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Modelling Roman concepts of copper-alloy recycling and mutability: the chemical characterisation hypothesis and Roman Britain

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Introduction

The potential of copper-alloy objects to be remelted and recast is a powerful property. Under the correct conditions it allows these materials to be reused, reshaped, merged, split, and recontextualised almost without limit. This profound mutability has significant implications for how archaeologists attempt to interpret Roman concepts of metals, their contemporary value, social significance, and details of their technological and economic processes. Without an appreciation for the long and possibly convoluted history of units of metal, we are forced to make unrealistic assumptions about the recovered archaeological record. However, identifying and quantifying recycling is a notorious and significant challenge to researchers. Paul Craddock even argued that more extensive scientific research on Roman artefacts has been avoided by the ‘daunting’ prospect of coping with the melting and mixing of scrap metals.[1] Similarly, Ponting and Levene highlight how recycling 'makes things complicated' for all flavours of specialist who are interested in metallurgy.[2]

These concerns have to be understood within the framework of the 'Provenance Hypothesis', which—to put it crudely—aims to establish a direct link between a chemical or isotopic signature of an artefact and its original ore source.[3] Mixing or alteration of a prime copper makes a simple match harder to demonstrate. This paper proposes alternative approaches to chemical data that we may broadly call a 'Characterisation Hypothesis'. Rather than chemically identifying a separate block of 'recycled metal', we can instead define a series of overlapping processes of metal melting, mixing, and manipulation.[4] Instead of replacing the search for a provenance signal with one for a recycling signal, we should instead embrace the intricacies of the archaeological and chemical record. This complexity more accurately represents the multifaceted Roman relationship with copper and its alloys.

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[1] Craddock (1985: 59).

[2] Ponting and Levene (2015).

[3] Pollard and Heron (1996); Wilson and Pollard (2001); Pernicka (2014).

[4] Bray and Pollard (2012); Bray *et al.* (2015).

Current top-down models of metal recycling

It should be stressed at the outset that the term recycling is not particularly useful here. There are a number of aspects of metal-use that can come under its umbrella and there is the danger that each author has a personal understanding of what constitutes ‘real’ recycling for copper alloys. The concept of shifting identities, forms, and compositions is a philosophically complex one, and we are often in danger of focussing too much on defining terms rather than interpreting the available data.

If we move beyond general philosophical tropes such as ‘my Grandfather’s axe’ or the ‘Ship of Theseus’, a number of important metal-specific questions can be quickly identified. Do old objects have to be completely molten and recast to be considered recycled? Is it only recycling when a range of scrap is mixed together, or can metal be recycled with itself? Is it important to distinguish when old objects are recast into new versions of the same class (for example old coins into new coins) from circumstances where objects are scrapped and cast into any new form? That is to say, is persistence of form through cycles of recycling an important separate case? Should we use the same term for altering copper-alloy objects in the solid state as for melting and recasting processes? Modern concerns have certainly raised the profile of saving and extending resources, but can we disentangle current views and definitions from those of the past? Overall, for some scholars it continues to be unclear whether existing scientific data can even be used to contribute to many of these questions.[5]

Recycling occupies a strange place within archaeometallurgy, perhaps due to the 'daunting challenge' mentioned earlier. When discussed, it is often from a top-down, definition-led and abstract perspective, in which recycling is a coherent, singular process that is either wholly present or wholly absent from a given system. This approach is in contrast to proceeding from the data upwards, and finding patterns that identify varieties of process and to what degree they were a significant factor in past practice. Within glass studies the use of data in this way appears to be more prevalent,[6] perhaps due to the fact that secondary production of objects and their reuse is accepted as intrinsic to this material.

One typical treatment of recycling within archaeometallurgy is a summary by Pernicka, who argues that:

> 'The modern recycling rate of copper is the highest among all engineering metals and well above 50%. But was this always so? The answer is most probably no […] Generally, one can assume that in expanding economies, the recycling rate should be small, because fresh metal must come into the system […] On the other hand, in

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[5] Dunnell (1993); Killick and Young (1997); Killick (2005).

[6] Freestone (2015); Duckworth *et al.* (2016); Jackson and Paynter (2016); Paynter and Jackson (2016).

> declining cultures, the recycling rate should increase, because the economic structures become obsolete or are destroyed so the metal supply is interrupted.'[7]

Forming part of a chapter discussing the Provenance Hypothesis, this section contains a series of broad assumptions that seem hard to apply to archaeological case studies. Why should modern industrial metallurgy be of relevance, without justification, to most periods of the past? How do we define expanding or declining economies or cultures, and are these reasonable terms for interpreting past metal use? In short, in this style of interpretation recycling is a switch that is turned fully on when people get desperate and need to extend their resources. This is a very limited interpretation of the range of reasons that existing metal objects may be manipulated.

Moving beyond this kind of descriptive model, recycling is commonly used in schematic models of metal use and flow. These vary widely from common-sense sequences of technological steps to extremely complex maps of the interplay of multiple inputs. Barbara Ottaway gives a clear example of a circular sequence that moves from ore, through smelting and crafting to object, then, due to loss and corrosion processes, back to ore.[8] Recycling is present as a line running from social use back to smithing. Her paper stresses that the schematic model is just a framework, which must be fleshed out by incorporating social

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[7] Pernicka (2014: 258–9).

[8] Ottoway (2001: fig. 1).

practice and historical context. However the production sequences Ottaway goes on to describe for the Alpine Chalcolithic do not include any discussion of recycling. The paper follows the traditional format of mine; ore; smelt; casting; and smithing. The figure allows for the possibility of recycling before it is then assumed to be absent.

Stuart Needham's work on creating schematic models for metal use is a world away from a schematic *chaîne opératoire*.[9] He builds upon four key parameters to create intricate models for the flow of metal over time: supply, stock in circulation, average use span of metal, and losses. The interplay of these is then plotted through a series of hypothetical case studies of a region's metal economy, including simulated upswings and declines in production. To simplify and cope with the web of interactions Needham discusses two main scenarios, a hypothetical region which uses metal objects which are only cast once,[10] and a second region that 'employed a pronounced recycling system'.[11] Needham's detailed figures plot the cumulative weight of metal entering and exiting the 'system' (defined as a region's active metal use domain) over time, and a second figure for the rate at which these processes are occurring over time. The recycling-heavy model shows much looser connections between metal production and loss, and more extreme swings in rates of metal loss and accumulation,

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[9] Needham (1998; 2001).

[10] Needham (2001: fig. 5).

[11] Needham (2001: fig. 6).

with both of these aspects buffered by metal reuse. Needham's models have the advantage of incorporating many more of the relevant factors for quantifying how metal may have moved around a variety of active and inactive contexts. The overall approach may allow archaeologists to set up a range of starting conditions and play with how altering key parameters would cause different metal accumulation and deposition patterns to unfold.

One weakness of the models as presented is that they do not include ranges or combinations of behaviour, and the processes that are plotted are static over considerable stretches of time. If we allow for attitudes to recycling to be different for different classes of artefact, or to alter over time, the broad parameters of metal accumulation or loss would vary dramatically and over a considerable range. A similar accumulation of metal could be arrived at by a number of routes, and combinations of routes, with no way of distinguishing them using the parameters presented by Needham.[12] A second weakness of this top-down approach to metal flow and recycling is that it is too detailed and divorced from the realities of most archaeological contexts. The time axis is presented as a continuous flow, which is of course close to how metal use would have been experienced. However it does not consider how the blockiness of archaeological time units would obscure and blur patterns of metal reuse. Whether we use

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[12] Needham (2001).

absolute or relative dating methods, apart from some special cases such as dendrochronology or coin minting dates, we are limited to linking chunks of time.

In general, top-down models of reconstructing potential recycling behaviour have to walk a line between appropriate levels of detail and sufficient flexibility to be applied to a range of realistic contexts. Compared to a small set of axioms or assumptions such as Pernicka's,[13] or pared-back technological sequences as discussed by Ottaway,[14] Needham certainly attempts to address metal reuse as a combination of complex factors. However if we try to apply it to the archaeological record we hit a series of problems, not least of which is the fragmentary and distorted nature of our available data, which will always fall short of Needham's thought experiments. The rest of this chapter takes an alternative approach and discusses what may be gained by a fresh, bottom-up approach to copper-alloy recycling in the Roman Imperial period, driven by archaeological data. This chapter focuses on the use of chemical analysis, though it is important to incorporate the entire field of available information where possible.[15]

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[13] Pernicka (2014).

[14] Ottaway (2001).

[15] Bray (2019).

Building a new characterisation hypothesis for chemical datasets

Within the Provenance Hypothesis, which seeks to identify chemical links between ore source and artefact, there are a number of qualifications. For example, as described by Wilson and Pollard,[16] for chemical provenance to work any unique chemical signature of a source must be carried through 'unchanged', 'or at least recognisably consistent[ly]', into the artefact. Similarly, they argue that any mixing must be accounted for in the interpretation of possible chemical structure. I would argue that the potential power of identifying the source of materials using scientific analysis has twisted the correct priority of interpretation, and in fact these provisos about alteration should share centre stage.

Rather than privilege one aspect of a unit of metal's history, its initial source, we should characterise the whole journey. The traditional provenance hypothesis, which both spurred and inhibited the application of chemistry to metals, then becomes a partner in a wider effort to understand the complete life histories of units or metal: their source, merging, splitting, recycling, alloying, working, casting, use, and social action. This integrated effort moves

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[16] Wilson and Pollard (2001).

towards a more realistic, socially embedded appreciation of metal technology, and demands that different academic specialisms work together.[17]

Three overlapping areas of research support this move towards identifying character in large chemical datasets, and therefore more closely understanding the range of Roman manipulation of copper-alloys: (i) process and physical metallurgy; (ii) representing relative and contextual chemistry; and (iii) identifying modes of stability and transformation.

The application of process and physical chemistry experiments

The chemical changes associated with melting and mixing copper alloys are relatively well understood and have significant applications in modern industrial metallurgy. The fact that repeated melting could alter a provenance signal was rarely considered during the first few decades of chemically analysing archaeological copper-alloys. In fact some argued that the absolute level of a chemical element was not required to link ore to artefact, and semi-quantitative approximations would suffice.[18] The mass of practical, industrial experience of the chemical variation caused by spills, segregation, and oxidative loss of some elements took

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[17] Bray *et al.* (2015); Bray (2019).

[18] Pittioni quoted in Coghlan *et al.* (1962: 126).

a great while to seep into our interpretations. This was a great concern to industry, illustrated for example by the work of the Institute of British Foundrymen, who set up a dedicated committee to 'survey metal losses occurring during the founding of copper-base alloys especially melting losses arising from the types of furnace in general use'.[19]

Within archaeology, awareness that the chemical composition of metal may not be fixed through use was particularly spurred by the experimental work of McKerrell and Tylecote who published a paper called 'Working of copper-arsenic alloys in the Early Bronze Age and the effect on the determination of provenance'.[20] This is a far broader paper than the title may suggest and includes universally applicable experimental results for how levels of arsenic and antimony within copper are affected by working and melting. Tylecote had long been worried that working and remelting copper with low levels of impurities may obscure a clean provenance fingerprint.[21] The laboratory-based experiments indeed showed that under oxidising conditions arsenic and antimony were vulnerable to loss through volatilization of their oxides.[22] Moreover, these elements show pronounced segregation in copper and would

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[19] Hampton *et al.* (1965: 225).

[20] McKerrell and Tylecote (1972).

[21] Tylecote (1970).

[22] McKerrell and Tylecote (1972).

readily concentrate on the surface, where they would be susceptible to loss through mechanical abrasion and more pronounced oxidation upon further melting or heating.

There now exists a substantial literature on the general process of how remelting and casting copper alloys, even in slightly oxidising conditions as would probably be encountered in a Roman workshop, can alter the overall chemical character of an assemblage.[23] Alongside these trends we can also demonstrate the blending of chemical character through mixing, for example the deviation away from the ingot signal into complicated recycled artefact assemblages.[24] The concerns that these processes would obscure useful provenance patterns[25] could be replaced by the attitude that instead they add great value to the chemical datasets, as changes can print other aspects of the history of a unit of copper-alloy onto the chemical datasets.[26]

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[23] Charles (1980); Budd (1991); Budd and Ottaway (1991); Godfrey (1996); Pickles (1998); Sabatini (2015).

[24] Bray (2016).

[25] Tylecote (1970); McKerrell and Tylecote (1972).

[26] Bray and Pollard (2012); Bray *et al.* (2015).

Identifying and interpreting relative rather than absolute chemical patterns

The chemical dataset for copper alloys is a palimpsest which contains an underlying signal from ores and smelting practice, which can be then overwritten, pulled and twisted by later mixing, working, remelting, and object use. If we use the analogy of archaeological dating methods, traditional provenance chemistry claims to produce 'absolute dates'—a signal that could be interpreted as a unique geographical location. What is more realistic is a *relative* chemical approach, in which there may be consistent order and structure caused by metallurgical and social processes, but these have to be interpreted in context. The usual methods for identifying and representing structure in chemical datasets are more applicable to the assumptions of 'absolute chemistry'. Therefore we see great use of clustering techniques, regional specific groupings, or chemical range 'rainbows'.[27] These are all bounded approaches, which expect or require clear gaps between chemical assemblages, and are therefore at odds with representing more complex situations that occur through the real use and reuse of copper-alloys.

One area where there is remarkable agreement within the archaeometallurgical community is on the set of elements that are in some way diagnostic within the broad envelope of copper

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[27] Junghans *et al.* (1960); Junghans *et al.* (1968); Ottaway (1982); Pernicka (1997; 2014); Krause (2003); Meliksetian and Pernicka (2010).

alloys. We have the major alloying elements of tin (for bronzes), zinc (for brasses), and lead, but also low levels (usually under 2% each) of other metals that pass from ore into the copper during the smelt. These latter are identified through practical experience of which elements show up routinely in analyses of ores and artefacts: arsenic, antimony, silver, and nickel are used in most interpretative schemes.

Rather than assuming that there are clusters, specific ranges, or any other structure within the data, an open visualisation approach has been developed by myself and applied in collaboration with several colleagues.[28] The key concept is to define a chemical space, into which metal chemistry assemblages can be placed, to see how they may fall together or apart, trend, or even space out chaotically.[29] Here 'assemblage' may refer to any archaeologically relevant grouping, so units that have been applied include geographical areas, artefact typologies, time periods, distance from mines or production areas, worked and unworked casts, and so on.

In the first stage, presence-absence combinations of key elements define the chemical space. This analysis is performed for the alloying set of elements (tin, zinc, lead) creating eight

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[28] Bray (2012; 2015); Cuénod *et al.* (2015); Liu *et al.* (2015); Perucchetti *et al.* (2015); Hsu *et al.* (2016); Pollard *et al.* (2017).

[29] Bray *et al.* (2015).

combinations in space (Fig. 7.1), and also for the low-level ‘impurity’ elements (arsenic, antimony, silver, and nickel), creating 16 copper space combinations (Fig. 7.2, and further detailed in Table 7.1). The cut-off level to be considered ‘present’ is taken to be the reasonable level of 1% for the alloying elements, and 0.1% for the impurity elements.[30] The second necessary step then plots how the levels of key elements are distributed within the chemical space. This identifies important trends such as whether an element trends high or low, or is spread randomly across its range.

<Fig. 7.1>
<Fig. 7.2>
<Table 7.1>

Defining an alloying chemical space, impurity chemical space, and then looking for trends within those elemental combinations allows us thoroughly to explore trends and structures in the data. Importantly it does this *without* making any prior assumptions about possible clusters, distribution shapes, or fingerprints. It allows the relationships within the data to guide interpretation, rather than using top-down models. The second half of this chapter

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[30] Bray *et al.* (2015).

contains a series of worked examples of Roman copper-alloy artefacts that will, I hope, make this jargon more clear.[31]

Unpacking the recycling box. Modes of manipulation

It was mentioned above that the term ‘recycling’ is often unhelpful. Even if we define a very limited toolkit of operations that may be applied to copper-alloys we can quickly build up a range of behaviours that could be covered by ‘recycling’. Fig. 7.3 shows a schematic list of simple alterations to a unit, or units, of metal. The solid shapes represent form, so one could imagine the circles as one class of object (bracelets) and the squares another (rings). The zigzag arrow represents work all in the solid state, such as hammering, grinding, annealing, and polishing. The straight arrow indicates that the metal was melted and recast; the straight arrows can therefore join or split as molten units metal can be merged into a larger object, or divided into new multiple smaller objects.

<Fig. 7.3>

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[31] A series of overview papers and case studies from other periods are also available: Bray (2012; 2015); Bray *et al.* (2015); Cuénod *et al.* (2015); Liu *et al.* (2015); Perucchetti *et al.* (2015); Hsu *et al.* (2016); Pollard *et al.* (2017).

From these simple criteria seven modes of ‘recycling’ can be defined, which show different aspects of metal manipulation. Solid state ‘Reworking’ such as hammering bracelets into finger rings,[32] are very different to the classic ‘Recycling’ mode, which is defined here as multiple scrap objects being melted together and then cast into multiple new objects. We can also add an eighth, more conceptual, category where a completely unaltered object is recycled through ‘Reclamation’ and placed in a new social and temporal context.

This schema leaves out operations that may be termed scrapping, spoiling, or breaking, such as cutting an old object into sections. Instead, it focuses on pathways by which a new object can be formed from an old one, even if the alteration is slight or even just contextual. These pathways highlight where the intent is the creation of a new thing, rather than the reclamation, consolidation, or liberation of the intrinsic material as a commodity. This schema also omits the creation of the first generation of objects from fresh or prime material. Of course, several of these processes may not be widely recognised as recycling at all. Re-sharpening a blade is certainly part of a life of many object classes, and may change its shape, extend its currency, and create new applications. It is at least conceptually adjacent to ‘mainstream’ recycling, but

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[32] Swift (2012).

for many it should be placed into a different set of processes, as the original object broadly persists.

This thought experiment is offered as possible way to unpack the recycling box, through considering form, process, and context. If there is some utility here, it may be to highlight the wide range of related behaviours that can be created from a few processes, each of which may have very different values and locations in the Roman world. Though they may represent plausible modes under the banner of recycling, I want to stress again that this model or any other is only useful if it can be practically applied to the available record. Rather than look for examples that may neatly match one of these types, a stronger approach is to allow the dataset and record to speak for themselves. The rest of the chapter will therefore explore several case studies from Roman Britain, from the first century AD onwards, to demonstrate how chemical characterisation may contribute to the debate over Roman metallurgical knowledge and object reuse.

Examples of various Roman recycling and metal manipulation processes

1) The minor element character of Roman and post Roman gunmetals

The steady increase in use of gunmetals (copper containing both tin and zinc) has been long recognised as implying the mixing of bronze and brass through recycling. In this scenario bronze and brass are deliberate, 'clean' alloys, which get scrapped and mixed into generic copper-alloy. As Ponting and Levene remark, 'The recycling of copper-alloys is sometimes mentioned in passing as a likely explanation for the increased use of mixed ternary alloys (gunmetals) from the later first century AD onwards, but then fades from the discussion.'[33]

By collating a combined scientific dataset for Roman copper alloys and the surrounding archaeological periods, we can confirm that recycling is a good explanation for the increased use of gunmetals, and explore further their nature. Fig. 7.4 shows the main alloy space classes (see Fig. 7.1 and the discussion above) that were employed and deposited in Britain from the Iron Age to Early Anglo-Saxon periods. This is feasible thanks to the work of David

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[33] Ponting and Levene (2015).

Dungworth and Nigel Blades, with other important datasets including those of Bayley and Butcher, Craddock, and Northover.[34]

<Fig. 7.4>

Brass was briefly the most common alloy composition in Britain in the Late Iron Age, due to cross-Channel trade between southern British tribes and the Romans in Gaul, and through into invasion and occupation of the first century AD. From then on, the complex mixtures of leaded-gunmetals steadily rise in importance, peaking at around 75% of all Anglo-Saxon metalwork. These objects can be best explained as being recycled late Roman objects, which themselves were plausibly recycled from earlier Roman objects. They contain a wide and complicated range of every major alloying element that preceded them.

This model can be further demonstrated through using the trace elements contained within the copper-alloy objects. As described above (Fig. 7.2 and Table 7.1), a 16-region 'chemical space' can be defined using arsenic, antimony, silver, and nickel. Low levels of these diagnostic elements are highly informative about the long-term metal system employed by the Romans and later periods. Table 7.2 summarises the level of these different combinations of

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[34] Dungworth (1995; 1997); Blades (1995); Bayley and Butcher (2004); Craddock (1985); Northover (pers. comm.).

elements, employing the data kindly provided by Peter Northover and Blades.[35] Particularly eye-catching is the level of ‘CS 3’ (Copper Space 3, antimony [Sb]), which contains a small amount of antimony. The diagnostic minor elements are found alongside the main alloy system, so for example a Roman brass could contain 30% zinc along with 0.2% antimony, with each chemical system giving us insight into technological processes.

<Table 7.2>

It appears that the antimony signal is particularly associated with Roman copper-alloys. In the huge analytical survey of European Early Bronze Age copper alloys called the SAM projects (*Studien zu den Anfängen der Metallurgie, Studies on the origins of metallurgy*),[36] only 398 out of 32,786 objects contain the CS 3, antimony copper pattern: just 1.21%.[37] Meanwhile Nigel Blades’ data show that 64.9% of the Romano-British objects he analysed have this pattern.[38] We could consider the more rudimentary Bronze Age metal technology as capturing the underlying European chemical pattern of copper-ores, and in this period antimony as the sole impurity is extremely rare. Given the size of the Roman metal economy it is hard to

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[35] Northover (pers. comm.); Blades (1995).

[36] Junghans *et al.* (1960); Junghans *et al.* (1968.

[37] Data digitised and made available in Krause (2003).

[38] Blades (1995).

envisage this chemical signal as resulting ‘naturally’ from the ore. It should be added that the CS 7 pattern, antimony and silver, is a closely related pattern, which is particularly associated with leaded metals. The silver passes from argentiferous galenas into the lead, and then to the copper object. So in total Blades’ data show that 85.1% of the Romano-British copper that he analysed are linked with copper that had a solo-antimony marker.

It remains unclear what process could add this marker so commonly into Roman metalwork, and this is worthy of a great deal of further study. At this stage, however, the character of the antimony signal can help us to understand the broad recycling pattern represented by the rise of gunmetals in Britain across the first millennium AD. First, it is important to note how prevalent and steady CS 3 is throughout the history of late Iron Age to Roman, and then onto Early Anglo Saxon metalwork, and beyond. During this time, there is a falling away of brass and bronze and their replacement with mixed gunmetals. Taken together, this underscores how internally focussed Romano-British metal recycling may have been, and how consistent the supply of fresh metal was. No matter what processes underlay the antimony signal, it was important and lasted over a century. Then this metal, whether bronze, brass, or early generations of gunmetal, continued to be churned together for many further centuries. Of course there are other chemical compositions present within each period’s metalwork, but the dominant signal is one of consistent reuse of similar metal. It is not until the Middle Saxon period that there is a significant injection of copper with a different chemical character into Britain (CS 12, copper alloy with small amounts of arsenic, antimony, and silver).

Ideally, we need to distinguish two key scenarios. The first has just been described, of increasingly old metal being reused down the years. A second possibility is fresh low-level antimony leaded bronze and brass being mixed to produce new leaded gunmetal each generation. The latter seems unlikely due to the consistently rising gunmetal signal, but an independent test is required. The chemical percentage of antimony within the objects (rather than its prevalence across the assemblage) demonstrates long lifetimes of reuse. As discussed earlier, McKerrell and Tylecote did a great deal of work on how losses of antimony (and arsenic, though that is not applicable here) were related to melting metal in an oxidising atmosphere.[39] Fig. 7.5 uses a box-and-whisker plot to summarise how the British assemblage progressively lost antimony over time. These losses are not linear, and experiments show that the lowest amounts are more resistant to oxidative attack. Overall, however, there is a clear pattern of decreasing amounts, and a squeezed lower range of values. This supports a progressive pattern wherein each period commonly recycled the metal of its predecessors, rather than using fresh input of high antimony copper-alloys.

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[39] McKerrell and Tylecote (1972).

2) Modelling the alloy distribution in gunmetals

A further important tool for understanding alloy mixtures is the pattern and distribution of their major elements. Indeed, this is probably one of the most accessible and direct methods, and, unlike the low level 'diagnostic' elements, does not rely on the highest quality chemical analysis. However, after identifying that a gunmetal mixture is present, many scientists have then moved on, feeling that there was no deeper pattern to interrogate; for example, David Dungworth argued that 'The proportions of bronze and brass that were mixed varied widely as there is no distinct peak within the distribution of the zinc and tin contents of gunmetals.'[40]

While it is true that we lose the dramatic, tight chemical distributions commonly associated with directly produced brass or bronze, there is a great deal of information to be gleaned from the gunmetal assemblage. However, it cannot be considered independently of the contemporary bronze and brass. The following case study therefore concentrates on the British assemblage from the first century AD, where bronze (*c.* 15%), brass (*c.* 30%) and (non-leaded) gunmetals (*c.* 20%) were all common. Compared to later periods where it is the only type of alloy in use and the signal has been highly churned, a central question for these relatively early gunmetals is, how far are they designed and deliberate? Were they formed

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[40] Dungworth (1997).

from mixtures of existing bronze and brass, or produced independently of that contemporary metalwork? Can rules for recycling and mixing be identified?

The approach followed here was to take the actual first-century brass pattern (for the zinc component, see Fig. 7.6) and the actual first-century bronze pattern (for the tin component, also Fig. 7.6) and then model whether they could be mixed using a set of reasonable rules to produce the actual first-century gunmetal pattern (zinc and tin in gunmetal, Fig. 7.7). When discussing different modes of recycling above, a simple merging of solid lines represented mixing (Fig. 7.3). Obviously Roman practice was more complicated than this, and Fig. 7.8 attempts to lay out more carefully the steps necessary to understand how mixed gunmetal may have been made from contemporary bronze and brass. This is still a simplified approach, but tries to capture the several points where decisions could be made. The blue section 'A' represents the contemporary bronze assemblage, from which metal could be taken out to mix into gunmetal. This could occur randomly, following deliberate rules, or as a flat addition (for example adding 2% tin to all objects made from brass). Similarly brass could be chosen from the red section 'B' by a range of processes.

When these groups of metal meet, they do not have to be mixed equally or consistently, therefore this model allows for different mix factors to be applied. The black central group represents some alternatives: again, the mixing could be random; a lot of the brass could be mixed with little bronze; high-tin bronze could be mixed with only a little brass while medium-tin bronze would be mixed with a great deal; and so on. This is all predicated on the reasonable assumption that Roman smiths could assess the relative alloy content of metals through colour, toughness, feel under the hammer, and so on.

Therefore a broad set of rules can be set up, applied to the Roman bronze and brass, and then compared with the real chemical distribution of the archaeological gunmetal. One example would be (Fig. 7.8):

A: Tin from bronze. From the contemporary bronze assemblage a random selection of bronze is made for gunmetal production

B: Zinc from brass. From the contemporary brass assemblage a random selection of brasses are chosen for gunmetals

Mixing factor: A random selection of bronzes from ‘A’ are added to a random selection of brasses from ‘B’ in varying, and random ratios [20:80, 5:95, 73:27 etc].

This rule set obviously priorities randomness, and would imply that the Roman smiths did not care about the output. In this scenario the special properties of bronze and brass are stripped out, and the end is a mixed, genericized ‘copper-alloy’ metal, perhaps only important for its volume and general utility.

Using the first-century AD bronze and brass composition datasets as inputs, and the first-century AD gunmetal composition as the test set, I ran a series of different selecting and mixing scenarios. These will be described in full separately; here I just want to discuss the most successful run. 'Test Seven' is a reasonable approximation of the actual Roman gunmetal composition set (Fig. 7.9). It was produced, not through random addition, but by following a broad set of principles. This is not to imply that this was precisely what occurred in the workshops of Roman Britain, but that this type of model could highlight a structure within the chemistry that has been overlooked.

'Test Seven' is a set of rules that focus on retaining the striking colour of brass where possible, while maximising the volume of metal that was being mixed. It aims broadly to simulate a scenario where value is being maximised, by extending but preserving high-quality brass, and producing a large volume of less prestigious (lower zinc content) but still useful metal. The rules therefore state that brass with the highest zinc contents is barely mixed with tin-bronze, while the lower the zinc content of the brass, the greater the amounts of tin-bronze that are mixed with it. Therefore the lowest zinc brasses are mixed 50–50 with tin-bronze. All the bronze being mixed is of random content under these rules; only the brass content is closely graded and ordered. Again, this is plausible using colour and broad mechanical properties.

Fig. 7.9 shows how both the test set and the real archaeological data anchor the highest zinc values (a small amount of slightly watered-down, but still valuable, high-brass gunmetal), and then a broad, slightly skewed distribution of zinc to lower levels. The tin distribution in both sets shows a characteristic shoulder. In real Roman artefacts, the high zinc gunmetals tend to be valuable horse gear, with the lower range made up of more quotidian household goods. Though by no means perfect, this brief case study aims to highlight the potential of these types of model. With more development, these broad similarities could be turned into probabilistic arguments about past mixing and recycling practice and the perception of metal. More work is required to see how each period, region, and even workshop may have had different rule sets, principles, or themes within their metal use and reuse. However even at this stage, this work helps support the idea that bronze and brass *objects* were the precursors of the early Romano-British gunmetal, rather than it being produced by mixing *ingots* of tin into fresh brass.

3) The production and manipulation of coins

Moving away from the domestic and military metal of Britain we come to one of the most beautiful datasets for understanding Roman metal use. From a selfish perspective as an archaeometallurgist coins are perfect—small, repeating pellets of metal, often stamped with iconography, dates, and texts or images referring to known people. Thanks to academic interest that stretches back almost to their production, they are also an ideal arena for interdisciplinary work and collaboration. The scientific dataset for many coin issues is rich, and through combining the work of several scientific teams from over a century a reasonable chemical sketch can be drawn from Augustus through to the Byzantine Empire. Within this time-span I wish to highlight two case studies that show the degree of control with which the Romans could assess and manipulate metal.

The first concerns the zinc-based coinage of Nerva to Lucius Verus, as analysed by several scientific teams, totalling 885 analyses.[41] Depending on the specific coin issue, around 40 to 80% of the copper alloy coinage for these Emperors was very pure brass, often with the minor antimony signal that was discussed earlier. However alongside these coins are almost identical ones that would be classed as gunmetal. These just creep into that category however, as the tin content tends to be only 1 to 3%. If the zinc distribution for the brass and gunmetal issues are plotted on the same chart (Fig. 7.10), the effect is barely noticeable, with the black line for gunmetal just moving down very slightly. One explanation could be a lack of control in the production process and accidentally tin has crept into the system in small amounts. However given the overall rigour and consistency seen in the coins at this time a more

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[41] Mattingly (1923); Caley (1964); Carter (1964); Cope (1972); Riederer (1974); Étienne and Rachet (1984).

plausible explanation is that this is a deliberate addition. Carefully diluting the brass with a flat 1 to 3% of tin, either raw tin or bronze, would have saved a great deal of value. Doing so in this way meant that the consumer would barely have noticed, the colour change would be slight, and the flat addition means the relative, internal range of the assemblage is maintained. Though not recycling, characterising this type of manipulation helps to show the interrelated spectrum of Roman metallurgy.

A broadly similar process of metallic shifting occurred for Nero’s brass coinage. Here rather than subtly debase some of the metal, there was a deliberate ‘cutting down’ of pure brass with more copper in order to create two distinguishable colours and values from the same raw ingredients. The zinc distribution, and separation, for the low- and high-value coins is truly beautiful (Fig. 7.11). This is based on data from 79 analyses.[42] The *dupondii* and *sestertii* both have a zinc level typical of brass from that period, while the lower-value coins have approximately half. This creates a clear colour and value difference between the denominations, which is essential for the creation of trust in the currency.

By assessing the trace element copper character alongside this alloying pattern we can hypothesise that more of the base copper that was used to make the brass was added back into

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[42] Mattingly (1923); Caley (1964); Cope (1972); Riederer (1974); Étienne and Rachet (1984); Carter and King (1980); Carter (1988).

the lower value coins. Both the high- and low-value coins mostly fall into CS 1 or CS 3 in a 2:1 ratio. The quality of the coins, their different weights, colours, and consistency all helped build confidence and maintain value. The metallurgical and economic skill is clear. Again, this is a manipulation of metal and changing of composition through mixing. So, despite not being recycling this case highlights conceptual links between processes that too often have been considered separately. It is of great profit to use the available data to assess the characters of metal assemblages and the likely processes that led to them, rather than get too concerned about defining 'true recycling'.

Conclusions

To be useful, these chemical patterns have to be fully integrated into a series of broader contexts. They must be compared to the extensive work on the recycling of other materials, glass in particular, to try and explore wider patterns of high temperature material manipulation. As other chapters in this volume highlight, there are also a number of low-temperature processes that can remodel old objects, and a wider world of building reuse and landscape alteration.

As discussed above ‘recycling’ is a crude term, which I have attempted to unpack slightly using the chemistry of metal objects. Much further unpacking and discussion is required, and each material or assemblage will have its own language and logic of reuse and manipulation, as would each region, period, and society. A data-rich, bottom-up approach to a range of processes seems fruitful, rather than attempting to separate out a more narrow definition of ‘true recycling’.

The addition of more copper to brass to create a clear difference in Nero’s coin issues may appear unrelated to recycling behaviour, but it *is* on a spectrum of deliberate metal change. From there, it is a short step to debasing brass coins slightly with bronze to make almost imperceptible gunmetal alloys, and a small further jump to mixing large volumes of scrap bronze and brass together, but still with rules and themes of behaviour.

This paper has focussed on areas of metallurgy for which we have large amounts of data. Having often worked on Bronze Age case studies it is striking how small the Roman chemical dataset is, particularly when the relative scales of production are considered. The vast world of Roman metalwork is barely analysed compared to the material of earlier periods. As mentioned above, the series of SAM projects in the 1960s produced data for over 30,000 Early Bronze Age copper-alloy artefacts from Europe. This one team probably produced more chemical information for their assemblage than has been achieved by all efforts directed at

Roman material. This is not a problem; it is a fantastic opportunity to keep discussions moving forward, invest in new science, and develop novel collaborations.

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