Environmental and health effects of early copper metallurgy and mining in the Bronze Age

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Abstract

Copper was a vital metal to the development of the Bronze Age in Europe and the Middle East. Many mine locations and mining techniques were developed to source the copper and other elements needed for the production of arsenic or tin bronze. Mining came with many associated health risks, from the immediate risk of collapse to eventual death from heavy metal poisoning. Severe environmental pollution from mining and smelting occurred, affecting the local mining community with effects that can still be felt today. This essay aims to establish that copper mining and manufacture had dramatic effects on the environment and health of people living in Europe and the Middle East during the Bronze Age. It goes on to speculate that heavy metal poisoning may have contributed to the increase in fractures seen between the Neolithic and Bronze Age.

Keywords

copper, Bronze Age, mining, health, environment

Introduction

The Bronze Age in the Middle East and Europe occurred approximately 3200–600 BCE. During this period, the importance of copper and its alloys grew to dominate society. The earliest uses of copper occurred in the Neolithic Period before its use in tools or weapons. Copper and its ores were used for colouring in ointments and cosmetics such as the vibrantly coloured oxide malachite. The trading and manufacturing of bronze weapons quickly became essential for the survival of Bronze Age societies in times of warfare. Bronze weapons were superior—in terms of sharpness, durability, weight and malleability—to other materials available at the time. They could be easily repaired and resharpened, or even melted down and made into another object (De Jesus 1980).

Although copper was easily found in surface outcrops, it would not have performed as well as tools or weapons fashioned from stone or flint, as the pure metal is considerably softer. The importance of copper began to rise with increased knowledge, such as the formation of harder copper compounds when combined with arsenic or tin. Pure copper can be hardened into smelted copper by the process of beating and quenching the meal to harden it (De Jesus 1980). Due to increasing demand for copper, native copper supplies became rare and other sources had to be found, as well as the development of more effective ways of processing the desired materials from the slag (stony waste material). The process of mining, smelting and roasting to separate out the desired metals released poisonous gases into the environment and resulted in a lot of physical waste in the form of slag piles. The released fumes and discarded materials affected not only the people in direct contact with them, but also the environment around them. The consequences of this environmental pollution can still be seen today in areas such as Wadi Faynan in Jordon, where waste from ancient copper mines continues to pollute the surrounding environment (Pyatt et al. 2000; Grattan et al. 2007).

This essay will focus on the dramatic effects that copper mining and manufacture had on the environment and health of people in Europe and the Middle East during the Bronze Age, 3200–600 BCE. It will examine where copper was sourced and how it was extracted in Europe and the Middle East, the important properties of tin and arsenic copper alloys, and dangers associated with mining. The environmental and health effects of copper mining will then be explored, focusing on the toxicity of the metals involved. A case study of the Wadi Faynan (also spelt Feynan, Fuynan, Feinan) in southern Jordan will be used to highlight the effects of metal manufacturing on the environment. Potential effects from increased levels of metal pollution across the ancient world will be proposed.

Copper mining: Locations, metal extraction and dangers

The major Middle Eastern and European copper sources utilised in the ancient world were located in Spain, Anatolia (now known as Turkey), Jordan and Egypt. The production and use of copper and its alloys began earliest in Anatolia and the Near East by 8000 BCE, and spread from east to west through the Mediterranean, with the earliest sites dating from 5500 BCE (Kassianidou and Knapp 2008).

Copper naturally occurs in three main forms: as native metal, an oxide or a reduced sulphide ore. The ores, in turn, are associated with other metals and the concentration of these metals can dramatically fluctuate depending on geographical location. In Turkey, the most common form in which copper is found is chalcopyrite, a copper sulphide. It is frequently found in association with lead and zinc, and when this occurs all three metals can be mined and smelted from the same source (De Jesus 1980). Copper ores could be identified using a number of methods. Some are brightly coloured, and are often found in association with other, less vibrantly coloured, ores. The taste of water and presence of copper tolerating plants such as *Silene inflate* can also be used to identify copper ores (De Jesus 1980; Kassianidou and Knapp 2008).

Active mining for metals most likely started on a small scale, with limited numbers of local people and simple 'open cast' pit mines, where material is removed directly from an open pit. As soon as tunnelling techniques were adopted, many more people were required (250–300 men according to estimates from De Jesus 1980). This included jobs outside of directly tunnelling, which would be needed to support the operation such as smelting, prospecting and food provision (De Jesus 1980). Another mining technique that was used was trench mines, which followed the vein of ore into the ground. These were only as wide as the ore vein itself. An example of this approach is seen in a tin mine in Karnab, Uzbekistan. It shows that women and children must have been involved in excavations, as in some places the mine was so narrow that no grown man could have worked in it (Cierny and Weisgerber 2003).

Once the ore is found, the desired metal must be separated. The ore was often first roasted to oxidise the copper and to get rid of components with lower melting points, such as water and sulphur (Erb-Satullo et al. 2014). The metal itself is removed by smelting, a process of heating the ore beyond the melting point of the desired metal. This is often done in the presence of either reducing or oxidising agents such as elements found in air. To get the high temperatures required to do this, furnaces and bellows had to be developed. Examples of these were discovered at the Wadi Faynan site and are thought to have been wind driven (Kassianidou and Knapp 2008).

There were many dangers associated with mining, in particular the toxic byproducts, risk of collapse, lack of ventilation and dust inhalation. Open furnaces that allowed air to circulate also enabled the toxic byproducts (such as the poisonous and foul-smelling gas sulphur dioxide) to escape into the environment (Thompson Rowling 1967), reducing inhalation by workers, but increasing environmental pollution. In extreme cases, the environmental pollution can lead to decreased crop productivity, increasing the risk of famine and food shortages. It also causes bioaccumulation of metals in plants and animals that is passed on to the humans consuming them, and leaves them severely physically weakened by the contaminates consumed (Pyatt et al. 1999, 2000). The specific effect of the contaminates would depend on the kind—for example lead or copper—and the concentration consumed over a period of time.

Collapse is always one of the biggest risks of tunnel and trench mining (Figure 1). In the trench mines of Karnab, not all of the ore vein was extracted, with miners leaving bridges of the original ore as support structures (Cierny and Weisgerber 2003). In tunnel mines, pillars made from wood or stones were very common, with many examples from all over the world being found. Other approaches to supporting tunnels were to support the roof with wood and to fill in old, unused tunnels with stones or debris. Nevertheless, collapses seem to have been very common in many ancient mines, as the remains of buried miners have been discovered inside. The danger of further collapse must have been clear to their fellows, as in many of these cases there does not appear to be a huge amount of effort made to free the trapped miners (De Jesus 1980). This can be seen in the discovery of more than 50 miners who had been trapped about 3,000 years ago by a collapsed tunnel entrance in Koniah, Turkey (Sharpless 1908).

Figure 1: Three vertical copper mine shafts in Wadi Faynan
Source: Volker Umpfenbach 2011, reproduced with permission.

Another major problem in long tunnel or shaft mines was ventilation. Oxygen was used up by the miners themselves and ventilation was necessary to overcome the effects of dust and heat buildup. This issue was exacerbated when fire had to be used to break the rock, as this used up all of the oxygen in the mine. Without adequate ventilation, work had to be abandoned until the fumes naturally left and oxygen levels were restored to a level supporting life. Aside from this, options included digging small parallel holes that joined the working tunnel at intervals to create a draft, or piercing air holes from above when the tunnel depth allowed for ventilation. Two other methods used to increase ventilation by creating a draft were lighting a fire under an air hole and shaking a linen cloth. While these methods would have partially worked, the mines would still have been incredibly unpleasant places to work in, being hot and stuffy with minimal oxygen and a large amount of dust (De Jesus 1980). The large levels of dust present in mines can lead to anthracosis, a condition resulting from long-term exposure to dust particles containing silicon, quartz or carbon (Thompson Rowling 1967; De Jesus 1980; Ghanei et al. 2011). However, it is difficult to definitively determine the cause of anthracosis in ancient cases as it can be caused by active tuberculosis or previous infection with *Mycobacterium tuberculosis* (Ghanei et al. 2011).

Properties of arsenic and tin bronze

Arsenic bronze, the addition of arsenic to copper, was the first kind of bronze to be made, followed by the addition of tin to copper to create tin bronze. Arsenic bronze is the most widely used metal alloy of the Bronze Age, being found at all important sites from this time period in the Middle East and Europe. Arsenic bronze was the first form of bronze to be created and widely used, later followed by tin bronze. There are two main theories about how arsenic came to be alloyed with copper: the copper deposits mined already had arsenic present or arsenic was mined separately and co-smelted (Merideth 1998; Oudbashi and Davami 2014). It is likely that both of these events occurred as copper ores containing arsenic do occur, and so could have been accidentally incorporated this way. However, these ores are a less common form of copper ore and are often associated with lead (De Jesus 1980). Tin bronze was introduced later than arsenic bronze and both alloys continued to be used, though the amount of arsenic bronze decreased over time (De Jesus 1980; Kassianidou and Knapp 2008). Interestingly, tin and arsenic bronze appear to have been kept actively separated, and not melted together, in either scrap form or after smelting, despite examples of both being used in the same object (De Jesus 1980).

Smelted copper was also used in the ancient world and is produced by a process of working and annealing, in which the copper is hammered and stretched towards the desired shape. It is then heated to a specific temperature and allowed to slowly cool to retain its ductility (Merideth 1998). Bronze never completely supplanted smelted copper, and items made from smelted copper have been found that date to the Bronze Age (Birmingham 1977).

Theories as to why the amount of arsenic bronze decreased include that tin was favoured for safety, given the highly poisonous nature of arsenic (Birmingham 1977; De Jesus 1980), or that tin ores were more readily available. Another theory proposes that arsenic bronze was harder to create with appropriate levels of arsenic as losses are high during roasting, smelting and refining. However, there is conflicting support for this theory (McKerrell and Tylecote 1972; Branigan 1974). It is likely that a combination of the poisonous nature, rarity of arsenic ores and difficulties in manufacturing led to the reduction in the amount of arsenic bronze produced after the middle Bronze Age approximately 1600 BCE (Birmingham 1977; Kassianidou and Knapp 2008).

Different ratios of tin or arsenic in copper change the characteristics of the bronze they produce. The addition of tin or arsenic results in a harder metal that is easily cast and hammered. However, the amount of metal (either tin or arsenic) that needs to be added to achieve the desired harder bronze is unclear. The optimal per cent of arsenic desired in bronze is not consistent across the literature. An intentional alloy is defined as one with more than 2 per cent arsenic or tin, as they could otherwise just be the result of impurities in the copper ore (Merideth 1998). Branigan (1974) states that more than 2 per cent arsenic makes the bronze brittle. This is in contrast to Merideth (1998), who establishes that ideal arsenic content is 5–7 per cent, which will result in a much harder and more durable metal than smelted copper when cold worked at under 300°C. The desired amount of tin in bronze is also inconsistent across sources, with proposed optimal amounts of 7–8 per cent (Primas 2003), 10 per cent (Cierny and Weisgerber 2003) and 18 per cent (Oudbashi and Davami 2014).

Another metal that is sometimes added to tin and arsenic bronze is lead. This is often found in association with copper ores and the effects that it has on bronze are disputed. Branigan (1974) maintains that lead is insoluble in copper and weakens it by forming globules in the copper matrix as the phases solidify at different rates. Merideth (1998) states that lead was added to tin bronze as it allowed better flowing capacities for casting objects. Morr and Modlinger (2014) add that while they are not sure that lead improved the castability of the metal, there is an association found between cast items and leaded alloys. This is elaborated on further in that the addition of lead was detrimental to copper alloys if they were then hammered. Another suggestion they propose for why lead was added is that it was used in areas with fuel shortages to reduce the melting temperature and therefore the amount of fuel needed. Primas (2003) concluded that lead was added for sound technical reasons rather than to save tin. This conclusion was reached using the grave goods of a bronze smith that date to 1100 BCE. These goods were technologically advanced compared to older examples and included items made of a copper-tin-lead alloy.

Toxicity and bioaccumulation of heavy metals

Copper is an essential element in human health; it is used in certain enzymes and for other bodily functions such as melanin transformation and forming links between collagen and elastin for the maintenance of connective tissue (Sandford 1993). As copper cannot be made in the body, it must be absorbed from the diet. Because of this, the body is also very effective at getting rid of excess copper; therefore many times more copper than required must be absorbed to produce adverse effects in the body. When this occurs, the symptoms include diarrhea, nausea, vomiting, coma, increased rates of lung and liver tumours and eventually death (Pyatt et al. 2005).

Tin is similar to copper in that it is an essential element (Sandford 1993); excess is poorly absorbed and 95 per cent is excreted. The remaining 5 per cent is absorbed in the gastrointestinal tract and circulates through the body before extraction through the kidneys. A small amount is deposited in the bones and lungs. For amounts in excess of 130 milligrams (mg) per day, buildup also occurs in the kidneys and liver. Effects begin as skin and eye irritation, progressing to nerve, liver and immune system damage (Winship 1988).

Lead and arsenic are much more toxic in smaller doses and are also carcinogenic, suppress enzyme activity and accumulate in bone (Flessel 1979; Aufderheide and Rodriguez-Martin 2006; Aufderheide 2011). Lead and arsenic are not essential in the human body and have a very slow excretion rate, so exposure results in cumulative effects (Aufderheide 1989).

There appears to be no minimal level of lead exposure for its toxic effects to be felt upon metabolism and neurophysiology (Needleman 1991) as it attaches to and inhibits enzymes (Bishop et al. 2013). As a result, acute (short-term) and chronic (long-term) poisoning can occur, showing slight variation in symptoms (Pyatt et al. 2000). General symptoms of lead poisoning are brain damage, anaemia, convulsions, nerve paralysis, osteoporosis and eventually death (Aufderheide 1989; Pyatt et al. 2005). At a minimum, blood levels should be below 0.05 parts per million (ppm) (4.2 ppm in bone from Martínez-García et al. 2005), as even at 0.1 ppm permanent intellectual and hearing defects can occur (Bishop et al. 2013). Lead retention in different areas of the body vary: the brain has a lead retention time of weeks while the bones retain lead for years. Bone is one of the most common places that lead builds up over time after being absorbed and transported in the soft tissue (Pastorelli et al. 2014). Lead can be taken up in a variety of ways, including eating contaminated food (especially cereals), animal products or water (Pastorelli et al. 2014), or inhaled after release from smelting lead containing ores (Grattan et al. 2002).

Arsenic toxicity is well established by Aufderheide (2011), Aufderheide and Rodriguez-Martin (2006), Flessel (1979) and Branigan (1974). Aufderheide and Rodriguez-Martin (2006) directly refer to mining of copper ores as a possible source of arsenic poisoning, and the smelting of said ores resulting in the production of highly toxic arsine gas. Poisoning can be either acute or chronic. In high enough acute doses, brain stem failure can occur, leading to coma and eventually death. At lower acute doses, damage to the kidneys, liver and gastrointestinal tract occur. After chronic exposure, symptoms are often peripheral neuropathy, skin changes, respiratory inflammation, increased risk of lung and skin cancer and blood clot formation (Aufderheide and Rodriguez-Martin 2006).

Lead and arsenic have detrimental long-term effects upon bone, which can be seen in the skeletal record. They both cause osteoporosis and increase the risk of fractures and breaks. Lead can also affect osteoblast cell number, leading to decreased bone formation (Beier et al. 2013). Arsenic poisoning has been associated with an increased cancer risk, particularly lung cancer (Järup 2003); but cancers caused specifically by arsenic are difficult to identify in the skeletal record (Ortner 2003; Aufderheide and Rodriguez-Martin 2006). If the level of arsenic is high enough to lead to cancer, the exposure would have been long term and result in arsenic deposited in the bones, which can be easily tested (Järup 2003).

The manifestations of high levels of heavy metal exposure in the skeletal record are varied. The main indication of heavy metal poisoning is assessed through analysis of the metal content of the bones and teeth. Care must be taken with this method as the leaching of metals from the soil into bone (and vice versa) can influence results so soil samples should be taken for comparison. Contamination can also occur from metallic grave goods and postexcavation exposure (Pastorelli et al. 2014). When comparing populations, samples should be taken from the same area of the skeleton, as heavy metal load in bone changes throughout the body. Some areas can have a much higher metal level than others (Martínez-García et al. 2005).

Environmental effects of widespread heavy metal pollution

The release of heavy metals from ancient mining and smelting offered an immediate danger to those extracting and processing them. On top of this, the released metals built up in the environment in a form that was easily accessible to plants, leading to bioaccumulation when they are eaten. This led to high levels of heavy metals in the soil surrounding processing and extraction areas, as well as being released into the atmosphere and spreading large distances around the world. This can be seen in high altitude mires of Switzerland, where accumulating concentrations of lead over natural levels began 5,500 years ago—the same time that more intensive mining methods began to be used (Grattan et al. 2007). The high levels of heavy metal pollution that are still present in ancient mining sites can also provide an insight into the effects that mining had on the immediate environment. By studying the impact of heavy metal loads on modern plants, animals and people, we are given insight into the impact of these loads on Bronze Age people (Pyatt et al. 1999, 2005).

Recent studies attempting to establish the effect of heavy metals on the ancient world have begun to focus on the environmental state of the modern sites. Wadi Faynan, a site of particular interest, is located in Southern Jordan and has been mined extensively for copper, iron and other ores from 6000 BCE through the Bronze Age and Roman-Byzantine times. The main metals polluting the site are lead and copper. It includes the site of the ancient Roman city of Phaino and consists of over 250 copper mines, associated spoil tips and extensive slag heaps, as well as a large field system used for food production (Pyatt et al. 1999, 2005).

The extensive mining that occurred in this location has left more marks than the obvious debris. Pyatt et al. (1999, 2005) studied this site, focusing on the current environmental impact of mining. In particular, they observed the animals that use the area, the growth rate of crops, and investigated the difference in heavy metal load between ancient and modern skeletons. The heavy metal load of the site is likely to be lower today than it would have been when mining ceased, as there has been time for extensive environmental weathering to occur. This weathering includes leaching, and atmospheric, sheet and gulley erosion. These processes ultimately pollute the areas surrounding them by redistributing the metal contamination (Pyatt et al. 1999, 2005).

Metals would have been slowly released into the soil and taken up by plants. To test the effects of heavy metals on plant growth, barley was grown on areas with varying pollution levels. Barley has been grown in this area for millennia, with wild barley still growing at the site. It would have been used as one of the primary cereals supporting the mining community and their animals. No difference in plant height was found between the polluted spoil tip and the control site; however, the number of viable seeds produced were almost doubled at the control site. At a more heavily polluted site, plant height was dramatically reduced from 13–15 to 6–10 centimetres. Seed potential was also adversely affected in the area of higher pollution, dropping to nine seeds per 20 plants. Because of the decrease in production effectiveness, food shortages would have been common. A much larger area would have needed to be dedicated to food production than at uncontaminated sites to compensate for the loss in production. Furthermore, workers would have been severely physically weakened from consuming contaminated food and direct inhalation of pollutants (Pyatt et al. 1999).

Herbivorous animals have few options for food in the Wadi Faynan, and had to eat contaminated material. Goats and sheep are the main domestic grazers in the area because when horses and cattle are grazed on grass grown in soils containing these levels of metal pollution (1,000 ppm lead detected) they die or become seriously ill. The bodies of goats and sheep grazed in the Wadi Faynan today were analysed for their heavy metal content. Goats have a higher resistance to copper and lead poisoning, but both species are able to tolerate higher levels of copper than lead. The highest concentration of metals was in the faecal matter, demonstrating that the metals could be excreted, and continue to be recycled into the soil. Despite this, the heavy metal content of the modern animals' bones was very high (293 mg/kilogram (kg) of lead and 46.5 mg/kg of copper from 24 goat skeletons), and all products such as milk and meat were contaminated. This has dangerous implications for the local Bedouin population, who rely on these animals (Pyatt et al. 2000). Contaminated animal products would have also adversely affected people working in this area in the Bronze Age, providing another source of heavy metal poisoning.

Pyatt et al. (2005) conducted a study comparing ancient human skeletal remains from the Bronze Age to modern copper and lead levels in human bone. The copper load of the Bronze Age sample was 27 times the typical amount of copper in human bone, and the lead load was also massively enhanced. It is unlikely that the ancient samples were contaminated from the grave environment as the heavy metal levels in the surrounding soil were considerably lower than the levels found in the bone (Pyatt et al. 2005).

Wider implications of increased heavy metal load

Higher levels of lead in bone have been noted across the ancient world after the intensification of mining practices. This is perhaps from atmospheric circulation spreading particles throughout the world's atmosphere (González-Reimers et al. 2005; Pastorelli et al. 2014).

A study by Erdal and Erdal (2012) provides an overview of the injuries sustained to skeletons dating from the Neolithic and Bronze Age in Anatolia (modern Turkey). They discovered that the number of fractures seen doubled from the Neolithic to the Bronze Age, and concluded that this was as a result of increasing interpersonal violence. However, they also added that these kinds of injures can also be attributed to accidents and daily activity.

A speculative explanation for the increase in fracture rates is heavy metal poisoning as a result of the increased mining in Anatolia. Heavy metal poisoning could both directly and indirectly lead to an increase in fracture rates. The direct effects of heavy metal poisoning by lead and arsenic is accumulation in bone and osteoporosis (Aufderheide 1989; Pyatt et al. 2005; Aufderheide and Rodriguez-Martin 2006; Aufderheide 2011), increasing the risk of fractures and breaks (Beier et al. 2013). The consequence of this decreased bone strength would be an increased likelihood of fractures or breaks occurring from accidents, daily activity or interpersonal violence.

Heavy metal pollution leads to an increased heavy metal load in the environment, which could have indirect effects on fracture rates. This increase can also affect locally grown crops, decreasing seed production the more polluted the site and increasing the amount of land needed to grow crops (Pyatt et al. 1999). It can also detrimentally affect or even kill grazing animals such as cattle or horses as the metals accumulate in their tissues. While sheep and goats are less affected by high metal loads, they still experience bioaccumulation of heavy metals through ingestion of contaminated feed or water (Pyatt et al. 2000). The effects of heavy metal accumulation on both plants and animals would have led to increased heavy metal loads in humans consuming the contaminated food. There would have also been reduced food productivity and an increased risk of famine and food shortages (Pyatt et al. 1999), placing stress on the local populations and potentially increasing interpersonal violence as people fight over resources.

The skeletal population from Titris Hoyuk studied by Erdal (2012) was in close proximity to mines used at that time. In particular, the silver and lead mines Keban and Pirajman, the lead and zinc mine Deri, and the copper mines Keydak, Ergani and Karabek were within 150 kilometres of the city (De Jesus 1980). This city was also reported to be experiencing resource stress and environmental deterioration during the Late Bronze Age because of both climate change and the overexploitation of the surrounding area (Erdal 2012). This is consistent with the environmental effects of heavy metal pollution detailed above. Further research, such as the heavy metal levels in the skeletons from Titris Hoyuk and the soil in which they were found, is required to add support to this theory.

Conclusion

This essay aimed to establish the dramatic effects that copper mining and manufacture had on both the environment and health of people in Europe and the Middle East during the Bronze Age. It detailed how and where copper was sourced and extracted, how bronze was made and the dangers to people conducting this work, both from injury during the work and the heavy metal poisoning they experienced. It was determined that the environmental pollution by heavy metals and the effect of this on people using the affected land was dramatic and can still be seen in areas such as Wadi Faynan today. It was speculated that heavy metal poisoning may have contributed to the increase in fractures seen between the Neolithic and Bronze Age.

The development of bronze and the mining associated with its production have had many unintended consequences. The miners were exposed to many dangers from the physical dangers of mining and the very real possibility of heavy metal poisoning during mining and bronze production. Arsenic bronze was eventually primarily supplanted by tin bronze, most likely because of the adverse health effects of arsenic and the increased availability of tin.

The release of heavy metals into the environment had detrimental effects upon the plants and animals living there, and the humans who depended on them for food. This can be clearly seen in Wadi Faynan, where the pollution levels are still very high and affect the living organisms there today. Heavy metals were spread around the world through the atmosphere and inhaled by the ancient population, resulting in increased heavy metal levels in bone. Lead and arsenic are particularly dangerous and may have caused the resource stress and increase in trauma injures seen throughout Bronze Age Anatolia. The discovery of bronze and its associated consequences paved the way for the development of modern life as we know it today. Our world has been greatly affected by it, and will never be the same.

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