottages, biscuits, etc. (McCormick et al. 2011). What is less well documented are the details of plough making and ploughing, archaeologically enigmatic yet crucial technologies during the early medieval period. This Twinning Project sought to investigate this by bringing the strengths of The Lauresham Open-Air Laboratory in Germany (Lauresham) and the Centre for Experimental Archaeology and Material Culture in University College Dublin, Ireland (CEAMC) together in the reconstruction of an early medieval Irish ard; a light plough with a symmetrical ploughshare.

Lauresham, at the UNESCO World Heritage Site Lorsch Abbey, and CEAMC at University College Dublin (UCD) are two complementary institutions. The first is a high-quality Archaeological Open-Air Museum (AOAM) dedicated to communicating daily life and work at an early medieval monastic manor associated with Lorsch Abbey while conducting scientific research on agricultural livestock management and technologies. CEAMC is an officially designated UCD Research Centre dedicated to researching and teaching material culture using a wide range of methodologies found in experimental archaeology. Its staff, students, and facilities are also committed to public outreach and engagement to showcase past material culture, ancient technologies, and the strengths of interdisciplinary research.

These sites are ideal Twinning partners, as together they encapsulate the ethos and pillars of EXARC; AOAMs, Experimental Archaeology, Ancient Technologies, Interpretation and Living History. They also share an interest in creating and communicating archaeological knowledge as well as a number of common research themes: early medieval architecture; agricultural technologies; crafts and production, including ironworking and non-ferrous metalworking. Importantly, both bring different strengths to a project of this kind. Lauresham has established knowledge in raising, training, and working with a range of domesticated animals, allowing investigation of past lifeways and living conditions. CEAMC has a longstanding research history investigating early medieval "hot technologies", such as metal work. Based within a university campus CEAMC also has access to a broad range of analytical possibilities. Together, this partnership provided the skillsets to create early medieval iron, forge a ploughshare, and ultimately assemble a suitable plough with the view to testing it under 'actualistic' conditions (Hurcombe, 2008, 85; Molloy, 2008, 119).

Reconstructing the evidence

Plough technologies and their development are key indicators of the character and productivity of early medieval agriculture, particularly from the 7th/8th century AD onwards, when cereal production intensified across Europe to support growing populations. They were a vital means of preparing soils for growing cereals such as wheat, barley, and oats, which were important food staples and a means of acquiring surplus goods for markets and exchange. However, there is still much that is not fully understood about the effectiveness of ploughs and their typological development (See Figure 1). Consequently, the aim of this project was to create new insights into evolving agricultural practice in early medieval Ireland and Germany (and more broadly throughout Europe) by undertaking the complete reconstruction of a particular example. Additionally, it sought to understand the detail of this agricultural practice, how ploughing was actually undertaken, and what components it involved.

There is quite a lot of archaeological evidence from Ireland for 8th/9th century ploughshares (the arrow-or sock-shaped iron object that lifted and sometimes inverted the soil) and iron coulters (the heavy iron blade that hung down from the wooden plough and cut the sod) (See Figure 2). In contrast, these iron implements are almost completely missing in the south-western part of Germany where the Lauresham Laboratory is situated. As such, the starting point of this project was a symmetrical ploughshare, excavated at Rathtinaun, Co. Sligo (See Figure 3) and dated c.500 AD (Brady 2016, p.146). Although only one component, this implies important information about other aspects of the wooden frame it was attached to and how it may have been used. According to Bentzien's typology (1990, 25 and 33), it can be categorised as an early medieval 'spear-shaped' share, which had 'elongated, tubular' spouts. Šach (1968, p.19) and Fries (1995, p.47) also held the opinion that such shares were mounted almost vertically on the ard, resulting most likely in a sole-less construction of the implement (Bentzien, 1990, p.25). The vertical position is important for a possible reconstruction as it is known that ards with shares in this position do not require coulters (Leser, 1931, cited by Fries, 1995, p.58; Brady, 1993, pp. 34 and 37). Accordingly, the plough types a, b, c, or e in Figure 1 can be considered as suitable for the chosen share. Of elementary importance for said types is the so-called Tegneby plough (Type 2), derived primarily from Bronze Age rock paintings (Fries, 1995, p.29).

The starting materials for the Tegneby plough might have been either a forked branch (in the form of a type 1 plough of Figure 1), to which an additional piece was added as a stilt, or two separate pieces were used for the beam and stilt with an 'ard-head' (Fries, 1995, p.30). Fries

(1995, p.30) claims that the stilt wore out faster than the beam and therefore the connection of the two parts would most likely have created a hole in the beam. Also, in the replica of Hansen (1969, p.68), the ard head was passed through the beam. However, results of experiments with earlier models at the Open-Air Laboratory show that the beam broke just as often and was therefore at least equally prone to wear (cf. Töngi, 2019, p.15).

A bipartite beam is the normal case in most ards (Lerche, 1994, p.12). This has been proven, among other things, by the discovery of the ard from Dabergotz, which was dated to the 8th century AD by means of radiocarbon dating and analysis (Bentzien, 1968, p.53). Its beam was located only a very short distance above the sole, making it impossible to attach it to the yoke. Therefore, the presence of a beam extension was concluded, which could be up to 2 metres long. Further research confirmed this (Bentzien, 1968, pp.50 - 53). A 2m long beam was also found on a plough find in Drumlee, Co. Down (Earwood and Beattie, 2008, pp.118). Possibly the extension was attached to the actual beam by means of bands of willow and wooden pegs (Bentzien, 1968, pp.50 – 53). A handle at the upper end of the stilt may also be archaeologically attested in a find from Hendriksmose. In this case, the stilt has a perforation just below the upper end, likely indicating the original presence of a handle (Coles, 1973, p.26).

(Re)constructing the ploughshare

Raw materials

The ore from which the iron (*iarainn* in old Irish) for this project was made was Irish 'bog ore' (Carlin et al. 2008, 91), formally known as goethite, collected from a raised bog in Co. Offaly. Bogs and other wetlands are ideal environments for the formation of this ore, as minerals, particularly iron, are leached from peat, stone, vegetation, and underlying geology by a weak reaction with humic acid (Feehan and O'Donovan, 1996, p.99; O'Neill et al., 2014). The exact location of this mineral just below the surface of many bogs (Dungworth, 2015) can be easily identified by following iridescent discolouration of ground water to its source and digging down, typically revealing varying quantities of nodular, "rusty" rocks.

Despite some initial scepticism surrounding the 'usually vague' (Scott, 1991, p.152) references to bog ore in excavation reports, more recently our understanding has been greatly advanced through a combination of increased archaeological excavations in Ireland and applied archaeological sciences. Finds of iron ores from early medieval Ireland are understandably few as the process of smelting does not lend itself to their preservation. While a small number of excavations have reported "haematite", these tend to be only tiny pieces found close to well-known sources, such as at Cahircalla More, Co. Clare (Keys, 2006; Taylor, 2006). Aside from these, the vast majority of ore finds are either bog ore, siderite, or limonite, each forming under similar wetland conditions.

Another source for determining the ores used in the production of iron is slag, a waste product of the smelting process. Importantly, the elemental composition of this substance is directly related to the parent ore and so may infer type (Paynter, 2006). Specifically, the presence of trace manganese (more correctly manganese oxide) has been cited as diagnostic of bog iron ore (Scott, 1991, p.153; Hall and Photos-Jones, 1998). This has also been borne out by analysis of archaeological slags (Photos-Jones, 2008, p.186; Wallace and Anguilano, 2010, p.70; O'Neill, 2017), corroborating bog ore as the primary ore used in early medieval Ireland. Indeed, similar evidence has been discovered from a range of near contemporary Viking sites where iron was also produced from this ore (Stenvik, 2003, p.123; Wallace, 2003, p.15; Smith, 2004, p.189), perhaps demonstrating a preference for its use during this time.

Smelting

Iron was made in early medieval Ireland in non-tapping, slag-pit, shaft 'bloomery furnaces' (Killick and Gordon, 1988, p.120). These features create specific conditions (thermal and atmospheric) that facilitate complex thermo-chemical reactions to make metal. For this twinning project the iron was made at the Centre for Experimental Archaeology and Material Culture (CEAMC), University College Dublin. Over two individual smelts (c.7 hours each) almost 10.5kg of iron was made by 9 participants from 45kg of ore and c.200kg of oak charcoal. These were only roughly consolidated to remove the bulk of the slag, after which the metal was analysed and delivered to Lauresham Open-Air Laboratory to be forged into ploughshares.

As smelting bloomery iron is a complicated and organic process (with no two smelts identical), only a generalised procedure is outlined here, reflecting years of research and testing at CEAMC. Before smelting, the ore was heated to temperatures of c.600-800°C, a process that is typically known as "roasting" (See Figure 4). Although the informal nature of this process leaves little archaeological traces, technologically it has two main advantages. Firstly, it allows the ore to be more easily crushed as it microfractures through heating. Although not strictly necessary, this makes smelting more efficient by providing a greater surface area of ore to react with the heat and atmosphere of the furnace. Additionally, in the case of bog ore, it converts the already quite reactive goethite into even more reactive magnetite.

A furnace was constructed as a 1m high tapering clay shaft over a cut basal pit (See Figure 5). On one side at ground level an arched opening was cut into the shaft that was resealed with a thin 'false door' of clay. This provided an opening allowing air to enter the furnace, and a means of retrieving the bloom once formed. Archaeological evidence for the use of similar non-tapping, slag-pit, shaft furnaces can be found throughout early medieval Ireland showing access to bloomery iron at all levels of this society.

During smelting of this kind, the hottest area inside the furnace is at ground level where oxygen is being bellowed into the feature (adding additional combustible ‘fuel’ and pressure). This creates something like a conveyor belt, allowing charcoal above to slip downwards into this “hot zone”. If all works well, this will create space at the top of the shaft where new charcoal and ore can be added throughout the smelt (See Figure 6). To create the right atmosphere (a reducing atmosphere) within the furnace, a high proportion of carbon (a reducing gas) is needed, which we estimate to be roughly 2:1 (charcoal:ore). Being non-tapping furnaces, the slag accumulates within the basal pits of these features throughout the smelt, providing an effective limit when it is filled with slag, blocking the air hole and stopping the smelt (Pleiner, 2000, p.141).

At this point, the bloom, a ‘spongy mass of reduced iron particles’ (Scott, 1991, p.156) and slag, must be retrieved while still hot to allow the malleable iron to be consolidated and the more liquid slag to be expelled. To do this, the “false door” where the bellows entered the feature is broken through and the ferrous mass removed using tongs (See Figure 7). In this instance, the bloom was placed on a wooden stump for repeated hammering and splitting until it was too cold to be worked.

Refining and Forging

On the first day of the refining process in the Lauresham Open-Air Laboratory, the material was fire-welded, forged, split and fire-welded again in several repetitions (See Figure 8). During this work process, it was noticed that only the layers in the core connected, while hardly any connected at the edge. Another problem was encountered during splitting, where the material often became brittle and broke.

Analysis of samples of ore, slag, blooms, and iron (cut, polished, and etched) was conducted at UCD to better understand if these issues were material in nature. Bulk chemical analysis of iron samples using SEM-EDS (Hitachi TM3030Plus) showed a consistent progression of elements from ore to the resulting iron (See Figure 9). Importantly, trace elements such as phosphorus (P) and sulphur (S), which might account for brittleness in the metal, are only in extremely low concentrations. There was, however, a somewhat elevated detection for carbon (C) specifically in the iron samples. Subsequent quantitative analysis of the original blooms using an Optical Emission Spectrometer (OES) confirmed only trace amounts of phosphorus and sulphur as well as elevated amounts of carbon, albeit in varying quantities across the samples (See Figure 10). Indeed, this variable carbon content can also be seen in the differing, uneven distributions of pearlite across micrographs of these samples.

One explanation for the incomplete connection of the partially flaky iron pieces in the edge areas may be insufficient heat during the welding process. This may be due to the design of the forge used at Lauresham, which seems to have produced inadequate heat for this size of iron stock (Holdermann and Trommer, 2017, 14f.). It should be noted at this point that the external forge located at Lauresham is normally operated by two bellows and used for smaller work pieces such as nails, brackets, or smaller tools. An initially used portable forge (usually used for damask manufacturing) failed and the Lauresham forge had to be used. In order to create a better air supply for all sides of the workpiece during the refining process, the forge was equipped with a second nozzle stone and finally operated with four bellows simultaneously on the second day of the process (See Figure 11). Nevertheless, the heating process remained rather long. Indeed, another part of this bloom was refined in the regular forge at Trommer Archäotechnik in Blaubeuren (Germany) using a forge with a larger heating area and modern machinery. After repeated working, the result was a thoroughly coherent bar.

In a final step, the actual ploughshare was forged from the bar that had been produced (See Figure 12). After the tip was forged out, the two flaps (as a spout) were worked out in a second step. The finalised ploughshare had an overall length of 17 cm and was 8 cm at its widest point (See Figure 13).

(Re)construction of the plough-body

The naturally curved branch of an oak (*Quercus petraea*) was selected as the stilt. The diameter of this piece was 20 cm. Another piece of oak with a diameter of 24 cm served as the main part of the beam. Willow (*Salix sp.)* with different curvatures was selected for the beam extension. A round log, also made of willow, was used as the material for the sheath. The tools used were a drawknife, beard axes, and splitting axes of various sizes. Furthermore, a hand saw, various chisels, and in connection with them a wooden hammer (german *Klüpfe*l), as well as a manual hand drill were used (See Figure 14).

The construction of the plough was completed by a couple of people within 5 days (07/27 - 07/31/2020). In the beginning, the stilt main piece was constructed. The first step consisted of debarking the wood with the drawknife and a bearded axe. The tool was also used to smooth out the surface. To reduce the diameter of the wood, successive notches were cut into the wood with a splitting axe. The area between each notch could eventually be chipped out with the axe. The lower end of the stilt (ard-head) was also axed with a bearded axe, and then its width and depth were adjusted to the size of the share with a chisel. A drawknife (*Zieheisen*) was useful to work the surface of the head into a flat shape (See Figure 15).

To model the beam, the selected wood had to be debarked and shortened again. The beam piece, which was to be passed through the stilt, was additionally worked down to 9x5 cm edge length. For the sheath, a round piece of willow was found in Lauresham, which only had to be sawn to the correct length. The sawn-off remainder was to serve as a handle in the stilt. The willow for the beam extension also had to be shortened and debarked. The branch attachments were cut off with an axe. A wooden nail was integrated at the front end of the beam extension, which would then be attached to the yoke. Furthermore, a support surface for the yoke was created, as well as notches for attaching the ropes.

After all the individual parts were made, they were joined together by plug-in connections. For this purpose, three mortises were cut in the stilt. A small mortise just before the upper end served as a holder for the handle. Below this, a mortised tenon joint was used to connect the beam to the stilt (See See Figure 16). The two-sided tenons of the beam were secured at the exit point with a wooden nail. A mortised tenon hole in the stilt served as a contact surface for the sheath, which was guided through a hole in the beam and was held in position by another wooden nail. Various chisels and a mallet were used as tools for all holes. The nails were created by means of a bearded axe and driven into the hole pre-drilled with a hand drill. For the connection of the beam and its extension, an overlap was chosen as the joint. For this purpose, the wooden parts joining each other were sawn to the same length up to the centre point and then flattened from the end of the wood to that point. To secure the overlap, two additional wooden nails were made. Finally, the share was fixed on the ard-head of the stilt after it was heated in the forge.

Experimental archaeological testing of the (re)construction

After completion of the reconstruction (See Figure 17), a detailed practical test was carried out in the Lauresham Open-Air Laboratory, including the associated draft measurements. A small field of slightly loamy sand served as the test area. During a total of three test measurements, a furrow depth of 7 cm was achieved. If force was applied to push the ard into the soil, a furrow depth of 13 cm could be produced (See Figure 18). The furrow width was around 11 cm. Depending on the ploughing depth, the average draft force varied from 24.2 kg to 67.4 kg. The maximum load at 13 cm ploughing depth was 133.8 kg. The plough generated V-shaped furrows, which fits well with corresponding archaeological plough marks (Lerche and Steensberg 1980, 60-63).

The present results allow the conclusion that light ard types, like the one reconstructed in the present report, may have been of great importance within early medieval Irish agriculture. This is because compared to heavier plough types (cf. Kropp, 2022 forthcoming) they could be pulled by 1-2 draught cows. This conclusion can be drawn from the fact that on average, draught cattle can pull between 10 and 15 percent of their live weight over a long period of time without major issues (Minhorst, 2015, p.154). Although the maximum pulling capacity over short distances is significantly higher, the average pulling capacity must always be used as the basis for calculation for the ploughing process. The cows of the Rhaetian Grey cattle breed used in the Lauresham open-air laboratory have a bodyweight of 400-450 kg and were considered as the basis for comparison. Due to the low height at the withers of female animals, usually less than 110 cm, this breed also falls within the general size range of the medieval comparative finds (Kropp, 2017, p.27).

The low furrow depth was compensated by the generally lower tractive force needed. Efficiency and feasibility were therefore in a special tension with one another. Finally, the time factor must not be disregarded. For example, a light ard may have required less tractive force than a heavy mouldboard plough, but the necessary crisscross ploughing pattern also required a considerably bigger time investment.

Discussion

If taken in isolation, the iron components that represent most of our archaeological evidence of early ploughs and ards provide limited understandings of what they actually represented for the people that depended on them. Not only are they just one small part of the physical structure of ploughs but they also suffer terribly from corrosion, creating a conceptual distance between the artefact and what it might have originally looked like. Aside from a very small number of fragmentary archaeological finds and a few iconographic depictions, the wooden components of these ploughs are even more poorly represented. This project demonstrates the complexity, not only in their production (including the choice of materials) but also in their specific engineering. This Twinning project successfully bridged this distance, bringing early medieval ploughs back to life.

What we now know is that even a light ard, like the one reconstructed for this project, represents a huge number of skills. Iron must be made by a community of people, transforming ores, charcoal, and clay into ingots of hard metal. The expertise of blacksmiths is needed to forge, weld, and shape reliable and robust shares (and coulters). In-depth knowledge of woods, individual wood characteristics, woodworking, no doubt common to most people in the early medieval period, was essential to making a frame that could withstand the forces exerted by draught animals pulling them through hard soil. Yet, these components brought together would be meaningless without the ability to read the land, control the animals, and work the plough. All of this is not to mention the bewildering number of associated tools and people intersecting with the extended biography of any plough during the early medieval period.

With this in mind, it is not surprising that early medieval sources not only attribute enormous importance to the process of ploughing (lat. *arare*), but also the plough (lat. *aratro*) itself. Perhaps similar to the possible sharing of draft animals between groups of farmers (as known from Charlemagne's decree concerning a complaint by vassals about the use of ploughing and manual labour from the year 800), ploughs might have been owned and/or used by groups rather than individuals. If true, this would fit well into the understandings of the production and use of these ploughs derived through this project.

Nevertheless, it can be assumed that at least the ploughshares must have been regularly in use over a quite long period of time. The long-term experiments carried out in the Open-Air Laboratory using different plough- and ard(re)constructions show significant signs of wear on the shares already over the course of a few years, but without any major functional constraints (See Figure 19). This even applies to collisions with stones on the arable land. If the effort in the production of such elementary farming implements was very high, they were also very durable. This finally adds even more value to them.

Conclusion

This EXARC Twinning project between Lauresham Open-Air Laboratory and UCD CEAMC provided a framework of collaboration and support for our two institutes. By making an early medieval ard, visiting each other, and writing up our results together we have established networks for future work together and already encouraged colleagues, students, as well as visitors to once more focus on the practical micro-level of medieval agriculture. Only in this way will it be possible to explore more about the functional interrelationships of work processes at that time.

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Gallery Image

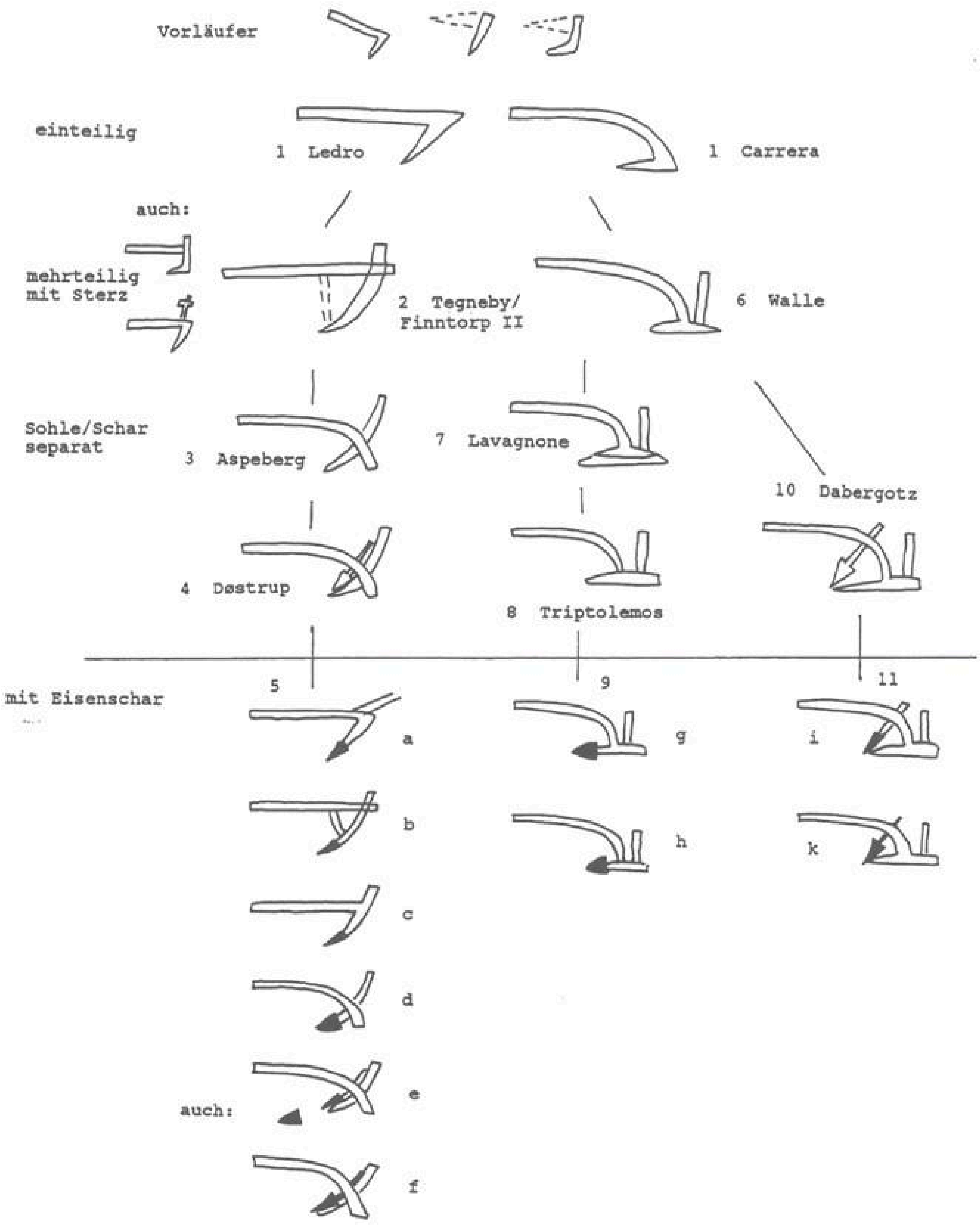


FIG 1. ARD TYPOLOGY AFTER JANINE FRIES (1995)

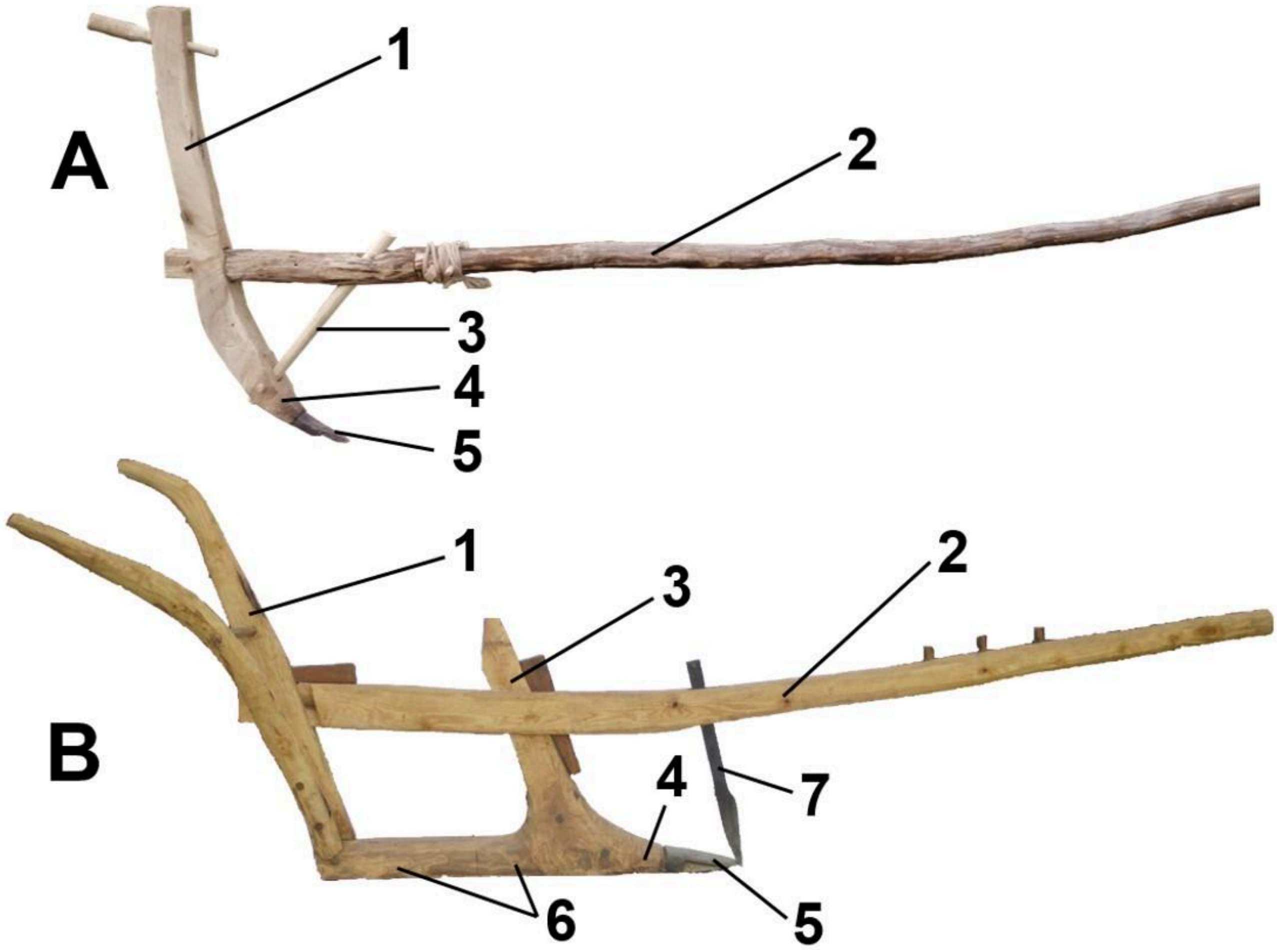


FIG 2. BASIC TERMINOLOGY AND TERMINOLOGICAL DIFFERENCE IN A SOLE-LESS (A) AND SOLE (B) ARD. 1) STILT; 2) BEAM; 3) SHEATH; 4) ARD HEAD; 5) SHARE; 6) SOLE; 7) COULTER. GRAPH BY C.KROPP

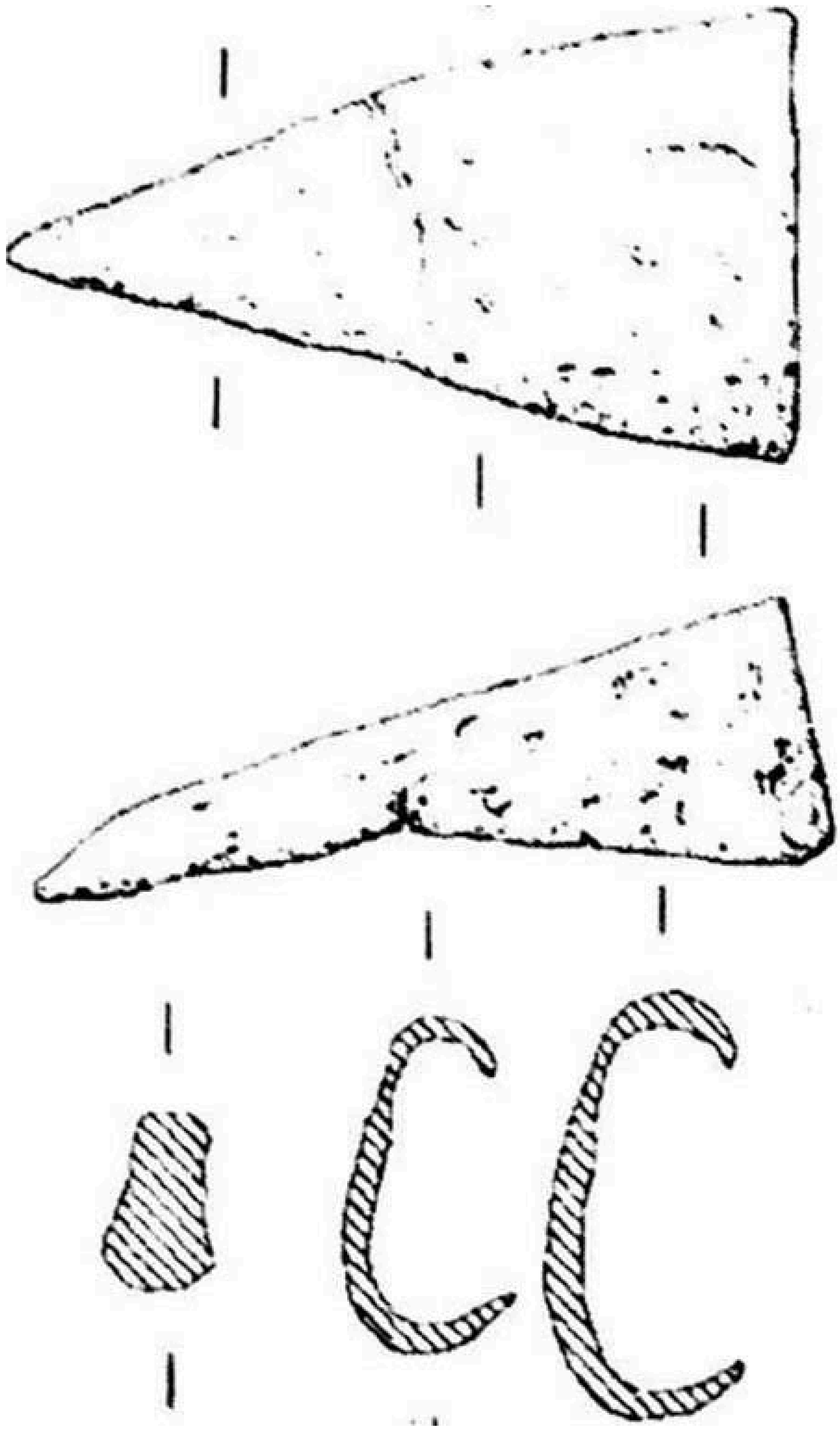


FIG 3. ARD SHARE OF RATHTINAUN, CO. SLIGO AFTER N. BRADY (2016)

FIG 4. ROASTING C.60KG OF BOG IRON ORE USING A LAYERED PYRE CONSTRUCTION AT UCD CENTRE FOR EXPERIMENTAL ARCHAEOLOGY AND MATERIAL CULTURE. LEFT SHOWS THE LAYERED STRUCTURE ALLOWING A LARGE QUANTITY OF ORE TO BE ROASTED. RIGHT SHOWS THE STRUCTURE ONCE LIT AND BURNING DOWN (EARLY MEDIEVAL ROUNDHOUSE IN BACKGROUND). (PHOTOS – UCD, CEAMC)

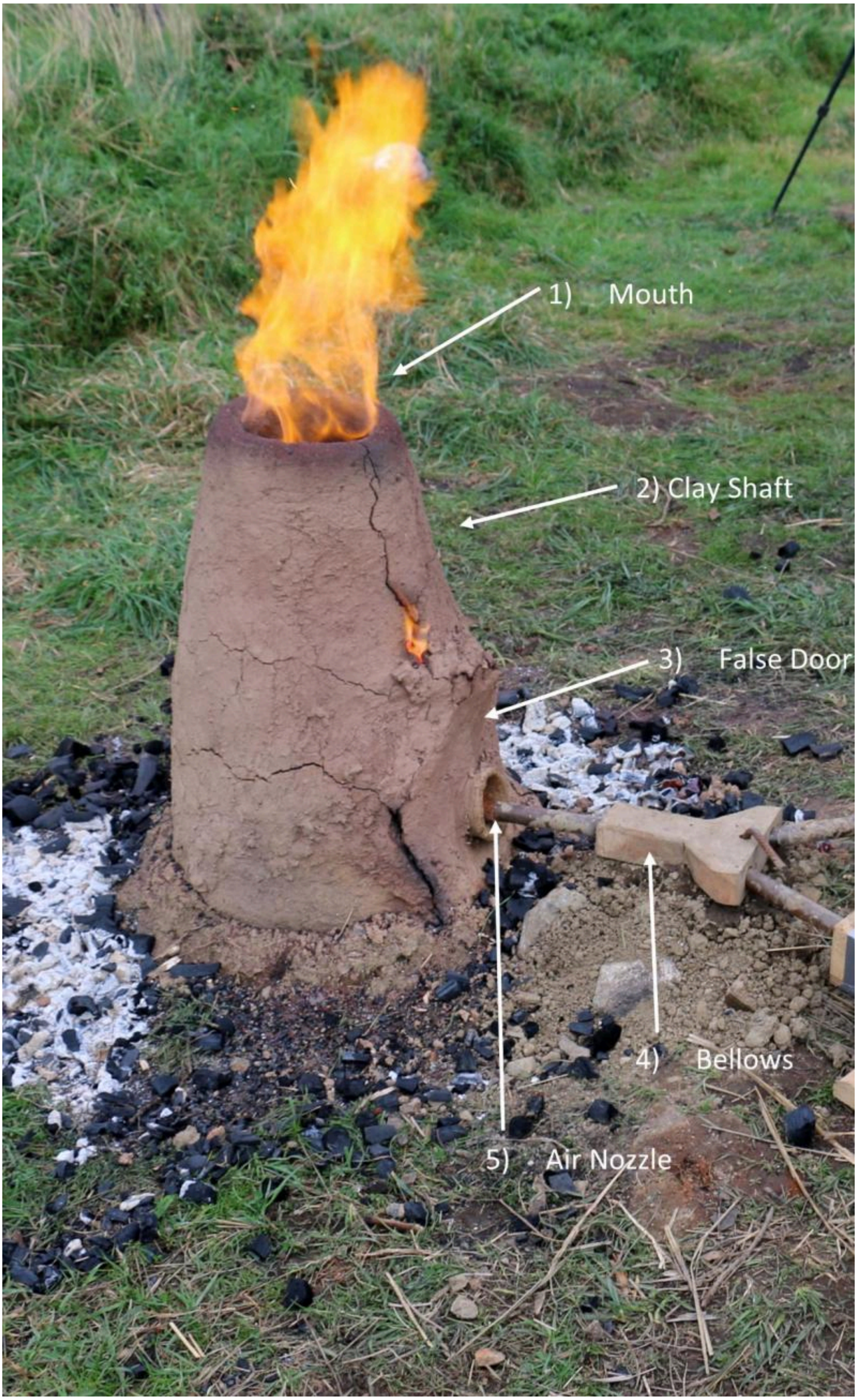


FIG 5. 1-METER-HIGH SHAFT FURNACE MID-SMELT, SHOWING MAIN ELEMENTS. 1) THE MOUTH OPENING OF THE FURNACE WHERE ORE AND CHARCOAL CAN BE ADDED. 2) HANDMADE CLAY SHAFT OF FURNACE WHICH ALLOWS THE CORRECT ATMOSPHERE TO REDUCE METAL ORE. 3) "FALSE DOOR" PROVIDING ACCESS TO THE INTERNAL FURNACE TO RETRIEVE BLOOM THROUGH A RELATIVELY THIN LAYER OF CLAY. 4) FORCED DRAFT PROVIDED BY A TWIN SET OF HAND BELLOWS. 5) A CLAY AIR NOZZLE ALLOWING FORCED DRAFT TO ENTER THE FURNACE. THIS SHAFT SITS OVER A SLAG-PIT THAT COLLECTS NON-IRON (UNWANTED) MATERIAL. (PHOTO – UCD, CEAMC)

FIG 6. "CHARGING" THE FURNACE WITH ADDITIONAL CHARCOAL. AS FUEL BURNS OUT IN THE LOWER FURNACE (ROUGHLY AT GROUND LEVEL) THE LEVEL OF CHARCOAL AT THE MOUTH OF THE FURNACE DROPS, PROVIDING SPACE FOR ADDITIONAL MATERIAL TO BE ADDED IN LAYERS. FOR THIS SMELT, ORE WAS ADDED FIRST FOLLOWED QUICKLY BY DOUBLE THE WEIGHT OF CHARCOAL. THIS WAS ALLOWED TO BURN DOWN UNTIL SUFFICIENT SPACE (ROUGHLY 10-12CM) WAS ONCE AGAIN CREATED. (PHOTOS – UCD, CEAMC)

FIG 7A. RETRIEVING THE BLOOM AT THE END OF THE SMELT. FIRST THE "FALSE DOOR" IS BROKEN THROUGH (PHOTOS – UCD, CEAMC)

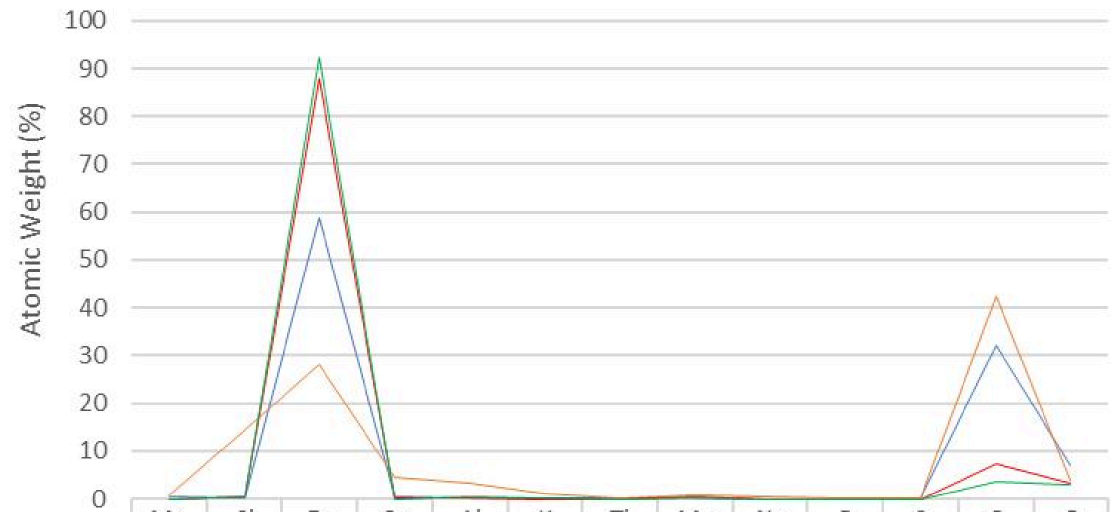
FIG 7B. RETRIEVING THE BLOOM AT THE END OF THE SMELT. THIS ALLOWS THE BLOOM TO BE IDENTIFIED AND GRABBED WITH A METAL TONGS. (PHOTOS – UCD, CEAMC)

FIG 7C. RETRIEVING THE BLOOM AT THE END OF THE SMELT. THE BLOOM CAN BE SEEN TO BE A LARGE, GLOWING, AMORPHOUS PIECE OF MATERIAL THAT LOOKS SIMILAR IN APPEARANCE TO OTHER SLAG, VITREOUS MATERIAL, ETC. ALSO INSIDE THE FURNACE. (PHOTOS – UCD, CEAMC)

FIG 7D. RETRIEVING THE BLOOM AT THE END OF THE SMELT. THE BLOOM IS PLACED ON A HARD SURFACE (A WOODEN STUMP IN THIS CASE) AND HIT REPEATEDLY. DURING THIS, THE BLOOM IS ALSO SPLIT TO ALLOW

SMALLER PIECE TO BE REHEATED LATER. (PHOTOS – UCD, CEAMC)

FIG 8. REFINING PROCESS FOR THE ARD-SHARE AT THE LAURESHAM OPEN-AIR LABORATORY. PHOTO BY M. THUMM



	Mn	Si	Fe	Ca	Al	K	Ti	Mg	Na	P	S	C	O
Bog Ore	0.59	0.33	58.74	0.51	0.24	0.05	0.08	0.07	0.03	0.03	0.04	32.18	7.13
Smelt Slag (Int)	0.68	14.36	28.01	4.63	3.42	1.15	0.16	0.76	0.57	0.17	0.04	42.26	3.78
Iron Sample 1 (Int)	0.03	0.59	87.94	0.16	0.17	0.03	0	0.5	0.03	0.01	0.03	7.18	3.32
Iron Sample 2 (Int)	0	0.52	92.44	0.02	0.38	0.06	0	0.07	0	0.01	0.02	3.66	2.84

FIG 9. SEM-EDS SPECTRUM SHOWING BULK CHEMISTRIES FOR FOUR DIFFERENT SAMPLES; 1) BOG ORE, 2) SMELTING SLAG, 3) IRON SAMPLE 1, 4) IRON SAMPLE 2. NOTE THE FLUCTUATIONS IN IRON CONTENT ACROSS SAMPLES CONSISTENT WITH THE REMOVAL OF IRON FROM THE ORE DURING THE SMELTING PROCESS.

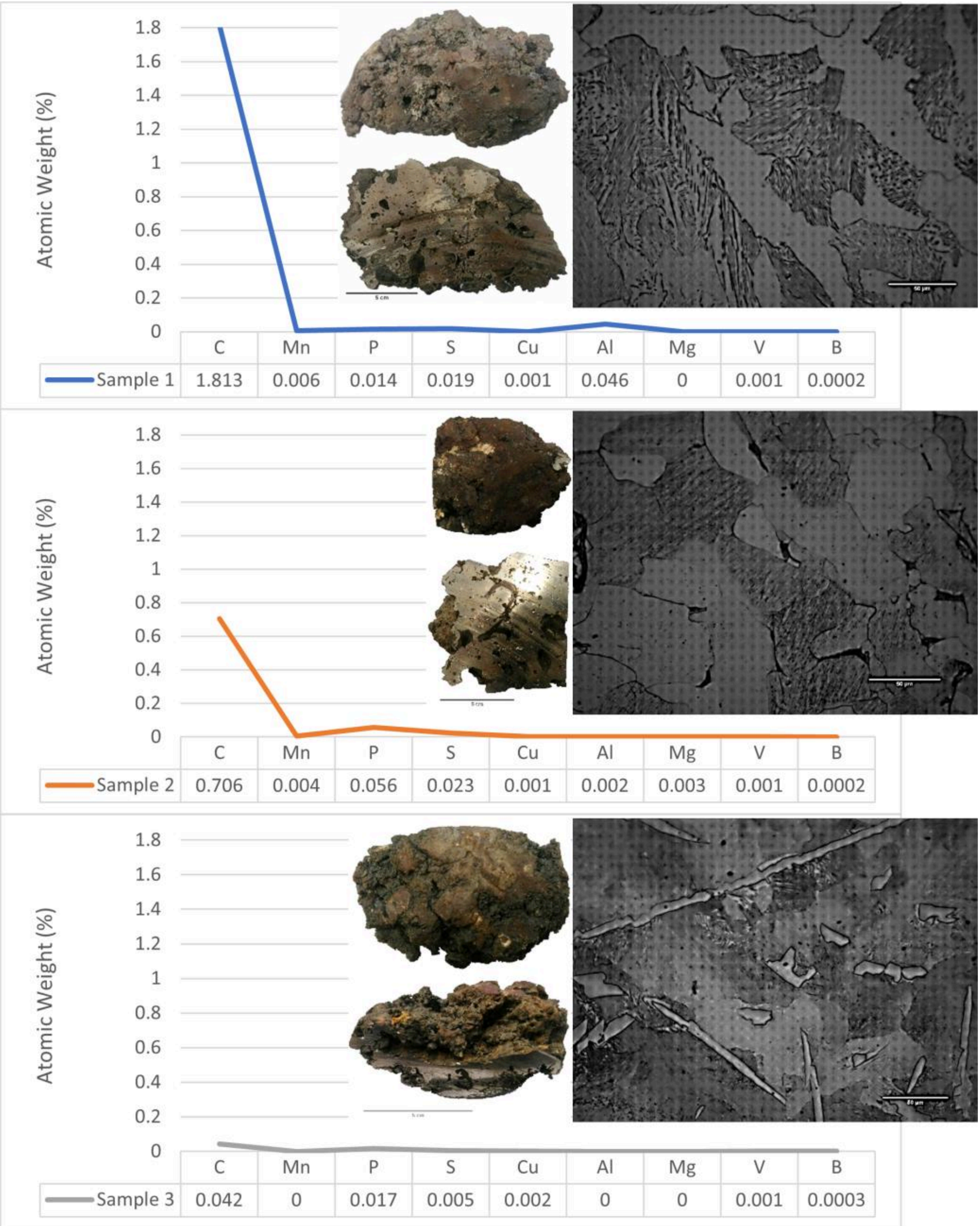


FIG 10. OES RESULTS SHOWING VARIABLE DETECTIONS OF CARBON ACROSS SAMPLES FROM THREE PORTIONS OF IRON BLOOM. PHOSPHORUS (P) AND SULPHUR (S) ALSO VARY BUT ARE IN SUCH LOW QUANTITIES THAT THEIR PRESENCE CANNOT IMPACT ON THE IRON MATERIALLY. THE DIFFERENT CARBON CONTENTS ARE ALSO VISIBLE IN THE PRESENCE OF PEARLITE, AN IRON/CARBON COMPOUND CHARACTERISED BY PARALLEL LIGHT AND DARK BANDS IN THE MICROGRAPHS ABOVE. NOTE THE INCREASE IN PEARLITE WITH CARBON DETECTIONS.

FIG 11A. FORGES USED FOR THE REFINING AND WELDING PROCESS AT THE OPEN-AIR LABORATORY DURING THE EXPERIMENT: PORTABLE FORE FOR TWO BELLOWS (FAILED). PHOTO BY M. THUMM

FIG 11B. FORGES USED FOR THE REFINING AND WELDING PROCESS AT THE OPEN-AIR LABORATORY DURING THE EXPERIMENT: REGULAR FORE AT THE OPEN-AIR LABORATORY OPERATED BY TWO BELLOWS. PHOTO BY M. THUMM

FIG 11C. FORGES USED FOR THE REFINING AND WELDING PROCESS AT THE OPEN-AIR LABORATORY DURING THE EXPERIMENT: MODIFIED FORGE FOR THE USE OF FOUR BELLOWS AT THE SAME TIME. PHOTO BY M. THUMM

FIG 11D. FORGES USED FOR THE REFINING AND WELDING PROCESS AT THE OPEN-AIR LABORATORY DURING THE EXPERIMENT: DETAIL OF THE MODIFIED FORGE. PHOTO BY M. THUMM

FIG 12. FORGING PROCESS OF THE ARD-SHARE ON A (RE)CONSTRUCTED HEAVY ANVILLE. PHOTO BY M. THUMM

FIG 13. ARD SHARE COMPLETED. PHOTO BY M. THUMM

FIG 14. SELECTION OF HAND-TOOLS AND REPLICAS USED FOR THE PLOUGH (1. AXE, 2. HAND-DRILL, 3. DRAWING IRON, 4. CHISEL, 5. WOODEN HAMMER). PHOTO BY V. TÖNGI

FIG 15. A RECONSTRUCTED DRAWKNIFE WAS USED TO FINALIZE THE SHAPE OF THE STILT AND ARD-HEAD. COPYRIGHTS BY STAATLICHE SCHLÖSSER UND GÄRTEN HESSEN

FIG 16A. CONSTRUCTION DETAILS OF THE ARD: CONNECTION OF STILT TO BEAM. PHOTO BY V. TÖNGI

FIG 16B. CONSTRUCTION DETAILS OF THE ARD: CONNECTION-DETAILS OF THE BEAM EXTENSION. PHOTO BY V. TÖNGI

FIG 16C. CONSTRUCTION DETAILS OF THE ARD: CONNECTION-DETAILS OF THE BEAM EXTENSION. PHOTO BY V. TÖNGI

FIG 17. THE RECONSTRUCTED ARD IN ITS FINAL STATE BEFORE TESTING. PHOTO BY V. TÖNGI

FIG 18. THE ARD IN USE DURING A FIRST SET OF PERFORMANCE TESTS. PHOTO BY V. TÖNGI

FIG 19. WEAR SIGNS ON AN ASSYMMETRICAL PLOUGH-SHARE FROM THE OPEN-AIR LABORATORY (AFTER FIVE YEARS OF REGULAR USE). PHOTO BY C. KROPP