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Recording plano-convex ingots (Gusskuchen) from Late Bronze Age Styria and Upper Austria – A short manual for the documentation of morphological and technological features from production and partition

ABSTRACT: *The plano-convex ingot (in short PCI) or casting cake (German: Gusskuchen) is the most common ingot type for copper and its alloys in Late Bronze Age in Central Europe. The PCIs were formed in an open casting process by pouring molten metal into a shallow pit in the ground or in a specific casting form. Because of their simple production this raw metal type is found across a wide chronological and geographical range and was used for several metals. Despite their importance for the reconstruction of prehistoric copper metallurgy, the PCIs are often described insufficiently, which complicates major comparative studies. The following study attempts to remedy this by presenting a recording system with a uniform terminology, which presents all important measurable parameters and visible morphological and technological features on the surface of the PCIs, supported by results from chemical analyses, metallographic examinations or imaging techniques, for a better understanding of their production and partition.*

KEYWORDS: LATE BRONZE AGE, PLANO-CONVEX INGOT, CASTING CAKE, RAW METAL, COPPER, METAL CASTING, RECORDING SYSTEM

Introduction

In Bronze Age metallurgy, plano-convex ingots (in short PCIs) representing semi-products are important links between producers and consumers and provide various technological information concerning production and processing. However, their recording is inconsistent: a handful elaborate publications and regional studies, partially with scientific analyses, are in contrast with numerous short descriptions with very rudimentary or vague data. The lack of basic information, such as size, weight or shape, the inconsistent definition of top and base side, the use of a diverse vocabulary and missing illustrations or photos in the publications not only complicated a reliable comparison of individual pieces, but also the realisation of transregional studies. The following paper attempts to remedy this by presenting a manual with appropriate terminology, which is designed to facilitate comparative work on morphological and technological features by an accurate description, and to address the major issues in the study of the production and partition of PCIs.

This manual is in turn part of an ongoing project in which the author undertook chemical analyses (ICP-AES/OES), metallographic examinations, imaging techniques (SEM, CT scanning) and radiocarbon dating (on trapped charcoal) on more than 100 PCIs and their fragments, as well as related metal ingots (e.g. rod ingots) from Bronze Age/Urnfield Period hoards, settlements and a burnt offerings site from Salzkammergut in Styria and Upper Austria (on the finding area: Modl, 2008; 2013; Windholz-Konrad, 2003; 2012; 2018). The manual is presented to the scientific community before the final publication of the project's outcome and should serve as stimulation for a better documentation of PCIs in the future. Before continuing with the manual, it is necessary to define PCIs, recap the current state of research and introduce the methodology.

Plano-convex ingots

Terminology

The regular 'plano-convex ingot' is characterised by a flat topside and a bulged underside. This raw metal type is often, contrary to the direction of production, referred to as 'bun ingot', which implies the opposite orientation of concavity (cf. Weisgerber & Yule, 2003, p.49; Weisgerber, 2004, p.31; Modl, 2010, p.127). In the countries around the Adriatic Sea, PCIs are sometimes assigned to a precoin monetary metal called ‘aes rude’, a Latin term (cf. Trampuž Orel et al., 2002, p.63; Murgan, 2014, p.66). Their traditional German name is ‘Gusskuchen’, a term which is very appropriate because it describes the production process well, but is not really common in the English-speaking world, like the sometimes used direct translation ‘casting cake’ (e.g. Romanow, 1995; Nessel, 2014; Stöllner et al., 2016). The author has therefore decided – contrary to his own linguistic usage – to apply the term ‘plano-convex ingot’ in this paper (German: plankonvexer Barren) or the acronym ‘PCI’, which refers to a formal criterium, the cross-section. The author understands this term as a hypernym, because this raw metal type can have a technically related variability of shapes.

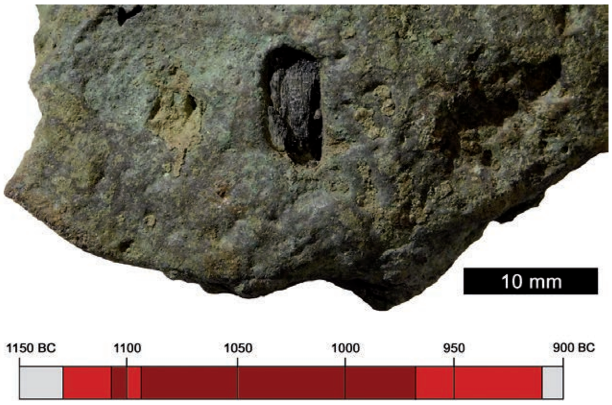


Fig. 1: Radiocarbon dating of a charcoal from the base side of a PCI from hoard IV (CNr. 6; Ha B1/B3; see Windholz-Konrad, 2018, p.124, 158, tab.7/13) in the finding area ‘Kainischtraun’ near Bad Aussee, Styria, with a calibrated date between 1100 and 1100 BC or 1090 and 975 BC at 68,2% probability and 1130 and 915 BC at 95,4% probability (VERA-6251) (graphic: D. Modl).

Historical and geographical frame

The PCI is formed in an open casting process by pouring molten metal into a shallow pit in the ground or in a specific casting form (subsequently referred to as “mould”). Because of the simple production of ingot and mould, this raw metal form is found across a wide chronological and geographical range and was used for several metals, such as copper and its alloys, as well as lead, tin, silver and gold.

Smelted copper with plano-convex shape has been known since early metallurgic times in the Middle East and Europe (e.g. Schubert & Schubert, 1999, p.668, fig.1/1, 2/1-2). In the course of the Bronze Age, the PCI is evidenced throughout Europe and the Mediterranean, especially in hoards and as shipwreck cargo material (see Muhly et al., 1977; Rothenberg, 1990, pp.65-66; Hauptmann et al., 2002; Hauptmann & Maddin, 2005; Müller-Karpe, 2005, pp.486-487; Yahalom-Mack et al., 2014; Lehner & Schachner, 2017, pp.413-415; Wang et al., 2018, pp.102-117). In Central Europe during the Early/Middle Bronze Age transition, the heterogeneous PCI replaced the standardised ingots with fixed denomination (like loop or neck-rings/Ösenringe; rib ingots/Rippen-/Spangenbarren) and evolved to the preferred raw metal form for copper and its alloys (see Möslein, 1998, p.252, pp.256-257). In the Late Bronze Age Mediterranean the PCI remained subordinate to the so called ox-hide ingots (Ochsenhautbarren; see Sabatini, 2016, pp.15-62).

In prehistoric times, this form was additionally produced in larger number in the Persian Gulf area (see Prange, 2001, pp.11-15, 31-33; Craddock et al., 2003; Weisgerber & Yule, 2003), in India (see Yule, 1985, p.44, tab.26/357-360; Pigott, 1999, p.123) and even in South-East Asia (see Bennett, 1998, p.337, 345) and China (see Wang et al., 2019, [p.2409, 2411, fig. 2/7]). Also in Roman times and especially between the Late Medieval to Early Modern Periods, ingots were increasingly produced in similiar form in Europe, as documented in the cases of the ancient copper ingots found in Northern Wales (see Tylecote, 1986, pp.22-24, tab.10-11, fig.10) and along the Languedoc shore in France (see Rico et al., 2005; Klein et al., 2007) or the hemispherical bars from the Portuguese trade vessel ‘Bom Jesus’ at the Namibian coast (see Hauptmann et al., 2016). PCIs were also the bottom part of a medieval ‘Reißscheiben’ cast, which were called ‘Könige’ (see Hänsel & Schulz, 1980, pp.13-17; Werson, 2015, pp.66-68, 87-88). Because of the partly identical shape and production technique, studies on non-prehistoric and non-European PCIs are of great interest for the analysis of Central European pieces from the Bronze Age.

Traditionally, the PCIs in Central Europe were dated to the Late Bronze Age/Urnfield period and judged to be chronologically insensitive. However, their time frame is much broader than the evaluation of metal hoards indicates (see Neumann, 2015, pp.145-147) and includes all time stages between the Early Bronze Age and the Hallstatt period. For individual regions even convincing chronologies for different types could be determined on the basis of morphometric data from complete PCIs (Krutter, 2015; Lutz et al., 2019, this volume). Basically, it turns out that in the Early Bronze Age, the PCI were the largest and then became smaller but thicker during the Bronze Age.

The dating of single ingot fragments without archaeological context, however, is still hampered by the lack of a clear chronological framework. Only very rarely the radiocarbon method has been used for dating charcoals embedded in the surfaces of PCIs (e.g. Wischenbarth, 2004, pp.149-150; Galili et al., 2013, p.171; Armada & García-Vuelta, 2015, pp.372-382; Jansen & Löffler, 2016, pp.130-131; Lutz et al., 2019, this volume). In the course of the project presented here, such an investigation was undertaken, which revealed a dating frame from the older to the younger Urnfield period (Ha A2-Ha B2) for a small PCI from a hoard in the Styrian Salzkammergut (Fig. 1;

cf. Windholz-Konrad 2003, pp.82-84, p.102, fig.60; 2018, p.124, 158, tab.7/13).

Metal composition and ingot manufacturing/partitioning

Metal analysis of Bronze Age PCIs in Central Europe revealed that they are originally made of chalcopyrite copper, fahlore copper or, less common, a mixture of both types, all of different composition (see Trampuž Orel et al., 1996, pp.178-211; Klemenc et al., 1999; Bachmann et al., 2002/03, pp.94-99; Sperber, 2004, pp.312-315, 318-321; Trampuž-Orel & Drglin, 2005; Pernicka et al., 2016, pp.31-34; Stöllner et al., 2016, pp.87-88, 92, fig.14, tab. 2; Radivojević et al., 2018; Möslein & Pernicka, this volume). As changeable copper contents and varying amounts of minor elements (arsenic, antimony, nickel, iron, tin, lead) show, impure and partly refined copper (black copper or blister copper), as well as nearly pure copper and even alloyed copper were used for their production. This material inhomogeneity and the fact that the PCIs display a surprisingly large variety in shape, size and weight, their interpretation as bars and subsequently as potential premonetary currency, or ‘special purpose money’, was controversially discussed.

However, an ingot is not defined by its quality or value, because rather practical reasons are crucial. The size and shape must merely be suitable for storing, transporting and further processing, a purpose fullfilled by PCIs. Another criterion relates to the production technique, as ingots are manufactured in an independent casting process (see Drescher, 1976, p.60; Ottaway, 1994, p.115; Primas & Pernicka, 1998, pp.29-32; Kuijpers, 2008, pp.73-77; Nessel, 2017, pp.169-170, 192). According to research tradition, the PCIs have been viewed as a primary product of copper extraction (see Tylecote, 1976, p.166, 170; Ottaway, 1994, p.98, fig.13 and the graphic in Eibner, 1982a, p.406, fig.3), forming during smelting at the bowl-shaped base of a furnace beneath a well-seperated layer of slag.

However, this formation process cannot be reconstructed in archaeological experiments (see Hanning, 2012; Modl, 2015) and is also in contradiction with features on the top surface of most of the PCIs. While the concentration of the ore into a copper-iron sulphide matte was well trialled in smelting experiments, the efficient converting of the matte into metallic copper and the formation of a homogenous copper cake as well as the purification of the metal by refining (e.g. oxidation, poling or melting with lead; see Rostoker, 1975, pp.312, 314; Eibner, 1982b, pp.309-311; Preßlinger, 2004, p.326) is to date inadequately replicable (summarising Hanning et al., 2015). In addition, apart from different slags just a few metallic semi- and endproducts from the smelting sites, mining settlements or nearby hoards are known for these last process steps and hardly any facilities, like pit or hearth furnances or crucibles for such pyrometallurgical operations are documented. The same applies also for the production of the alloy bronze by co-smelting of copper and metallic tin, by cementation of copper with the tin oxide cassiterite (SnO_2) or by co-smelting a mixture of copper and tin ores, which is also hardly detectable in the archaeological record but good to repeat in archaeological experiments (see Herdits et al., 1995, pp.78-85; Rovira et al., 2009, pp.407-414).

Currently, it can be assumed that the end product of the smelting process were probably amorphous copper lumps or smaller prills mixed with slag which needed to be remelted and recast. Therefore the PCI in its usual form was not the primary product of smelting, it is rather the product of a secondary casting process between refining, alloying and recycling in which the metal is cast into a bowl-shaped mould. Whether the pour was carried out by use of crucibles or by discharging molten metal from the bottom of the furnance into a forehearth or a tapping pit will be the subject of further discussions (Fig. 2/A-B; see Modl, 2010, pp.129-132, 138-140; Holdermann & Trommer, 2010, pp.792-795).

Such moulds are to date unknown in Europe. The only validated finds of clay moulds for casting a PCI are known from the Iron Age site 30 at Timna (Israel; see Rothenberg, 1987; 1990, p.54, 67, fig.81-82), while small casting pits were detected at the Bronze Age settlement Maysar-1 (Oman; see Weisgerber, 1981, p.209, fig.38; Weisgerber & Yule, 2003, p.48; Weisgerber, 2004, p.22). The fact that the majority of the PCIs were actually cast is indicated for example by flow structures at their top surface or an internal multilayer structure, formed by repeated or interrupted casting batches. Their varying purity (mostly between 94-98 wt% copper) and alloying degree as well as different contents of copper oxides and sulphides or an arsenic loss reflect that the PCIs are not the result of a simultaneous manufacturing process but rather products of an entire series of pyrometallurgical processes commencing with copper smelting and continuing with several refining, alloying or recycling procedures, while PCIs are being poured and broken up again and again (Fig. 3). A special position among the PCIs is occupied by pieces which consist of recycled metal and are possibly produced in two ways: by casting molten metal in a mould filled with scrap metal, or by adding scrap metal into an existing melt (Fig. 2/C-D).

For the definition of the PCI as an ingot the metal quality and production stage play only a subordinate role, but an almost plano-convex shape and a minimum size are more determining factors. For this reason some foundry remains should not be included in the group of PCIs. These include, for example, casts or remains of the bottom of crucibles or ceramic vessels (‘reguli’) with a plano-convex cross-section, but with a diameter of only a few centimeters (e.g. Czajlik, 1996, p.171, fig.16; Bachmann et al., 2002/03, p.90, fig.10/D/2-6; Weisgerber, 2004, p.31; Czajlik, 2006, p.58, fig.6; Kytlicová, 2007, p.163, tab.138/D/3-5; Lauermann & Rammer, 2013, p.96, tab.23/3-4; Le Carlier de Veslud et al., 2014, pp.514-515),

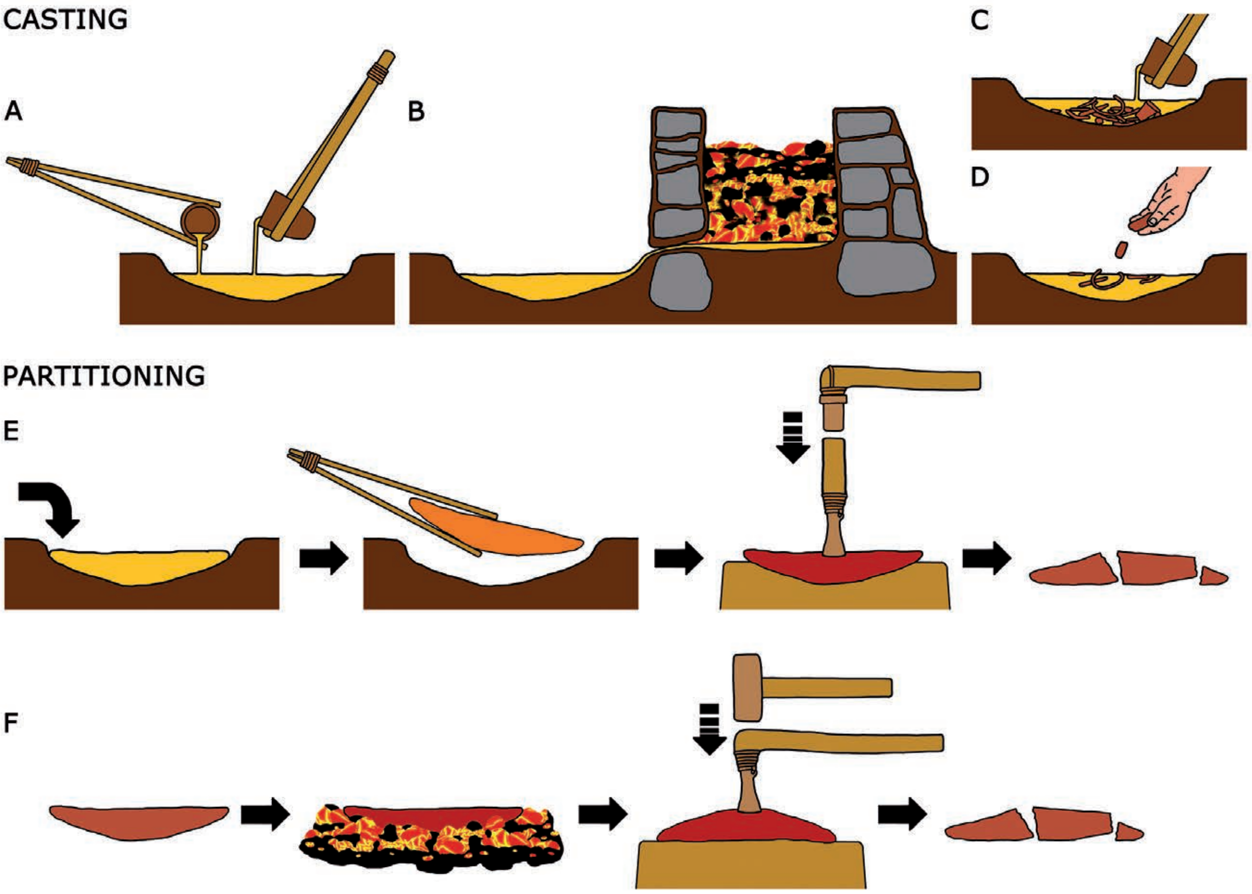


Fig. 2: Simplified representation of the possible casting techniques for the production of PCIs by (A) using crucibles or (B) by discharging molten metal from a furnace into a bowl-shaped mould, forehearth or tapping pit, as well as the manufacturing of PCIs out of recycled metal (C) by casting molten metal in a with scrap metal fullfilled mould or (D) by adding scrap metal into a existing melt. Furthermore the two potential options for the partitioning of PCIs by using a hammer and different cutting tools are depicted with the (E) primary partitioning immediately after the casting and the (F) secondary partitioning by reheating the PCI (graphic: D. Modl).

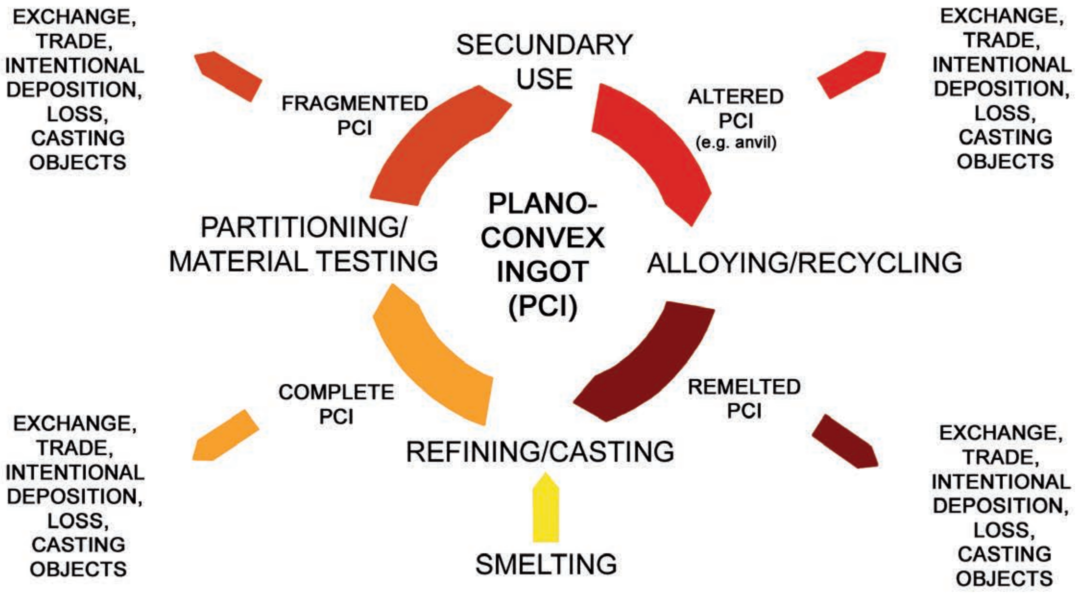


Fig. 3: Visualisation of the production and processing cycle of PCIs (graphic: D. Modl).

amorphous smelting waste (e.g. Gruber & Preßlinger, 1983, pp.1255-1256; Preßlinger & Eibner, 2004, pp.70-71) and socket-shaped castings ('tüllenförmige Gusskuchen'; e.g. Höglinger, 1996, p.77, 141, tab.27/515; Engelmann, 1997, p.31, 75, 114, fig.48-49, tab.19/14; Pühringer, 2000, pp.195-197).

Most of the PCIs in Late Bronze Age hoards are fragmented (see Modl, 2010; Nessel, 2014; 2017). This is the result of a targeted breaking in red-hot state immediately after casting (primary partitioning) or after a later heating in a charcoal fire (secondary partitioning) when they were traded, processed, hoarded or sacrificed. Principally the PCIs show various deformations and tool marks that suggest the use of different hammers, axes and chisels during the dividing process. The partition did probably not take place directly in the casting pit, but rather a hard base like a wooden block or a stone was used here (Fig. 2/E-F).

State of research

Already around the middle of the 19th century, antiquarians in Austria and Hungary comprehend 'Gusskuchen' or PCIs as own archaeological object group (see Pratobevera, 1856, p.27; Érdy, 1861, p.38). A more detailed typological classification of the PCIs based on metrical data and including technological features commenced in Europe in the 1970s and 1980s with the analysis of Late Bronze Age hoards (see Stein, 1976, p.22, 28; Rusu, 1981, pp.375-379, 382-384; Mozsolics, 1984, pp.35-39).

Of particular importance is the paper of Czajlik (1996), who was the first to combine qualitative and quantitative aspects of PCIs from western Hungary, including shape, cross-section, size, weight, metal composition and manufacturing technique. Besides an inconsistent typology, this important and influential study presents an implausible reconstruction of the production process that results in an inverted orientation of the PCIs, which the author sees mainly confirmed in density differences in their inside. However, this approach must be rejected because he did not consider various degassing effects in the core and on the surface as well as the pouring in different batches, which can explain the density differences and speaks against the proposed manufacturing process.

Thanks to experimental archaeological investigations particularly into the production of ox-hide ingots, where PCIs were sometimes by-products, we know more about the manufacturing of copper ingots in different mould materials (see Tylecote, 1976, p.164; Merkel, 1986a; 1990, pp.107-109, 113-116; Craddock et al., 1997; Van Lokeren, 2000; Bunk & Kuhnen, 2008; Larson, 2009; Modl, 2010, pp.138-140; Laschimke & Burger, 2012; Galili et al., 2013, p.21; Hauptmann et al., 2016). Just a few years ago, also in the course of archaeological experiments, some authors began to study the partitioning of copper ingots with different techniques and tools, however, too many questions remained unanswered regarding optimal processing temperature or fracture behavior due to the chemical composition of the ingots (see Merkel, 1986b, p.269; Van Lokeren, 2000, p.275; Modl, 2010, pp.140-146; 2011, pp.147-155; Hauptmann et al., 2016, p.758). Based on this work, the fragments of PCIs got more into the focus of research, which made it possible to distinguish several fracture patterns or weight ratios in European hoards (see Primas & Pernicka, 1998, pp.45-50; Pühringer, 2000, pp.203-214; Modl, 2010, pp.147-148; Nessel, 2014, pp.404-409; 2017, pp.175-192; Reiter & Linke, 2016, pp.150-151, fig.22-23).

Over the last two decades, for many European countries, such as Spain (Montero-Ruiz et al., 2010/11), France (Czajlik, 2006, pp.52-62; Le Carlier de Veslud et al., 2014), England (Loughton, 2017; Wang et al., 2018, pp.102-117), Switzerland (Rychner, 1984), Germany (Reinecke, 1938; Wischenbarth, 1995; Primas & Pernicka, 1998; Bachmann et al., 2002/03), Czech Republic (Salaš, Stránský & Winkler, 1993; Kytlicová, 2007, pp.162-164), Austria (Klose, 1918, pp.31-33; Sperl, 1988, pp.111-114; Höglinger, 1996, pp.76-77; Pühringer, 2000, pp.179-205; Windholz-Konrad, 2003, pp.66-68; 2018, pp.44-46; Modl, 2010, pp.127-137; Krutter, 2015), Hungary (Hampel, 1896, pp.180-187; Mozsolics, 1981; 1984; Czajlik, 1996; 2012, pp.64-77, 85-98; Tarbay, 2016, pp.97-101), Italy/Sardinia (Stech, 1989; Lo Schiavo, 1990; Begemann et al., 2001; De Marinis, 2006; Jung et al., 2011, pp.237-241, 242-245), Slovenia (Turk, 2000, pp.141-146), Croatia (Bertol & Farac, 2012; Karavanić, 2017, pp.102-109), Bosnia-Herzegovina (König, 2004, p.90, 124, 153), Romania (Rusu, 1981, pp.375-379, 382-384), Bulgaria (Leshtakov, 2007, pp.452-453; Doncheva, 2012, pp.679-683, 688), Greece (Mangou et al., 2000) and Ukraine (Kobal', 2000, pp.70-71) some hoard analyses and regional studies were carried out not only allowing a more elaborate differentiation between several raw metal forms, but also permitting a more refined dating of the PCIs. These studies are supplemented by detailed metallographic examinations and chemical analyses (e.g. Tylecote, 1976, pp.160-165, 169-170; Gruber & Preßlinger, 1983; Angerbauer, 1985, pp.49-60; Maddin & Merkel, 1990, pp.42-199; Roman, 1990, pp.176-181; Scott, 1991, p.97; Czajlik et al., 1995; 1999; Trampuž-Orel et al., 2002; Franceschi et al., 2004; Preßlinger, 2003, p.68; 2004, pp.327-328; Wischenbarth, 2004; Ciugudean et al., 2006, pp.98-100; Jansen & Löffler, 2016; Reiter & Linke, 2016, pp.161-165; Haubner et al., 2017; Wang et al., 2018, pp.106-115; Windholz-Konrad & Modl, 2018, pp.47-48), which make their manufacturing process more transparent or allow conclusions about the origin of the copper from chalcopyrite or fahlore.

Recording system

The following manual lists important measurable parameters and visible features of PCIs and illustrates that it is possible to draw conclusions about their production or

<table>
<tr><th></th><th>COMPLETE PCI (without fracture surface)</th><th>FRAGMENTED PCI</th></tr>
<tr><td rowspan="27">VERBAL DESCRIPTION / VISUAL DOCUMENTATION</td><td colspan="2">FORM AND PRESERVATION</td></tr>
<tr><td>PRIMARY SHAPE
round, ovoid, drop-shaped (triangular), sub-rectangular, irregular</td><td>SECONDARY SHAPE
half, circular segment, quarter, eighth, wedge-shaped segment, pieces in varying geometric shapes (e.g. rectangular, quadratic, triangle, trapezoid, polygon), D-shaped edge piece, amorphous piece</td></tr>
<tr><td>PRIMARY CROSS-SECTION
flat/flat (flat, rectangular), flat/convex (plano-convex, hemispherical, catenary, triangular/conical, trapezoid, bun-shaped, bell-shaped, bell-shaped/constricted, asymmetrical), concave/convex (curved, shrunken, bell-shaped/campanulate), convex/convex (umbonate, biconvex), multi-poured ingots (vacancies at the top/bottom, flat slabs with hook-shaped edges), ingots with large cavities, not definable</td><td>SECONDARY CROSS-SECTION
complete or half cross-section, edge piece, slope piece, core piece, not definable</td></tr>
<tr><td colspan="2">CASTING EDGE
pointed, rounded, edged, tapered, steep, stepped, hook-shaped, bead-shaped, not definable</td></tr>
<tr><td>DIMENSIONS
major/minor diameter (ma./mi. diam.), thickness (th.), weight (wt.)</td><td>DIMENSIONS
length (l.), width (w.), thickness (th.), weight (wt.), rec. diameter (diam.)</td></tr>
<tr><td colspan="2">SIZE GROUP
large (size class 1: >20 cm diam., >3 cm th., >4 kg w.), medium (size class 2: 15-25 cm diam., 2-4 cm th., 2-5 kg w.), small (size class 3: <15 cm diam., <3 cm th., <2 kg w.), not definable</td></tr>
<tr><td colspan="2">MAGNETISM
not magenitc, slightly magnetic, strong magnetic</td></tr>
<tr><td colspan="2">PATINA
colour, texture, special features (e.g. oxidation coatings, rust spots, fire patina)</td></tr>
<tr><td colspan="2">CASTING SURFACE AND PARTITION FEATURES</td></tr>
<tr><td colspan="2">TEXTURES - TOP SURFACE
smooth, grainy or wrinkly surface, slight swellings or spherical bulges, burst/collapsed blisters, deep bubble craters/holes, cooling cracks</td></tr>
<tr><td colspan="2">IMPRINTS/COATINGS - TOP SURFACE
embedded charcoals or their imprints, slag coating, non-existent</td></tr>
<tr><td colspan="2">TEXTURES - BASE SURFACE
smooth, porous or pitted surface</td></tr>
<tr><td colspan="2">IMPRINTS/COATINGS - BASE SURFACE
embedded sand/grit, burned clay/ceramic or charcoals or their imprints, slag coating, non-existent</td></tr>
<tr><td colspan="2">POURING CHARACTERISTICS - TOP SURFACE
directed or concentric flow textures, concentration of pores and shrink holes, extensions, half-smelted and protruding objects on the surface</td></tr>
<tr><td colspan="2">TOOLMARKS / DEFORMATIONS
round punctures from wooden poles, scratches and notches from axes or chisels (blade length), marks from hammers with round or elongated fins (diameter of the imprints), mushroom head, deformations/flattenings, stress cracks, straight breaking edges</td></tr>
<tr><td colspan="2">INNER STRUCTURE AND FRACTURE SURFACE</td></tr>
<tr><td></td><td>GENERAL HOMOGENEITY
homogenous, heterogeneous, not definable</td></tr>
<tr><td></td><td>SHAPE - MACROPORES
spherical, ovoid, drop-shaped, elongated, irregular, connected pores</td></tr>
<tr><td></td><td>SIZE - MACROPORES
small pores (<3 mm), medium pores (3-15 mm), large pores (>15 mm), pores of all size classes, no pores visible</td></tr>
<tr><td></td><td>DENSITY - MACROPORES
low porosity (<5 vol%), medium porosity (5-15 vol%), high porosity (>15 vol%), non-porous</td></tr>
<tr><td></td><td>DISTRIBUTION - MACROPORES
uniformly/unevenly distributed, on the top side/base side, along a internal cooling rim</td></tr>
<tr><td></td><td>MACROSCOPIC INCLUSIONS
slag, charcoil, non-existent</td></tr>
<tr><td></td><td>GRAIN STRUCTURE
columnar grains, equiaxed grains, no grain structure visible</td></tr>
<tr><td>CASTING LAYERS
circumferential necking on the surface of the base side</td><td>CASTING LAYERS
two-layered, multi-layered, no layering visible</td></tr>
<tr><td></td><td>FRACTURE TYPES
comminuted fracture, unilateral V-notched fracture, bilateral V-notched fracture, splitting, not definable</td></tr>
<tr><td></td><td>FRACTURE EDGE
vertical, slanting, stepped, irregular</td></tr>
<tr><td></td><td>FRACTURE SURFACE PRESERVATION
sharp-edged (grainy/columnar/spiky), rounded (by annealing)</td></tr>
<tr><td rowspan="10">ADDITIONAL SCIENTIFIC ANALYSIS</td><td colspan="2">CHEMICAL/ISOTOPIC ANALYSIS</td></tr>
<tr><td colspan="2">atomic absorption spectroscopy (AAS), neutron activation analysis (NAA), energy dispersive X-ray fluorescence spectrometry (EDXRF), scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDS), inductively coupled plasma – atomic emmission spectroscopy (ICP-AES/OES), mass spectroscopy (ICP-MS), lead isotope analyses (LIA)</td></tr>
<tr><td colspan="2">METALLOGRAPHIC EXAMINATIONS</td></tr>
<tr><td colspan="2">macroscopic, light microscopic and/or electron microscopic structural examination of an etched microsection, hardness test</td></tr>
<tr><td colspan="2">IMAGING TECHNIQUES</td></tr>
<tr><td colspan="2">scanning electron microscopy (SEM), industrial computed tomography (CT), neutron tomography (NT)</td></tr>
<tr><td colspan="2">DATING METHODS</td></tr>
<tr><td colspan="2">radiocarbon dating of enclosed charcoal</td></tr>
<tr><td colspan="2">ARCHAEOBOTANICAL ANALYSIS</td></tr>
<tr><td colspan="2">wood identification on enclosed charcoal</td></tr>
</table>

Fig. 4: 'Checklist' for the recording of complete and fragmented PCIs with additional scientific analysis (graphic: D. Modl).

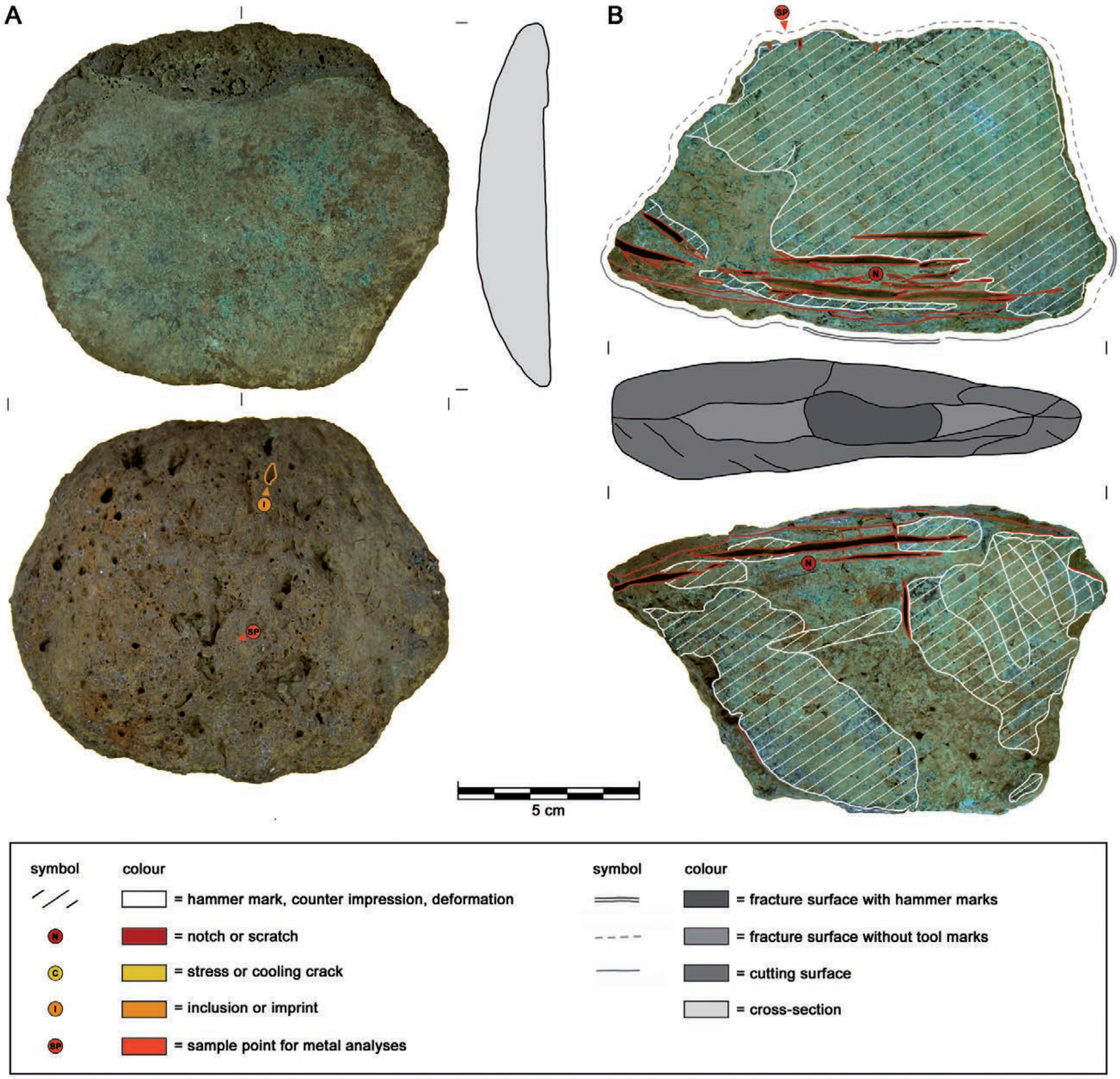


Fig. 5: Examples for the visual documentation of PCIs: (A) PCI from hoard XIX (CNr. 37; Bz D/Ha 1; see Windholz-Konrad, 2018, p.151, 175, tab.51/8) from the finding area 'Hallstatt-Seeufer', Upper Austria, (B) fragment of a PCI from hoard I (CNr. 11; Bz D/Ha A1/A2; see Windholz-Konrad, 2018, p.130, 160, tab.13/82) beneath the so-called 'Rabenwand' near Bad Aussee, Styria, together with a legend for the used symbols and colours (graphic: D. Modl).

partition by simple observation even without elaborate scientific laboratory analyses. In addition, the manual attempts to define a documentation standard that enables comparative studies. The practical work requires no equipment more sophisticated than a digital camera, photo scale, calliper, triangel ruler, circular graph paper, magnifying glass, neodymium magnet (N35) and a strong desk lamp.

However, the suggested approach cannot replace any scientific investigations if one wants to obtain more detailed information about smelting technology and material composition. For this purpose imaging techniques, like industrial computed tomography (CT) or neutron tomography (NT) and metallographic examinations with a hardness test (Brinell, Rockwell or Vickers) as well as quantitative chemical or isotopic analyses have to be applied (see Hauptmann, 2008; Pernicka, 2014; Pollard & Bray, 2014). Various methods were in use for the trace element analysis and provenance studies of copper PCIs, like atomic absorption spectroscopy (AAS), neutron activation analysis (NAA), energy dispersive X-ray fluorescence spectrometry (EDXRF), proton-induced X-ray emission (PIXE), electron probe micro analysis (EPMA)/scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDS), inductively coupled plasma – atomic emmission spectroscopy (ICP-AES/OES) or mass spectroscopy (ICP-MS) and lead isotope analyses (LIA). Especially the impure and partly refined coppers (black copper) are most suitable for provenance studies because their geochemical fingerprint was not altered by alloying, mixing or recycling.

Furthermore it is possible to date the PCIs directly over charcoal inclusions and to determine the firewood used in their production through archaeobotanical analysis. Additional information can be obtained by comparing original PCIs with specimens from archaeological experiments.

The following manual was developed on the basis of scholarly literature and tested on an archaeological record from Styria and Upper Austria, which is a total of two dozen complete PCIs and quarter pieces as well as over 1000 fragments from the Bronze Age. The recording system describes a large number of external qualities by using a uniform terminology under the three headings of ‘form and preservation’, ‘casting surface and partition features’ as well as ‘inner structure and fracture surface’ which have been summarised in a useful ‘checklist’ (Fig. 4). This content outline shows that the recording system is not designed as a rigid typological study, but rather explains the individual characteristics of PCIs, which should allow for their better description in find catalogues.

For the visual documentation of the PCIs photographs of the top and base side and drawings of the cross-sections in scale of 1:1 or 1:2 were used (Fig. 5). With colored lines, hatchings and symbols, the sampling points for metal analysis as well as all specifics and modifications on the surface were marked, which are related to the production and partition of PCIs such as inclusions, imprints, cracks, plastic deformations and toolmarks. Various outlines drawn around the top side of the PCI finally show whether it has original casting edges or artificial fracture edges with and without toolmarks.

Since the here proposed visual documentation and verbal description is relatively time-consuming, larger quantities of PCIs can also be recorded in lists and presented with selected examples. For closed find complexes, like hoards, statistical evaluations of weight or partition shape should also be carried out.

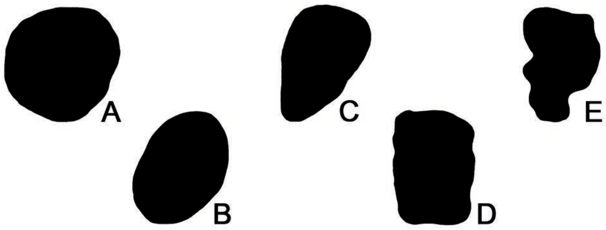


Fig. 6: The primary shape of PCIs: (A) round, (B) ovoid, (C) drop-shaped (triangular), (D) sub-rectangular, (E) irregular (graphic: D. Modl).

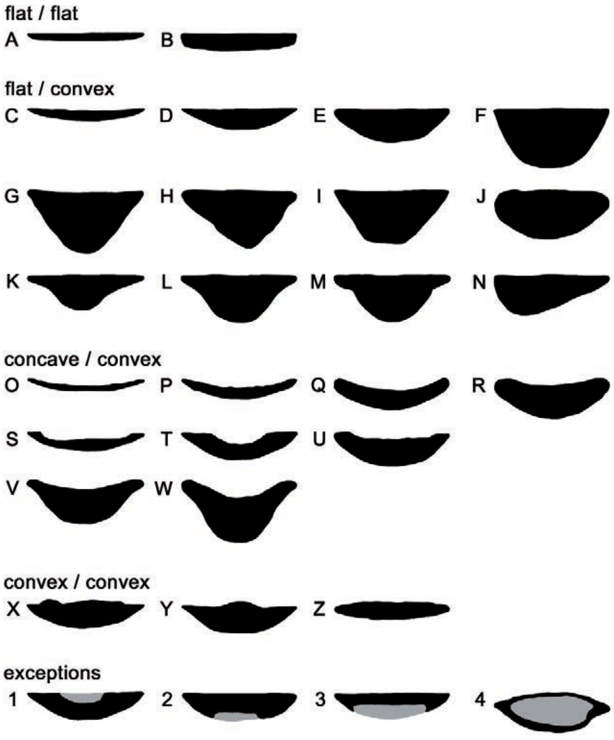


Fig. 7: The primary cross-section of PCIs (not to scale): (A) flat, (B) rectangular, (C-E) plano-convex, (F) hemispherical, (G) catenary, (H) triangular/conical, (I) trapezoid, (J) bun-shaped, (K-L) bell-shaped, (M) bell-shaped/constricted, (N) asymmetrical, (O-R) bowl-shaped/curved, (S-U) shrunken, (V-W) bell-shaped/campanulate, (X-Y) umbonate and (Z) biconvex. Furthermore cross-sections of multi-poured ingots with (1-2) voids at the top or bottom, (3) flat slabs with hook-shaped edges and (4) ingots with very large cavities (graphic: D. Modl).

Form and preservation

To define the form of a PCI, its shape, cross-section and maximum dimensions must be recorded. The primary form and dimensions of a PCI result from the shape, slope and size of the casting mould, which in most cases may have been a simple depression in the ground. In connection with the evaluation of the cross-section, the shape of the original casting edge, where the convex side meets the flatter top, should also be described in detail. In the course of manual partition the PCI is fragmented and receives a secondary form, which makes a conclusive morphological identification without experience usually difficult. The degree of fragmentation of the PCIs in hoards is typically high, so only a few intact specimens are contrasted with a large number of broken pieces, which in most cases can be assigned to the edge, slope or core areas of the ingot by applying the cross-section. As the evaluation of partition patterns and archaeological experiments has shown, most of the PCIs were not broken completely arbitrarily and irregularly, but according to certain rules that can be reconstructed according to the shape of the fragments.

It is not possible to assess the metal composition from the shape or from the surfaces of the PCIs. But to

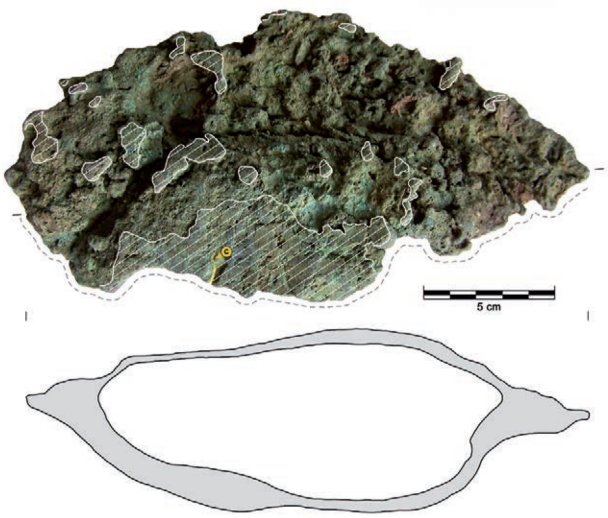


Fig. 8: PCI with a very large cavity and a very smooth inner surface from finding area 'Hallstatt-Seeufer', Upper Austria; unpublished single find (No. 32M07; see Windholz-Konrad, 2018, p.183) (graphic: D. Modl).

get a first idea about the metal composition of a PCI, it is sometimes helpful to inspect the patina and to determine the magnetic properties of the piece. A rust-brown patina and a strong magnetism indicate an increased iron content in the copper, which could be confirmed in following chemical analysis.

Primary shape (after casting)

Complete PCIs usually have a roughly round shape when viewed from above. But there are also more elongated specimens with ovoid, sub-rectangular or drop shape (triangular). Entire ingots that do not correspond to any of the preceding shapes are called irregular (Fig. 6/A-E).

Primary cross-section (after casting)

Intact PCIs are typically flat along the top and convex on the base. In cross-section, they are thickest at or near the center, then incline gradually towards the edges. The inclination of the ingot could possibly be related to the material of the mould, since pits in a loamy soil may have steeper walls than in a sandy ground.

However, the cross-sections of the PCIs are much more diverse and show variable cross-sections consisting of different combinations of the flat, concave or convex top and bottom sides (flat/flat, flat/convex, concave/convex, convex/convex; see Fig. 7). The PCIs can reach extreme manifestations in their cross-section. On the one hand, almost hemispherical and bell-spaped specimens exist - e.g. Czajlik, 1996, p.170, fig.13; Turk, 2000, pp.27-28, tab.22/25) and on the other hand, there are very flat pieces that do not really taper to the edges and look like slabs or 'flat cakes' ('Fladen'; e.g. Höglinger, 1996, p.142, tab.31/542; Bachmann et al., 2002/03, p.79, fig.9/A/2-3, 18/5, 14).

As a result of the faster solidification and shrinkage of the liquid metal around its perimeter during the solidification, a narrow, flat ring evolves often without blisters at the outer edges of the top surface of some PCIs, in which the center arches slightly because of rising gas bubbles (e.g. Pietzsch, 1964, pp.39-40, fig.16) or subsides in a depression due to intense shrinkage. Accordingly, in cross-section the top sides of the PCIs look more or less concave or convex. Secondary use of PCIs can cause their deformation at the edges or at the central base when pieces are used as workaround anvil.

Rarities are well preserved multi-poured ingots with voids on top of theirs bases where individual metal layers were detached because of poor adhesion (e.g. Höglinger, 1996, p.77, 141, tab.29/529; Turk, 2000, p.29, tab.25/37; Tarbay, 2014, p.220, 247, fig.72/85; 2016, p.108, fig.21/121). This group includes also thinner metal disks or fragments with characteristic hook-shaped edges (see Fig. 7/1-3, 9/G, 27), which should not be confused with another type of raw metal, double-flat slabs with very thin cross-sections of approximately 1 cm (e.g. Miske, 1908, p.20, tab.XX/2; Kytlicová, 2007, p.162, 302, 314, tab.56/A/82, 93/249; Tarbay, 2016, p.111, Fig 28/237; Nessel, 2017, p.172, 187, fig.2/c, 20). The different casting layers are sometimes also visible in the cross-section or at the bottom surface of the PCIs with a circular necking or collar (Fig. 7/M; e.g. Viertler, 1973, p.11, fig.2/6, 3/6; Engelmann, 1997, p.30, 74, 113, fig.43, tab.18/1; Weisgerber & Yule, 2003, pp.40-43, 49).

Extremely rare are PCIs with a core consisting of a different material (e.g. lead, slag; see Dörfler et al., 1969, pp.69-77; Weisgerber & Yule, 2003, pp.40-43, 49-51) or showing very large cavities that can not be explained by a simple gas distension (e.g. Mozsolics, 1984, p.37, 57, p.67, tab.16/3, 21/1) and rather seem to be caused by breaking off of such cores (Fig. 7/4, 8).

Casting edge

When describing the periphery of a complete PCI or an edge fragment, it is important to distinguish between the primary casting edge and the secondary fractured surface. The appearance of the casting edge is not only determined by the shape and slope of the mould wall, but also by the surface tension of the liquid metal and the cooling rate. In principle, several edge forms can occur, which can be described as pointed, blunt, edged, steep, round, stepped, hook-shaped ('hakenförmig') and bead-shaped ('wulstförmig') (Fig. 9).

Of particular interest are the two latter types: a hook-shaped edge is a possible indicator for a multi-layered ingot. These edges emerge when the molten metal gets in contact with an already solidified surface and surrounds it at the rounded edge (e.g. Moosleitner, 1982, p.467, fig.9/52; Enăchiuc, 1995, p.291, no. 341, fig.9/15; Teržan, 1995, p.170, tab.68/111; Engelmann,

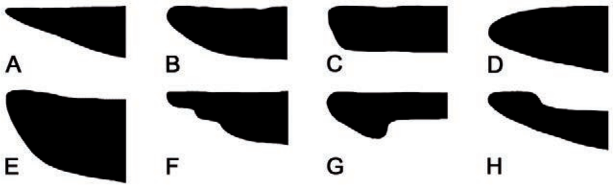


Fig. 9: Common forms of casting edges from PCIs: (A) pointed, (B) rounded, (C) edged, (D) tapered, (E) steep, (F) stepped, (G) hook-shaped, (H) bead-shaped (graphic: D. Modl).

1997, p.31, 74, 113, fig.44-47, tab.19/1-2; Bachmann et al., 2002/03, p.79, fig.9/A/1). Because of a weak bond between the two batches the ingot can break along the contact surface. A bead-shaped edge – sometimes together with cooling cracks on the top surface – is most commonly the result of a much faster cooling and hardening at the periphery of the PCI than in its central region. The outermost edges of the top surface are then marked by a cooling ridge or bulge, where molten metal of an ingot first solidifies (e.g. Krutter, 2015, p.48-49, fig.3). Furthermore it has to be taken into account that edges can be secondarily deformed in the course of partitioning so that they appear, for example, curved upward (e.g. Windholz-Konrad, 2004, p.325, 336, tab.10/11).

Secondary shape (after partition)

Most of the round PCIs may have been partitioned according to the principle of a continuing bisection into halves (e.g. Lauermann & Rammer, 2013, p.192, tab.88/7; Tarbay, 2016, p.99, 108, fig.22/127), quarters (Fig. 10/A-B; e.g. Höglinger, 1996, p.77, 141, tab.31/534; Windholz-Konrad, 2004, p.325, 336, tab.10/8-9) and eighths (e.g. Lauermann & Rammer, 2013, p.8, 23, tab.2/4; Tarbay, 2016, p.99, 109, fig.21/142). The quarter and eighth pieces were partially divided again, resulting in pieces with the shape of a triangle and an isosceles trapezoid (Fig. 11/A). In addition to the halves, there were also narrower circular segments, which were separated towards the edge of the ingot (Fig. 11/B). By splitting them into thirds, middle

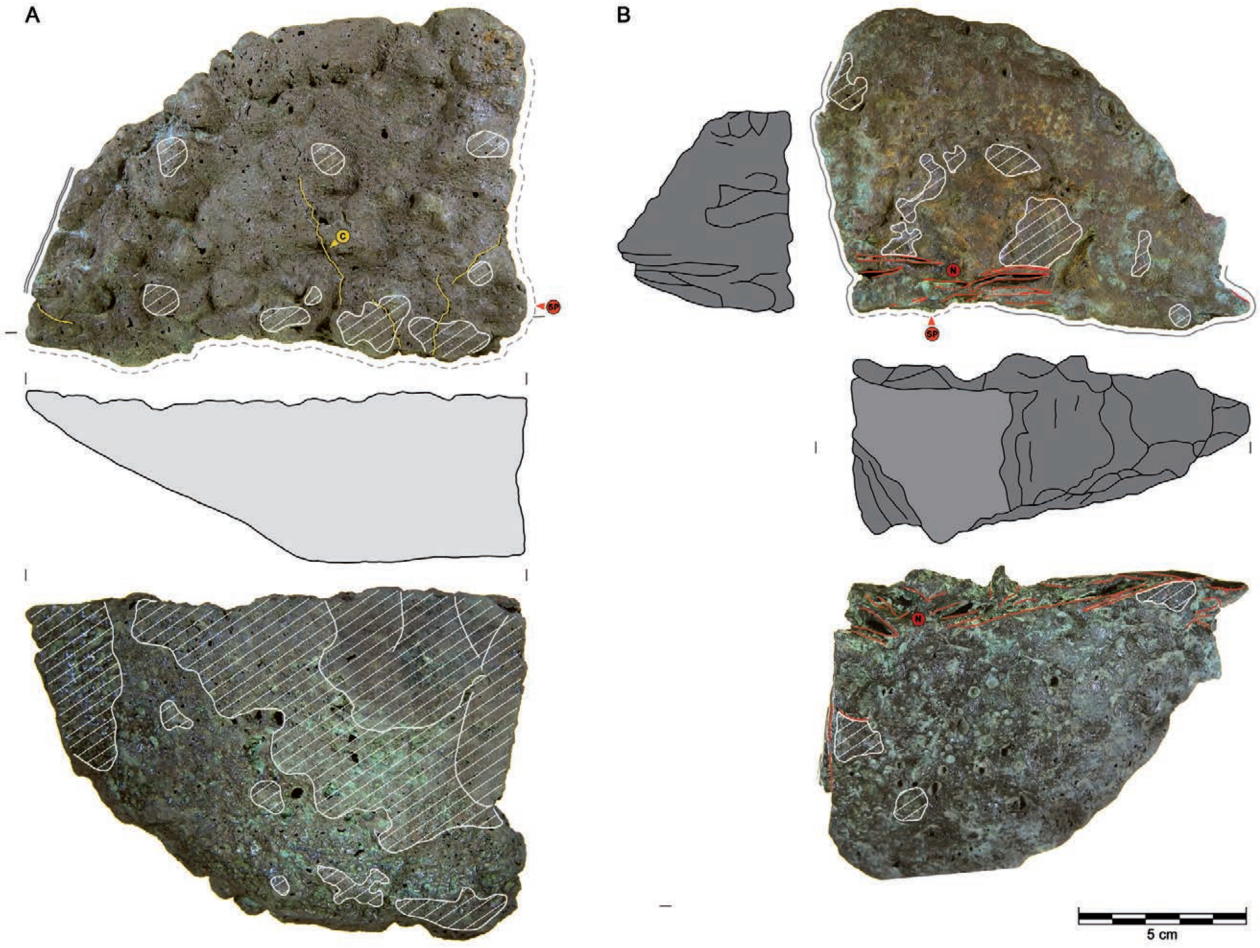


Fig. 10: Quarters of PCIs (A) from hoard III (CNr. 13; Ha A2/Ha B1; see Windholz-Konrad, 2004, p.318, 335, Fig. 33, tab.8/16) at the so-called 'Rabenwand', Styria, and (B) from a hoard near Pichl (CNr. B; Ha A2/Ha B1; see Windholz-Konrad, 2018, p.111, 119, 156-157, Fig. 75-76, tab.2/Cnr. B/3), both close to Bad Aussee, Styria (graphic: D. Modl).

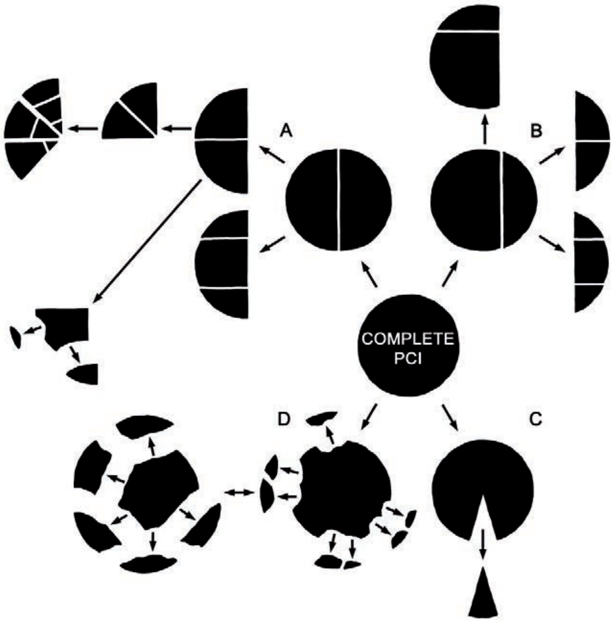


Fig. 11. The most common partition shapes of PCIs: (A) bisection into halves, quarters and eighths, (B) partition of circular segments, (C) separation of wedge-shaped segments and (D) circumferential edge fractions (graphic: D. Modl).

pieces with quadrangular shape were created. In principle, all geometric shapes can arise during partition (see Nessel, 2014, pp.404-405, fig.2; 2017, pp.178-179, fig.8; Tarbay, 2016, pp.99-100, fig.10/1).

The separation of wedge-shaped segments (Fig. 11/C), which approximately correspond to the sixteenth part of a whole ingot, belong to the exceptions (e.g. Mozsolics, 1984, pp.39, 69-70, tab.16/4, 17/2a-b; Czajlik, 1996, p.170, fig.13; Pühringer, 2000, pp.198-200, fig.6; Turk, 2000, p.28, tab.23/31; Ciugudean et al., 2006, pp.96, 98-99, fig.5/1, 9; Nessel, 2014, p.410, 425; 2017, pp.178, 192-193, fig.23). Other recurring partition patterns are isolated or circumferential edge fractions on complete ingots or their quarters (e.g. Windholz-Konrad, 2004, p.305, 334, tab.4/72; Lauermann & Rammer, 2013, p.185, tab.84/2), resulting in small D-shaped edge pieces (Fig. 11/D, 12). These thin edge pieces were probably chipped for a rapid production of minor quantities of copper or as a kind of material testing (see Modl, 2010, p.135, 148; Nessel, 2014, pp.407-408, 410; 2017, pp.187-188, 192). The largest part of the known ingot material is so small and irregularly broken that its emergence can not be reconstructed and must be called amorphous.

Secondary cross-section (after partition)

If fragments have no edge, it seems difficult to match them with a specific part of a PCI. However, by looking at the cross-section of the fragments, it is possible to determine also the inner parts of a PCI and assign them either to the core or to the area between the center and the edge. While the 'edge piece' has a triangular cross-section, the 'core piece' has a rectangular shape with a flat top and plane or slightly convex base and the 'slope piece' is more trapezoid with a significantly inclined base (Fig. 13). The transitions between these three areas are of course fluent and cannot always be clearly defined.

Dimensions

In addition to the major and minor diameter (ma./mi. diam.), the length (l.) and width (w.) of intact PCIs or their partitions and also the thickness (th.) and weight (wt.)

Fig. 12. Nearly complete PCI with circumferential hammer marks and edge fractions from hoard I (CNr. 11; Bz D/Ha A1/A2; see Windholz-Konrad, 2018, p.130, 160, tab.13/72) at the so-called 'Rabenwand' near Bad Aussee, Styria (graphic: D. Modl).

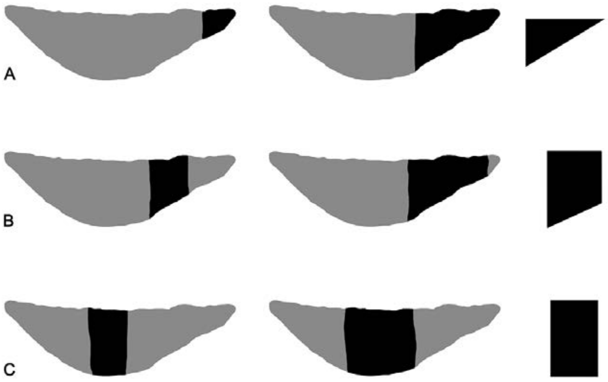


Fig. 13: Identification of different fragments of PCIs according to their cross-section (with the basic geometric form on the right side) in (A) edge pieces, (B) slope pieces or (C) core pieces (graphic: D. Modl).

should be determined (Fig. 14). Due to the fact that PCIs are mostly of a round shape, it is possible to reconstruct the original diameter by using well-preserved edge pieces (>10% from the perimeter) and a circular graph paper. The diameter of complete PCIs mostly varies between 8 and 30 cm, while their thickness ranges frequently between 1 and 10 cm. Some specimens even reach diameters over 45 cm (e.g. Wischenbarth, 1995, p.25). The weight of complete examples is an average between 0.5 and 8 kg, but examples of up to nearly 15 kg are known (e.g. Hild, 1948, p.90). Since PCIs were often poured in several casting batches, the capacity of the crucibles or furnaces cannot be derived from the size of the ingots.

Because of the heterogeneous structure of the PCIs with occasionally numerous gas bubble cavities, the relation between diameter, thickness and weight is not linear and can fluctuate. This will be clarified by the attempt to divide the PCIs with these measured values into different size groups (see Rusu, 1981, p.382; Höglinger, 1996, pp.76-77; Primas & Pernicka, 1998, pp.35-36; Bachmann et al., 2002/03, p.81; Modl, 2010, p.134), which can be roughly defined as large (size class 1: >20 cm diam., > 3 cm th., >4 kg wt.), medium (size class 2: 15-25 cm diam., 2-4 cm th., 2-5 kg wt.) and small (size class 3: <15 cm diam., <3 cm th., <2 kg wt.).

Patina

The patina of PCIs depends primarily on corrosive substances in the soil and secondarily on the chemical composition of the metal. This is why their colour only provides evidence about the metal composition in rare cases. Isolated rust spots, as well as a complete rust-brown coating on PCIs (see Preßlinger, 2004, pp.327-328; Weihs 2004, p.91; Windholz-Konrad, 2004, p.305, 325; Kytlicová, 2007, p.164), are quite reliable evidence of an increased (metallic) iron content above 3 wt%, which can be a result of strongly reducing conditions during primary smelting (see Bachmann, 1982, pp.17-18; Craddock & Meeks, 1987; Trampuž Orel et al., 2002, p.66, 71). But sometimes corrosion and patina can also be adverse because they hide tool marks or cover surface details on the PCIs such as gray-violet oxidation coatings of cuprous oxide, which emerge when the melt was exposed to the oxygen-containig atmosphere during casting or heating.

Magnetism

When the iron content of the copper exceeds 1 wt%, a PCI can show low or high magnetism that can be detected with a strong hand magnet (Fig. 15).

Casting surface and partition features

Depending on the country and research tradition, the definition of the top and base side of a PCI differs. It seems evident to align them according to their orientation during

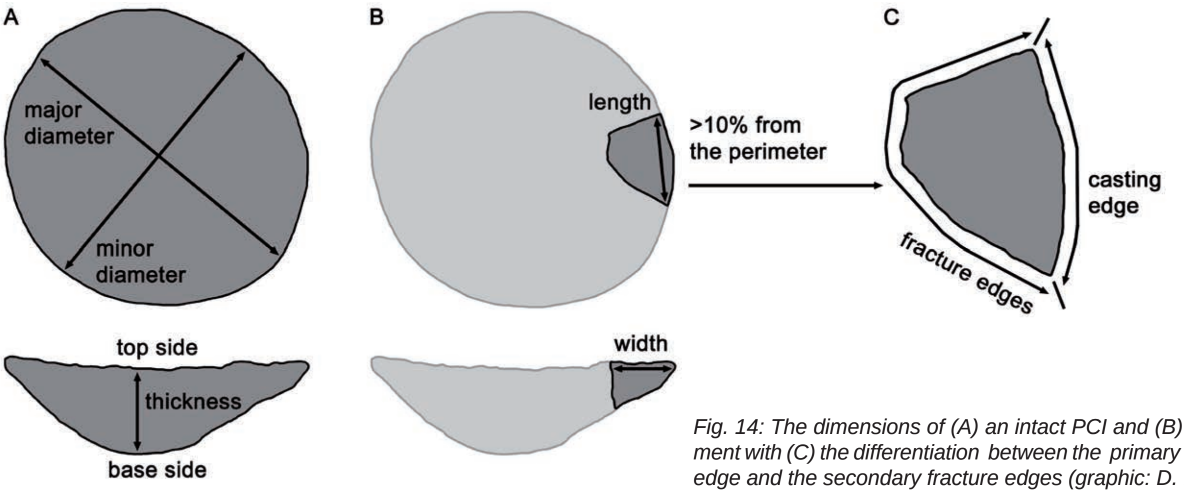


Fig. 14: The dimensions of (A) an intact PCI and (B) a fragment with (C) the differentiation between the primary casting edge and the secondary fracture edges (graphic: D. Modl).

Fig. 15: Ferrous PCI with an adhere neodymium magnet ring (N35) (photo: D. Modl).

casting and solidification. While the flat side at the top is exposed to the air, the convex side at the bottom stands in permanent contact with the mould material. Depending on the enviroment, the surface of the top and base has a distinctly different texture, which is primarily characterised by the formation and escape of gases or by imprints of the mould face and the fuel (Fig. 16). Additionally, the surface of the PCIs shows numerous metallurgical and technological features from pouring and partitioning, like flow structures of the liquid metal, as well as toolmarks or deformations.

Solidification textures and imprints at the top surface (upper side)

One of the distinctive features of PCIs is their blistered and humpy surface on the flat top, which is on the one hand a result of degassing during the solidification of the molten metal, and on the other hand an indicator of pouring into an open mould. Size and density of the blisters depend on the gas saturation, viscosity and the cooling rate of the melt. The violent escape of gas bubbles at the surface – a phenomenon known in metallurgy as crackling (‘Spratzen’) – shows different stages of development and ranges from slight swellings or spherical bulges over burst and collapsed blisters to more or less deep bubble craters or holes (Fig. 10/A, 16/A, 17/D-F; e.g. Barth & Unterberger, 1983, p.7, fig.2, 4; Mozsolics, 1984, p.36, 63-64, tab.9/2; Windholz-Konrad, 2003, p.66, fig.62; 2018, p.124, 158, tab.7/16). At low gas evolution, the PCIs can also have no blistering on their top and instead show an even surface with a smooth, grainy or wrinkly texture (Fig. 5/A, 17/A-C). Smooth surfaces are the result of well-dried moulds and rapid solidification, but an additional coverage of the melt – possibly by another metal or slag phase or charcoal powder – cannot be excluded. While fine wrinkles can be compared with a ‘milk skin’, the coarse wrinkles have the appearance of ripples, which can be interpreted as flow structures from the casting. Compared to the bottom side, imprints of charcoals on the top are very rare. The top surface can be considerably compressed and deformed in the course of the secondary partition of the PCI, so that, for example, the protruding blisters are flattened.

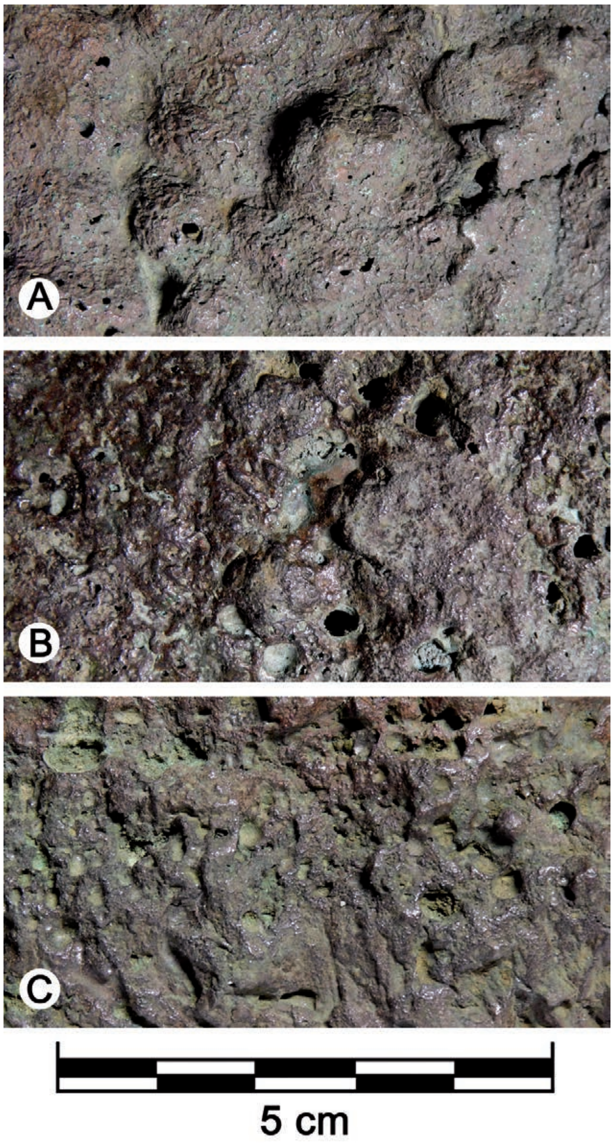


Fig. 16: Detailed views of the (A) top and (B) base as well as the (C) fractured surface of a PCI quarter from hoard III (CNr. 13; Ha A2/Ha B1) at the so-called ‘Rabenwand’ near Bad Aussee, Styria (see Windholz-Konrad, 2004, p.318, 335, Fig. 33, tab.8/16) (graphic: D. Modl).

Solidification textures and imprints at the base surface (bottom side)

The bottom side of a PCI is also determined by gas evolution, but especially by the material properties or the surface texture of the mould (see Larson, 2009). For example, irregularities or spalling in stone or clay moulds

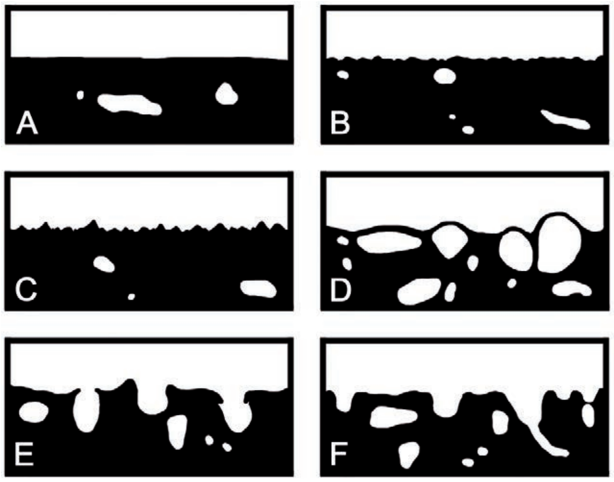


Fig. 17: Textures at the top surface (shown in cross-section): (A) smooth surface, (B) grainy surface, (C) wrinkly surface, (D) slight swellings or spherical bulges, (E) burst and collapsed blisters, (F) deep bubble craters or holes (graphic: D. Modl).

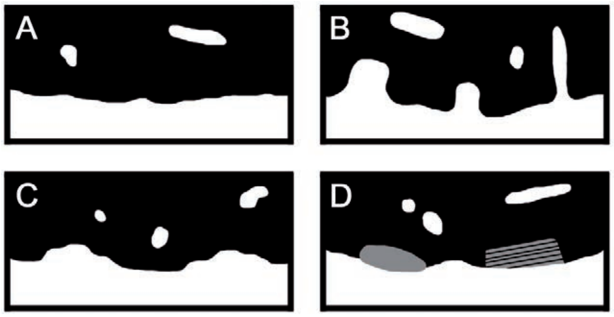


Fig. 18: Textures and imprints at the base surface (shown in cross-section): (A) smooth surface, (B) porous surface, (C) pitted surface, (D) surface with embedded sand/grit or imprints of charcoals (graphic: D. Modl).

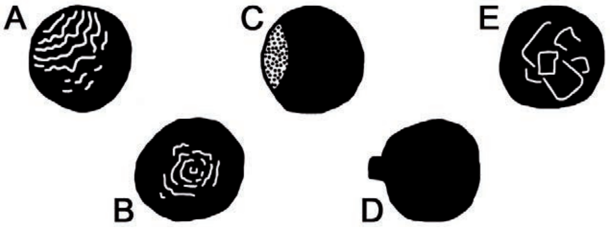


Fig. 19: Pouring characteristics on PCIs: (A) directed flow textures, (B) concentric flow textures, (C) concentration of pores and shrink holes, (D) extensions and (E) half-smelted and protruding objects (graphic: D. Modl).

or deformations in sand moulds with malleable surfaces, which can easily be distorted by the pressure of the molten metal, ensure that no PCI possesses a completely even bottom. Three different surface configurations can be differentiated at the base with smooth, porous and pitted areas (Fig. 16/B, 18/A-C). The round gas pores are either superficial cavities with semi-spherical shape or deep tubular pinholes that are a result of gas exchange between the molten metal and the mould surface, provided that the material of the mould is gas-permeable.

The irregular pits are small, synclinal and interrelated (Fig. 5/A, 12). Their emergence is mainly due to the rough material used to create the mould or because of a sloppily smoothed mould surface. As burnt clay/loam remains or embedded sand/grit on the lower surface shows, the moulds were mostly simple pits in a clayey or sandy/stony ground. Some PCIs also show bulges that could be tree roots (e.g. Viertler, 1973, p.11, fig.2, 3). Sometimes vitreous slag residues can be observed on the base surface which could be a reaction product of the contact between the molten metal and the mould material.

While imprints of small-sized charcoals with relatively sharp edges and unambiguous wood grain are often recognizable (Fig. 18/D), complete charcoal fragments are rarely incorporated in the lower surface (Fig. 1). These charcoals were maybe a temper of the mould material, fuel rests from preheating the mould or impurities that were incorporated into the mould during casting through the liquid melt. However, the well preserved charcoals are an important source for direct dating of PCIs by using the radiocarbon method. The most unusual inclusions on the bottom side of PCIs are ceramic fragments (e.g. Engelmann, 1997, p.30, 73, 113, fig.41-42, tab.18/2).

Pouring characteristics

PCIs are mainly produced by using the open-mould process. This is not only supported by the fact that some PCIs were cast in several batches and consist of two ore more metal layers, but they also display flow textures and features, like a possible 'sprue'. These casting characteristics are rarely visible on the top, because the surface of the ingots is greatly altered by the rising gas bubbles. The flow textures show a wrinkled or billowy texture that extends in one direction or spreads concentrically (Fig. 19/A-B; e.g. Höglinger, 1996, p.141, tab.27/516, 29/518), sometimes forming a large swelling which can be a sprue from production. These ripples are a result of the movement of the liquid metal under a nearly congealing skin, compressing them in the flow direction. At the edge of some PCIs there are distinct concentrations of pores and shrink holes (Fig. 5/A, 19/C; e.g. Windholz-Konrad, 2003, p.93, 129, fig.128; Modl, 2010, p.130, fig.1; Windholz-Konrad, 2018, p.151, 175, tab.51/8) as well as narrow extensions (Fig. 19/D; e.g. Modl, 2010, p.130, fig.6; Lauermann & Rammer 2013, p.130, tab.44/2; Reiter & Linke, 2016, pp.150-151, fig.48/1), which could indicate a lateral inflow of the metal into the mould. PCIs made from recycled scrap metal sometimes reveal only half-smelted bronze objects on their top surface that protrude slightly (Fig. 19/E; e.g. Mozsolics, 1981; 1984, pp.35-36, tab.5-6; Kacsó, 2013, pp.228-229, fig.5/5; Tarbay, 2014, p. 220, p.247, fig.68/80; Reiter & Linke, 2016, p.150, pp.168-169, fig.45/3, 52/6).

Fig. 20: Complete PCI with hammer marks and shallow notches at the base surface, which possibly originate from the use as primitive anvil; unpublished single find (No. 2MM05) from finding area 'Unteres Koppental', Styria (graphic: D. Modl).

Toolmarks and deformations

On some of the PCIs, a single, round puncture could be observed, presumably from wooden poles stabbed into the viscous copper shortly after the casting, possibly for degassing the melt or to determine the degree of viscosity (e.g. Willvonseder, 1940, p.10, tab.3/1; Drescher, 1976, p.62, fig.15/e; Mozsolics, 1981; Töchterle, 2002, pp.120-122, fig.3/1; Kacsó, 2013, p.228, fig.5). Relatively often, even complete PCIs display superficial scratches or deeper notches that were accrued in the viscous or doughy copper on the top surface to determine where to divide the piece into halves or quarters during a later stage (e.g. Hild 1948, p.90, fig.1/1; De Marinis, 2011, p.93, fig.2; Stöllner, 2015, p.101, fig.7; Nessel, 2017, p.186, fig.13). The further procedure was depending on the porosity and thickness of the PCI and on the intended specific shape of the partitioned section.

If an ingot was rich in gas bubbles and cuprite or copper sulphide inclusions, it could be broken under cold and warm conditions by crashing it with a hammer or a similiarly heavy tool on a massive support (Fig. 2/E-F). The result are pieces with irregular shape and uneven fractures as well as brittle cracks and deformations, like areas with concave and sometimes overlapping imprints caused by blows with a hammer with rounded face (Fig. 5/B, 10/A, 12).

To achieve a definite breaking shape the reheated ingot (over 300°C) was notched on one or both sides and broken or split completely by the use of different wedge-shaped cutting tools (e.g. Drescher, 1976, p.61, fig.15/c-d; Mozsolics, 1984, p.38, 51, 71, tab.10/2, 4; Teržan, 1995, p.203, tab.92/74, 162; Windholz-Konrad, 2004, p.305, 313, 334-335, tab.4/82, 6/18; 2018, p.122, 130, 158, 160, tab.5/2, 13/82; Kytlicová, 2007, pp.162-163, 258, tab.163/2; Nessel, 2014, p.407, fig.7-8; 2017, p.186, fig.14-15). Therefore bronze axes or width chisels ('Abschröter') with a blade lenght of approximately 3-4 cm are used, which typically penetrate 0.5-1 cm into the annealed metal (see Modl, 2010, pp.136-137, 142-144, fig.13, 19, 23, 26). Usually, around the notches single or several imprints of hammers with round and elongated fins are visible (Fig. 5/B). The PCIs broken in this way have surprisingly straight or vertical fracture edges (see Mozsolics, 1984, p.38, 67, tab.21/3; Windholz-Konrad, 2003, p.85, 110, cat.no. 251/1, fig.103; 2018, p.142, 167, tab.39/Cnr. 21/1; Nessel, 2014, p.407, fig.9-10; 2017, p.186, 188, fig.16-17).

Some complete PCIs show flattening of their base with several hammer marks and randomly oriented, shallow notches, which originate from the use as primitive anvils (Fig. 20; e.g. Nessel 2017, p.186, fig.10). The same applies to pieces of PCIs showing a mushroom head (Bartbildung) on one side and a plain face from countless hammer blows from using it as an anvil in a wooden block (see Jockenhövel, 1983; Bachmann et al., 2002/03, p.78, 88, fig.8/B/1; Gogâltan, 2005, p.373, tab. XII/b). The saw marks mentioned by some authors may be misinterpretations (cf. Höglinger, 1996, p.77; contra Modl, 2010, p.144). If the analysed PCIs come from older museum collections, previous cleaning and restoration treatments or metal sampling can obliterate or add tool marks on their surface (see Modl, 2012, p.99, fig.10).

Inner structure and fracture surface

The cooling rate of the molten metal and the solidification conditions in the mould have a big effect on the inner structure of the PCIs. This concerns the development of gas pores and shrinkage cavities, but also the distribution of non-metallic inclusions and the formation of copper

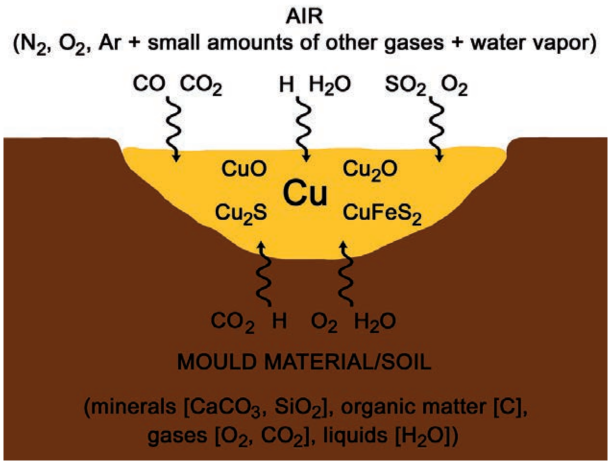


Fig. 21: Simplified representation of the gas apsorption in copper PCIs (graphic: D. Modl).

Fig. 22: Fragmented PCI with a good visible slag grain and a elongated gas cavity on the fracture surface; single find (see Windholz-Konrad, 2003, p.93, 127, cat.no.534, fig.124) from finding area 'Obertraun-Traunweg' near Hallstatt, Upper Austria (photo: D. Modl).

crystals/grains in the solid metal. These characteristics can be macroscopically observed on the fracture edges of PCIs and are important for the evaluation of their general homogeneity. This can also be determined by the fact that numerous PCIs were not poured in a single casting event, but in several batches, which are visible in definable metal layers when broken. In contrast, there exist also numerous very massive PCIs that show an extraordinary density without shrinkage or gas bubbles as well as striations from multiple castings on the fracture surfaces. In addition, the fractured surface provides hints concerning the stress factors and temperature conditions during partition.

Porosity

A characteristic feature of the majority of the PCIs is their high porosity caused by gas evolution and shrinkage that forms numerous pores and cavities inside as well as blisters on the surface during solidification. Liquid copper has the tendency to absorb gases such as oxygen (O_2), hydrogen (H) and water vapour (H_2O), as well as carbon monoxide (CO), carbon dioxide (CO_2) and sulfur dioxide (SO_2). These gases derive, among others, from a combustion reaction between the liquid copper and the mould material, from the burning charcoal, from the evaporation of residual moisture in the mould and charcoal, from the exchange with the humid air and from oxidation of copper sulphide inclusions in the copper (Fig. 21; see Hauptmann, Maddin & Prange, 2002, pp.4-5; Hauptmann & Maddin, 2005, pp.133-136; Bunk & Kuhnen, 2008, pp.310-313; Modl, 2010, pp.129-130, 140-141; Laschimke & Burger, 2012, pp.89-95; Hauptmann et al., 2016, pp.752-759). Because of the transgression of the solubility limit of gases in the melt, the dissolved gases are released while cooling and as a result rapidly increased gas bubbles from greater depth try to escape on the top surface of the ingot. However, slowly growing gas bubbles can easily be trapped in the solid. If the surface is already solidified, it is likely that the gas bubbles will form flat as well as large closed cavities in the upper part of the ingot (Fig. 22).

Accordingly, the size of the cavities ranges from a few micrometres (micropores) up to centimetre scale (macropores). The macropores can be roughly divided into small (<3 mm), medium (3-15 mm) and large pores (>15 mm). Gas pores are generally spherical or ovoid in shape and have a smooth pore boundary. In contrast, shrinkage cavities ('Lunker') created by volume deficits in the solidified molt during cooling have a more or less fissured, irregular shape. Together, gas pores and shrinkage cavities occupy often 15-40% of the volume of a PCI (Fig. 23/C). This high macroporosity was advantageous for breaking the ingots into fragments because the fractures could spread along the pores and cavities through the brittle copper matrix (cf. Hauptmann et al., 2002, p.19; Laschimke & Burger, 2012, p.94; Hauptmann et al., 2016, p.758). For this reason, the porosity of a PCI should not be considered a negative quality characteristic. Often, the PCIs have a much lesser density of pores and cavities in their cross-section, so that a distinction furthermore can be made between a low (<5% of the volume) and medium porosity (5-15% of the volume) (Fig. 16/C; 23/A-B). To characterise the porosity of a PCI, the shape, size, density and distribution of the pores should be described briefly.

Inclusions

Because this manual deals with visible features, microscopic and macroscopic inclusions have to be differentiated. Inclusions of slag, tenorite/cuprite (CuO/Cu_2O) and copper sulphides ($Cu_2S/CuFeS_2$) are usually microscopic in size and can only be clearly seen in metallographic sections (see Tylecote, 1976, pp.159-165; Hauptmann et al., 2002, pp.6-12, 19; Hauptmann & Maddin, 2005, pp.137-139; Hauptmann et al., 2016, pp.753-754; Wang et al., 2018, pp.108-111). While copper sulfides reduce during remelting

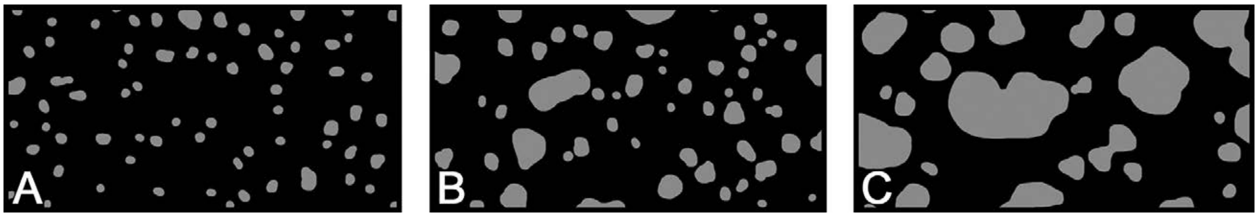


Fig. 23: A comparative standard for the densities of gas pores and shrinkage cavities in the cross-section of PCIs: (A) low porosity with <5 vol%, (B) medium porosity with 5-15 vol% and (C) high porosity with >15 vol% (example with 30 vol%) (graphic: D. Modl).

processes, the metal normally accumulates copper oxides during recasting. Accordingly, both impurities are – together with the chemical composition – important criteria to distinguish copper from primary smelting or from later refining, recasting or recycling operations.

While slag and copper sulphides are relics of the smelting process, especially the cuprite is the result of a reaction between the molten metal and an oxygen-enriched atmosphere during remelting and casting. These oxide droplets are well distributed in the metal and can dramatically deteriorate the mechanical properties of the copper and make it brittle. Due to imperfect refining or sloppy casting, larger slag grains (Fig. 22) well visible to the naked eye and charcoal bits as well as foreign refractory particles from the mould can enter the metal and are sometimes recognizable on the fracture surface (e.g. Modl, 2010, pp.141-142, fig.22; Jansen & Löffler, 2016, pp.129-130). Because of their lower density such inclusions are usually found on the ingot surface (cf. Pietzsch, 1964, p.15, fig.1), however if the solidification happens fast, they can be trapped inside the ingot.

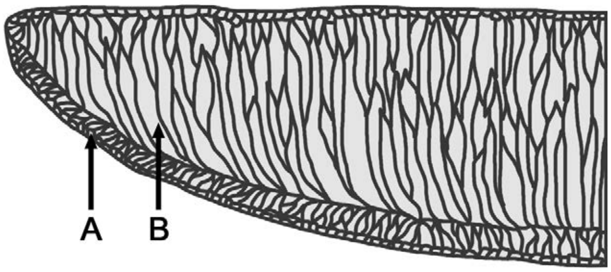


Fig. 24: Grain structure of a PCI: (A) Equiaxed grains and (B) columnar grains. Graphic adapted after a photo with the section of an experimental ingot cast into a drysand mould [see Tylecote, 1976, p.164, Fig. 1.3; University of Oxford, Research Laboratory for Archaeology and History of Art, Tyl_316]; the top surface was exposed to air, while the bottom was at room temperature (graphic: D. Modl).

Fig. 25: Fragmented PCI with good visible columnar grains and hammer marks on the fracture surfaces from a hoard (HaA1) near Lannach, southwest of Graz, Styria (photo: D. Modl).

Crystal/grain structure

When metal begins to solidify, multiple crystals start to grow inside the liquid. In metallurgy, crystals or more precisely the smaller crystallites are preferably termed as grains. The interface formed between grains is called a grain boundary. The size, shape and orientation of the grains depend on several parameters, like cooling rate and direction. While rapid cooling generally results in smaller grains, slow cooling creates larger grains, which can be large enough to be visible to the unaided eye.

There are two major types of grain structures in pure copper: The equiaxed grains have a globular or polygonal shape and extend equally in all directions, while columnar grains are elongated and thin and orientated towards the course of the heat flow. Depending on whether the metal is cast into a cold or preheated mould, two grain structures for uninterrupted single-poured PCIs seem likely. The casting in a cold mould will give a distinctive two-stage cooling structure with an outer layer of many small equiaxed graines reflecting the rapid chilling when it has come into contact with the cold mould wall and an inner layer with columnar grains running in the direction of cooling. The casting into a preheated mould will give the ingot a more columnar structure, whereby the grains grow perpendicularly to the mould in direction of the upper surface, where the heat removal is very high (Fig. 24). These columnar grains are best seen in polished and etched metallographic sections (see Tylecote, 1976, pp.160-165, 170; Scott, 1991, p.6, 97), but can also be

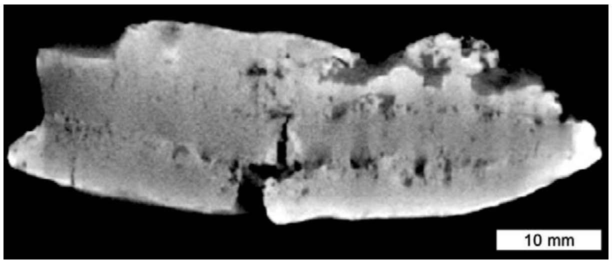


Fig. 26: CT scan of a PCI from a hoard (CNr. A; Ha A2/Ha B1; see Windholz-Konrad, 2018, p.107, 119, Fig. 74, tab.1/8) in Pichl, Styria, with at least three casting layers (photo: Austrian Foundry Research Institute (ÖGI), Leoben).

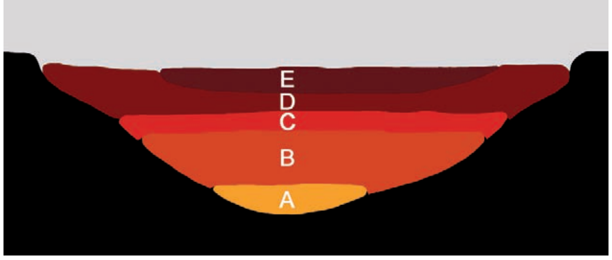


Fig. 27: Highly schematic representation of variants of multi-poured ingots with their characteristic cross-sections and casting edges: (A) small PCI, (B) PCI with a void at the base side, (C) PCI fragment with hook-shaped edges, (A-D) PCI with a void at the top side, (A-E) bell-shaped PCIs with an circumferential necking at the base side and (E) flat PCI (graphic: D. Modl).

relatively frequently observed on fracture surfaces of PCIs (Fig. 25; e.g. Kytlicová, 2007, p.162, tab.28/98, 35/17; Modl, 2010, pp.131-132, fig.7; Le Carlier de Veslud et al., 2014, p.517; Nessel, 2014, p.406, fig.5; 2017, pp.186-187, fig.12). They allow the conclusion that the ingots were cast in a dry and warm environment where they cool relatively quickly because of the open mould. The specific fracture along the columnar grains could be related to cuprite or copper sulphide inclusions along the grain boundaries. How far the primary cast structure of PCIs changes during the partitioning with possibly several heating and dividing episodes has not yet been researched. From a recrystallised structure could be concluded that the PCI comes from a secondary dividing process in which it was alternately reheated and chrushed-up.

Casting Layers

Striations on the fracture surfaces reveal that many of the PCIs consist of two ore more layers and were consequently formed by several casting batches, performed in close succession or separated by a longer interval (e.g. Moosleitner, 1982, p.467, 473, fig.9/49, 51; Engelmann, 1997, p.73, 113; Krauss, 1998/1999, pp.117-118, fig.4/2, 7, 12; Bachmann et al., 2002/03, p.77, fig.7/C/6; Tarbay, 2016, p.99, 110, fig.24/161). Depending on how much time has elapsed between the batches, the result is the complete fusion of the metal layers or the formation of internal cooling rims between them (see Modl, 2010, p.132; Hauptmann et al., 2016, p.754, 756, 759). The rims can be described as sharp cracks, blurred gas bubble horizons or corrosion coating of cuprite among the layers. These interfaces can be clearly seen with the naked eye or in a CT scan (Fig. 26), when the molten metal hits an already cold and solidified surface after an interruption, which makes a complete fusion impossible. The liquid metal of this pour has seeped only into the irregular surface of the previous pour and has created a weak, interlocking, mechanical bond between both batches that could be cracked when the ingot was partitioned.

Accordingly, there exist PCIs with voids on the top or the base, where individual layers have obviously been detached as a consequence of poor adhesion (Fig. 7/1-3, 27). The same applies to thinner metal disks or fragments with hook-shaped edges. As a result of insufficient smelting or refining, also thin layers of slag and other metallic phases (Fig. 28; see Modl, 2011, p.273), like speiss (see Angerbauer, 1985, pp.16-19; Ottaway, 1994, p.103; Trampuž-Orel & Heath, 2001, pp.150-151, 155, 167; Thornton et al., 2009, pp.308-310), can also form layers on PCIs, which lie on top of the copper because of their lower density and specific gravity.

Fig. 28: PCI fragment (presumably base-metal speiss with 60,76 wt% Cu, 15,13 wt% As, 0,36 wt% Ni, 13,91 wt% Fe) with an adherent, silvery metallic phase on the top side (80,50 wt% Cu, 0,93 wt% As, 0,03 wt% Ni, 15,44 wt% Fe) from the so-called Brandgraben hoard (CNr. 15; Bz D/Ha A1/A2-Ha B3; see Windholz-Konrad, 2018, p.46, 60, Fig. 34/189) near Bad Aussee, Styria (photo: D. Modl).

Fracture edges

The fracture behaviour of PCIs and the appearance of their fractured surfaces are determined by the chemical composition, homogeneity (porosity/inclusions) and crystal/grain structure of the metal, as well as the temperature

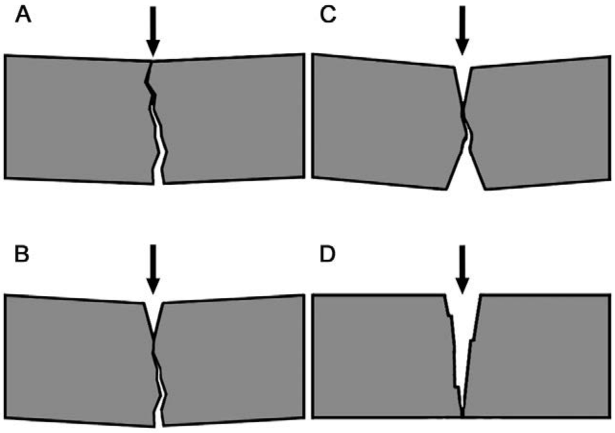


Fig. 29: Fracture types: (A) comminuted fracture, (B) unilateral V-notched fracture, (C) bilateral V-notched fracture, (D) splitting (graphic: D. Modl).

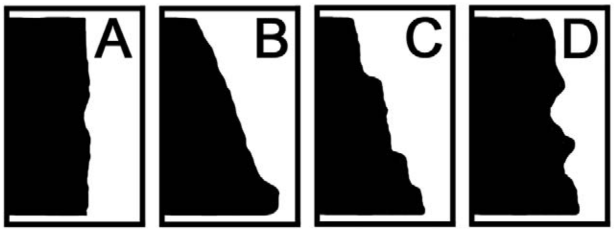


Fig. 30: Fracture behavior: (A) vertical, (B) slanting, (C) stepped, (D) irregular (graphic: D. Modl).

which they were exposed to during partition. Pure copper is very ductile and therefore hard to break under cold conditions. However, a higher content of elements, such as arsenic or iron, as well as impurities along the grain boundaries, like cuprite or copper sulphide inclusions, make it possible to break the metal even in a cold state because of its brittleness, although this is only possible with relatively thin PCIs. This effect is enforced by an increased porosity of the metal, since the fracture can spread out irregularly along the gas pores and shrinkage cavities, which are virtually predetermined breaking points. In this way, even thicker PCIs can be comminuted with a hammer or a similiarly heavy tool ('comminuted fracture'; Fig. 29/A; see Modl, 2010, pp.135-136, fig.11; Nessel, 2014, pp.405-406; 2017, p.182, 186).

At the microstructural level, the cold fracture has frequently run through the individual grains (transgranular fracture) and produced a grainy or spiky surface. When the metal is broken the brittleness increases under hot conditions and a crack propagates mostly along the weakened grain boundaries (intergranular fracture) and the elongated columnar grains often become clearly visible. However, this characteristic grain structure with a splintery surface can disappear in the course of further heating, when the metal is annealing and the sharp-edged surface develops a smooth doughy texture and grain borders or edges begin to round off (e.g. Primas & Pernicka, 1998, p.27, fig.2/1-2, 4; Modl, 2010, p.135, fig.3, 32).

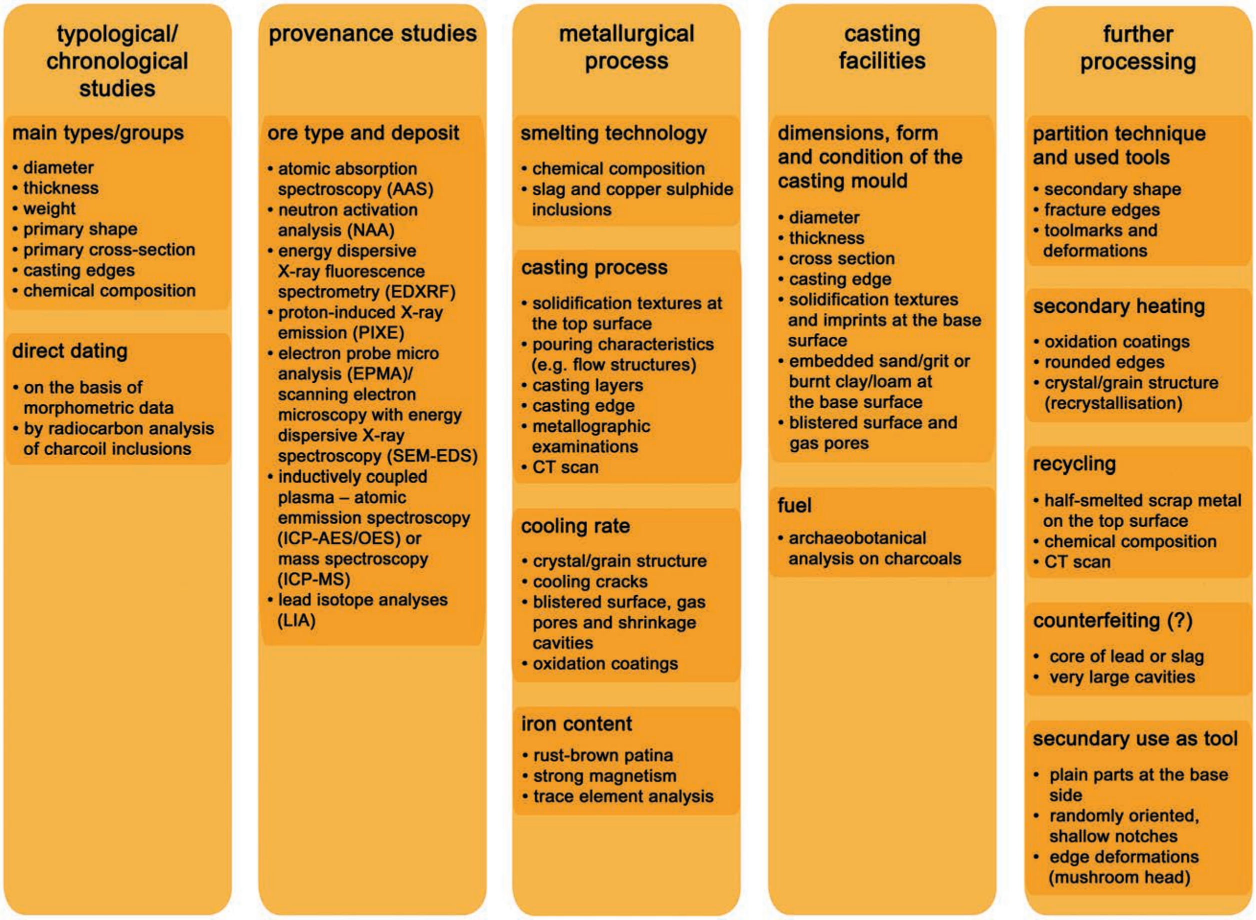
Overall, considerably more – often intergranular – brittle fractures appear on PCIs, while ductile fractures with clear visible plastic deformations are rather rare. The reason for this lies in the multiple notching of many PCIs on one or both sides by axes or chisels ('unilateral or bilateral V-notched fracture'; Fig. 29/B-C), which facilitates the formation of a fracture originating from these structural defects. The surface of the fractures can be vertical, slanting, stepped or irregular (Fig. 30). If the thickness and homogeneity of a PCI did not allow its comminution, the piece was completely split, leaving a vertical cutting edge with a smooth surface and sometimes well visible impressions of the tools ('splitting'; Fig. 10/B, 29/D; e.g. Mozsolics, 1984, p.38, 72, tab.20; Modl, 2010, p.136, 146, fig.32).

Conclusio … or a critical remark

PCIs are amongst the largest cast objects in Bronze Age Europe, as far as the processed amount of metal is concerned. They provide a range of technological information on prehistoric copper metallurgy, given that they are properly described and evaluated, for which this paper offers a first approach. On the basis of the here described parameters and features, future studies will have a basic framework that hopefully simplifies the determination of individual groups of PCIs in the archaeological material trough formal similarities (as well as chemical composition) and allow a better reconstruction of the metallurgical process guidance, the appearance of the casting facilities and the further processing (Fig. 31).

As emerges from the proceeding discussion, the variables that determine the shape and appearance of a PCI are very diverse. The efficiency of the pyrotechnical facilities and the skills representing the experience of the prehistoric smelters as well as their access to the raw metal determined the amount of processible copper and thus the weight of the PCIs. Because of the multilayer structure of many PCIs and their production in several casting batches, their weight is no indication for the size of furnaces. The shape, dimensions and appearance of the PCIs depended on the individual design of the mould, the type of moulding material, the potential preheating of the mould and the external conditions during cooling, whereby external and internal features such as porosity or surface conditions could only be influenced to a limited extent by the prehistoric smelter.

The same applies to the partition of the PCIs. The association of shapes of fragmented PCIs or special geometric fracture forms with certain material qualities, provenances, production areas, distribution networks or weight standards should be done very carefully and with considerable caution.



typological/ chronological studies

main types/groups
- diameter
- thickness
- weight
- primary shape
- primary cross-section
- casting edges
- chemical composition

direct dating
- on the basis of morphometric data
- by radiocarbon analysis of charcoil inclusions

provenance studies

ore type and deposit
- atomic absorption spectroscopy (AAS)
- neutron activation analysis (NAA)
- energy dispersive X-ray fluorescence spectrometry (EDXRF)
- proton-induced X-ray emission (PIXE)
- electron probe micro analysis (EPMA)/ scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDS)
- inductively coupled plasma – atomic emmission spectroscopy (ICP-AES/OES) or mass spectroscopy (ICP-MS)
- lead isotope analyses (LIA)

metallurgical process

smelting technology
- chemical composition
- slag and copper sulphide inclusions

casting process
- solidification textures at the top surface
- pouring characteristics (e.g. flow structures)
- casting layers
- casting edge
- metallographic examinations
- CT scan

cooling rate
- crystal/grain structure
- cooling cracks
- blistered surface, gas pores and shrinkage cavities
- oxidation coatings

iron content
- rust-brown patina
- strong magnetism
- trace element analysis

casting facilities

dimensions, form and condition of the casting mould
- diameter
- thickness
- cross section
- casting edge
- solidification textures and imprints at the base surface
- embedded sand/grit or burnt clay/loam at the base surface
- blistered surface and gas pores

fuel
- archaeobotanical analysis on charcoals

further processing

partition technique and used tools
- secondary shape
- fracture edges
- toolmarks and deformations

secondary heating
- oxidation coatings
- rounded edges
- crystal/grain structure (recrystallisation)

recycling
- half-smelted scrap metal on the top surface
- chemical composition
- CT scan

counterfeiting (?)
- core of lead or slag
- very large cavities

secundary use as tool
- plain parts at the base side
- randomly oriented, shallow notches
- edge deformations (mushroom head)

Fig. 31: Parameters and features as well as scientific investigations, which allow typological/chronological and provenance studies on PCIs as well as the reconstruction of the metallurgical process, the appearance of the casting facilities and the procedure of further processing (graphic: D. Modl).

Many characteristics of complete and fragmented PCIs are rather individual or a product of alteration during their processing, which is too often ignored when creating studies and typologies concerned with these artefacts.

Acknowledgements

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Bibliography

Angerbauer, A., 1985. *Werkstoffkundliche Untersuchungen an Kupferfunden aus der Bronzezeit*. Diploma thesis. University of Leoben.

Armada, X.-L. & García-Vuelta, Ó., 2015. Dating Iron Age goldwork: First direct AMS ^{14}C results from Northwestern Iberia. Primeras dataciones directas de ^{14}C AMS para la orfebrería protohistórica del Noroeste de la Península Ibérica. *Trabajos de Prehistoria*, 72(2), pp.372-382.

Bachmann, H.-G., 1982. *The Identification of Slags from Archaeological Sites.* Institute of Archaeology, Occasional Publication 6. London: Institute of Archaeology.

Bachmann, H.-G., Jockenhövel, A., Spichal, U. & Wolf, G., 2002/03. Zur bronzezeitlichen Metallversorgung im mittleren Westdeutschland: Von der Lagerstätte zum Endprodukt. *Berichte der Kommission für Archäologische Landesforschung in Hessen*, 7, pp.67-120.

Barth, F.E. & Unterberger, H., 1983. Ein neuer urnenfelderzeitlicher Depotfund aus Hallstatt? *Fundberichte aus Österreich*, 22, pp.7–11.

Begemann, F., Schmitt-Strecker, S., Pernicka, E. & Lo Schiavo, F., 2001. Chemical composition and lead isotopy of copper and bronze from Nuragic Sardinia. *European Journal of Archaeology,* 4(1), pp.43-85.

Bennett, A., 1998. The contribution of metallurgical studies to South-East Asian Archaeology. *World Archaeology*, 20(3), pp.329-351.

Bertol, A. & Farac, K., 2012. Aes rude and aes formatum – a new typology based on the revised Mazin hoard. *Vjesnik Arheološkog muzeja u Zagrebu*, 45(1), pp.93-113.

Bunk, W.G.J. & Kuhnen, H.-P., 2008. Roman Time Copper Ingots Found at Trier: Original and Experiment. In: F. Verse, B. Knoche, J. Graefe, M. Hohlbein, K. Schierhold, C. Siemann, M. Uckelmann & G. Woltermann, eds., *Durch die Zeiten … Festschrift für Albrecht Jockenhövel zum 65. Geburtstag. Internationale Archäologie.* Studia honoraria, 28. Rahden-Westfalen: Verlag Marie Leidorf. pp.307-313.

Ciugudean, H., Ciută, M. & Kádár, M., 2006. Consideratii privind câteva piese din depozitul de bronzuri de la Pănade (com. Sâncel, jud. Alba) / Short observations regarding several objects belonging to the bronze hoard from Pănade (Alba district). *Apulum*, 13(1), pp.95-110.

Craddock, P.T., Freestone, I.C. & Dawe, C.D., 1997. Casting metals in limestone moulds. *Historical Metallurgy*, 31(1), pp.1-7.

Craddock, P.T., La Niece, S. & Hook, D.R., 2003. Evidences for the Production, Trading and Refining of Copper in the Gulf of Oman during the Third Millenium BC. In: Th. Stöllner, G. Körlin, G. Steffens & J. Cierny, eds., *Man and Mining – Mensch und Bergbau. Studies in honour of Gerd Weisgerber on occasion of his 65th birthday. Der Anschnitt*, Beiheft 16, Bochum: Deutsches Bergbau-Museum. pp.103-112.

Craddock, P.T. & Meeks, N.D., 1987. Iron in Ancient Copper. *Archaeometry*, 29(2), pp.187-204.

Czajlik, Z., 1996. Ein spätbronzezeitliches Halbfertigprodukt: Der Gusskuchen. Eine Untersuchung anhand von Funden aus Westungarn. *Archaeologia Austriaca*, 80, pp.165-179.

Czajlik, Z., 2006. La distribution du cuivre des origines à la fin de l'âge du Bronze en France – Essai de comparaison des demi-produits provenant de France orientale et de l'Europe centrale. *Acta Archaeologica Academiae Scientiarum Hungarica*, 57, pp.47-65.

Czajlik, Z., 2012. A Kárpát-medence fémnyersanyag-forgalma a későbronzkorban és a vaskorban (Trade in Metallic Raw Materials in the Carpathian Basin in the Late Bronze Age and the Iron Age). *Tálentum Könyvek* 2012. Budapest: ELTE BTK.

Czajlik, Z., Molnár, F. & Solymos, K.G., 1995. Angaben zu der spätbronzezeitlichen Metallrohmaterialversorgung am Velem/St. Veit-Berg, Westungarn. Französisch-ungarische Forschungen am Velem/St.-Veit-Berg. *Archäologie Österreichs*, 6(2), pp.30-35.

Czajlik, Z., Molnár, F. & Solymos, K.G., 1999. On the Origin of Late Bronze Age Semi-products Found at Celldömölk-Sághegy According to Electron-mikroprobe (EPMA) Studies. *Communicationes Archaeologicae Hungariae* 1999, pp.35-46.

De Marinis, R.C., 2006. Circolazione del metallo e dei manufatti nell'età del Bronzo dell'Italia settentrionale. In: *Atti della XXXIX Riunione scientifica - Materie prime e scambi nella preistoria italiana nel cinquantenario della fondazione dell'Istituto italiano di preistoria e protostoria, Firenze, 25-27 novembre 2004, vol. III*. Florence: Instituto italiano di preistoria e protostoria. pp.1289-1317.

De Marinis, R.C., 2011. Metallurgie südlich der Alpen. In: R. Gebhard, F. Marzatico & P. Gleirscher, eds., *Im Licht des Südens: Begegnungen antiker Kulturen zwischen Mittelmeer und Zentraleuropa. Ausstellungskatalog, Archäologische Staatssammlung München, 16.12.2011-27.05.2012 in Kooperation mit dem Museo Castello del Buonconsiglio, monumenti e collezioni provinciali, Trento*. München: Deutscher Kunstverlag. pp.90-97.

Doncheva, D., 2012. The Northern 'Jorney' of Late Bronze Age Copper Ingots. In: E. Paunov & S. Filipova eds., *Herakleous Soteros Thasion. Studia in honorem Iliae Prokopov sexagenario ab amicis et discipulis dedicate*. Veliko Tarnovo: Faber Press. pp.671-714.

Dörfler, G., Neuninger, H., Pittioni, R. & Siegl, W., 1969. Zur Frage des Bleierz-Bergbaues während der jüngeren Urnenfelderkultur in den Ostalpen. *Archaeologia Austriaca* 46, pp.68-98.

Drescher, H., 1976. Barren. *Reallexikon der Germanischen Altertumskunde*, II. Berlin: de Gruyter. pp.60–70.

Eibner, C., 1982a. Kupfererzbergbau in Österreichs Alpen. In: B. Hänsel, ed., *Südosteuropa zwischen 1600 und 1000 v. Chr.* Prähistorische Archäologie in Südosteuropa, 1. Berlin: Wissenschaftsverlag Volker Spiess. pp.399-408.

Eibner, C., 1982b. Kupferverhüttung – Das Vorstadium für Gießereihütten der Urzeit. *Archaeologia Polski*, 27(2), pp.303-313.

Enăchiuc, V., 1995. Der Bronzefund von Dridu, Kr. Ialomiţa. In: T. Soroceanu, ed., *Bronzefunde aus Rumänien.* Prähistorische Archäologie Südosteuropa, 10. Berlin: Wissenschaftsverlag Volker Spiess. pp.279-310.

Engelmann, J., 1997. *Der spätbronzezeitliche Depotfund von Ohlsdorf, p.B. Gmunden*, OÖ. Diploma thesis. University of Vienna.

Érdy, J., 1861. II. Kelenföldi pogány sírok. *Archaeologiai Közlemények* II, pp.27-45.

Franceschi, E., Luciano, G., Delfino, D. & Del Lucchese, A., 2004. Studio multidisciplinare di un lingotto metallico a sezione piano-convessa ritrovato in Val Bormida. *Ligures – Rivista di Archaeologia, Storia, Arte e Culturale Ligure*, 2. Bordighera: Istituto internazionale di studi liguri. pp.298-304.

Galili, E., Gale, N. & Rosen, B., 2013. A Late Bronze Age Shipwreck with a Metal Cargo from Hishuley Carmel, Israel. *The International Journal of Nautical Archaeology*, 42(1), pp.2-23.

Gogâltan, F., 2005. Zur Bronzeverarbeitung im Karpatenbecken. Die Tüllenhämmer und Tüllenambosse aus Rumänien. In: T. Soroceanu, ed., *Bronzefunde aus Rumänien II – Beiträge zur Veröffentlichung und Deutung bronze- und älterhallstattzeitlicher Metallfunde in europäischem Zusammenhang/ Descoperiri de bronzuri din România II – Contribuţii la publicarea şi interpretarea descoperirilor de metal din epoca bronzului şi din prima vârstă a fierului în context european*. Bistriţa and Cluj-Napoca: Accent. pp.343-386.

Gruber, A. & Preßlinger, H., 1983. Werkstoffkundliche Untersuchungen an prähistorischen Kupfergußkuchen aus den Ostalpen. *Metall*, 37(12), pp.1254-1256.

Hampel, J., 1896. *A bronzkor emlékei Magyarhonban. III: Áttekintő Ismertetés*. Budapest: Az Orsz. Rég. És Embertani Társulat Kiadványa.

Hanning, E., 2012. Reconstructing Bronze Age Copper Smelting in the Alps: an ongoing process. *Experimentelle Archäologie in Europa*, 11 (Bilanz 2012), pp.75-86.

Hanning, E., Herdits, H. & Silvestri, E., 2015. Alpines Kupferschmelzen – technologische Aspekte. In: T. Stöllner & K. Oeggl, eds. 2015. *Bergauf Bergab. 10000 Jahre Bergbau in den Ostalpen. Wissenschaftlicher Beiband zur Ausstellung Bochum und Bregenz.* Veröffentlichungen DBM 207, Bochum-Rahden: Deutsches Bergbau-Museum Bochum in Kommission bei Marie Leidorf, pp.225-231.

Hänsel, B. & Schulz, H.D., 1980. Frühe Kupfer-Verhüttung auf Helgoland. *Spektrum der Wissenschaft*, 1980/2, pp.10-20.

Haubner, R., Ertl, F. & Strobl S., 2017. Examinations of a Bronze Ingot Made of Fahlore. *Practical Metallography*, 54/2, pp.107-117.

Hauptmann, A., 2008. Vom Erz zum Metall – naturwissenschaftliche Untersuchungen innerhalb der Metallurgiekette. In: A. Hauptmann & V. Pingel, eds., *Archäometrie – Methoden und Anwendungsbeispiele naturwissenschaftlicher Verfahren in der Archäologie*. Stuttgart: E. Schweizerbart'sche Verlagsbuchhandlung, pp.125-140.

Hauptmann, A. & Maddin, R., 2005. Die Kupferbarren von Uluburun. Teil 1: Qualitätsmetall für den Weltmarkt? In: Ü. Yalçin, C. Pulak & R. Slotta, eds., *Das Schiff von Uluburun - Welthandel vor 3000 Jahren.* Katalog der Ausstellung des Deutschen Bergbau-Museums Bochum vom 15. Juli 2005 bis 16. Juli 2006. Veröffentlichungen DBM 138. Bochum: Deutsches Bergbau-Museum. pp.133-140.

Hauptmann, A., Laschimke, R. & Burger, M., 2016. On the making of copper oxhide ingots: evidence from metallography and casting experiments. *Archaeological and Anthropological Sciences* 8(4), pp.751-761.

Hauptmann, A., Maddin, R. & Prange, M., 2002. On the Structure and Composition of Copper and Tin Ingots Excavated from the Shipwreck of Uluburun. *Bulletin of the American Schools of Oriental Research* 328, pp.1-30.

Hauptmann, A., Schneider, G. & Bartels, Ch., 2016. The Shipwreck of Bom Jesus, AD 1533: Fugger Copper in Namibia. *Journal of African Archaeology*, 14(2), pp.181-207.

Herdits, H., Keen, J. & Steinberger, M. 1995. Wie kommt das Zinn in die Bronze? Ein Beitrag zur experimentellen Archäologie. *Archäologie Österreichs* 6(1), pp.78-85.

Hild, A., 1948. Ein Verwahrfund aus Feldkirch, Vorarlberg. *Archaeologia Austriaca* 1, pp.88-90.

Holdermann, C.-St. & Trommer, F., 2010. Verfahrenstechniken und Arbeitsaufwand im frühbronzezeitlichen Metallhandwerk – Technologische Aspekte der Himmelsscheibe von Nebra – Ein Erfahrungsbericht. In: Meller, H. & Bertemes, F., eds., *Der Griff nach den Sternen.* Internationales Symposium in Halle (Saale) 16.–21. Februar 2005. Tagungen des Landesmuseums für Vorgeschichte Halle, 5(II), pp.791-806.

Höglinger, P., 1996. *Der spätbronzezeitliche Depotfund von Sipbachzell/OÖ.* Linzer Archäologische Forschungen, Sonderheft XVI, Linz: Stadtmuseum Linz.

Jansen, M. & Löffler, I., 2016. Das bronzezeitliche Gusskuchendepot von Kleinbardorf (Rhön-Grabfeld). In: G. Körlin, M. Prange, Th. Stöllner & Ü. Yalçın, eds., *From Bright Ores to Shiny Metals. Festschrift for Andreas Hauptmann on the Occasion of 40 Years Research in Archaeometallurgy and Archaeometry. Der Anschnitt, Beiheft* 29. Bochum/Rahden: Leidorf. pp.125-132.

Jockenhövel, A., 1983. Ein bemerkenswerter späturnenfelderzeitlicher Amboß. *Germania*, 61(2), pp.586-588.

Jung, R., Mehofer, M. & Pernicka, E., 2011. Metal exchange in Italy from the Middle to the Final Bronze Age (14th-11th century B.C.E.). In: Ph.B. Betancourt & S.C. Ferrence, eds., *Metallurgy: Understanding How, Learning Why. Studies in honor of James D. Muhly.* Prehistory Monographs, 29. Philadelphia: INSTAP Academic Press. pp.231-248.

Kacsó, C., 2013. Beiträge zur Kenntnis des bronzezeitlichen Metallhandwerks in der Maramuresch. In: Rezi, B., Németh, R.E. & Berecki, S., eds., *Bronze Age Crafts and Craftsmen in the Carpathian Basin.* Proceedings of the International Colloquium from Târgu Mureş, 5–7 October 2012. Bibliotheca Musei Marisienisis, Seria Archaeologica, VI. Târgu Mureș: Editura MEGA. pp.225-238.

Karavanić, S., 2017. Brončano doba i recikliranje brončanih predmeta. In: I. Miloglav, A. Kudelić & J. Balen, eds., *Recikliraj, ideje iz prošlosti*. Zagreb: AMZ. pp.99-111.

Klein, S., Rico, Ch., Lahaye, Y., von Kaenel, H.-M., Domergue, C. & Brey, G. P., 2007. Copper ingots from the western Mediterranean Sea: chemical characterisation and provenance studies through lead- and copper isotope analyses. *Journal of Roman Archaeology* 20, pp.202-221.

Klemenc, S., Budic, B. & Zupan, J., 1999. Statistical evaluation of data obtained by inductively coupled plasma atomic emission spectrometry (ICP-AES) for archaeological copper ingots. *Analytica Chimica Acta*, 389(1-3), pp.141-150.

Klose, O., 1918. Die prähistorischen Funde vom Mitterberge bei Bischofshofen im städtischen Museum Carolino-Augusteum zu Salzburg und zwei prähistorische Schmelzöfen auf dem Mitterberge. In: *Urgeschichte des Kronlandes Salzburg.* Österreichische Kunsttopographie 17, Beitrag II. Wien: Kunstverlag Anton Schroll & Co. pp.1–40.

Kobal', J.V., 2000. *Bronzezeitliche Depotfunde aus Transkarpatien (Ukraine).* Prähistorische Bronzefunde, XX(4). Stuttgart: Franz Steiner Verlag.

König, P., 2004. *Spätbronzezeitliche Hortfunde aus Bosnien und der Herzegowina*. Prähistorische Bronzefunde XX(11). Stuttgart: Franz Steiner Verlag.

Krauss, R., 1998/1999. Ein urnenfelderzeitlicher Kupferdepotfund aus Saalfelden-Wiesersberg, Land Salzburg. *Archäologie Österreichs* 9-10, pp.115-121.

Krutter, S., 2015. Ein bronzezeitliches plankonvexes Gusskuchenfragment vom Klemmstein bei Golling im Salzachtal, Land Salzburg. In: S. Krutter & F. Schröder, eds., *Durch die Schichten der Zeit! Neue Erkenntnisse zwischen Mesozoikum und Gegenwart. Festschrift für Erich Urbanek zum 75. Geburtstag.* Forschungen des Museum Burg Golling, 1. Golling a. d. Salzach: Museum Burg Golling. pp.47-51.

Lutz, J., Krutter, S. & Pernicka, E., 2019. Composition and spatial distribution of Bronze Age planoconvex copper ingots from Salzburg, Austria - First results from the "Salzburger Gusskuchenprojekt". [this volume]

Kuijpers, M.H.G., 2008. *Bronze Age Metalworking in the Netherlands (c. 2000-800 BC): A research into the preservation of metallurgy related artefacts and the social position of the smith*. Leiden: Sidestone Press.

Kytlicová, O., 2007. *Jungbronzezeitliche Hortfunde in Böhmen.* Prähistorische Bronzefunde, XX(12). Stuttgart: Franz Steiner Verlag.

Larson, T.S., 2009. *Experiments Concerning the Mold Materials Used in the Production of the Copper Ingots from the Late*

Bronze Age Shipwreck Excavated at Uluburun, Turkey. M.A. Thesis. University of San Diego.

Laschimke, R. & Burger, M., 2012. Versuche zum Gießen von bronzezeitlichen Ochsenhautbarren aus Kupfer. *Experimentelle Archäologie in Europa*, 11(Bilanz 2012), pp.87-99.

Lauermann, E. & Rammer, E. 2013. *Die urnenfelderzeitlichen Metallhortfunde Niederösterreichs. Mit besonderer Berücksichtigung der zwei Depotfunde aus Enzersdorf im Thale.* Universitätsforschungen zur prähistorischen Archäologie 226. Bonn: Habelt.

Le Carlier de Veslud, C., Edme, L. & Fily, M., 2014. Lingots et déchets de fonderie dans les dépôts de l'horizon de l'épée à pointe en langue de carpe (Bronze final IIIb): proposition de typologie. *Bulletin de la Société préhistorique française* 111(3), pp.509-522.

Lehner, J.W. & Schachner, A., 2017. The Organization of Metal Production at Hattuša: A First Assessment. In: Ç. Maner, M.T. Horowitz & A.S. Gilbert, eds., *Overturning Certainties in Near Eastern Archaeology. A Festschrift in Honor of K. Aslıhan Yener.* Culture and History of the Near East, 90. Leiden: Brill. pp.403-435.

Leshtakov, K., 2007. The Eastern Balkans in the Aegean economic system during the LBA. Ox-hide and bun ingots in Bulgarian lands. In: I. Galanaki, H. Tomas, Y. Galanakis & R. Laffineur, eds., *Between the Aegean and Baltic seas: Prehistory across borders.* Proceedings of the International Conference, Bronze and Early Iron Age Interconnections and Contemporary Developments between the Aegean and the Regions of the Balkan Peninsula, Central and Northern Europe, University of Zagreb, 11-14 April 2005. Aegaeum, 27. Liège and Austin: Université de Liège / University of Texas. pp.448-457.

Loughton, E., 2017. Erme Estuary ingots – Emily Loughton dissertation, internet publication from the South West Maritime Archaeological Group. [online] Available at: <http://www.swmag.org/index.php/stories-reports/erme-estuary-ingots> [Accessed 29 May 2017].

Lo Schiavo, F., 1990. Lingotti oxhide e piano-convessi in Sardegna – Copper oxhide and plano-convex ingots in Sardinia. In: F. Lo Schiavo, R. Maddin, J. Merkel, J.D. Muhly & T. Stech, eds., *Analisi metallurgiche e statistiche sui lingotti di rame della Sardegna – Metallographic and Statistical Analyses of Copper Ingots from Sardinia*. Quaderni 17. Ozieri: Torchietto. pp.14-40.

Maddin, R. & Merkel, J., 1990. Analisi metallografiche e statistiche – Metallographic and statistical analyses. In: F. Lo Schiavo, R. Maddin, J. Merkel, J.D. Muhly & T. Stech, eds., *Analisi metallurgiche e statistiche sui lingotti di rame della Sardegna - Metallographic and Statistical Analyses of Copper Ingots from Sardinia*. Quaderni 17. Ozieri: Torchietto. pp.42-199.

Mangou, H. & Ioannou, P.V., 2000. Studies of the Late Bronze Age copper-based ingots found in Greece. *The Annual of the British School at Athens*, 95, pp.207-217.

Merkel, J.F., 1986a. Ancient Smelting and Casting of Copper for 'Oxhide Ingots'. In: M.S. Balmuth, ed., *Studies in Sardinian Archaeology II: Sardinia in the Mediterranean*. Ann Arbor: University Of Michigan Press. pp.251-264.

Merkel, J.F., 1986b. Colloquial discussion on copper "oxhide" ingots. In: M.S. Balmuth, ed., *Studies in Sardinian Archaeology II: Sardinia in the Mediterranean*. Ann Arbor: University Of Michigan Press. pp.265-271.

Merkel, J.F., 1990. Experimental Reconstruction of Bronze Age Copper Smelting Based on Archaeological Evidence from Timna. In: B. Rothenberg, ed., *The Ancient Metallurgy of Copper: Archaeology – Experiment – Theory. Researches in the Arabah 1959-1984, Vol. II*. London: Institute for Archaeo-Metallurgical Studies. pp.78-122.

Miske, K. v., 1908. *Die prähistorische Ansiedlung Velem St. Vid. Bd. 1: Beschreibung der Raubbaufunde.* Wien: Verlagsbuchhandlung Carl Konegen.

Modl, D., 2008. Urnenfelderzeitlicher Brandopferplatz und römische Wegstation – Archäologische Untersuchungen im Koppental, Steiermark. In: *schätze.gräber.opferplätze – traunkirchen.08. Archäologie im Salzkammergut.* Katalog zur Ausstellung im ehemaligen Kloster Traunkirchen, 29. April bis 2. November 2008. Fundberichte aus Österreich, Materialhefte A, Sonderheft 6. Horn: Verlag Berger. pp.82-89, 186-196.

Modl, D., 2010. Zur Herstellung und Zerkleinerung von plankonvexen Gusskuchen in der spätbronzezeitlichen Steiermark, Österreich. *Experimentelle Archäologie in Europa*, 9 (Bilanz 2010), pp.127-151.

Modl, D., 2011. *Vom Kupfererz zur Bronzenadel - Experimentalarchäologische Untersuchungen zur urgeschichtlichen Kupfergewinnung und -verarbeitung im Bereich der heutigen Steiermark*. Diploma thesis. University of Graz.

Modl, D., 2012. Walter Modrijan und die Montanarchäologie – Resümee der Erforschung des urgeschichtlichen Kupferbergbaus und Buntmetallhandwerks in der Steiermark. *Schild von Steier*, 25 (= *Forschungen zur geschichtlichen Landeskunde der Steiermark*, 58), pp.94-125.

Modl, D., 2013. Archäologische Untersuchungen in einer Siedlung der Urnenfelderzeit und der Römischen Kaiserzeit in Pichl, Steiermark – Ein Vorbericht, *Fundberichte aus Österreich*, 52, pp.43-64.

Modl, D., 2015. Experimentelle Archäologie zu ostalpinen Aufbereitungs- und Hüttenprozessen. In: T. Stöllner & K. Oeggl, eds. 2015. *Bergauf Bergab. 10000 Jahre Bergbau in den Ostalpen. Wissenschaftlicher Beiband zur Ausstellung Bochum und Bregenz.* Veröffentlichungen DBM 207, Bochum-Rahden: Deutsches Bergbau-Museum Bochum in Kommission bei Marie Leidorf, pp.221-224.

Montero-Ruiz, I., Rovira Hortala, M.C., Renzi, M., Murillo-Barroso, M., Hunt, M., Gener, M. & Castanye, R. P., 2010/11. Lingotes plano-convexos de cobre en la primera mitad del I milenio ac en la península ibérica. *Boletín de Asociación Española de Amigos de la Arqueología*, 46, pp.99-119.

Moosleitner, F., 1982. Ein urnenfelderzeitlicher Depotfund aus Saalfelden, Land Salzburg. *Archäologisches Korrespondenzblatt* 12(4), pp.457-475.

Möslein, S., 1998. Ein Depotfund der ausgehenden Frühbronzezeit von Pfakofen, Lkr. Regensburg. *Beiträge zur Archäologie in der Oberpfalz und in Regensburg*, 2, pp.251-260.

Möslein, S. & Pernicka, E., 2019. The Metal Analyses of the SSN-Project. [this volume]

Mozsolics, A., 1981. Gusskuchen aus wieder eingeschmolzenem Altmetall. *Beiträge zur Ur- und Frühgeschichte I, AFD Beiheft*, 16, pp.403-417.

Mozsolics, A., 1984. Ein Beitrag zum Metallhandwerk der ungarischen Bronzezeit. *Bericht der Römisch-Germanischen Kommission*, 65, pp.19-72.

Muhly, J., Wheeler, T. & Maddin, R., 1977. The Cape Gelidonya Shipwreck and the Bronze Age Metals Trade in the Eastern Mediterranean. *Journal of Field Archaeology*, 4(3), pp.353-362.

Müller-Karpe, A., 2005. Metallbarren bei den Hethitern. In: Ü. Yalçin, C. Pulak & R. Slotta, eds., *Das Schiff von Uluburun - Welthandel vor 3000 Jahren.* Katalog der Ausstellung des Deutschen Bergbau-Museums Bochum vom 15. Juli 2005 bis 16. Juli 2006. Veröffentlichungen DBM 138. Bochum: Deutsches Bergbau-Museum. pp.485-492.

Murgan, A.M., 2014. Heavy metal in hallowed contexts - Continuity and change in aes deposits in Central Italy and Sicily. In: A. Bokern and C. Rowan, eds., *Embodying Value? The Transformation of Objects in and from the Ancient World.* BAR International Series, 2592. Oxford: Archaeopress. pp.65-75.

Nessel, B., 2014. Bronze Age portioning of raw metal – concepts, patterns and meaning of casting cakes. In: N. Boroffka, G.T.

Rustoiu & R. Ota, eds., *Carpathian Heartlands. Studies on the prehistory and history of Transsylvania in European contexts, dedicated to Horia Ciugudean on his 60th birthday. Apulum* 51. Alba Julia: Muzeul Național al Unirii Alba Iulia. pp.401-425.

Nessel, B., 2017. Von warmen und kalten Brüchen – Bruchmuster und Konzepte der Portionierung bronzezeitlichen Rohmaterials am Beispiel plankovexer Gusskuchen. In: D. Brandherm & B. Nessel, eds., *Phasenübergänge und Umbrüche im bronzezeitlichen Europa. Beiträge zur Sitzung der Arbeitsgemeinschaft Bronzezeit auf der 80. Jahrestagung des Nordwestdeutschen Verbandes für Altertumsforschung.* Universitätsforschungen zur prähistorischen Archäologie 297. Bonn: Habelt. pp.169-198.

Neumann, D., 2015. *Landschaften der Ritualisierung – Die Fundplätze kupfer- und bronzezeitlicher Metalldeponierungen zwischen Donau und Po,* Topoi – Berlin Studies of the Ancient World 26. Berlin and Boston: De Gruyter.

Ottaway, B.S. 1994. *Prähistorische Archäometallurgie*. Espelkamp: Verlag Marie Leidorf.

Pernicka, E. 2014. Provenance Determination of Archaeological Metal Objects. In: B.W. Roberts & Ch.P. Thorton, eds., *Archaeometallurgy in Global Perspective. Methods and Syntheses*. New York: Springer. pp.239-268.

Pernicka, E., Lutz, J. & Stöllner, Th., 2016. Bronze Age Copper Produced at Mitterberg, Austria, and its Distribution. *Archaeologia Austriaca* 100, pp.19-55.

Pietzsch, A., 1964. Zur Technik der Wendelringe. *Arbeits- und Forschungsberichte zur Sächsischen Bodendenkmalpflege*, Beiheft 4. Berlin: Deutscher Verlag der Wissenschaften.

Pigott, V.C.: 1999. The Archaeometallurgy of the Asian Old World. *University Museum Monograph*, 89 (= *University Museum Symposium Series*, VII = *MASCA Research Papers in Science and Archaeology*, 16). Philadelphia: Museum University of Pennsylvania.

Pollard, A.M. & Bray, P., 2014. Chemical and Isotopic Studies of Ancient Metals. In: B.W. Roberts & Ch.P. Thorton, eds., *Archaeometallurgy in Global Perspective. Methods and Syntheses*. New York: Springer. pp.217-238.

Prange, M., 2001. 5000 Jahre Kupfer im Oman, Band II: Vergleichende Untersuchungen zur Charakterisierung des omanischen Kupfers mittels chemischer und isotopischer Analysenmethoden, *Metalla*, 8(1-2), Bochum: Deutsches Bergbau-Museum.

Pratobevera, E., 1856. *Die keltischen und römischen Antiken in Steiermark.* Graz: Leykam.

Preßlinger, H., 2003. Bewertung von Gusskuchenfragmenten. In: M. Windholz-Konrad, *Funde entlang der Traun zwischen Ödensee und Hallstätter See. Vorlage der prähistorischen bis neuzeitlichen Metallfunde aus den von Karl Gaisberger und Mitarbeitern vorgenommenen Prospektionen im Salzkammergut, mit besonderer Berücksichtigung der Altfunde.* Fundberichte aus Österreich, Materialheft A 13. Horn: Verlag Berger. p.68.

Preßlinger, H., 2004. Metallkundliche Untersuchungen an Depotfunden in Bad Aussee. In: M. Windholz-Konrad, Die Rabenwand – ein neuer prähistorischer Depotfundplatz im Ausseerland, Steiermark. *Fundberichte aus Österreich* 43, pp.325-330.

Preßlinger, H. & Eibner, C., 2004. Montanarchäologie im Paltental (Steiermark). Bergbau, Verhüttung, Verarbeitung und Siedlungstätigkeit in der Bronzezeit. In: G. Weisgerber & G. Goldenberg, eds., *Alpenkupfer. Rame delle Alpi.* Der Anschnitt, Beiheft 17. Bochum: Deutsches Bergbau-Museum. pp.63-74.

Primas, M. & Pernicka, E., 1998. Der Depotfund von Oberwilfingen. Neue Ergebnisse zur Zirkulation von Metallbarren. *Germania*, 76, pp.25-65.

Pühringer, E., 2000. *Der Weg in die Urzeit – Archäologie und Film*. PhD. University of Vienna.

Radivojević, M., Roberts, B.W., Pernicka, E., Stos-Gale, Z., Martinon-Torres, M., Rehren, Th., Bray, P., Brandherm, D., Ling, J., Mei, J., Vandkilde, H., Kristiansen, K., Shennan, St.J., Broodbank, C., 2018. The Provenance, Use, and Circulation of Metals in the European Bronze Age: The State of Debate. *Journal of Archaeological Research*, 27(2), pp.131–185.

Reinecke, P., 1938. Neue frühbronzezeitliche Hortfunde aus Südbayern. *Germania* 22, pp.4-7.

Reiter, V. & Linke, R., 2016. Ein Werkplatz mit Brucherzdepot der ausgehenden Bronzezeit aus Rannersdorf, Niederösterreich. *Fundberichte aus Österreich* 55, pp.144-180.

Rico, Ch., Domergue, C., Rauzier, M., Klein, S., Lahaye, Y., Brey, G. & von Kaenel, H.-M., 2005. La provenance des lingots de cuivre romains de Maguelone (Hérault, France). Étude archéologique et archéométrique. *Revue archéologique de Narbonnaise*, 38-39, pp.459-472.

Roman, I., 1990. Copper Ingots. In: B. Rothenberg, ed., *The Ancient Metallurgy of Copper: Archaeology – Experiment – Theory. Researches in the Arabah 1959-1984, Vol. II*. London: Institute for Archaeo-Metallurgical Studies. pp.176-181.

Romanow, H.P., 1995. Archaeometallurgical investigations of 'casting-cake' and a copper ore sample from the Klinglberg excavations. In: S.J. Shennan, ed*., Bronze Age Copper Producers of the Eastern Alps: Excavations at St. Veit-Klinglberg.* Universitätsforschungen zur prähistorischen Archäologie 27. Bonn: Habelt. pp.263-273.

Rostoker, W., 1975. Some Experiments in Prehistoric Copper Smelting. *Paléorient*, 3, pp.311-315.

Rothenberg, B., 1987. Clay Moulds for Copper Ingots – a first discovery. *Institute for Archaeo-Metallurgical Studies***,** 10-11, pp.11-12.

Rothenberg, B., 1990. Copper Smelting Furnaces, Tuyures, Slags, Ingot-Moulds and Ingots in the Arabah: The Archaeological Data. In: B. Rothenberg, ed., *The Ancient Metallurgy of Copper: Archaeology – Experiment – Theory. Researches in the Arabah 1959-1984, Vol. II*. London: Institute for Archaeo-Metallurgical Studies. pp.1-77.

Rovira, S., Montero-Ruiz, I. & Renzi, M., 2009. Experimental Co-smelting to Copper-tin Alloys. In: T.L. Kienlin & B.W. Roberts, eds., *Metals and Societies. Studies in honour of Barbara S. Ottaway.* Universitätsforschungen zur Prähistorischen Archäologie, 169. Bonn: Habelt. pp.407-414.

Rusu, M., 1981. Bemerkungen zu den großen Werkstätten- und Gießereifunden aus Siebenbürgen. In: H. Lorenz, ed., *Studien zur Bronzezeit - Festschrift für Wilhelm Albert v. Brunn*. Mainz: Verlag Philipp von Zabern. pp.375-402.

Rychner, V., 1984. La matière première des bronziers lacustres. *Archäologie der Schweiz*, 7(2), pp.73-78.

Sabatini, S., 2016. Revisiting Late Bronze Age oxhide ingots: Meanings, questions and perspectives. In: Aslaksen, O.Ch., ed., *Local and global perspectives on mobility in the eastern Mediterranean.* Papers and Monographs from the Norwegian Institute at Athens, 5. Athens: Norwegian Institute at Athens. pp.15-62.

Salaš, M., Stránský, K. & Winkler, Z., 1993. Příspěvek ke studiu měděných slitků doby popelnicových polí na Moravě – Ein Beitrag zum Studium der urnenfelderzeitlichen Gusskuchen in Mähren. *Acta Musei Moraviae, Scientiae sociales* 78 pp.59-74.

Schubert, E. & Schubert, F., 1999. Die Hammeräxte vom Typus Handlová. In: F.-R. Herrmann, I. Schmidt & F. Verse, eds., *Festschrift für Günter Smolla II.* Materialien zur Vor- und Frühgeschichte von Hessen 8. Wiesbaden: Landesamt für Denkmalpflege Hessen. pp.657-671.

Scott, D. A., 1991. *Metallography and Microstructure of Ancient and Historic Metals*. Los Angeles: The Getty Conservation Institute.

Sperber, L. 2004. Zur Bedeutung des nördlichen Alpenraumes für die spätbronzezeitliche Kupferversorgung in Mitteleuropa mit besonderer Berücksichtigung Nordtirols. In: G. Weisgerber & G. Goldenberg, ed., *Alpenkupfer. Rame delle Alpi.* Der Anschnitt, Beiheft 17. Bochum: Deutsches Bergbau-Museum. pp.303-345.

Sperl, G., 1988. *Montangeschichte der Erzberggeschichte nach archäologischen und schriftlichen Dokumenten ergänzt durch praktische Versuche*. Habilitation, University of Vienna.

Stech, T., 1989. Nuragic Metallurgy in Sardinia. Third Preliminary Report. In: A. Hauptmann, E. Pernicka & G.A. Wagner, eds., *Archäometallurgie der Alten Welt.* Beiträge zum Internationalen Symposium „Old World Archaeometallurgy", Heidelberg 1987/Old World Archaeometallurgy. Proceedings of the International Symposium "Old World Archaeometallurgy", Heidelberg 1987. Der Anschnitt, Beiheft 7, Bochum: Deutsches Bergbau-Museum. pp.39-43.

Stein, F., 1976. Bronzezeitliche Hortfunde in Süddeutschland. Beiträge zur Interpretation einer Quellengattung. *Saarbrücker Beiträge zur Altertumskunde*, 23. Bonn: Habelt.

Stöllner, Th., 2015. Die alpinen Kupfererzreviere: Aspekte ihrer zeitlichen, technologischen und wirtschaftlichen Entwicklung im zweiten Jahrtausend vor Christus. In: T. Stöllner & K. Oeggl, eds., *Bergauf Bergab. 10000 Jahre Bergbau in den Ostalpen. Wissenschaftlicher Beiband zur Ausstellung Bochum und Bregenz.* Veröffentlichungen DBM 207, Bochum-Rahden: Deutsches Bergbau-Museum Bochum in Kommission bei Marie Leidorf, pp.99-105.

Stöllner, Th., von Rüden, C., Hanning, E., Lutz, J. & Kluwe, S., 2016. The Enmeshment of Eastern Alpine Mining Communities in the Bronze Age. From Economic Networks to Communities of Practice. In: G. Körlin, M. Prange, Th. Stöllner & Ü. Yalçın, eds., *From Bright Ores to Shiny Metals. Festschrift for Andreas Hauptmann on the Occasion of 40 Years Research in Archaeometallurgy and Archaeometry. Der Anschnitt*, Beiheft 29. Bochum: Verlag Marie Leidorf. pp.75-107.

Tarbay, J.G., 2014. Late Bronze Age depot from the foothills of the Pilis Mountains. *Dissertationes Archaeologicae ex Instituto Archaeologico Universitatis de Rolando Eötvös nominatae* 3(2), pp.179-297.

Tarbay, J.G., 2016. The Late Bronze Age "Scrap Hoard" from Nagydobsza, Part I. *Communicationes Archaeologicae Hungariae*, 2015-2016, pp.87-146.

Teržan, B., 1995. *Depojske in posamezne kovinske najdbe bakrene in bronaste dobe na Slovenskem / Hoards and Individual Metal Finds from the Eneolithic and Bronze Ages in Slovenia I.* Katalogi in monografije / Catalogi et monographiae, 29. Ljubljana: Narodni muzej.

Thornton, C.P., Rehren, Th. & Pigott V.C., 2009. The production of speiss (iron arsenide) during the Early Bronze Age in Iran. *Journal of Archaeological Science*, 36, pp.308-316.

Töchterle, U., 2002. Ein Gebläsetopf für metallurgische Prozesse aus Ampass im Tiroler Landesmuseum Ferdinandeum. *ARCHEOTIROL - Kleine Schriften*, 4, pp.119-122.

Trampuž Orel, N. & Drglin, T., 2005. ICP-AES comparative study of some Late Bronze Age hoards: Evidence for low impurity bronzes in the Eastern Alps. *Nuclear Instruments and Methods in Physics Research*, B 239/1-2, pp.44-50.

Trampuž Orel, N. & Heath, D.J., 2001. Depo Kanalski Vrh – študija o metalurškem znanju in kovinah na začetku 1. tisočletja pr. n. š. / The Kanalski Vrh hoard – a case study of the metallurgical knowledge and metals at the beginning of the 1st millennium BC. *Arheološki vestnik*, 52, pp.143-171.

Trampuž Orel, N., Heath, D.J. & Hudnik, V., 1996. Spektrometrične raziskave depojskih najdb pozne bronaste dobe / Spectrometric research of the Late Bronze Age hoard finds. In: B. Teržan, ed., *Depojske in posamezne kovinske najdbe bakrene in bronaste dobe na Slovenskem / Hoards and Individual Metal Finds from the Eneolithic and Bronze Ages in Slovenia II.* Katalogi in monografije / Catalogi et monographiae 30. Ljubljana: Narodni muzej, pp.165-242.

Trampuž Orel, N., Paulin, A., Spaić, S. & Orel, B., 2002. Premonetary Objects from the South-Eastern Alpine Region – Chemical and Metallographic Analyses. In: A. Giumlia-Mair, ed., *I bronzi antichi. Produzione e tecnologia.* Atti del XV Congresso Internazionale sui Bronzi Antichi organizzato dall'Università di Udine, sede di Gorizia, Grado-Aquilieia, 22-26 Maggio 2001. Monographies instrumentum 21. Montagnac: Editions Monique Mergoil. pp.63-75.

Turk, P., 2000. *Depoji pozne bronaste dobe med Panonskim in Apeninskim prostorom (Late Bronze Age Hoards between Pannonia an the Appenines)*. PhD. University of Ljubljana.

Tylecote, R.F., 1976. Properties of Copper Ingots of Late Bronze Age Type. *Archaeologia Austriaca, Beiheft*, 14, pp.157-172.

Tylecote, R.F., 1986. *The prehistory of metallurgy in the British Isles*. London: The Institute of Metals.

Van Lokeren, S., 2000. Experimental reconstruction of the casting of copper 'oxhide' ingots. *Antiquity*, 74(284), pp.275-276.

Viertler, J., 1973. Ein urnenfelderzeitliches Depot von Kupfergußkuchen in Zensweg bei St. Veit an der Glan. *Carinthia* I(163), pp.9-12.

Wang, Q., Strekopytov, St. & Roberts B.W., 2018. Copper ingots from a probable Bronze Age shipwreck of the coast of Salcombe, Devon: Composition and microstructure. *Journal of Archaeological Science* 97, pp.102-117.

Wang, L., Chen, F., Wang, Y., Qian, W., Mei, J., Martinón-Torres, M. & Chen, K., 2019. Copper metallurgy in prehistoric upper Ili Valley, Xinjiang, China. *Archaeological and Anthropological Sciences*, *Anthropological Sciences, 11*(6), pp. 2407-2417.

Weihs, A., 2004. *Der urnenfelderzeitliche Depotfund von Peggau (Steiermark).* Universitätsforschungen zur prähistorischen Archäologie 114. Bonn: Habelt.

Weisgerber, G., 1981. Mehr als Kupfer in Oman. Ergebnisse der Expedition 1981. *Der Anschnitt*, 33(5-6), pp.174-263.

Weisgerber, G., 2004. Schmelzanlagen früher Kupfergewinnung – ein Blick über die Alpen. In: G. Weisgerber & G. Goldenberg, eds., *Alpenkupfer - Rame delle Alpi.* Der Anschnitt, Beiheft 17. Bochum: Deutsches Bergbau-Museum. pp.15-36.

Weisgerber, G. & Yule, P., 2003. Al Aqir near Bahlā' – an Early Bronze Age dam site with planoconvex 'copper' ingots. *Arabian archaeology and epigraphy*, 14, pp.24-53.

Werson, J., 2015. *Metal Trade in the Baltic Sea: The Copper Ingots from Mönchgut 92*. Master thesis, University of Southern Denmark, Esbjerg.

Willvonseder, K., 1940. *Bronzeeimer und Gußkuchen der jüngeren Urnenfelderzeit von Absberg-Bierbaum, Ldkr. Tulln.* Niederdonau – Natur und Kultur 6, Wien and Leipzig: Kühne.

Windholz-Konrad, M., 2003. Funde entlang der Traun zwischen Ödensee und Hallstätter See. Vorlage der prähistorischen bis neuzeitlichen Metallfunde aus den von Karl Gaisberger und Mitarbeitern vorgenommenen Prospektionen im Salzkammergut, mit besonderer Berücksichtigung der Altfunde. *Fundberichte aus Österreich, Materialheft* A 13. Horn: Verlag Berger.

Windholz-Konrad, M., 2004. Die Rabenwand – ein neuer prähistorischer Depotfundplatz im Ausseerland, Steiermark. *Fundberichte aus Österreich*, 43, pp.289-350.

Windholz-Konrad, M., 2012. Das Deponierungsareal bei der Rabenwand im steirischen Kainischtal in Österreich. Zum ausgeprägten Hortphänomen entlang der Traun im Alpendurchgang zwischen Zinkenkogel und Hohem Sarstein. In: S. Hansen, D. Neumann & T. Vachta, eds., *Hort und Raum. Aktuelle Forschungen zu bronzezeitlichen Deponierungen in Mitteleuropa.* Topoi – Berlin Studies of the Ancient World, 10. Berlin and Boston: De Gruyter. pp.117-149.

Windholz-Konrad, M., 2018. *Urnenfelderzeitliche Mehrstückhorte aus dem Salzkammergut zwischen Ödensee und Hallstättersee.* Österreichische Denkmaltopographie, 2. Horn: Verlag Berger.

Windholz-Konrad, M. & Modl, D. 2018. Metallkundliche Untersuchungen des Rohmaterials. In: M. Windholz-Konrad, *Urnenfelderzeitliche Mehrstückhorte aus dem Salzkammergut zwischen Ödensee und Hallstättersee.* Österreichische Denkmaltopographie 2. Horn: Verlag Berger. pp.47-48.

Wischenbarth, P., 1995. Ein metallzeitlicher Depotfund bei Straß. *Geschichte im Landkreis Neu-Ulm*, 1, pp.23-36.

Wischenbarth, P., 2004. Zwei Gusskuchenfragmente der jüngeren Urnenfelderzeit aus dem Donaukies in Neu-Ulm. *Heimatkundliche Schriftenreihe für den Landkreis Günzburg*, 27. pp.145-165.

Yahalom-Mack, N., Galili, E., Segal, I., Eliyahu-Behar, A., Boaretto, E., Shilstein, S. & Finkelstein, I., 2014. New insights into Levantine copper trade: analysis of ingots from the Bronze and Iron Ages in Israel. *Journal of Archaeological Science*, 45, pp.159-177.

Yule, P., 1985. *Metalwork of the Bronze Age in India.* Prähistorische Bronzefunde XX(8), München: Verlag C.H. Beck.

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