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# Geological and Mining Constraints on Historical Mine Production: The Case of Early Medieval Lead-Silver Mining at Melle, France

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**Keywords**

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## Abstract

Early Medieval silver production for the Melle Pb-Ag deposit in western France has been estimated up to 15 tonnes per year over hundreds of years (Téreygeol, 2013) which would place it amongst the top silver mines of all times prior to the New World discoveries. However, this deposit has geological and mining characteristics economically unsuitable for substantial production, because it is thin, sub-horizontal and comprised of discontinuous pods. Furthermore, it is a Mississippi Valley type (MVT) base metal deposit, which are typically not major silver producers. There is no geological evidence for primary or secondary enrichment to generate silver-rich ore. In addition, the fact that Melle remained unmined in all later historical periods is enigmatic compared to the almost ubiquitous re-working of significant ore deposits elsewhere.

In this paper, I discuss the geological characteristics, mining parameters, documented historical mining rates and workforce considerations, all of which can be used to constrain production estimates for Melle. The largest uncertainty for production estimates is the workforce size, which reflects scarce information about Carolingian Melle and its surroundings. A model employing realistic mining parameters and a workforce appropriate for a small mining village (100 miners/fire-setters, within a workforce of 250-300, from a settlement of at least 400-500) yields 52 tonnes of lead metal and 150 kg of silver per year. Doubling the workforce would double this estimate. Conversely, it could be half or less if mining was a seasonal activity between agricultural priorities such as harvesting and seeding.

The previously claimed production rates require improbable mining assumptions together with at least 500 dedicated full-time miners and a population in the thousands. Furthermore, it would yield per capita silver productivity more than four times higher than in well-documented Early Modern operations that were leading silver deposits of their time. This seems unlikely. However, even at the much lower production levels, favoured here, Melle still might have been a major factor in the Carolingian economy, with its lead production perhaps as important as its silver.

## Introduction

One of the challenges for geologists, historians and archaeologists alike is to estimate historical production from past mining episodes at an ore deposit. Information from many sources can be applied, including: sampling of remnant ores; estimation of mining spaces; estimating waste or slag as proxies for ore processed; comparison with better-known mining operations; historical records; mint outputs; or through the indirect effects of mining output on economies. None of these is reliable in all circumstances.

Application of geological and mining knowledge can provide important constraints on production, yet these areas of expertise are generally under-utilized in historical and archaeological contexts (Killick, 2014). Appropriate mining parameters can be determined from orebody characteristics, while feasible mining rates can be established by comparison with other better-documented operations. Finally, the size and composition of the available workforce can be constrained from historical records or, where these are not available, more crudely through consideration of the settlement size and the range of tasks involved in the *chaîne opératoire*.

The Melle Pb-Ag deposit (Deux-Sèvres, Aquitane region) in western France is a good test case because



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it is well preserved and very well documented from an archaeological perspective (Téreygeol, 2007; 2013; 2018). Radiocarbon dating of charcoal in the workings indicates that it was mined continuously (or at least regularly) from about 400 AD to about 1000 AD (Téreygeol, 2013). However, one of the highly unusual features of this deposit is that mining apparently ceased around the end of the tenth century, and it has remained undisturbed; this is in marked contrast with almost all other sites of significant historical mining across the world.

Based mainly on an estimate of the volume of ore mined as indicated by the scale of historic workings, Téreygeol (2013) calculated total production over 600 years of 2,460 tonnes of silver at an average 4.1 tonnes per year (discussed further below). He also identified a peak period lasting some 250 years (650-900 AD), in which production is inferred to have reached and remained at some 15 tonnes of silver each year. Although Bartels (2014) has questioned these claimed production levels, based on comparisons with later and better-documented deposits, nevertheless they seem to be widely accepted amongst archaeologists, historians and numismatists.

Melle has been proposed as a major source of lead pollution in ice core records (Loveluck, et al., 2018; McConnell, et al., 2019). Others have identified its mine and coin mint output as major factors in monetisation of the Carolingian economy. For example, Coupland (2018, p.437) states that: "*Merovingian coins are known from Melle, but the very large number of finds from the pre-reform period reveals that it must have been Charlemagne who was responsible for the exploitation of new seams of silver on a grand scale at the Melle mines, offering a significant boost to the Frankish economy.*"

## Methods

This paper makes no new contribution of facts to either the geology or archaeology of Melle; rather, it seeks to demonstrate that important constraints on feasible production levels of lead and silver can be proposed, based on what is already known (or at least generally accepted) about the deposit type, the likely mining conditions, and the available technology.

The geology is first described, followed by the deposit type and its resource and production statements. Constraints on production are then evaluated, starting with those related to the geology (including deposit type and the potential for either primary or secondary enrichment), then those arising from available technology for mining, processing and refining. Last, the all-important (but poorly known) aspects of workforce size and allocation are considered.

All these are then brought together in a quantitative model for which three scenarios are presented and discussed in the paper. The model itself is contained in the online supplementary data. Data on mining rates and per capita productivity from numerous sources are compiled in tables to support the modelling. Several further issues such as mining waste and alternative silver sources are covered briefly in subsequent discussion.

## Geology of Melle

### General description

Melle mineralisation is distributed over an area of about 47 km$^2$ and occurs within flat-lying carbonate-platform sediments of Early Jurassic age. The carbonates overlie a basement ridge (the Poitou High) and are adjacent to thicker successions of deep-sea sediments of the same age in the Aquitaine Basin to the south, and Paris Basin to the north. Regional and detailed maps, together with a cross section for Melle, are presented in BRGM (Bureau de Recherches Géologiques et Minières, 1977, following p.29) and interested readers should also consult Karnay, et al. (2004) for additional geological information. Mineralisation extended beneath the current Melle Township, which sits on a low, incised plateau with stream valleys 40-60 metres below the ridge crest. It is part of a larger district of mineral occurrences over some 50 x 50 kilometres (BRGM, 1977).

Mineralisation is "epigenetic", being younger than the host sediments and related to Late Jurassic or Early Cretaceous hydrothermal fluids. Notwithstanding that, it is strata-bound and restricted to a single thin (6 m) marl unit, which was extensively altered to dolomite before mineralisation (Cathelineau, et al., 2012). Most occurs within the basal 3 m with galena the dominant sulphide and only important source of silver. Téreygeol (2018) noted the rare presence of acanthite and/or argentite, but only as minute inclusions in galena crystals. Analyses of galena reported in Sarah et al. (2012) contain 1-3 ‰ Ag by weight (note this grade was erroneously reported as 1-3 % by Téreygeol (2007), presumably as a typographic mistake for "parts per thousand"). Pyrite and chalcopyrite are minor components, whilst sphalerite occurs in the southern part of the deposit. Barite is present only in the north, along with traces of fluorite (Karnay, 2004). Other minerals reported include cerussite (lead carbonate, from weathering of galena), covellite, marcasite, and the iron oxide minerals goethite and limonite.

Cathelineau, et al. (2012, p.104) described the mineralisation as follows: "*Galena that occurs as centimeter-size nodules and disseminated grains in the doloarenite* [sic] *slightly precedes the growth of associated quartz, both minerals filling the geodic cavities and vugs in the silicified dolarenite*." Flat-lying veins and fracture infills are also described. Oxidised ore exposed in valley walls was the first target for mining, which then continued beneath the plateau. Eventually, vertical shafts would have been required to ventilate working faces and dissipate fire-setting fumes; Téreygeol and Dubois (2003) state that they were sunk every 10 metres. Workings are concentrated in areas where mineralisation was closest to the surface (Téreygeol, 2007) whereas Sarah, et al. (2012) noted that the distribution of workings was influenced more by proximity to the valleys than by grade of ore, an important point we will return to.

It is widely accepted that Melle belongs in the family of Mississippi Valley Type (MVT) base metal deposits (BRGM, 1977; Karnay, et al., 2004; Cathelineau, et al., 2012; Téreygeol, 2013). MVT deposits are major base metal producers around the world and their geology is well documented and well understood (Paradis, Hannigan and Dewing, 2007; Leach, et al., 1995; Taylor, et al., 2009; Ma, 2018). Melle is unusually zinc-poor but shares this character with a sub-set of lead-rich MVT deposits, including the famous Viburnum trend in the USA (Lasmanis, 1997). As discussed below, the fact that Melle is an MVT deposit has important implications for its potential as a silver producer.

### Resources and production estimates

Modern resource drilling described by Téreygeol (2013) shows that remnant mineralisation at Melle occurs in elongate and partly coalescing zones. He gives a remnant resource of 750,000 tonnes of lead and 1,400 tonnes of silver, a figure that is compatible with the descriptions, the stated maximum grades around 60-80 grams Ag per tonne (Karnay, et al., 2004, p.65) and the Pb/Ag ratio (see below). The resource is quoted in two categories: a low grade of "<40 kg Pb/m$^2$ "and a higher grade of "40-160 kg Pb/m$^2$".

The remnant resource has a Pb/Ag ratio of 536, which is within the normal range for MVT deposits: the median for 35 deposits compiled by Taylor, et al. (2009) for which silver data are available is 730, with 50 % lying in the range 390-1225. Since natural galena contains about 86.3 % Pb (86.6 % Pb if pure), then the "resource" ratio of 536 corresponds to a silver content in galena of approximately 0.16 % (assuming both Pb and Ag are entirely in galena, which is reasonable given the mineralogical descriptions).

It should be noted that both BRGM (1977) and Karnay, et al. (2004) incorrectly report the Melle remnant resources as 750,000 tonnes of lead and 14,000 tonnes of silver. Aside from yielding a Pb/Ag ratio of 53 (which is unlike any other MVT deposit), this claimed silver endowment would place Melle amongst the top ten silver deposits in the world, even excluding its historical production. For example, it would be twice the size of the famous Comstock Lode in the USA and two-thirds as big as Cerro de Pasco in Bolivia, arguably the world's largest known single deposit (Laznicka, 2006, p.127, 136). Presumably, the BRGM silver resource figure is a typographic error, but it is curious that it is repeated uncritically twenty-seven years later.

Téreygeol (2013, p.83, Tab.4) estimated that historical production at Melle amounted to 2,460 tonnes of silver. However, my re-calculation based on figures provided in Téreygeol's Figure 5 leads to a much higher production estimate than given in his Table 4. Adding the stated annual averages for each 50-year interval yields 4,900 tonnes of silver overall, with 3,870 tonnes in the 250-year "peak period" alone. This production profile would place Melle at the top of all silver deposits mined before the New World discoveries, substantially larger than estimated for the famed Lavrion mine of the Classical Greeks (~3,500 tonnes, Conophagos, 1980).

## Constraints on production

In the following sections, I will examine each aspect of the geology, mining conditions, available technology, workforce tasks and population size. The objective is to establish broad limits for developing a quantitative production model for Melle. Where information is inadequate, this is supplemented by comparisons with other, better-documented mining campaigns.

### Constraints from deposit type

Stable isotope and fluid inclusion studies (Cathelineau, et al., 2012) show that the mineral system at Melle developed at low temperatures (probably 100-110° C, but possibly as high as 160° C); this is entirely consistent with its classification as an MVT deposit. There is strong consensus amongst geologists that these deposits originate from reduced or weakly oxidized sedimentary brines derived ultimately from evaporated seawater (Leach, et al., 1995).

To better understand the hydrothermal geochemistry of the deposit, I will explain the significance of these observations. Within fluids of that character, and at temperatures of 200° C or less, the metals are transported predominantly as chloride complexes (Pal'yanova, 2008). However, the stability of silver chloride complexes in hydrothermal solutions at low temperatures is much lower than lead and zinc complexes (Shang, Hu and Fan, 2005). As a direct consequence of this, MVT deposits are much lower in silver relative to lead and zinc, when compared with other base metal ore systems that formed from fluids at higher temperature (such as epithermal deposits, magmatic-associated veins, etc.). In his authoritative book on silver geochemistry, Boyle (1968) discussed all major silver deposit types of the world but gave just passing reference to MVT deposits, noting they are generally low in silver. Likewise, as Paradis, Hannigan and Dewing (2007, p.187) noted in their compilation: "*Silver and copper content in MVT deposits is low and often not reported. When reported, silver grades vary from 10 to 161 g/t Ag.*"

The key message for non-geologists here is that MVT deposits like Melle have much lower potential for major silver production than is the case for many other deposit types. While a few MVT style deposits have yielded significant silver despite their characteristically low-silver tenor, this simply reflects their large production of lead and zinc concentrates. For example, the Viburnum trend deposits produced nearly 46 million ounces (1,400 tonnes) of silver as a by-product of over 10 million tonnes of lead metal and 1.3 million tonnes of zinc (Lasmanis, 1997). It is difficult to imagine medieval miners achieving substantial production rates of silver from an MVT deposit unless they encountered pockets of extraordinary silver grade or through supergene enrichment in now-removed portions; both these possibilities are further evaluated below and evidence is presented as to why they can be rejected for the Melle deposit.

## Was there primary or secondary enrichment?

Mining operations can cease for many reasons, including depletion of known high-grade ore. Normally any remnant ore will be similar in terms of mineralogy, but at lower grade than that formerly mined. However, two circumstances must be considered in which the ore removed by previous miners might have been markedly different, namely: i) where primary (hypogene) zoning operated to concentrate metals in specific zones; or ii) where supergene (weathering) processes acted to enrich some parts of the deposit in the weathering profile. Both mechanisms are well-documented in silver deposits, but did either occur at Melle?

Primary mineral zonation in an orebody can be either vertical or lateral. It is favoured in mineral systems where substantial variations in pressure or temperature are involved in ore formation, or where this occurred because of fluid mixing. While some genetic models for MVT deposits invoke fluid mixing, their formation does not involve substantive temperature or pressure gradients. Some MVT deposits change to more Cu-rich ore at depth and some districts have broad lateral variations in metal content. However, wholesale changes in silver grade or Pb/Ag ratios, either laterally or vertically within individual MVT deposits, is not expected and has not been documented in any hypogene (unoxidized) ore system so far as I am aware. At one deposit where this was proposed, further study revealed that a typical low-grade MVT ore had been overprinted by an unrelated and later stage of high-temperature Ag-rich veins (Brown and Ahmed, 1986). Likewise, silver enrichment in now-exhausted zones has been claimed in some Pb-rich deposits in England and Wales (Blanchard, 2001; Dunham, et al., 2001). However, those arguments seem to be constructed more to justify claims of high silver production than on any geological reasoning or hard evidence (refer detailed compilation and rebuttals by Claughton, 2003; 2010).

The thin and sub-horizontal, irregular but interconnected mass of MVT-style mineralization at Melle is highly unlikely to have possessed primary metal zonation sufficient to enable preferential extraction and exhaustion of silver-rich zones. Likewise, there is no evidence for the presence of any economically significant Ag-bearing minerals other than galena. I conclude, therefore, that the only realistic possibility for zones of higher-grade silver in Melle ore was at a small scale within the discontinuous pods of higher galena concentration described in the section on geology.

Supergene enrichment occurs when a particular horizon or zone in an orebody near the Earth's surface becomes enriched in metal relative to the primary ore on account of weathering processes. Therefore, supergene enrichment implies that weathering has occurred; however, weathering and the presence of supergene minerals do not necessarily indicate supergene enrichment. Any sulphide ore exposed to air or surface waters rapidly forms supergene minerals. For example, pyrite decomposes within months in the presence of air and humidity. Less well known is that galena weathers even faster. However, in normal (non-acidic) weathering conditions a thin layer of lead carbonate or sulphate grows on the galena crystals thus inhibiting continued breakdown (Anderson, 1930).

Supergene enrichment in a silver deposit requires three things: i) dissolution of a substantial quantity of silver-bearing primary mineral; ii) transport of the silver in groundwater; and iii) precipitation within secondary minerals in response to a change in conditions (pH, salinity, etc.). Its existence in many silver deposits is well documented and vital to their mining economics (Boyle, 1968, pp.118-207). For example, the Broken Hill region of Australia has spectacular examples (Liversidge, 2011, pp.39-43). Bonanza silver grades above 20 % Ag were mined in the oxide zone of many narrow veins which later produced no viable ore once mining reached the primary sulphides. Another example is Roman silver mining at Rio Tinto in Spain, which focussed on silver at grades of about 0.2 % in jarosite ore at the base of the ferruginous zone in a deeply weathered pyrite-rich orebody (Anguilano, 2012); by contrast, the primary ore was not economic for Roman technology.

While each supergene deposit is different, the characteristic silver minerals (Boyle, 1968, p.189) are native silver, halide species such as chlorargyrite, the hydrated sulphate mineral argentojarosite, and secondary sulphides like acanthite (argentite). Typically, these are accompanied in the weathered ore by clay minerals and abundant iron and manganese oxides, plus widespread weathering of galena to the lead carbonate mineral cerussite. Favourable conditions for supergene enrichment include: sustained and repeated deep weathering events; significant orebody thickness so that groundwater can percolate from weathered ore into underlying fresh ore; and (perhaps most importantly) abundant pyrite-rich ore so that weathering fluids are acidic; acting in concert with the last is the requirement for low content of buffering minerals such as carbonates that would otherwise neutralise the acid. It is exceptionally rare that supergene zones can develop in low-pyrite deposits, perhaps requiring long periods of aridity and recent uplift (Tuduri, et al., 2011).

Significant weathering profiles are more prevalent in Western Europe and France than is commonly realized (Migoń and Lidmar-Bergström, 2001). However, none of the other conditions listed above for supergene enrichment applies at Melle: here the ore is thin, sub-horizontal, pyrite-poor, and enveloped in carbonate-rich rocks. Galena, the dominant silver-bearing primary mineral, is still the dominant ore mineral in the mined areas. Hence, while minor supergene minerals are present, I conclude that supergene-enriched ore would not have been available in any significant quantity for early miners to exploit at Melle.

## Mining constraints

Highest mining production rates can be achieved in orebodies that can be mined by open pit. However, production rates in most historic operations dropped sharply once underground mining became necessary. Individual mine faces were then worked by small teams, with at best periodic supervision and coordination. These generalizations probably apply to all mining periods but would be even more the case before mechanisation and blasting.

Wherever underground mining becomes necessary, highest production is from wide veins in mountainous terrain. Horizontal adits from the valley side can be employed to drain the deposit, mine it upwards and haul out the ore without the expense of lifting against gravity. Additionally, more efficient mining techniques, like overhand and underhand stoping can be used. By contrast, the worst deposits for achieving high underground production rates are narrow veins or thin flat-lying deposits that are too deep to be open-pitted. The former can be uneconomic in any conditions whereas the latter must be developed by drives and "room and pillar" mining accompanied by sinking multiple shafts to aid ventilation and ore removal. Melle is in this second category because the host unit is flat-lying and most galena is concentrated in a zone no more than 2-3 metres thick (BRGM, 1977; Téreygeol, 2013). Furthermore, the fact that galena occurs in discontinuous pods would also limit mining productivity, as discussed further below.

There is no way of establishing the grade of ore mined by the Carolingians, although Téreygeol (2013, p.82) notes that fire-setting experiments on some underground faces yielded ore that was "not lower than 5 % mass" of galena. Given that all silver in this deposit is effectively in galena, and that the ratio of Pb:Ag is well constrained, then the mined silver grade depends on the galena content of the ore that can be mined. Hypothetically, as a starting point then, let us assume that ore with a grade of 10 % by weight galena was mined. Given the Pb:Ag ratio of 536, then the silver grade would be about 0.016 % Ag, and each tonne of that ore could yield only 160 grams of potentially-recoverable silver. Of course, the actual mined grade might have been lower and hence with even less silver per tonne.

Due to its lustre and cleavage reflections, galena would be evident in the mining face even in poor lighting; hence the Carolingian miners could focus on extracting good ore while the galena pod continued. However, once a mineralized pod was exhausted then miners would have to remove waste material from the face (even if it was immediately discarded underground) until a new pod was discovered. This could lie just be-

Table 1. Summary of fire-setting information and experiments conducted at various sites.

| Place | Summary | Reference |
|---|---|---|
| Kongsberg Ag mine | 9 parts by volume wood were required for each one part rock yield; hence rock:wood yield by weight = 0.4:1 using wood density 0.7 and rock density 2.65. | Timberlake (1990) |
| Melle Pb-Ag mine | 3,205 kg of rock obtained from "more than 45 fires" between 1996 and 1999 - so average is less than 71 kg rock per fire [wood quantity not given]. | Téreygeol (2000) |
| Melle Pb-Ag mine | Rock:wood yield by weight up to 2.8:1 (using 0.7 density to convert from wood volume). | Téreygeol and Dubois (2003) |
| Melle Pb-Ag mine | 4 fire-set experiments at Melle yielded 30.5-401 kg of rock (including one large overhang in the roof), average 170 kg, with rock:wood yield by weight of 0.7:1. | Téreygeol (1998) |
| Great Orme Cu mine | 3 experiments gave rock:wood yield by weight of 0.8:1, 1.5:1 and 3:1 with 170-615 kg rock obtained by a 2-person team. | Lewis (1990) |
| Pantywrach Cu mine | 1 fire-set experiment gave rock:wood yield by weight of 2.1:1. | Crew (1990) |
| Fournel Pb-Ag mines | 66 fire-set experiments gave rock:wood yield by weight in the range 0.3-1.2:1 with average 0.6:1. Individual rock yields ranged from 7.3 to 86.1 kg, with an average of 24.8 kg. | Py and Ancel (2006) |

hind the mining face or several metres away. Hence it would be impossible to mine only the high-grade ore. Consequently, a substantial proportion of material extracted from the mining faces at Melle (and originally contained in the open workings) would not have been viable ore. While it is reasonable to use the volumes of mine workings as an estimate of rock removed, it is not reasonable to assume this comprised entirely or even mostly of processable ore.

## Mining technology constraints

Today we take for granted numerous technical advances in mining (such as blasting, forced ventilation, wire cabling, hardened steel implements, mechanical winching, electric pumps, pneumatic drilling, bogging machines, etc.). However, prior to these recent innovations, miners used only fire-setting and crude hand-held equipment. Furthermore, their ability to locate concealed ore was time-consuming, requiring off-ore driving or "wildcat" shaft-sinking.

Téreygeol (2007, 2013) confirms that fire-setting was the main technique used at Melle. Presumably this was accompanied by mining with hand-held iron implements, but no such equipment has been located (Téreygeol and Dubois, 2003). No technological improvements in mining can be identified between the Romans and the Carolingians; in fact, it is quite possible that techniques were lost, resulting in lower efficiencies. Hence, Carolingian miners were unlikely to have been more efficient, and possibly were less efficient, than those of Classical times.

Mining rates are not well documented in any period but nevertheless there are some widely scattered data to provide broad constraints. Outcomes of various experiments and historic evidence for fire setting are given in Table 1, while available data for quantities of rock and ore mined are summarised in Table 2. Interpretation is complicated by different ways that productivity is expressed: as rock mined per session, ore per miner per year, ore per underground operator per year, or ore per mine employee per year. Nevertheless, by analogy with the well-documented Early Modern operations (Kongsberg, Falun, Banská Štiavnica, Kremnica, etc. - refer references in Table 2), some generalizations can be made inter-relating these expressions of productivity.

Based on data assembled in Tables 1 and 2, conceivable mining rates for Early Medieval miners at Melle lie in the broad range 25-250 kg of rock per miner per day and probably 50-150 kg. Much of this output would have been barren rock from removal of sub-grade ore from around the mineralized pods, shaft sinking, and off-ore prospecting drives. Although there is no information about the degree of specialization or technical ability of the Melle workforce, it would be difficult to envisage these Early Medieval miners could have been more productive than their Late Medieval/Early Modern counterparts at major operations like Falun and Kongsberg. Table 3 gives estimates from these later operations for silver produced per worker and these can be used as a cross-check on productivity yields from modelling.

Table 2. Historical and modern estimated daily mining production rates (kg), compiled from various sources as indicated. Note that estimates are made in several different categories as rock vs. ore, and per miner or per-worker.

| Period/Place | Value or range | Attribute | Source and explanation |
|---|---|---|---|
| Fire-setting records and experiments<br>Bronze Age and onward | 20-250<br><br>0.25-2.5 (most 0.4-0.8) | Rock per fire session<br><br>Rock produced per kg of wood burned | Various (refer to Table 1 for details). Experiments either in open air on quarry faces or in ancient mines. |
| Classical Greece | 145 | Rock/miner/day | Ardaillon (1897) for the Lavrion third contact deposits. "It would take a good worker about two hours to carve a block of lower limestone with a section of 12 cm x 12 cm and a depth of 60 cm". Assume density 2.8 and a 12-hour mining day. |
| 12$^{th}$ & 13$^{th}$C England | 18-36 | "Ore"/miner/day | Blanchard (1972). A yield of Pb ore was typically 1 ton by each miner in a "year" (perhaps 2 tons only in "exceptional mines"). A "year" here means a mining season between agricultural commitments. Assumed 2 months of 25 days each. Note "ore" here is probably dressed ready for transport after hand-sorting; hence the quantity originally mined and brought to the surface for hand-sorting is possibly much higher. |
| Early 17$^{th}$C Falun, Sweden | 75-120 | Rock/miner/day | Based on records of time taken in shaft sinking and "drift" driving by 4 person teams (Lindroth, 1955). Information extracted and provided by Johana Nybelius, December 2019. |
| 17$^{th}$-18$^{th}$C Kongsberg Norway | 100-128 (in 1650)<br>330-470 (in 1670)<br>c. 420 (in 1740)<br>1,150 (in 1760) | Ore/miner/day | Berg (1988). Figures in original tables are based on workforce at "pits" (i.e., not processing staff). Recalculation on a 300-day year and for those identified as miners amongst "pit workers" (variously 60 % - 40 % of the total over time). |
| 1763 Banská Štiavnica, Slovakia | 11.5 | Ore/miner/day | Vozár (2000) based on original itemised record of all production and people compiled for a Royal visit in 1764. Information extracted and translated by Fero Bakos, March 2020. |
| 1763 Ŝpania Dolina, Slovakia | 13.5 | Ore/miner/day | Vozár (2000) based on original itemised record of all production and people compiled for a Royal visit in 1764. Information extracted and translated by Fero Bakos, March 2020. |
| Late 19$^{th}$C Kongsberg, Norway | ~ 385 | Rock/miner/day | Timberlake (1990) quoting Collins (1883). To advance one fathom in a drive 6.5 feet high and 5 feet wide took 37.5 man-days in 1860-64 and 38.5 man-days in 1881-85 using fire-setting (2.65 rock density assumed). |
| 1860<br>USA<br>& 2000 | 2,000<br>(i.e. 2 tonnes)<br>22,000 | Ore/employee/day (Iron mining) | Humphreys (2019, Fig. 2). Converted to daily using 300 days per year. |
| 1939-41 Carlton Tunnel USA | 35,000 (i.e. 35 tonnes) | Rock/miner/day | Hunter (1998). Maximum daily and average advances to complete 6.3-mile tunnel. Assuming 5.5 x 6 m dimensions and rock density (granite) of 2.65. Assume 15-person team. |
| Current | 76,000 (i.e. 76 tonnes) | Rock/miner/day | Stewart, Ramezanzadeh and Knights (2006). Based on average drive advance of 7 m, assuming 8-person team and, rock density 2.65, "standard" drive dimensions 5.5 x 6m. |

Table 3. Annual metal productivity per capita. Data from various sources as indicated.

| Period/Place | Per-capita Production (kg of Silver per year) | Property reported | Source and explanation |
|---|---|---|---|
| Approx. 1180 Bere Ferers (Devon UK) | 1.9 | Ag/worker/year | Claughton (2010). At the peak of production in last years of the 13th century the mines produced over 20,000 ounces per annum [~567 kg] with a maximum of 300 workers. |
| 13th-14thC Kutná Hora (Czech Republic) | 2 - 2.33 | Ag/mine worker/year | Ettler, et al. (2010). At "the most significant centre of silver mining in the European civilization at the time, with advanced organization and technology" 3,000 people working at the mines produced 6-7 tonnes Ag annually. |
| 1442 Kremnica (Slovakia)<br>1764 | 1.5<br><br>2<br>4 | Ag/worker/year<br><br>Ag/mine worker/year<br>Ag/miner /year | Vozar (2000) based on original itemised record of all production and people compiled for 1764 Royal visit Information extracted and translated by Fero Bakos, March 2020 (calculated as Ag equivalent from Au and Ag production, converted using Au:Ag = 14 prevailing at the time). |
| 1535 Banská Štiavnica (Slovakia)<br>1763 | 1.4<br><br>3.8<br>8.1 | Ag/worker/year<br><br>Ag/mine worker/year<br>Ag/miner /year | Vozar (2000) based on original itemised record of all production and people compiled for a Royal visit in 1764. Information extracted and translated by Fero Bakos, March 2020 (calculated as Ag equivalent from given Au and Ag production, converted using Au:Ag = 14). |
| 1623-29<br>** See note<br><br>1650<br>Kongsberg (Norway)<br><br>1670 | 9<br>12<br><br>4.5<br>7<br><br>2.8<br>4.3 | Ag/mine worker/year<br>Ag/miner/year<br><br>Ag/mine worker/year<br>Ag/miner/year<br><br>Ag/mine worker/year<br>Ag/miner/year | Berg (1988). Recalculation made here for those identified as miners and fire-setters amongst "pit workers" (variously 70 % - 40 % of the total workforce over time). Figures in Berg's original tables are based on total workforce including processing but excluding supervisors (Berg, pers. comm. by email 4 May 2020).<br><br>** Note: Earliest production figures are high because of near-surface mining within numerous vein systems including weathered and fractured rock (Berg, pers. comm. 4 May 2020). |
| c. 1800 Himmelsfürst (Saxony) | 4.3 | Ag/mine worker/year | von Humboldt (1811, p.413). Calculated from production (10,000 marks Ag) and stated workforce (550 within mine). Described as the "richest silver mine of its time in Saxony". |

## Processing technology constraints

At Melle, the silver-bearing galena was separated from its ore by a multi-step procedure involving sorting, crushing and gravity separation before smelting; Téreygeol (2007) mentions seventeen different steps. The important point is that any loss of galena during processing and prior to smelting would include loss of its contained silver.

There are four ways that silver-bearing galena would be lost during ore processing:

- Upgrading of ore by hand picking (either underground or at surface) was common in Early Modern mining operations and would inevitably result in loss of any galena that was hidden within the rock fragment, rather than showing on its surface.
- The unusually brittle nature of galena causes loss of fines to dust if excessive force is used during crushing; this is a long-recognized problem (Price, 1788, p.243).
- In wet gravity separation, friction and turbulent fluid motion become increasingly dominant over density as particle grainsizes decrease (Das and Sarkar, 2018; nominally less than about 200 microns). Hence some galena losses to tailings as "slimes" would be inevitable.
- Composite particles of galena and gangue minerals would be less dense and, depending on grain size and composition, inevitably some of these would be lost as well.

Processing losses are difficult to measure even in operating mines and there is scarce information from earlier periods. However, it was only the relatively recent development of the froth flotation technique after 1900 that enabled base metal mines to achieve the high metal recoveries that we take for granted today. As Blainey (1968, p.75) remarks about the world-famous Australian Pb-Zn-Ag mine of Broken Hill, where flotation was perfected: "*The best performance of the very best gravity mills at the turn of the century [1900] was to recover two-thirds of the lead, almost half of the silver, and none of the zinc; the rest ran to waste. The best flotation plant at Broken Hill today can produce a silver-lead concentrate containing 97 per cent of the lead and 94 per cent of the silver contained in the ore…*".

Well preserved ore processing facilities of High and Late Medieval age have been documented at Brandes-en-Oisans in France (Bailly-Maître and Bruno-Dupraz, 1994; Bailly-Maître, 2010) and at Černov-Cvilínek in the Bohemian-Moravian Highlands of the Czech Republic (Hrubý, Hejhal and Malý, 2012). Whilst these provide insights into the technologies of grinding (with stone) and gravity separation (in wooden races, troughs or tanks, perhaps with fabric lining to trap ore minerals), they do not permit estimation of recoveries. Holub's (2018) compilation of High Medieval production in the Kutná Hora district of Czech Republic, concluded that total processing and smelting/refining losses were in the order of 20-30 % from rich silver ores at what was considered to be the most technologically-advanced silver mine of its time (Ettler, et al., 2010).

In summary then, processing losses of silver-bearing galena at Melle were inevitable but difficult to estimate. Losses of up to 40 % of the contained metal is quite conceivable and less than 20 % is extremely unlikely by analogy with later operations.

## Refining and smelting technology constraints

Any lead lost to the atmosphere during either smelting or cupellation would not involve silver loss- the lead being preferentially oxidized and volatilized while the silver is relatively unaffected. However, lead lost into slag (such as unmelted galena fragments, or any metallic lead particles that did not separate from the slag) would contain silver, as might the slag matrix itself (e.g., Merkel, et al., 2013). This silver would be lost unless the slag was crushed and re-smelted, but the process of loss would then repeat to some degree. Téreygeol and Dubois (2003) record evidence for slag re-processing at Melle, so clearly loss of silver into slag was a recognized issue.

Loss of silver during the cupellation stage was a well-known problem in more recent times. For example, Kerl, Crookes and Röhrig (1868, pp.286-287) list poor construction of vessels, over-zealous oxidation and maintaining either too high or too low a temperature as key issues. Although it can be predicted that Melle lead (like that of most MVT deposits) would be quite pure and hence relatively easy to cupel, it is doubtful that the Early Medieval metallurgists would have been as skilful or as knowledgeable as their Early Modern counterparts. Therefore, some silver loss is inevitable - perhaps not in every cupellation procedure but over time in some.

## Workforce and work patterns

By far the most challenging factor for quantitative modelling of Melle production lies in establishing the likely size of the workforce. In the absence of records, we must use indirect information such as the size of the related population centre to infer this. The size of the town or settlement together with its rural surrounds is important because this constrains the size of the maximum workforce available for mining and related activities. Workers could be drawn from the townsite(s) and immediately surrounding rural areas with daily commuting to the mine; however, the quality of roads and likely isolation of population centres within forested areas would constrain this to the scale of kilometres, not tens of kilometres.

Frustratingly, however, almost nothing is known about Early Medieval Melle, except that it was the site of lead-silver mines and an important mint. The mines are thoroughly researched and documented, largely through the work of Florian Téreygeol, but the location of the mint is unknown (Bourgeois and Téreygeol, 2005). Melle lies to the southwest of and outside "*The heartlands of the Carolingian empire, that is the region between the Loire and the Rhine,…*" (Verhulst, 2002, p.123). It was part of an Empire with strong central control (Bachrach, 2016) but dominated by agricultural activity (Verhulst, 2002, pp.125-127). McKitterick (1983, p.20) envisioned that it comprised mainly of rural communities separated by extensive forest areas. Prior to the High Medieval period more than 60 % of France was forested (Morin, 1996) with substantial re-growth having occurred after the collapse of the Western Roman Empire (Deforce, et al., 2020).

The distinctive, surviving "Melle School" of architecture was all built in the twelfth century, in part replacing wooden structures (Tcherikover, 1997). Hence there is nothing substantial by which to judge the size of Melle in Carolingian times. In fact, the size of even the largest Carolingian towns is not known with any certainty: the compilation by Bairoch, Batou and Chèvre (1988) lists only fifteen Carolingian towns at or above a population of 10,000 in 800 AD including Poitiers, located about

50 kilometres northeast of Melle. Poitiers was probably the largest town in the vicinity and was a high-profile diocese in Carolingian times (Rennie, 2007). By contrast, it is generally accepted that Melle was not a major administrative or religious centre at any time, though intriguingly there is some evidence that it became a more important regional centre after the closure of the mines (Bourgeois and Téreygeol, 2005). Grierson and Blackburn (1986, p.238) noted that: "*The existence of a mint at Melle, a mere vicus with no pretensions to secular or ecclesiastical importance, was in itself anomalous.*"

Perhaps Melle was like the earliest documented mining towns in Late Medieval times, with a dedicated workforce and most people obtaining their livelihood directly or indirectly from the mines. For example, Kutná Hora (German: Kuttenberg) had some 3,000 people working in the mines in the mid-14th century (Ettler, et al., 2010). Banská Štiavnica (German: Schemnitz) was described as the "third largest town in Hungary" with 1,230 dwellings in the 14th century (Siems, 2008). Brandes-en-Oisans, established specifically for silver mining (Bailly-Maître and Bruno-Dupraz, 1994, p.147), is estimated to have had 150 dwellings at its peak in the mid-13th century (ibid. p.172); the centre was described (ibid. p.1) as "mine moyenne à l'échelle européenne" (a medium-sized mine on a European scale).

By analogy with documented Early Modern English mining, we can hypothesize that both children and women were involved at Melle, especially in ore dressing and sorting (e.g., Henderson, 1858). According to an early census in 1769, Kongsberg, had about 50 % of the total population involved in the mining activities, and about 85 % directly dependant on those activities (Berg, personal communication by email, 4 May 2020). I am not aware of any other data relating settlement size to mining workforce. However, if we exclude infants and nursing mothers, the old and infirm, artisans like millers, butchers, bakers, coopers etc., we could imagine that up to a maximum of 50-75 % of the total population could be available for mining activities. The true proportion might have been smaller but is unlikely to have been larger.

Another unknown is work patterns. Although we have no information from Carolingian times, nevertheless there are limits we can set to constrain our modelling. A working year of 300-days would be a reasonable maximum, given that the Empire was Christianised with strong central church control (Noble, 2015); hence, work would have ceased for Sundays and on at least some saintly holidays. Perhaps they worked closer to 250 days as is widely used for estimating High and Late Medieval worker's wages in England and Western Europe (Allen, 2015; Malanima, 2013). Alternatively, perhaps the "mining season" was sandwiched between essential agricultural activities like seeding and harvesting, as was the case for lead mining in High Medieval England (Blanchard, 1972). In that last scenario less than 100 days might have constituted a "mining year", in which case annual output would be much lower than for a full-time operation.

For the purposes of establishing some broad reference points, let us assume that Carolingian Melle and its immediate surrounds (including the nearby communes of Saint Léger de la Martinière, Saint Martin-lès-Melle and Sepvret; refer Bourgeois and Téreygeol, 2005) was a cluster of settlements and surrounding farms with total population of no more than 4,000 and perhaps as low as 400. Using the logic above, I propose that reasonable limits for production modelling at Melle are set by a workforce of between 3,000 and 300 persons. Their maximum output would involve a dedicated mining community working a full year of 300 days.

## Workforce allocation

Whatever its size and work pattern, the workforce had to service three primary operations, namely: i) mining; ii) processing (crushing, separation, smelting and refining); and iii) wood sourcing. Manpower for charcoal production is omitted because it was possibly sourced from distant forest areas beyond competition from other wood uses, much as has been documented in Early Modern times (Schmidt, et al., 2016; Ludemann, Michiels and Nölken, 2004). Such activities might involve a separate workforce which traded their commodity but were otherwise unconnected to the mine.

The wood-sourcing activities are commonly neglected, but nevertheless crucial. Wood is the prime requirement for underground mining using fire-setting but also for stabilizing underground workings, probably as a supplement to charcoal in ore processing, and for the construction of ladders, processing equipment, storage containers, buildings, and transport vehicles. At least six steps are required to source this wood: tree felling, trimming, hauling to an access track, loading, freighting to the mine and unloading. Useful production estimates can be obtained from well-documented early American lumber operations. A two-person team using cross-cut saw and axes can fall and trim 7,500-15,000 board feet of timber per day depending on conditions (Bryant, 1923, p.32); this equates to approximately 20-40 $m^3$ or 12-24 green wood tonnes converted at a density of 0.7. With a minimal estimate of three additional persons for the remaining haul and freight tasks, perhaps 2.5-5 green wood tonnes could be delivered to the consumption point per forest worker per day.

In modern but poorly mechanized operations employing hand-operated chainsaws and horse hauling, the critical parameters for productivity include the diameter of trees, topography and haulage and freight distances (Borz and Ciobanu, 2013). In ideal circumstances, productivity can reach 3-4 green wood tonnes per person per day (Klepac and Rummer, 2002), as delivered to the freight point. However, given some additional staff to load, transport, unload and stack, this is probably more like 2.5-3.5 green wood tonnes per forest worker per day.

Hence, both modern "manual" and early American estimates are roughly comparable and provide an upper estimate of wood-sourcing productivity without mechanization. However, it is likely that Early Medieval woodcutting would be significantly less efficient than recent operations given the poor roads and lack of high-quality steels for saws, cables, chains etc. Hence, a realistic estimate might be that somewhere in the order of 1-1.5 tonnes of green wood per forest worker per day, could be sourced and delivered to the Medieval mine, while exploitable forest was still within a few kilometres.

There is no information on whether timber was used green or dry for fire setting at Melle although Timberlake (1990) states that some historical records from elsewhere mention dry wood. Even simple and short-duration air-drying of wood involves substantial weight loss, commonly greater than 40 % of the green weight (Peck, 1959). Hence, the output estimated above for each forestry worker could sustain perhaps several fire-sets (each using 200-250 kg of dry wood) plus a similar amount for all remaining wood requirements. That being the case, it is quite possible that as many people were employed to supply Melle with wood as were engaged in the mining operation itself.

Turning next to the ore processing, some constraints can be set by later and better-documented operations. Typically, these show that approximately as many persons were required in ore processing as were employed at the mine itself. The range is great - from about 30 % in the early years at Kongsberg (Berg, 1988), to 50-65 % of the total staff in the various Early Modern Slovakian operations (Vozár, 2000). Hence, with the caveats of huge uncertainty, perhaps a reasonable starting point is that the medieval workforce at Melle was distributed about equally across the three primary areas identified above, namely the mining, the processing operations, and the forest.

Focussing now on those working at the mines, we can envisage the tasks involved: hauling wood to the faces; setting and tending fires; digging loosened ore; hauling out ore; perhaps making an initial selection of high-grade material and discarding the waste; sinking ventilation shafts; perhaps controlling water and stabilizing the workings - including scraping down dangerous overhangs caused by fire-setting (which is notoriously difficult to control and focus, see for example, Timberlake, 1990). It is clear then, that the two "front-line" mining tasks of setting the fires and digging loosened ore from the face could occupy only some of the time for all workers, or all the time for just some. Either way, we can model this by assuming that some people were mining full-time, while others took care of support activities. Overall productivity is unlikely to have been higher if all tasks were spread equally. At some Early Modern operations that have good records of staffing levels and tasks, the personnel identified as "miners" and "fire-setters" comprise somewhere between 40 % and 70 % of all staff working at the mines, the rest being either underground in support roles or on the surface lifting and moving ore to processing sites (Berg, 1988; Vozár, 2000).

## Mining and processing models

A simple mining and processing model has been developed for Melle by bringing together all the different constraints discussed above. This is summarised in Table 4, which presents the inputs and outcomes for three different scenarios. The online supplementary data expands on these as well as offering a working spreadsheet enabling calculation on any desired parameters.

The "Realistic" version of the model is pragmatic and honours both the available data and comparative information from other historical mining operations. Using 100 dedicated miners (from 250-300 workers and a population centre of 400 persons), it yields 52 tonnes of lead and 150 kg silver per year, assuming mining was a full-time operation for the participants. This output could be doubled by assuming 200 miners working full time from a community and its surrounds comprising some 1,000 persons. Naturally, however, output would be less if mining had been a seasonal operation as was the case in High Medieval England (Blanchard, 1972).

The "Optimistic" version stretches all parameters to the extreme of being still credible. It yields around 1-2 tonnes of silver (depending on workforce assumptions) and a per capita mining productivity that is comparable with the best of those documented in Early Modern operations. It would be surprising if the Early Medieval operators achieved comparable efficiencies, but perhaps some unrecognized factor like unusually amenable rock characteristics facilitated this.

Table 4. Summary of outcomes from production models for Melle [refer also to spreadsheet in supplementary information].

| | Extreme model | Optimistic model | Realistic model | Units | Notes |
|---|---|---|---|---|---|
| **Assumptions** | | | | | |
| Number of dedicated full-time miners at the mining face | 500 | 200 | 100 | | 1 |
| Rock broken per miner per day (kg) | 425 | 250 | 150 | kg | 2 |
| No of workdays in year (6 working days per week) | 300 | 300 | 300 | days | 3 |
| Proportion of all rock mined ore presented for smelting | 65 | 60 | 50 | % | 4 |
| Average grade of ore (weight % galena) as presented for crushing | 14 | 10 | 6 | % | 5 |
| Pb/Ag ratio in ore | 300 | 450 | 530 | | 6 |
| % Silver-bearing galena lost in crushing and concentrating | 10 | 20 | 25 | % | 7 |
| % Pb lost in smelting & refining to slag and air | 10 | 20 | 30 | % | 8 |
| % Pb lost in cupelling and then re-smelting of litharge | 5 | 15 | 15 | % | 9 |
| % Silver lost in smelting and refining (but not cupellation) | 1 | 2 | 5 | % | 10 |
| % Ag lost in cupelling | 0 | 1 | 2 | % | 11 |
| **Calculations & Outcomes** | | | | | |
| Derived Pb content in ore (natural galena @ 86.3 weight % Pb) | 12.08 | 8.63 | 5.18 | % | |
| Total ore mined by all miners per year | 41,438 | 9,000 | 2,250 | tonnes/yr. | |
| Total contained Pb mined per year | 5,005.7 | 776.7 | 116.6 | tonnes/yr. | 12 |
| Total contained Ag mined per year | 16.69 | 1.73 | 0.22 | tonnes/yr. | 12 |
| Pb in recovered concentrate available for smelting | 4,505.1 | 621.4 | 87.4 | tonnes/yr. | 13 |
| Ag in recovered Pb concentrate available for smelting | 15.02 | 1.38 | 0.16 | tonnes/yr. | 14 |
| Final Pb produced after cupellation and re-smelting | 3,851.8 | 422.5 | 52.0 | tonnes Pb metal/yr. | |
| **Final Ag produced after cupellation** | **14.87** | **1.34** | **0.15** | tonnes Ag/yr. | |
| Productivity per miner per year | 29.7 | 6.7 | 1.5 | kg Ag/yr. | 15 |
| Productivity per mine worker per year | 14.9 | 3.4 | 0.8 | kg Ag/yr. | 16 |

Notes for Table 4 (these apply to the "Realistic" case. Refer supplementary information for others):

1 Not including other underground workers like ore carters, wood carriers etc., and not including workers involved in ore processing, smelting and refining, or wood sourcing.
2 Similar to best high-medieval and Lavrion estimates, and with outcomes of fire-setting experiments.
3 300 days seems a reasonable maximum for a Christian society - Sundays off and a few selected saint's days (could have been much lower if mining was seasonal).
4 Allowance (probably insufficient) for shaft sinking, exploratory development, mining of waste in the faces, accidental dilution, discarded proportion during ore dressing.
5 More than twice as good as the best "remnant" ore today, but similar to the visual observations and experimental recoveries reported from underground faces.
6 Equivalent to the existing remnant ore value, and at the mid-point of galena contents reported from Melle.
7 This would still be significantly better than most mines pre-1892 (introduction of flotation). 30-40 % is quite possible and probably more realistic.
8 Could be as high as 50 % on some estimates but does not influence silver recovery.
9 In Roman times, Pliny claims this was 2/9 or 22 % (Bostock and Riley, 1855, Plin. Nat. 34. 47). Early Modern losses during this process were as low as 5 % or better. Does not affect silver recovery.
10 Trapped in slag within unrecoverable galena particles and/or alloyed in fine Pb metal droplets. Affects silver recovery -unless slag was crushed and re-smelted which would involve extra wood and labour.
11 Difficult to quantify but unlikely to be zero!
12 But some will be lost in crushing, separating, smelting, and refining.
13 Total lead mined, minus crushing/dressing loss.
14 Total silver mined, minus crushing/dressing loss, based on estimated galena lost and Pb/Ag ratio.
15 Compare Kongsberg long-term average approximately 4-6 kg for miners only (see Table 3).
16 Compare Kongsberg long-term average ~ 2 kg/year for all mine workers, 2 kg Kremnica in 1763, 1.4 kg Kremnica in 1492 (see Table 3).

The "Extreme" version of the model relaxes all parameters to the extent necessary to achieve the claimed yearly output at Melle of 15 tonnes of silver. It requires 500 dedicated miners and hence a workforce numbered in thousands, together with a substantial population centre to provide and support these. It uses assumptions that are highly unlikely given what is known about the geology of this deposit. Likewise, from a mining perspective, the chosen parameters are improbable and unsupportable in comparison with other historic data. Most tellingly, however, it results in a productivity of some 30 kg of silver per miner per year. This would be at least four times better than the best rates achieved 700 years later in some of the best European silver mines of their time.

## Discussion

Although it would be possible to simply increase the workforce in either the Realistic or the Optimistic models to reach the claimed output levels, the implied population centre involved would make Melle amongst the largest towns in the Carolingian Empire. This seems contradictory to the available evidence. A town of many thousands existing for 250 years or more should have left a stronger archaeological footprint than seems to be the case. This might, however, be a useful focus for additional research.

Another important issue is mining waste, though space precludes a full discussion here. All mining operations produce volumetrically greater waste materials (low-grade dumps, tailings, slimes, slag, etc.) than the volume of ore mined; this is a consequence of air and water filling the voids between crushed fragments. Even if we assume highly selective mining and efficient ore sorting before processing, a long-term operation at Melle involving mining of some 38 million of tonnes of ore (Téreygeol, 2013, p.82) should have produced waste and tailings of at least 17 million cubic metres, in addition to a substantial footprint of surface lead contamination. Significant base metal mines elsewhere result in tailings contamination of major drainages for tens of kilometres (e.g. Jennet and Foil, 1979; Knittel, Klemm and Greif, 2005). Despite the time elapsed since mining, some evidence for this huge quantity of waste should be evident in the Melle landscape, yet no evidence for this has been documented.

This is not the first paper to conclude that both lead and silver production at Melle have been overstated. Bartels (2014) came to the same conclusion based on comparisons with later and better-documented deposits especially in the Harz district of Germany. The fact that the Melle deposit has not been mined since Early Medieval times is also highly significant. Even in periods of silver scarcity for Western Europe (of which there were several, though their extent and duration are contested, refer Blanchard, 2001; Spufford, 1989, pp.339-352; Miskimin, 1993), no later polities were motivated enough to recommence mining operations here. While it is conceivable that the Carolingian miners totally depleted the deposit of mineable ore, the very nature of MVT deposits (i.e. multiple orebodies, irregular and unpredictable forms) makes this much less credible than for other more predictable deposit types like vein deposits. Likewise, constraints such as physical access (Sarah, et al., 2012), problems with maintaining ventilation under deeper areas of the plateau (Bourgeois and Téreygeol, 2005), and even forest depletion (Téreygeol and Dubois, 2003) may have limited mining at Melle. If any of these operated to curtail production, then some ore comparable to that mined in Carolingian times should still be present.

Alternative silver sources also must be considered. Externally, there was abundant opportunity for the Carolingians to obtain silver through trade with their neighbours: many areas controlled by Islamic polities have well-documented Early Medieval silver mining including Spain (Riart, Martínez, and Echevarria, 2007), Morocco (Baron, Souhassou and Fauvelle, 2020), Yemen (Merkel, et al., 2016), probably the broader Arabian Peninsula (Heck, 2010; Morony, 2019), Iran (Kovalev, 2014) and certainly numerous major fields in Central Asia which had prodigious output in various cycles from the $4^{th}$ to the $11^{th}$ century AD (Morony, 2019; Blanchard, 2001). In at least some of these last-mentioned areas there is emerging evidence for exploitation of very rich "dry silver" ores containing discrete silver minerals or native silver (Merkel, 2021), thus enabling much higher production of silver for equivalent tonnage of ore mined, compared to galena-dominated deposits like Melle. Furthermore, although direct evidence is lacking, silver mining within the Byzantine Empire is also likely to have continued (Vryonis, 1962) particularly in western Anatolia and possibly in the southern Balkans. Important silver deposits are also known close by in England, Wales and Ireland although Early Medieval mining is not documented in any of these areas.

Melle is currently the only locality inside the former Carolingian Empire at which Early Medieval silver mining has been documented and no doubt the complete lack of disturbance by later exploitation explains why this can be proved. However, it has not yet been established that it was the sole, or even the best, silver mine of its time in Western Europe. Using geographic limits accepted by most authors (e.g. Bachrach, 2016, Map 8.1)

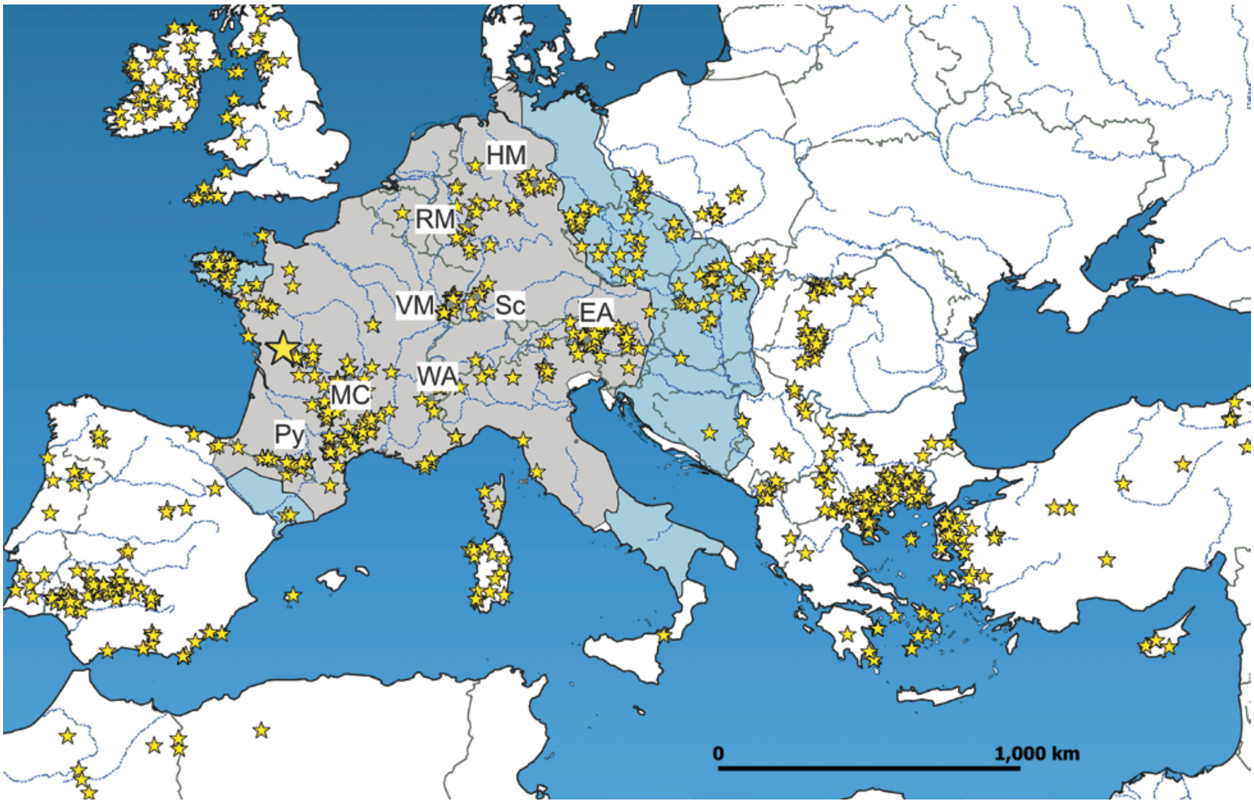


Figure 1. Currently known silver-bearing deposits (yellow stars) in Western Europe from the Promine database (Cassard, et al., 2015). Melle is shown as the largest yellow star. Deposits in Africa, Turkey and Asia were compiled by the author. The light grey area is the extent of Carolingian Empire in c. 840 AD, with tribute territories shown as pale blue (after Bachrach, 2016, Map 8.1). Major rivers in dark blue and present-day country borders in grey. General localities: EA: Eastern Alps, HM: Harz Mountains, MC: Massif Central, Py: Pyrenees, RM: Rhenish Massif, Sc: Schwarzwald (Black Forrest), VM: Vosges Mountains, WA: Western Alps. Projection: Europe Lambert Conformal Conic (ESRI: 102014).

the Carolingian Empire at its zenith around 814 AD spanned over 1.2 million km$^2$. Within its primary border (excluding vassal states and tribute territories), according to the Promine GIS-based mineral occurrences database (Cassard, et al., 2015) there are 235 known deposits or mineral occurrences specifically mentioned as containing silver (Figure 1). These include numerous deposits in and around the Massif Central; in the northern foothills of the Pyrenees, in the European Western and Eastern Alps; in Schwarzwald; in the Vosges Mountains; in the Rhenish Massif; and in the Harz Mountains.

It should be noted also that the Promine database is mostly a generalized coverage of "mineral districts" rather than individual deposits. For example, within the Schwarzwald district of south-western Germany, six silver-bearing localities are identified in Promine. However, there are in fact more than 400 individual vein systems, of which nearly half are known to contain silver minerals (Baatartsogt, et al., 2007). Hence the true number of discrete silver deposits is much larger than implied from Promine.

From a geological viewpoint, many of these districts within the former Carolingian Empire are highly prospective for silver. Some were mined previously in the Bronze Age and/or by the Romans (Servera Vives, et al., 2014; Durali-Mueller, et al., 2007) and many provided important silver mines in later history (Nef, 1941; Deroin, 2018). Hence, although there is no currently identified evidence for carolingian-age mining at any of these sites, this might result from destruction of evidence during later mining. Otherwise, were the Carolingians such poor prospectors that none of these major systems attracted attention, even with evidence of former mining activity at some? It is a conundrum as to why Melle should have been mined, and allegedly at enormous rates for hundreds of years while other and arguably far better silver deposits (at least in terms of geological character) apparently remained unrecognized or unexploited. Clearly, there is scope for further research here.

Of course, Melle still might have been vital to the Carolingian economy even at the production levels proposed here: a yearly output of 150 kg silver could be minted into some 85,000 silver deniers of 1.7-1.8 g each. De Callataÿ (2018) noted the apparent contradiction between estimates of Carolingian money supply and the estimated Melle silver production levels, while conceding that the former is poorly constrained. Furthermore, the availability of some 50 tonnes of high-quality lead per year from Melle could have been just as significant as its silver, a suggestion also made by Bartels (2014). Metallic lead would be easily recovered after cupellation by re-smelting the litharge and then could be re-used (perhaps multiple times) to treat impure silver mined elsewhere from lead-poor or metallurgically-problematic deposits, or even to re-process and recycle local or foreign coinage - such as Islamic dirhams derived through trade. In all these cases, it is more likely that the less bulky silver-bearing materials would be transported to the lead, rather than the reverse. Furthermore, cupellation of these diverse silver sources would imprint the Melle Pb isotopic signature into the purified silver product (although the trace element content would reflect to some extent the silver source rather than the lead source). Sarah (2018) presents some evidence in support of this possibility.

## Conclusion

This study has focussed on demonstrating that estimates for Early Medieval silver mining and production at Melle can be tested and improved by considering the geological character, orebody geometry and mining constraints of the deposit. Potential workforce sizes can be similarly constrained by considering likely settlement sizes together with the necessary additional mining-related activities to be performed (including the commonly neglected requirements for a wood-sourcing team). Ore productivity and mining estimates derived from later and better-documented deposits can be used for comparisons and to set reasonable limits. Models can be then developed to test various scenarios. Additionally, estimates of per capita metal productivity from other operations can be applied to evaluate whether the modelling outputs are realistic.

In its geological character, Melle is clearly a Mississippi Valley type (MVT) deposit. Throughout the world MVT's are major base metal producers but they are characteristically low in silver. Those that produce significant amounts of silver do so because of their huge economies of scale in base metal concentrate production – something only achievable with modern technologies. When compared to these, Melle presents as a silver-bearing but low-grade lead deposit with severe mining constraints, not as a "silver-rich galena deposit" (Sarah, 2012, p.326) and certainly not one having any probability of containing "seams of silver on a grand scale" (Coupland, 2018, p.437).

Depletion of *all* high-grade ore by the medieval miners at Melle is unlikely. A feature of MVT deposits is the unpredictable nature of their high-grade zones, even for today's miners with advanced prediction tools and drilling capabilities. Similarly, on geological grounds, there is no evidence that either primary zoning or supergene enrichment could have significantly enriched the ore mined in Early Medieval times. In fact, rather than high-grade resource depletion, mining may have ceased here because of access issues (Sarah, et al., 2012) or depletion of readily accessible timber (Téreygeol and Dubois, 2003). If either was the cause, then the grade of at least some of the remnant mineralisation should be comparable to that mined in Medieval times. Regardless, the remaining lead and silver at Melle has not attracted any attention since Early Medieval times, a fact that is atypical of all other major mineral deposits.

The Carolingian Empire controlled a vast territory including many regions that would later yield many major and rich silver deposits. Whilst there is currently no firm evidence for Carolingian silver mining anywhere except at Melle, this is an enigma: other, and arguably richer, silver deposits within the Empire were mined both before and after Carolingian times.

The previously claimed annual production of around 15 tonnes of silver can be achieved only with extreme modelling parameters and quite unrealistic mining assumptions. It would require many hundreds of miners and a total workforce numbered in the thousands. Furthermore, the per capita silver production at Melle under these parameters would have exceeded by at least a factor of four the well-documented levels at some of the leading silver mines of the Early Modern period. This seems quite unrealistic for what is a thin and low-grade deposit that was mined by a workforce with primitive techniques.

The preferred production model for Melle, honouring the geological characteristics of the deposit and using the most realistic mining parameters, yields annual production of about 52 tonnes of lead and 150 kg of silver, in other words two orders of magnitude less than formerly proposed.

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