INNOVATION, PRODUCTION AND SPECIALIZATION IN EARLY PREHISTORIC COPPER METALLURGY

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Abstract: The process of the production of copper and bronze is presented in this paper as a sequential operation. Each stage of this process may influence the final product. The deconstruction of the process is a convenient way of examining each individual stage, using archaeological case studies from different places within the Old World and, where useful, ethnographic studies. The examination will focus on two aspects: innovation and specialization. It seeks to move beyond technological determinism by relating the study of technology to the context of those societies which shaped and practised it and which exercised certain choices in its execution.

Keywords: Bronze Age, Chalcolithic, Copper Age, innovation, production sequences, specialization

INTRODUCTION

Production of metal and metalworking are often treated as being synonymous. Indeed, prehistoric metallurgy is regularly discussed as if it were a single technological process. Furthermore, this technological process is all too often considered as if it were devoid of social or any other context. Yet many individual stages are involved and numerous choices have to be taken in the entire sequence of production for the successful transformation from the metalliferous ore to the finished metal object; each stage in the process may influence the final product.

The study will try to get away from technological determinism and attempt to look at the concept of metal technology as a social phenomenon. The social organization of technology has been under discussion for some time (e.g. Dobres and Hoffman 1994; Lemonnier 1989, 1990; Pfaffenberger 1992), but only a few articles have been devoted to the social aspects of metallurgical processes (for example Lechtman 1977). This is perhaps not surprising since many researchers in archaeometallurgy, who laid the foundations of this branch of archaeology, have either come directly from the domain of metallurgy (for example Maddin 1974; Tylecote 1986, 1987) or concentrated on mastering and increasing the vast and rigourous technological

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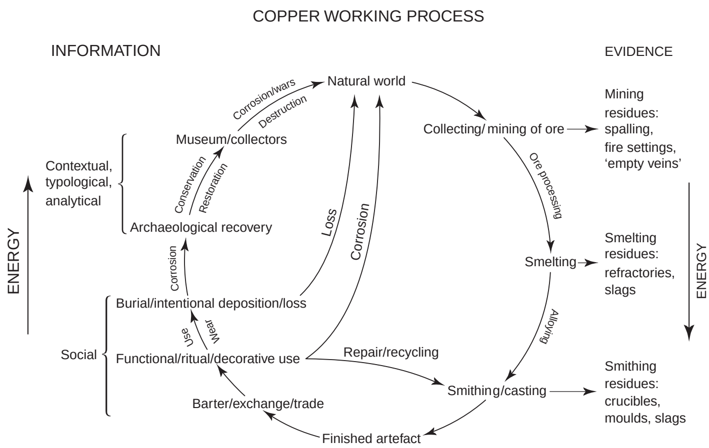

Figure 1. *Cycle of copper production and working (after Ottaway 1994, Fig. 1).*

and empirical knowledge demanded by the subject. In doing so, the idea that 'technology is a dynamic, meaningful, and embodied (that is physically experienced) form of social practice' (Dobres 1999) has been somewhat neglected.

The concept of *chaîne opératoire*, introduced by Leroi-Gourhan (1964) into Palaeolithic research in France and more recently in Britain (Edmonds 1990; Scarre 1999), provides a framework capable of linking material and social practices, but only if one goes beyond the descriptive technical sequencing of transforming matter by 'disembodied hands' (Dobres 1999) and includes the social structure and historical context in which these technical systems were taking place (Edmonds 1990). The technical sequencing, often depicted by flow charts, will still be a necessary starting point (Fig. 1). However, it will be important to complement the right-hand side of the copper production and working cycle in Figure 1 by teasing out information on the extent to which production sequences were shared, the range of tolerated variability, whether this tolerance was confined to some materials and not others, to some social spaces and not others and the extent of sharing or restriction of technical knowledge.

In this paper, the production sequences of copper and bronze will be deconstructed and each stage will be examined in the framework just described, focusing on two aspects: innovation and specialization. Innovation is taken here as defined by Renfrew (1984:391), reinforced by Torrence and van der Leeuw (1989) and reiterated by Spratt (1989), where innovation is distinguished from invention. 'It is the adoption of the new product, not simply the discovery of a new technical process, that constitutes true innovation' (Renfrew 1986:142). The creative phase of invention is often characterized by a great deal of experimentation, often based on variations on existing knowledge and technologies. Only when the invention was accepted and adopted by the community did it become an innovation, which was then integrated into the spectrum of existing skills, activities, symbolic schemes and ideological structures of that society. In this sense, it can be seen that 'the decisive innovation is social rather than technical. Often the technology is already there' (Renfrew 1986:146). Although Renfrew's definition has been called 'somewhat limited', it is far less cumbersome than those proposed by others. It also allows us to focus more on the circumstances under which inventions lead to adoption, an approach which has been explored by Torrence and van der Leeuw (1989) and developed by Lemonnier (1993). Ideally, it leads to a multi-dimensional perspective of innovation as suggested by van der Leeuw (1989) and achieved by Vandkilde (1996) in her admirable study of early metalwork in Denmark. This is a welcome shift away from the preoccupation with analytical results in archaeometallurgy, which, though a necessary basis for new studies, are only one step towards the examination of existing knowledge which led to change in technological processes (for further references and discussion of all steps involved, see Ottaway 1994).

The key element to invention and subsequent innovation is creativity (McGlade and McGlade 1989). By discussing these phenomena in one paper together with specialization, it is not implied that only specialists preserve the right to be creative. Rather, an attempt is made to look at innovation and specialization at each of the stages involved in making a metal artefact, in order to avoid the assumption that they must be connected.

There is considerable literature on the subject of specialization, more often than not relating to ceramic material (Brumfield and Earle 1987; Clark 1995; Clark and Parry 1990; Costin 1991; Rice 1991; Wattenmaker 1998) and only rarely relating to metal (Gilman 1987; Kristiansen 1987). The term carries a great deal of baggage, most of it evolutionary and/or economical, often leading to the interpretation of specialization from the viewpoint of increased efficiency in production, leading to increased output of standardized products. Usually it is assumed that the rarest goods – those that have required most labour to produce – have the greatest potential for signing and symbolism and, for this reason, are associated with ranked and stratified societies. Though often implied, these assumptions have only rarely been tested for prehistoric metal products.

The following definition for craft specialization is suggested as the most appropriate for this present study: *consistent production of things by some people for others* (pers. comm., Mark Edmonds). There are several components in this definition. First, production involves acquired skill. Secondly, the things produced, apart from having their own role or function, for instance, as part of the operational chain, may also carry their own message. Thirdly, the commodities exchanged by others to obtain the products may be of social or economic value. Exchange within one household or its dependants is excluded. It is assumed that specialists participate in production to a greater degree than do other members of the community. No frequencies or lengths of time involved in the production are implied and the process can be ad hoc, part-time or full-time. In the absence of supporting evidence, it is not assumed that there is an evolutionary, monolithic progression from small household production to large-scale industrial production in any one area.

In the following pages, the individual stages from prospecting for metalliferous copper ore to the finished product will be discussed with respect to early prehistory in the Old World. These stages are: prospecting, mining, beneficiation, smelting, or roasting *and* smelting, refining, alloying, casting and smithing. Production of fuel is an integral part of metal production and will be discussed briefly.

PROSPECTION

Prospecting for ore that contains copper requires an observant eye. An experienced prospector would most probably obtain clues from indicator plants, as well as from the colour and taste of water near a mineral source. However, prospection for and the collection of minerals was not a new activity. There are many examples which indicate that mineral resources were known and exploited in the Palaeolithic and Neolithic periods. For instance, ochre was widely used from the Palaeolithic onwards (Meurers-Balke 1981:38), ornaments of opal and jaspis are known from the Neolithic, cinnabar, a red mercury sulphide, provided a red colorant in the Neolithic and powdered malachite as well as malachite beads have been recovered in purely Neolithic contexts (Glumac and Tringham 1990). It cannot, therefore, be said that prospecting was an innovation, rather that it was the application of existing knowledge of the environment, focusing more specifically on copper-bearing minerals such as malachite and azurite. Any member of a community involved in upland transhumance (Chapman 1981) or the collection of other raw material resources (Tringham and Krstic 1990:600) may have been involved in this activity, but only a trained eye would locate the right minerals and ores.

MINING

Early mining of copper ores involved either the collection of outcropping pieces of ore, the digging of open pits and trenches or following a vein of copper-bearing ore, often below surface level. Ore extraction from the bedrock required stone hammers, antler and bone picks, sometimes with the aid of fire-setting to loosen the rock (Ottaway 1994; Fig. 7). These activities were all part of the existing technology which included, for instance, mining for flint and opal, quarrying for stone and flint, sinking shafts and building wells to obtain clear water.

In south-east European Neolithic contexts, malachite has been found as pieces of mineral, as powder and as beads (Glumac and Tringham 1990). From a polymetallic deposit at Rudna Glava in former Yugoslavia, copper ore was extracted in the fifth millennium cal BC by following narrow veins down to a depth of about 25 m.

A seemingly tight cohesion of the Vinča mining group is glimpsed from cultural material excavated in the shafts. Furthermore, in so-called storage chambers, between one and three amphora had been deposited, sometimes together with hammerstones (Jovanović 1982:138), most probably reflecting ritual acts in the mine. The ores mined were the copper carbonates malachite and azurite, but significantly, sulphide copper and iron ores were deliberately left behind, indicating a conscious choice and careful selection of raw material (Jovanović and Ottaway 1976).

In the Feinan region in Jordan, copper was exploited from the Neolithic period onwards (Hauptmann et al. 1996). Here too, malachite was found in powdered form, perhaps for cosmetic products, and as beads. In the Chalcolithic/earliest Bronze Age I period (*c.* 4500–3000 cal BC), copper was mined in open galleries from the massive brown sandstone deposit, which consisted of thick layers of the copper carbonate malachite and chalcocite, a copper sulphide. The galleries showed evidence that stone hammers had been used in extraction. At the beginning of early Bronze Age II, around 3000 cal BC, extraction of the brown sandstone deposit was abandoned in favour of mining a dolomite-limestone-shale deposit, with intensive impregnation of malachite and the copper silicate chrysocolla. This deposit, however, could only be reached by deep mining, i.e. by sinking shafts and building galleries (Adams 1999:94).

A distinction thus has to be made between surface collection, open cast mining and underground mining of ore (Weisgerber 1989a, 1989b). The first two need relatively little experience, yet, although the knowledge about choosing the right ore can be acquired, it needs an experienced person to train the novice's eye to recognize and identify the ore correctly. Underground mining, on the other hand, needs specialists to be in charge of sinking shafts and building underground galleries, producing, using and maintaining the tool kit for extraction work, extracting the ore safely and bringing it to the surface. All these are actions which need a great deal of experience for safe and successful execution. Edmonds (1995:66) warns against the notion of full-time specialist (flint) miners and suggests that the intensive episodes of (flint) mining might have provided the context in which skills could be learned and appreciated and may also have helped to sustain concepts of experience and authority.

The choice of resource location may have been of special significance. Examples of resource selection for stone axes have been discussed by Edmonds (1995:59), where the raw material was obtained from locations that were difficult to access even though other outcrops would have yielded identical raw material. Perhaps special value was bestowed on raw material procured from specific locations, imbuing it with meaning and power which followed the finished artefact through its life.

Shennan (1999) pointed out that there have been, until recently, no studies of the social organization of copper production in Bronze Age mining areas of central Europe. This is as true for processing as it is for the actual mining of the ores and not only in central Europe but also in other parts of the world. Detailed work focusing on social aspects has not been carried out, partly because traces of early prehistoric copper mines are usually destroyed by later mining activities and thus there is a lack of sufficient data for such studies. Furthermore, there is usually no evidence of contemporary settlements or smelting places associated with early copper mines, as in former Yugoslavia, thus denying us knowledge about the continuity or otherwise of contact between settlements and mines. Perhaps when the material from the excavations of the Feinan area is fully published, information on the demarcation of mining areas and people's physical and social relationship to each other (Edmonds 1995:63) may be obtained by studying the practical organization of working in copper mining areas. Even then, it is not clear whether hypotheses about access and rights to the mining areas, participation in mining expeditions, the use of child labour which is suggested by the extreme narrowness of many shafts and galleries, and other divisions of labour can be tested and verified.

Beneficiation

Figure 2. *Dressing stones/anvils (length varies between 40 and 60 cm) and hammerstones for crushing ore from the Great Orme, Wales. (Photo: author's own.)*

Copper-rich minerals were crushed and either hand-sorted to pick out the coloured and heavier minerals from the gangue or, in later periods, separated by gravity with the aid of wind or water. This is ore concentration or beneficiation. The hammerstones used for crushing, commonly smaller than those used for mining but with similar traces of wear, stone slabs, often with numerous concave depressions (Fig. 2), and 'tailings' – the heaps of crushed and discarded gangue – can indicate the location where this process has taken place.

Beneficiation has been found, through experimental work, to be an extremely important stage in metal production and one that can exert a strong influence on the composition of the final product. It has been suggested that minor and trace element patterning of the final metal is greatly influenced by the choice of ore grade and the labour invested at this stage (Merkel 1985). Furthermore, one of the few studies published on this subject shows that the more time that is spent on beneficiation, the less fuel is needed in the smelting process (Doonan 1994). It is usually assumed that crushing and separation could be carried out by anyone. However, crushing involves skill, technique and the correct choice of tools. And selection, if done expertly, can concentrate the copper ore manifold.

Such crushing and subsequent selection of ore in preparation for smelting are the first true innovations in the sequence of copper production. As experiments conducted at the University of Sheffield have shown, it certainly needed trained people to carry out the work. Repeated production of the beneficiated ore required a specialist, or a group of specialists. Variations in the analytical results of the final metal and the waste product (the slag) may be as much a reflection of the attention to detail or the ability of the specialist involved at this stage, as an indication of other factors discussed later. It must be assumed that this knowledge was gained by trial and error and passed on carefully.

In one small region within the Mitterberg mining district in Austria, there is evidence for beneficiation close to the mining area and it was thus probably carried out by the same people who did the mining (Gale and Ottaway 1990). At the Bronze

Age copper mine on the Great Orme in Wales, the area where beneficiation, now dated to the BA, was carried out was also not far away from the mine, near a spring (Wager et al. in press). However, at Selevac there is evidence that beneficiation was carried out in the settlement and was thus probably carried out by the people who did the smelting. At Timna, in Israel, the earliest beneficiation also seems to have been carried out away from the mine in a small enclosure, associated with evidence for habitation. This site lay at the foot of the hill where the smelting was subsequently done (Rothenberg 1990a, 1990b). Later beneficiation locations at Timna were found within enclosed areas where smelting was also carried out. Yet another arrangement was found at one of the early Bronze Age mines in the Feinan region, where evidence for ore beneficiation was excavated within the mine itself (Hauptmann and Weisgerber 1987:424).

These are important indicators of social practices within the mining and processing communities. In some cases, miners seem to have done the beneficiation, in other cases it was the smelters. Sometimes the beneficiation sites were close to or inside the mine, while, at other times, they were separated from the mine. These different types of arrangements illustrate clearly that there can be no generalization and each situation warrants careful analysis.

Smelting

The application of heat to convert one material into another was not in itself an innovation. It was part of the repertoire of existing knowledge which was applied to the hardening of clay figurines in the Palaeolithic, or the firing of clay to produce ceramics. The necessity to achieve consistently high temperatures and a reducing atmosphere to smelt the copper from its oxide or carbonate ore required the adaptation and refinement of the techniques. The multitude of solutions to this technical problem found in archaeological and ethnographic records bears witness to the readiness of craftspeople to experiment. It led to several regionally different innovations.

Crucible smelting has been found in Selevac, a Chalcolithic settlement of the fifth/fourth millennium cal BC in former Yugoslavia (Ottaway 1998; Tringham and Krstic 1990); in the late Neolithic settlement on the Götschenberg in the fourth millennium cal BC in Austria (Lippert 1992); and in the early Bronze Age I settlement of Wadi Fidan 4 of the fourth millennium cal BC in Jordan (Adams 1999:112; Hauptmann et al. 1996). Smelting was carried out within a crucible, probably embedded in a small hearth-like oven. The heat was applied from above, since the whole crucible would not have withstood the high temperatures required to smelt the ore. The products indicate that the smelting process was incomplete – i.e. insufficiently high temperatures had been achieved to produce a liquid slag through which the molten copper could have fallen and collected at the bottom. This incomplete process led to the embedding of the copper prills in the solidified slag. Smelted copper was obtained by crushing the slag and removing the prills by hand.

Figure 3. *Feinan furnace: clay-lined bowl with stone setting. Scale = 10 cm. (Photo: author's own.)*

By contrast, there are furnaces of the early Bronze II phase, such as those excavated in the Feinan region in Jordan, which consisted of clay-lined, bowl-shaped stone settings with a flat stone slab base (Fig. 3). The likelihood that these stones had a grid at the front was suggested by the presence of slagged clay coils (the so-called 'ladyfingers'). Experiments carried out in the Feinan region have shown that the wind created enough forced draught to obtain temperatures of 1200°C and smelt the copper ore (pers. comm. A. Hauptmann and W. Bunk). However, in the prehistoric smelting operations, the process was only taken to the stage where the copper prills were embedded in the solidified slag. The location of the smelting sites on top of the hills, rather than within settlement sites of the Feinan region, is recognizable by dint of the dark areas of crushed slag surrounding the disintegrated furnaces.

In contrast, Bronze Age smelting installations in the Austrian and Italian Alps generally showed a completely different, but uniform, arrangement. Furnaces were built into the slope of the hills, often in pairs (Fig. 4) or as batteries of several furnaces along a roughly straight line. On a terrace above the furnaces were roasting beds, recognizable by burnt red soil, and surrounded by stone settings. Below the furnaces are substantial slag heaps (Cierny et al. 1995; Doonan et al. 1996; Eibner 1982; Herdits 1993).

Figure 4. *A pair of Austrian furnaces built into the slope of the hill. Length of each furnace: about 25–30 cm. (Photo: author's own.)*

Chalcolithic and early Bronze Age smelting sites in the Trentino, in the Italian Alps, were almost all situated in the valleys, below 700 m, where no copper deposits are known. Late Bronze Age smelting sites, on the other hand, were all found in the mountains, between 1000 and 1500 m above sea level, near copper deposits. Interestingly, slag analyses indicated that process temperatures and furnace conditions did not change significantly from the early to the late Bronze Age. In other words, the same sulphide copper, chalcopyrite with pyrites and quartz as gangue, was smelted throughout the whole Bronze Age by a method that did not alter much, even though the location of the smelting sites changed from the valley up to the mountains. The only difference was the increase in size of slag cakes from the early to the late Bronze Age – an increase from 2– 3 kg to 5–6 kg in weight (Hohlmann 1997:107).

The following scenario may be inferred from these records. During the Chalcolithic and early Bronze Age, smelters in the Trentino carried out their smelting activity in the valleys. Periodically they went up into the mountains to mine the copper ore. In the later Bronze Age, the demand for copper increased and they moved their smelting up into the mountains, closer to the ore deposits and perhaps also closer to new resources of fuel. They now took the process from the ore through to the finished copper artefact, as can be seen by the presence of some axe moulds (Hohlmann 1997:105).

The skill of smelting had to be learnt painstakingly and transmission of accurate knowledge was probably carefully guarded. There are many phases involved in a successful smelt: building the furnace, choosing its correct dimensions, drying and preheating the furnace prior to the smelt, choosing the number, position and inclination of the tuyeres, choosing the type and size of fuel, choosing the ratio of ore to fuel, timing the addition of ore to the smelt and determining the length of the smelt. A small mistake or omission of any of these operations would lead to partial or total failure of the smelt. In addition, the powerful influence of ritual actions must not be underestimated, as ethnographic studies have all too clearly shown (Rowlands and Warnier 1993). These might have included the correct rites of fertility, observing the appropriate rituals such as celibacy prior to the smelt, chants, libations and adding the right 'medicine'.

Smelting is thus a clear case of craft specialization, though not necessarily a full-time one. The main smelter was probably assisted by a few less well trained apprentices, who would not know the full range of actions to be taken nor of the choices that could be made during the smelting. Indeed, the full knowledge was probably kept by the main smelter, who would surround the technique with magic and taboos, thus deepening the feeling of mystification which surrounded the smelt, excluding outsiders and keeping them in ignorance of the skills and techniques (Frazer 1978).

The material remains do not allow us to draw conclusions about the status of the smelter and smith in society. Ethnographic records cover the entire spectrum from high status (e.g. the Dogon of western Sudan: Griaule 1965) to those with low status, who often had to set up their working places well outside villages (Champion 1967; Torbert 1985). The location of smelting sites in relation to any known settlement sites may thus be taken as an indication of the status of the prehistoric smelters, although it could equally be a reflection of the desire to keep the process secret from the rest of the community or to keep the settlement free from pollution and danger.

Figure 5. *The king of Leija, Nigeria, with his council of elders, sitting on blocks of slag. (Photo: author's own.)*

Remains of smelting activities, such as slag, can still carry strong symbolic meaning in traditional societies. The King of Leija in Nigeria uses blocks of slag as seats for his council of elders when holding court and conducting trials (Fig. 5) and the uninitiated, particularly women, are not allowed even to touch these blocks of slag without incurring the wrath of the King and necessitating lengthy and costly (to the offender) cleansing rituals (Okafor 1992; pers. comm., Eze-Uzomaka).

Although most African ethnographic studies show that smelting is an exclusively male occupation, Stig Sørenson's (1996) stricture that African societies are very differently organized from those of the European Bronze Age has to be accepted. There is, a priori, no reason why women should not have been involved in many parts of the smelting or smithing process and we must keep an open mind about this issue.

The product of the smelt – the raw copper – was either exchanged for another commodity or re-melted, refined, alloyed and cast into its final shape by the same person or group of persons who did the smelting. The latter case can be inferred when the smelting site also includes remains such as moulds, as has been mentioned earlier for the Trentino.

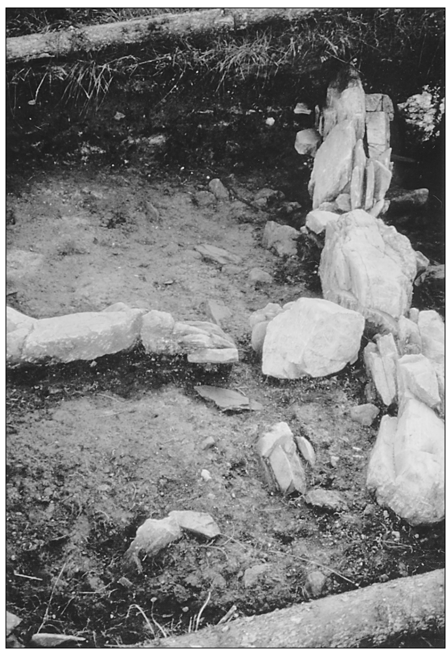

Figure 6. *A roasting bed in Austria, recognisable by burnt red earth and stone setting. Each roasting bed is usually about 70 cm wide. (Photo: author's own.)*

Roasting and smelting of sulphide ores

A further innovation is the smelting of sulphide copper ores. Although direct co-smelting of oxide and sulphide copper ores without prior roasting has been shown to work experimentally (pers. comm., R. Doonan), sulphide copper ore usually requires roasting, under oxidizing conditions, to drive off the sulphur before the smelt. Roasting can be carried out in shallow pits, surrounded by stones to contain the process (Fig. 6) and using wood as the most common fuel. The process left behind beds of red scorched earth (Doonan 1996:106; Eibner 1982; Herdits 1993). Roasted ore can then be smelted, as discussed earlier.

Roasting itself could have been carried out by unskilled workers. The composition of the mined and beneficiated ore affects the way in which the ore has to be roasted. For this reason, bringing the process to a successful conclusion would have necessitated a skilled person supervising the process to make choices about the temperature, the length and termination of the process.

REFINING

Depending on the raw material and the smelting process used, the product of the smelting process could be copper prills, black copper – iron-contaminated copper from smelting copper oxide ores using a flux (Merkel 1990:83) or matte – mixed iron and copper sulphide (Tylecote 1987:201). All of these products had to be further processed, from simply re-melting to refining, to prepare the copper for the next stage in the process. A crucible, ideally covered with charcoal to provide reducing conditions and thus to prevent the copper from oxidizing, could have been used. Perhaps later, small furnaces were used for this process. Achieving the right temperature while at the same time avoiding oxidization of the copper requires specialist knowledge.

ALLOYING

Contrary to commonly expressed opinions, it is not necessary to alloy copper. Depending on their intended function, perfectly useable artefacts can be made from pure copper. Experiments on flanged axes have shown that un-alloyed copper axes are suitable for cutting thick branches of wood continuously for about 30 minutes before re-sharpening is needed. It is true that an artefact of the same type and size made of tin bronze could be used for the same activity for six times as long (Kienlin and Ottaway 1998). However, colour, not time, may have been the most important consideration in tool manufacture. In any case, our notion of time is not necessarily the same as that of prehistoric populations. This has been highlighted in a recent study which showed the discrepancy of attitude to time in present-day and earlier Nigerian indigenous Igbo populations (Eze-Uzomaka 2000).

It is perfectly possible that pure, un-alloyed copper artefacts can be multi-purpose implements, which could be put to occasional practical use but may also have been valued for symbolic or prestige purposes. They could also have covered the entire range from tool, to tool-weapons, weapon-tool and weapon, as proposed by Chapman (1999). For instance, most of the shaft-hole axe-adzes of the Chalcolithic Tiszapolgár culture of Hungary were made of pure, un-alloyed copper (Bognár-Kutzian 1972). As suggested by Patay (1984:18) they could have been used as tools, as real or symbolic weapons or as status symbols. A priori assumptions on classifying objects, e.g. as weapons, will not further the study (Carman 1997) and only new contextual studies combined with use-wear analysis will provide reliable answers (Bridgford 1997, 2000). All these considerations on the problems of determining the function of copper implements hold equally true for alloyed copper artefacts.

The earliest alloy in prehistoric Europe found prior to the Bronze Age was arsenical copper, also called arsenical bronze. By the Bronze Age, this was replaced by bronze, a tin-copper alloy. The advantages of an arsenical copper alloy against pure copper are a lowering of the melting point, improved quality of the cast, increased hardness through cold-working, improved hot-workability and its changed aesthetic value through the creation of a more silvery colour. Inverse segregation can heighten this silver colour on the surface of an artefact, which, over time, turns into a more golden colour (Northover 1989). It is sometimes assumed that it was the silver colour of an object which persuaded prehistoric smiths to alloy copper with arsenic (Mohen 1990). Except for the silver colour, the advantages of tin bronzes are essentially the same as those of arsenical copper (Charles 1985; Ottaway 1994:129).

It is debatable whether the earliest alloys are intentional or accidental (Budd and Ottaway 1995; De Marinis 1992; Hauptmann and Weisgerber 1985). Both scenarios are equally possible, as copper does occasionally occur in association with arsenical ores. One way of testing whether an alloy was chosen for its technologically superior quality over pure copper is investigation of the metallographic structure, which shows whether an alloy has been hardened thereby making optimal use of the alloy's properties (Budd and Ottaway 1991; Hook et al. 1991; Vandkilde 1996:268). Another way of testing the intentionality of alloying is to see if certain types of objects were consistently made of a particular alloy. This has been shown for so-called prestige items from the fourth millennium BC Nahal Mishmar hoard, and from Shiqmim, Israel, where rings (crowns), ornamental tubes (standards) and mace heads were made of copper alloyed with arsenic and sometimes antimony and nickel. Tools such as axes, adzes, chisels and awls, on the other hand, were made of pure copper (Shalev 1991; Shalev and Northover 1993). It is thus suggested that, even if the earliest alloys were accidental, it is more than likely that prehistoric smiths recognized the changed properties, such as colour and hardness, and would have aimed to reproduce the effect by an intentional search for the minerals which could enhance the properties of pure copper.

The intentional alloying of copper with another mineral is an innovation. It enabled the smith to influence and determine the final end product, as well as choosing the most desirable property, be it a more silvery colour, a metal which could fill a mould more readily, a metal that could be work-hardened to a higher degree without cracking, or a metal which gave a specific sound and colour and acted thus as a cultural signifier (Hosler 1995). The degree to which tradition can influence the choice of metal or alloy has been shown recently by Lahiri (1995). In the prehistoric Harappan culture, with additional information from the ancient *Vedas* text (from 1500–600 BC), the choice of metal had no technological implication but indicated ritual dimensions, some of which are still in force today. It was also found that craftspersons dealing in pure copper were, like their products, superior to those dealing in alloys.

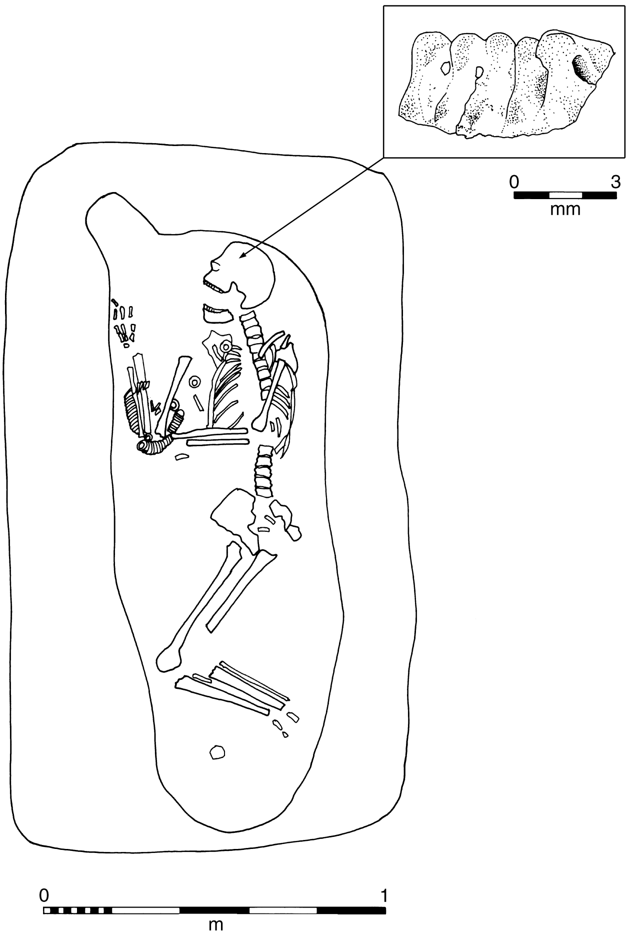

Figure 7. *A row of very small tin beads found positioned on the skull probably of a young woman in an early Bronze Age grave at Buxheim, Bavaria (re-drawn by Jo Mincher with kind permission of Dr K.H. Rieder).*

Many aspects of alloying indicate that it is a craft specialization. An example is that the potentially poisonous fumes given off by arsenic can effectively be contained by covering the crucible with a layer of charcoal – a technique known only to the specialist. The relatively uniform composition of some alloys produced in prehistory still astounds modern metallurgists. The degree of control necessary to achieve the desired alloy indicates the involvement of a specialist. Perhaps the early Bronze Age grave, probably of a young woman, excavated recently in Buxheim near Ingolstadt, in Bavaria, belonged to such a specialist, for it contained a necklace of 47 very small (5–6 mm) uniformly cast and perforated tin beads (Fig. 7) (Möslein and Rieder 1998). The tin beads could represent a perfect, although small, unit of tin to be added to small amounts of copper to make tin bronze.

Casting

Almost the final stage in the sequence of operation of producing a metal artefact was to bring the metal into its intended shape. It is possible to produce many of the early simple artefacts by hammering alone, either by cold hammering or by a cycle of cold hammering and heating of the metal (annealing). Most of the more complex shapes were, however, produced by casting. Sand, stone, clay and bronze may all have been used as casting medium (Ottaway 1994:111). For intricate

Figure 8. *Successful experiment of casting a socketed bronze axe in a bronze mould. (Photo: Tony Swiss.)*

metal artefacts, the lost wax method was most suitable. Each one of these methods of casting are innovations and probably the result of many more or less successful inventions. Only metallographic analysis of prehistoric artefacts, of which there is a great dearth, can tell whether an object was cast or shaped by hammering and there is work in progress which may eventually be used to show which moulding medium was used (Swiss and Ottaway, in press).

Although some moulds are known from early Bronze Age contexts such as the Feinan region (Adams 1999:230) and in Italy (Hohlmann 1997; Pearce 1991), with numbers increasing in the later Bronze Age, only a few moulds have been found in the earliest contexts of metal-working. Their number does not match the cast objects found in these early periods and it has been suggested that sand moulds, which do not leave any trace in the archaeological record, may have been used (Seibel and Ottaway 1998).

The simplest forms cast in moulds are ingots, such as the crescent-shaped ingots in the Levant (Adams 1999:105). Most had a standard shape and were used for exchange purposes. For Europe, it has been suggested that flat axes were used as ingots (Krause 1988; Krause and Pernicka 1998; Pearce 1998), a thesis which has been accepted and discussed by Lenerz-de Wilde (1995) who also suggests that, from the early Bronze Age onwards, ring and rib ingots of a standardized weight were probably in use as exchange medium in central Europe. According to new results, some of them may even have been subjected to material testing procedures and indirect control of composition (Schmalfuss and Pernicka in press).

Our experience in casting with sand and metal moulds indicates that the process of casting needs specialist knowledge, or failure is certain (Fig. 8) (Eccleston and Ottaway in press; Kienlin and Ottaway 1998; Swiss and Ottaway in press). Experience and expertise were clearly of paramount importance if composition and properties of the alloys were tested. It follows that early Bronze Age craftspeople had to master production processes sufficiently well to satisfy and pass these controls.

SMITHING

The final stage, smithing, involved the hammering, grinding and polishing of the artefact after it emerged from the mould. Several purposes were served: removal of the feeder, of the flashing and of the casting seam if it was cast in a two-part mould; possibly hardening of the cutting edge(s); the finishing of decorations; and bringing the object up to its final state. This involved many hours of hard work, using sandstone, water, sand, and probably fleece or skin. While many of these activities could have been carried out by unskilled workers or by apprentices, careful

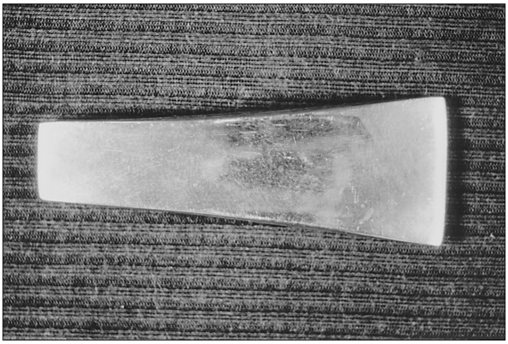

Figure 9. *Replica of the Iceman's axe. Length 9.3 cm. (Photo: author's own.)*

supervision by a skilled craftsperson was required for the success of the final product.

Even when a metal object was not of a standard shape, size or weight, there is no doubt that it was exchanged widely as part of social transactions which carried with it its own message (Ottaway and Strahm 1975). Only in this way can we explain the intriguing fact that almost all flat and flanged axes, such as the Iceman's (Ötzi) axe (Fig. 9), daggers and many other 'tools' were polished over the entire surface, even though most of that surface would be hidden by the haft (Fig. 10). Indeed, Nakou (1995) has observed that many hafted daggers looked very similar to the beholder of the finished object, although differences in shape were masked by the haft. Only the maker of the dagger would know what was underneath. This gives a fascinating glimpse into the attitudes towards the giving or withholding of knowledge, which must be studied further.

PRODUCTION OF FUEL

The production of fuel is a vital aspect of metal production, yet there have been no comprehensive studies on this subject. There are several steps in the *chaîne opératoire* of making metal from its ore where a good supply of fuel is essential. These are mining, roasting, smelting, refining, alloying, casting and smithing, all of which require a fire whose temperature and atmosphere must be controllable.

Depending on the geographical location, fuels can include wood, charcoal, peat, bone, dung, date kernels and other organic material and, in later periods, coke and coal. Tylecote (1986:223) has identified two primary groups of fuel, both of which are used in metallurgical processes. He distinguishes between long-flame fuels, such as wood, and short-flame fuels, such as

Figure 10. *Replica of the Iceman's hafted axe. (Photo: Leo Gosland.)*

charcoal. While the former produce an oxidizing atmosphere, useful for roasting ores, the latter produce high heat, are slow-burning and produce a reducing atmosphere required for smelting copper oxide and carbonate ores. It is assumed that, in temperate Europe, the most common fuel in metal production was charcoal.

Medieval European sources, as well as ethnographic evidence, suggest that there are basically two types of charcoal production: one type uses an underground pit, or pit kiln (Horne 1982), or pitstead (Kelley 1986:9), the other an above-ground stack, also called the 'heap burning process' (Schubert 1957:222). In both methods, the wood is set alight and then left to carbonize by the control or exclusion of air. Depending on the amount of wood and type of production method used, the duration of carbonization ranged between 1 and 15 days. During this time, the process had to be continuously monitored and success or failure, as well as quality of the charcoal, depended on the experience of the operator.

Different timbers have distinct characteristics and it is probable that these were exploited. Hard woods are the best types of wood and analysis of charcoal from prehistoric mining and metalworking sites show that oak and beech were indeed two of the most commonly used species (Marshall et al. 1999; Mighall and Chambers 1993:72). Hillebrecht's (1989) study of medieval charcoal production in the German Harz region indicates intense exploitation of certain resources, leading to a decrease in biodiversity. At the same time, archaeological evidence for the production of charcoal is often ephemeral and can be easily overlooked (Hillebrecht 1989, Figs 23.3 and 23.4).

Depending on the intensity and type of the metal-working process, the quantity of requisite fuel could be considerable. However, Marshall's research on the environmental impact of mining and metal production in Austria from the Roman period to the present has been able to show that it did not have the drastic effect on the environment usually assumed (Marshall 1992; Marshall et al. 1999). The only noticeable effect on woodland noted in the pollen record by Marshall was a decrease in beech. Documentary evidence from nearby copper works shows that *Fagus* was, indeed, preferentially exploited as a source of charcoal for copper-producing furnaces. The absence of wholesale woodland clearance suggested careful management of woodland resources. These results are supported by research from Wales and Ireland (Mighall and Chambers 1993, 1994), which also suggest that Bronze Age mining did not have an overly destructive impact on the environment.

The maintenance of long-term and effective fuel production thus requires extensive and wise woodland management. That this was not always the case has been demonstrated by the gradual deforestation around the village of Toumra in the Sudan, where, in the early 1980s, blacksmiths had to walk two days to get wood for their work since the supplies nearer the village had been completely used up (Haaland 1985). Similar deforestation could have been seen in the medieval copper mining region of the Radmer in Austria during the sixteenth century AD (Gröbl 1986:161). Here forests had been assigned to certain producers and their owners were compelled to sell their wood at a fixed price. The result, however, was competition for limited wood resources and the start of a strong illegal trade, particularly in periods of rising copper prices. In the end, the costs of charcoal production and transport exceeded those of mining and smelting.

On the other hand, Lindsay's (1975) study on the Lorne iron furnace of Argyllshire in Scotland in the eighteenth century AD has shown that, from the beginning, the industry ensured its charcoal supply by long-term contracts with local landowners, and careful protection, coppicing and management of woodland. The demise of the industry removed the incentive to maintain the forest, leading to its progressive neglect and deterioration.

It can thus be seen that effective charcoal production required long-term planning, organization, skill and knowledge. It involved one specialist or a group of experts who where conversant with the techniques needed for the successful production and continuous supply of fuel.

SUMMARY

To summarize: in studying the operational sequence of producing a metal artefact from copper ore, innovation could be observed from the moment the copper ore had to be crushed to a certain size in preparation for smelting. From then on, every single step in the production sequence required the invention of a new method to carry the process through to its final result: the copper object. Innovative techniques had to be developed to reach the reducing temperatures necessary to achieve even partially smelted copper from carbonate or oxide ores. By contrast, lower oxidizing temperatures were needed to roast sulphide copper ores prior to smelting under reducing conditions and this needed innovative procedures. Refining and alloying were both completely new processes, not hitherto known in the repertoire of knowledge. And finally, casting and smithing required a multitude of inventions before they could successfully and repeatedly be conducted. All these inventions had to be accepted by the community and passed on to members of the group other than the inventor before they were innovations which had any chance of surviving more than one generation – and thus had a chance of producing material remains which were incorporated in archaeological sites.

The earliest metal objects, for example those excavated in Romania, Bulgaria and Yugoslavia, from Neolithic contexts, are often called 'trinket metallurgy' because they were made in the shape of objects such as awls, beads and fishhooks. These objects already existed in other materials, such as bone and stone. It is possible that this was a reflection of the inventor 'playing safe' and not wishing to 'violate community norms' (Arnold 1985:220). This meant staying within the framework of known forms with the new material until such a time when the invention had been accepted by the community. Only then would it be culturally possible to experiment with new forms. Sometimes these new forms showed the beginning of an invention, as in the case of the copper shaft-hole axe from the Ai Bunar copper mine, in Bulgaria, which had been laboriously perforated by grinding out the metal as if it were a stone axe (Chernykh 1978). Later, these shaft holes were created during the casting process by inserting a core into the mould. In fact, the core was a small but profound innovation allowing hollow objects and hafting holes to be cast at the same time as the object was cast.

When examining the extent to which the metal production sequence involved specialists, it became obvious that specialists had to be included right from the beginning of the sequence. Several stages of the sequence could have been achieved by non-specialists, including ore collection, hand sorting of the crushed ore, operating the bellows during the smelting, the actual roasting of ore and the grinding and polishing of the object to its finished state. Nonetheless, specialist guidance of the overall operation was vital to ensure success. All the rest of the operational chain in the production of copper – viz., smelting, refining, alloying, casting and smithing – involved direct action from specialists. As the consistent production of things by some people for others, specialization in the archaeo-metallurgical case mostly meant producing something that was a necessary step in the next part of production. Only rarely is archaeological evidence good enough to distinguish between exchange of these intermediate products between groups and the concentration of the sequence of production in the hands of a single group. In this domain, analytical results are ahead of archaeological ones and the social organization of any of the production stages must now be investigated with rigour.

Sometimes we get a glimpse of the social organization of metal-producing communities. More than 10 years ago, I suggested a model which tried to explain the following complex situation. Two copper axes, excavated at the fifth-millennium cal BC Bulgarian copper mine of Ai Bunar, were not made of the copper mined at Ai Bunar. At the same time, analysis of copper mineral samples from settlements in the vicinity of Ai Bunar and copper implements excavated all over Bulgaria and further afield in south-west Russia, were found to have been made of copper mined in Ai Bunar (Chernykh 1978). A hypothetical central place was proposed for the smelting of ores from a number of different mines (Ottaway 1981). Todorova (1978) suggested that such a metallurgical centre might have been located near the Lake Varna settlements and recent excavations at Durankulak seem to provide support for this hypothesis (Todorova in press). The nearby Copper Age Varna I cemetery, with its striking indication of ranking in the form of high-status weapon-rich (male) graves (Chapman 1999; Ivanov 1988; Renfrew 1986), could also support the existence of such a hypothetical central place.

At Rudna Glava, in former Yugoslavia, no smelting sites have been found in the vicinity of the mine. However, excavations at Selevac, a Vinča settlement site of the fifth and fourth millennium cal BC, *c.* 80 km from Rudna Glava, revealed traces of smelting of copper ore as well as production of malachite beads (Glumac and Tringham 1990). It is likely that, in this region, the earliest smelting of carbonate ores took place in settlements at a very small scale, thus explaining the absence of smelting sites near the mine.

Sometimes, it can be seen how an invention was lost or lacked the specialization necessary for its continuation. Analysis of a small number of copper objects and copper prills from late Neolithic contexts at the Götschenberg, in the Austrian ore region of Mitterberg, indicated their derivation from oxide copper ores. However, one piece of sulphide copper ore from the area was found to have been roasted

(Lippert 1992:41; Moesta 1992). Could this indicate a period of experimentation with smelting of the more commonly occurring copper sulphide ores? Later Bronze Age occupants at the same site used crushed pieces of slag from smelting sulphide copper ore as a filler in their pottery, clearly showing that, somewhere in the vicinity, smelting of sulphide ore was now a successful process (Lippert 1992; Ottaway 1998). At the Klinglberg, not far away, the same filler, crushed slag, was used in pottery, indicating that smelting copper sulphide ore was now a regionally accepted technique (Shennan 1998, 1999).

At the Trentino the picture was different again. It seems that a fully developed smelting technology was introduced into the region during the Chalcolithic/early Bronze Age. When more metal was demanded, the smelting process was moved up into the mountains to be close to the resources. From this time on, there is evidence that the production sequence included all the steps from mining to casting ingots or artefacts.

From these examples, fragmentary though they are, it can be seen that a mosaic of individual regional patterns emerges. This does not imply that the original idea of metallurgy arose independently in each region. Rather, it could imply incomplete transmission of knowledge, deliberate or otherwise, by human agency and/or by the information given by the metal artefacts themselves, and local adaptation of the various stages in the operational sequence. Some of the material showed a tight control of the end product but this seemed to have been confined to certain special types of artefacts (ingots, prestige items) and not to others. Each region followed its own trajectory of innovations and developments which could be reflections of social organization or the structure and worldview of local communities, sometimes coupled with environmental factors within that region.

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BIOGRAPHICAL NOTE

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ABSTRACTS

Innovation, production et spécialisation dans la métallurgie du cuivre au début de la préhistoire

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Le processus de la production du cuivre et du bronze est présenté ici comme une opération continue. Chaque étape du processus peut influencer le produit final. L'analyse de ce processus, étape par étape, est donc un moyen adapté pour examiner chaque stade séparément, en utilisant des études-type archéologiques de différents endroits de l'Ancien Monde, et, au besoin, des études ethnographiques. Cette recherche se concentrera sur deux aspects: l'innovation et la spécialisation. Il faut dépasser les seules limites technologiques, c'est-à-dire situer l'étude technologique dans le contexte des sociétés qui pratiquaient et agençaient cette technologie et donc influençaient son exécution.

Innovation, Produktion und Spezialisierung früher prähistorischer Kupfermetallurgie

B.S. Ottaway

Die Kupfer- und Bronzeherstellung wird in diesem Beitrag als Abfolge verschiedener Schritte dargestellt. Jeder Schritt dieses Prozesses kann das Endprodukt beeinflussen. Diese Untergliederung ist eine praktikable Möglichkeit, um unter Einbeziehung archäologischer Fallstudien aus der Alten Welt und - wo es sinnvoll erscheint - ethnographischer Untersuchungen, jeden einzelnen Abschnitt des Produktionsablaufes zu analysieren. Die Untersuchung konzentriert sich auf zwei Aspekte: Innovation und Spezialisierung. Sie versucht, über technologische Aussagen aufgrund der Beziehungen der Technologie mit dem Kontext metallverarbeitender Gesellschaften hinauszukommen.