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Research Article

Aldborough and the metals economy of northern England, *c.* AD 345–1700: a new post-Roman narrative

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Increasing interdisciplinary analysis of geo-archaeological records, including sediment and ice cores, permits finer-scale contextual interpretation of the history of anthropogenic environmental impacts. In an interdisciplinary approach to economic history, the authors examine metal pollutants in a sediment core from the Roman metal-producing centre of Aldborough, North Yorkshire, combining this record with textual and archaeological evidence from the region. Finding that fluctuations in pollution correspond with sociopolitical events, pandemics and recorded trends in British metal production *c.* AD 1100–1700, the authors extend the analysis to earlier periods that lack written records, providing a new post-Roman economic narrative for northern England.

Keywords: Britain, North Yorkshire, Roman, medieval, ICP-MS, pollution, lead production, iron production

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Introduction

Since the mid-1990s, geoarchaeological records accessed through ice and sediment cores have been revealing the impact of human industrial activities across the planet. In Europe, analyses have focused on continuous records of lead pollution over the past two millennia; as air- and water-borne lead is a by-product of silver extraction and coinage production, variations in the level of this pollutant in ice cores and lake- and peat-sediment records may be interpreted as markers of fluctuating economic production (Hong *et al.* 1994; Brännvall *et al.* 1999; Le Roux *et al.* 2004; Loveluck *et al.* 2020, OSM 2). During the past decade, collaborations between archaeologists, historians and environmental scientists have produced more informed historical interpretations of macro-economic and societal trends. The chronological resolution of ice-core and speleothem (mineralogical cave deposit) records has increased to annual from decadal, to match varved lake sediments (McFarlane *et al.* 2014; More *et al.* 2017; McConnell *et al.* 2018), and age-depth models for sediment cores have improved considerably (Trachsel & Telford 2017), as have techniques for identifying pollution sources and transport mechanisms (Loveluck *et al.* 2018, 2020). Yet, high-quality continuous pollution records in the immediate proximity of the largest historic metal-producing industries in central-to-western Europe are exceptionally rare (e.g. Kempter & Frenzel 2000; MacFarlane *et al.* 2014).

Here, we present one such rare record, recovered 500m from the Roman town of *Isurium Brigantum* (Aldborough, North Yorkshire), located on the margins of the Yorkshire Dales, one of the largest lead-producing regions of Europe between the Roman and modern periods, *c.* AD 80–1700 (Figure 1). We apply an interdisciplinary approach to the interpretation of levels of anthropogenic metal pollution in a sediment core from a palaeochannel of the River Ure, integrating pollen analysis, radiocarbon/optically stimulated luminescence (OSL) dating and multi-element ICP-MS (inductively coupled plasma mass spectrometry) analysis with textual and archaeological evidence. Consilience between this sediment-based record of pollution and documented historical fluctuations in metal production cycles in the period *c.* AD 1100–1700 allows confidence in projecting such concurrences further back in the record, identifying hitherto unrecognised production patterns in the late Roman to early medieval periods.

Aldborough-Boroughbridge and Yorkshire Pennines metal production

The earliest archaeological evidence for metal extraction from the Yorkshire Dales (North and West Yorkshire) comes from Roman lead ingots from Nidderdale and Swaledale. Ingots from Heyshaw Moor (Nidderdale) are dated epigraphically to AD 81 (RIB 2404.61–62; Frere *et al.* 1990), with others (now lost) bearing inscriptions that suggest production under the reigns of Trajan and Hadrian, AD 98–138 (RIB 2404.63–64; Frere *et al.* 1990). Recent intensive survey and excavation at Aldborough has clarified the chronological development of the Roman town of *Isurium Brigantum*, which acted as the administrative centre of the region—the *civitas* of the Brigantes—through the Roman period (Ferraby & Millett 2020a). The site was founded *de novo*, probably as a trading centre between AD 70 and 80,

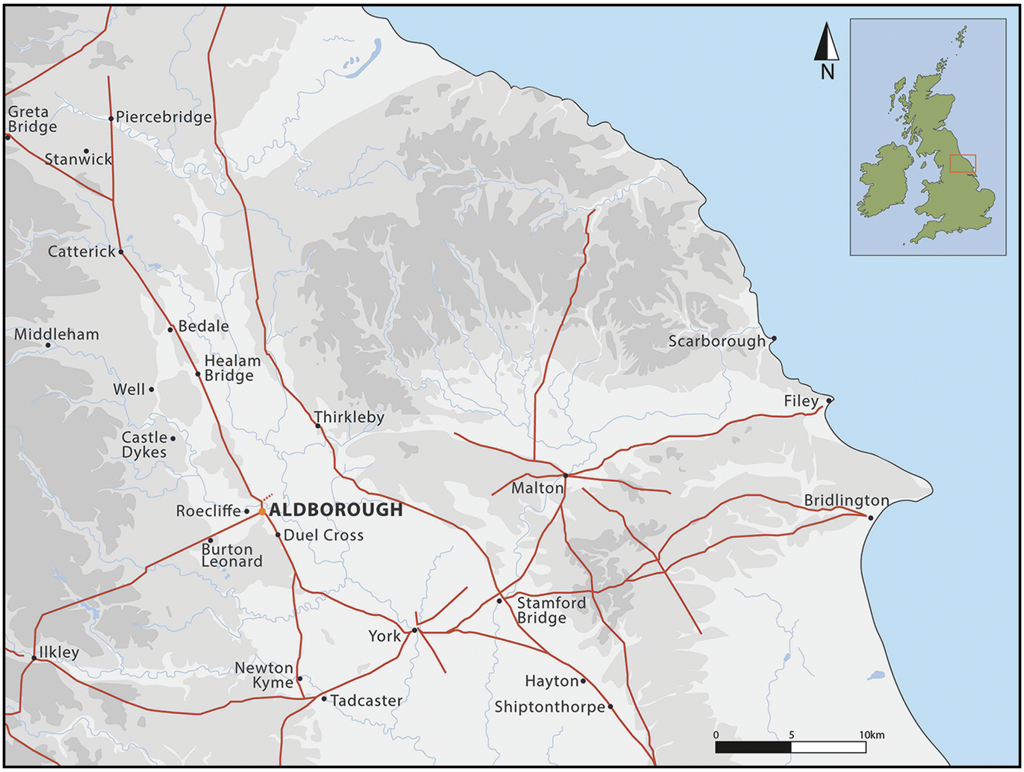

Figure 1. Location of Aldborough in northern England (figure by R. Ferraby).

with a planned town laid out later, *c.* AD 120. Excavations in its northern sector have revealed large-scale industrial activity with substantial evidence for iron-smithing using coal as fuel. Chemical analysis of soils confirms high levels of iron and arsenic, alongside lead, copper and zinc, suggesting the production/working of these metals in the vicinity (Ferraby & Millett 2020b, 2021, 2023, 2024) (Figures 2 & 3).

The duration of Roman lead and iron production in the Dales is unknown as no other datable ingots have been found in the area. The stamp on a pair of lead ingots from Châlons-sur-Saône, France (RIB 2404.72a; Frere *et al.* 1990), perhaps reads 'Legio VI', suggesting Yorkshire production in the late second century. Absence of later ingots reflects a wider pattern, however, indicating a change in the control of production rather than its cessation (Hirt 2010: 100–106). Fourteen of 271 lead ingots from the shipwreck at Ploumanac'h (Sept-Iles), France—probably dating from the fourth century AD—have inscriptions referencing 'BRIG' and 'BRIGAN', presumably indicating a Brigantian origin (L'Hour 1987: 120–25). However, other inscriptions attest origins in *civitates* that were not lead producing, and it is likely that all the ingots represent recycled material (Boon 1991: 320). In the absence of epigraphic evidence for the exploitation of lead in the Dales after the early third century, other approaches are required.

Substantial activity appears to have continued in the area of Aldborough into the fifth century and beyond, with evidence of urban replanning (Ferraby & Millett 2020a:

Figure 2. Aerial photograph of Aldborough showing the extent of the walled town and the location of the sediment core (figure by D. Powlesland & V. Herring).

120–24). The *Domesday Book* lists the area as the focus of a royal manor of Edward the Confessor (AD 1042–1066) that was still in royal hands under William the Conqueror in 1086 (*DB. Folio 299d*; Faull & Stinson 1986). No mines were recorded in the Dales in the *Domesday Book,* but this absence may not mean that there were none. Alluvial deposits from the River Ouse in York demonstrate lead production upriver in the Dales, delivering pollutants continuously from the ninth/tenth to thirteenth centuries (Hudson-Edwards *et al*. 1999: 813–17). Furthermore, isotopic analysis of lead objects and ingots from Coppergate in York and from Viking-Age Scandinavian ports confirms production and export of Dales/north Pennine lead *c.* AD 800–850 (Kershaw & Merkel 2023: 265–66, 276). These apparent disparities between early medieval textual and archaeological evidence highlight the need for new research.

By the twelfth century, Boroughbridge (Aldborough's medieval successor, 1.8km westward) became the administrative centre for the 'mine of Yorkshire', comprising the Yorkshire Dales, whose lead was distributed via the linked Ure-Ouse-Humber river system, and the River Tees. Entries in the *Pipe Rolls* (the taxation records of the English Exchequer), indicate that the 'mine of Yorkshire' was the third largest lead-producing region in England, after the Peak District and 'the mine of Carlisle' (Loveluck *et al*. 2020: 478–79). The zenith of twelfth-century Yorkshire production occurred between 1180 and 1184, when lead was directly requisitioned by Henry II in 'cartload' (*carreta*) weights and transported to major

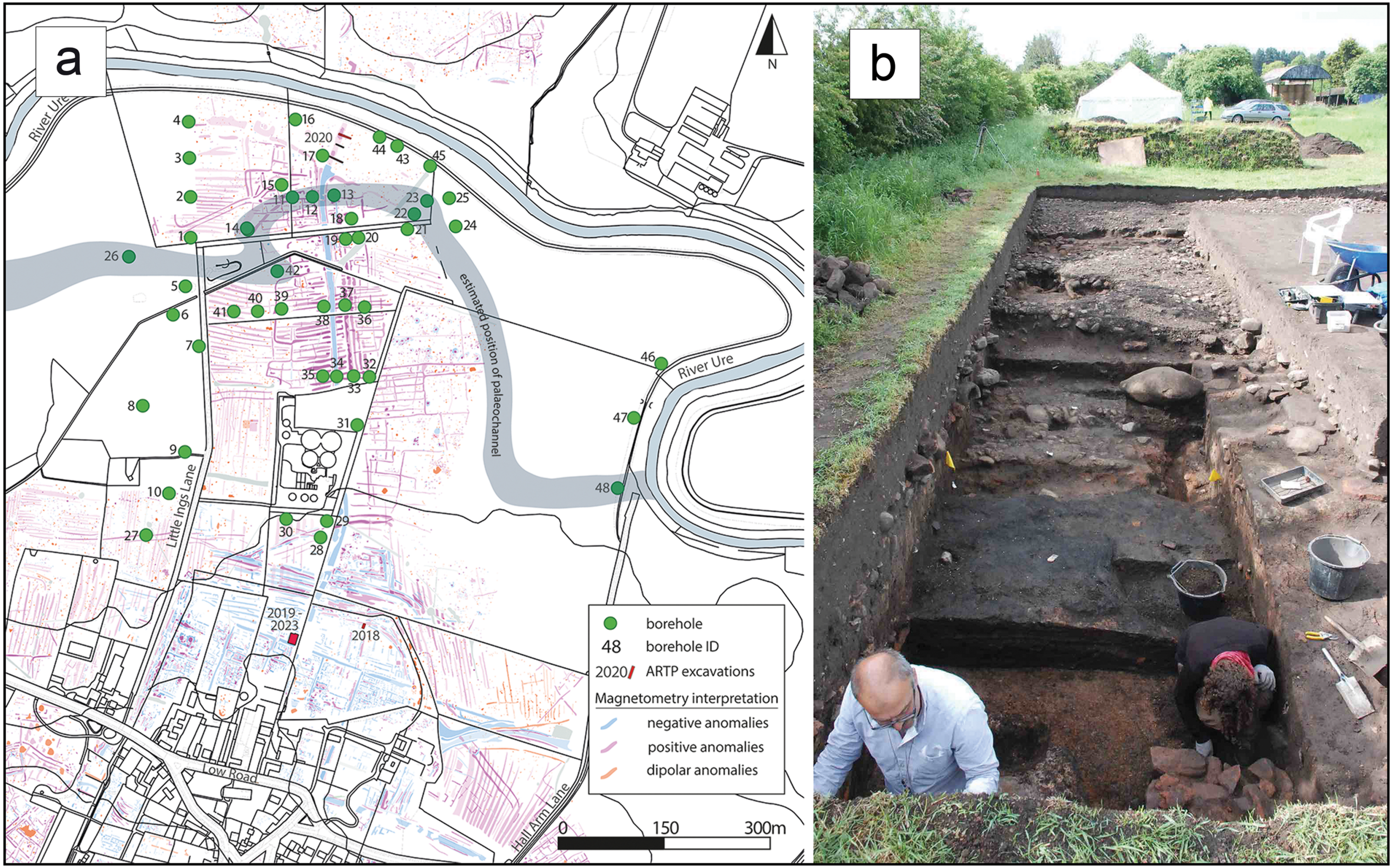

Figure 3. a) Plan showing features detected by geophysical survey and the location of boreholes and excavations undertaken at Aldborough; b) the Roman metal-working complex under excavation in 2021 (figure by R Ferraby & M.J. Millett).

building projects in England and France (Loveluck *et al.* 2020, OSM6: 52–54). A confirmatory charter of 1145 also records the rights of the Cistercian abbey at Jervaulx in North Yorkshire to mine iron ore and lead in the Forest of Wensleydale (Gill 1988: 49). Cycles of 'boom' and 'bust' in Dales lead production have been identified from the thirteenth to fifteenth centuries from abundant textual data: notably troughs in *c.* 1230–1260, 1310, 1345–1355 and 1457–1464, and peaks in *c.* 1290–1300, 1370s–1395 and 1420s–1435 (Blanchard 2005: 1400). Growth continued until the dissolution of the monasteries in 1536–1538 flooded the market with salvaged lead, resulting in recession (Burt 1995: 30–1). Following economic recovery in the 1560s, the region was one of the largest lead exporters worldwide by 1700 (van Duivenvoorde *et al.* 2013: 164–65).

Interdisciplinary approach

Questions remain concerning economic activity between AD 200 and 1150, when evidence is limited or absent, and the representativity of trends suggested from textual records. An opportunity to investigate the metals economy through time in the Aldborough area was provided by survey work around the Roman town, which identified a palaeochannel of the river Ure. A 5.96m-sediment core (Figure 3a; NGR: SE 4061567253) was extracted from the palaeochannel enabling an integrated sedimentological, landscape and multi-element analysis of proxies for metal production (see OSM1–4 for full details).

Sedimentological analysis was conducted at 0.02–0.05m resolution, using the 'loss on ignition' method to measure organic and carbonate content, and particle size and portable x-ray fluorescence (pXRF) analysis for sediment texture. Sub-samples for pollen analysis were taken along the core at 0.08–0.1m intervals following standard techniques (OSM1). Five pollen assemblage zones were identified along the core—based on species presence—providing a relative chronology by comparison with species profiles from sites and landscapes of different periods in Britain. Zone 'ALD 4' from 2.44–1m was equated with the Bronze Age, Iron Age and Roman periods, c. 2000 BC–AD 400. At around 1.85m, the palaeochannel ceased to be the main active channel of the river and from 1.6–1.5m pollen of cereals (wheat and rye) increased, reaching a peak in the upper part of ALD 4 (suggested as the Roman period). Subsequently, the appearance of species diagnostic of the early–late Medieval periods (c. AD 400–1500), e.g. hemp, at 1–0.24m defined the chronological span of pollen zone 'ALD 5'. Between the Roman and modern periods, the palaeochannel was subject to slow, seasonal and superimposed accumulation of overbank alluvium, which would have provided surfaces for the deposition of metal aerosol pollution. The adjacent landscape comprised arable land, pasture and heath.

An age-depth model was then created using four radiocarbon dates, two OSL dates and Bacon age-depth-modelling software (Figure 4, Table 1; OSM2a & 2b). The pollen zone phasing and age-depth model were then compared, demonstrating close consilience. This study focuses on the part of the core from 1.12m–0.2m, encompassing the upper 0.1m of the ALD 4 and the entire ALD 5 pollen zones, and the transition between the uppermost alluvium and topsoil. Following the age-depth model, this covered the period from *c.* AD 345–1700 (OSM2a & 2b). However, the outlier date at 1.02m widens the error margin in the age-depth model from about 0.6m to 1.12m

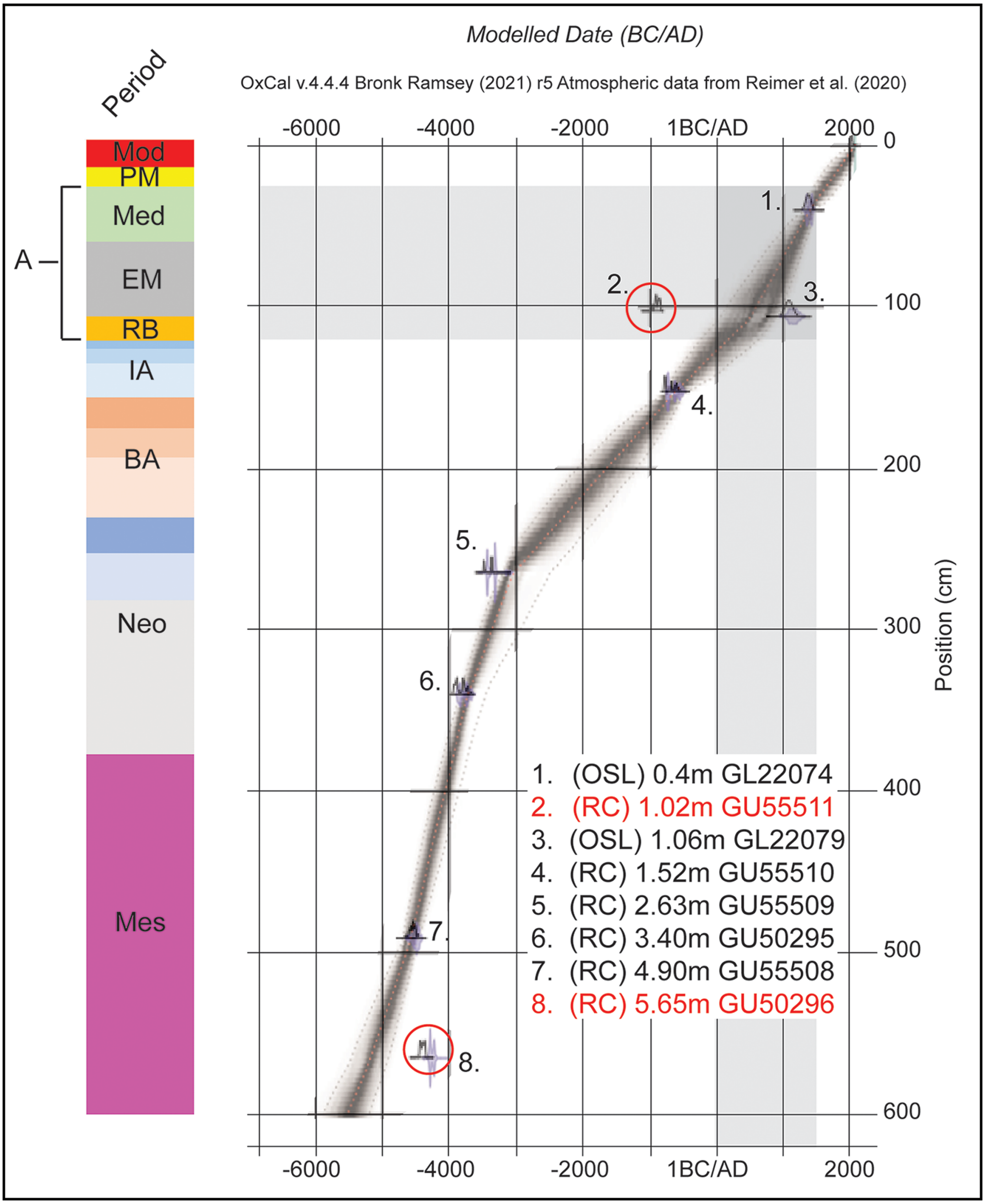

Figure 4. Bacon age-depth model based on absolute dates from the core. Label A and grey shading indicates the Romano-British to medieval period. Outlier radiocarbon dates are circled in red. Mod: Modern period (AD 1750–present); PM: post medieval (AD 1540–1750); Med: medieval (AD 1066–1540); EM: early medieval (AD 410–1066); RB: Romano-British (AD 43–410); IA: Iron Age (800 BC–AD 43); BA: Bronze Age (2400–800 BC); Neo: Neolithic (4000–2400 BC); Mes: Mesolithic (7000–4000 BC) (figure by B. Pears).

Table 1. Radiocarbon and OSL dates from the core.

Sample depth (m)	OSL date	Radiocarbon years (BP)	Calibrated radiocarbon date (95.4% probability)	Lab number
0.40	AD 1330–1420			GL22074
1.02		2761±24	976–833 cal BC*	GU55511
1.06	AD 1020–1140			GL22079
1.52		2543±24	799–553 cal BC	GU55510
2.63		4604±23	3499–3347 cal BC	GU55509
3.40		5021±26	3942–3711 cal BC	GU50295
4.90		5714±22	4617–4485 cal BC	GU55508
5.65		5467±27	4358–4261 cal BC*	GU50296

*These outlying dates were removed from the age-depth model.

(*c.* AD 345–1100; see OSM2a & 2c), although the pollen-phasing remained consistent with the medieval to Roman periods and excavated archaeological evidence.

Pollution analysis proceeded by taking samples within 0.02m units along the core from 1.12m–0.1m. The dried samples were freezer-milled and prepared for ICP-MS. A range of 56 major elements associated with natural minerals/phases and anthropogenic trace elements (heavy metals) was analysed by their concentrations in mg/kg and compared through time. Lead isotopes were not used in this instance due to extensive isotopic-range overlaps between regions (see OSM3), and immediate proximity of large-scale local and regional lead production to Aldborough-Boroughbridge. Statistical representativity of the anthropogenic metal pollution results was confirmed by normalising lead, silver and iron values against titanium as a crustal (natural dust) proxy (Figures 5b, 6b & 8b; OSM4). This normalisation screened out geogenic (natural) fluctuations leaving only statistically significant anthropogenic records. Understanding of relationships between elements was then further elucidated using principal components analysis/factorial analysis (OSM4). Despite establishing statistical validity of the anthropogenic records, our study focuses on major trends and fluctuations.

Interdisciplinary linkage and interpretation of major pollution trends alongside textual/archaeological evidence follows established practices for pollution and climate records from sediment cores, ice cores and speleothems over the past decade (e.g. Xoplaki *et al.* 2016; More *et al.* 2017; Loveluck *et al.* 2018, 2020; McConnell *et al.* 2018; Longman *et al.* 2020). Dated trends from the upper part of the core with lower error margins (*c.* 1100–1700) can be interpreted alongside textual, archaeological and other environmental records. Agreement between these sources then provides confidence in our identification of trends in the earlier, less closely dated section of the core (*c.* 345–1100; see OSM2c).

Tracking of elements from lead and iron production

Our results indicate a discrete relationship between silver and lead, with silver being elevated above 0.4mg/kg only in the later fifteenth, mid–late fourteenth and early–mid fifth centuries in the model (Figures 5 & 6). There were also generally elevated levels of copper

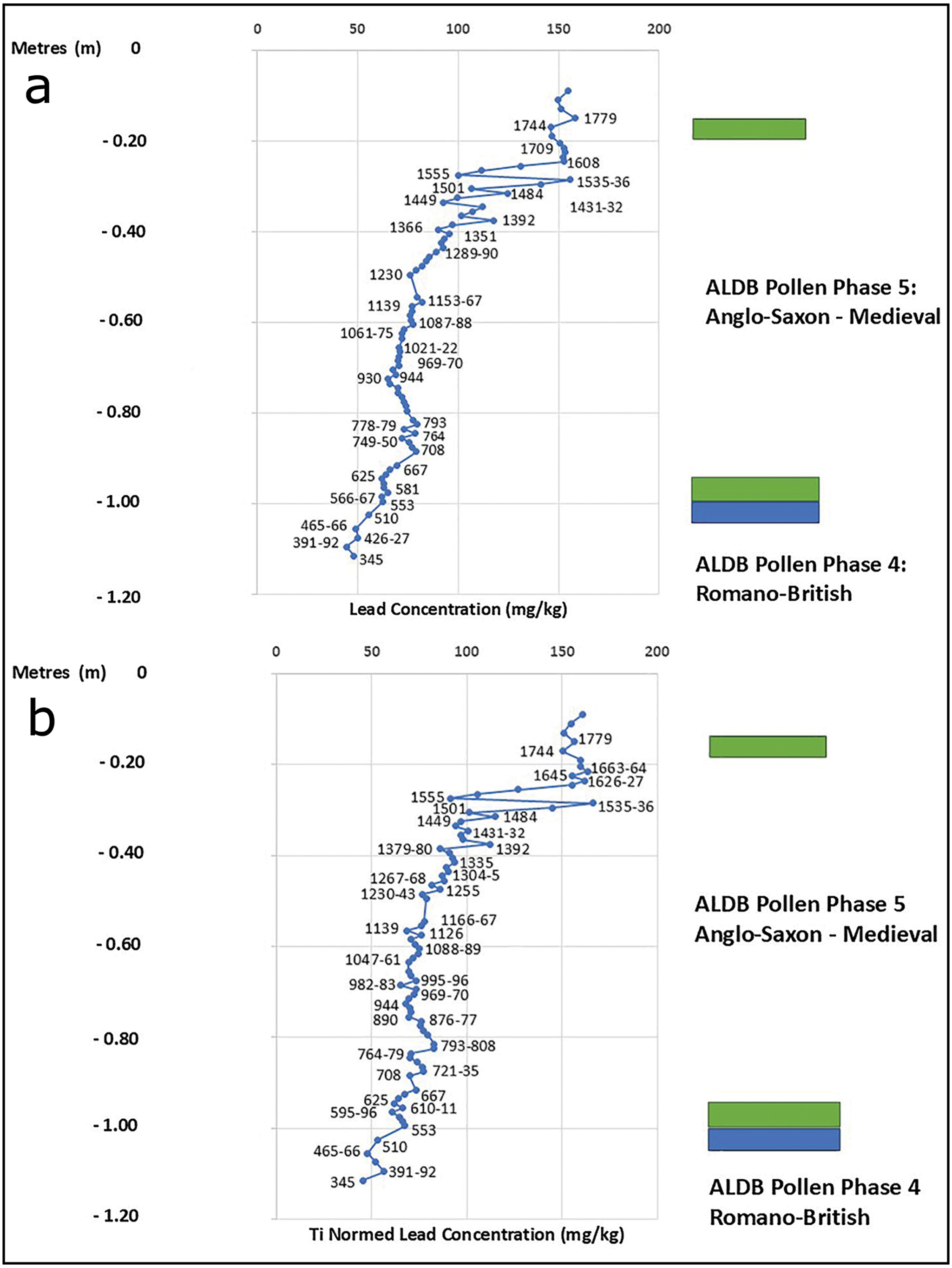

Figure 5. Chronological pattern of lead pollution in the Aldborough core: a) lead concentration; b) lead concentration normalised against titanium. See OSM 2c for dating error margins (figure by C.P. Loveluck & S. Chenery).

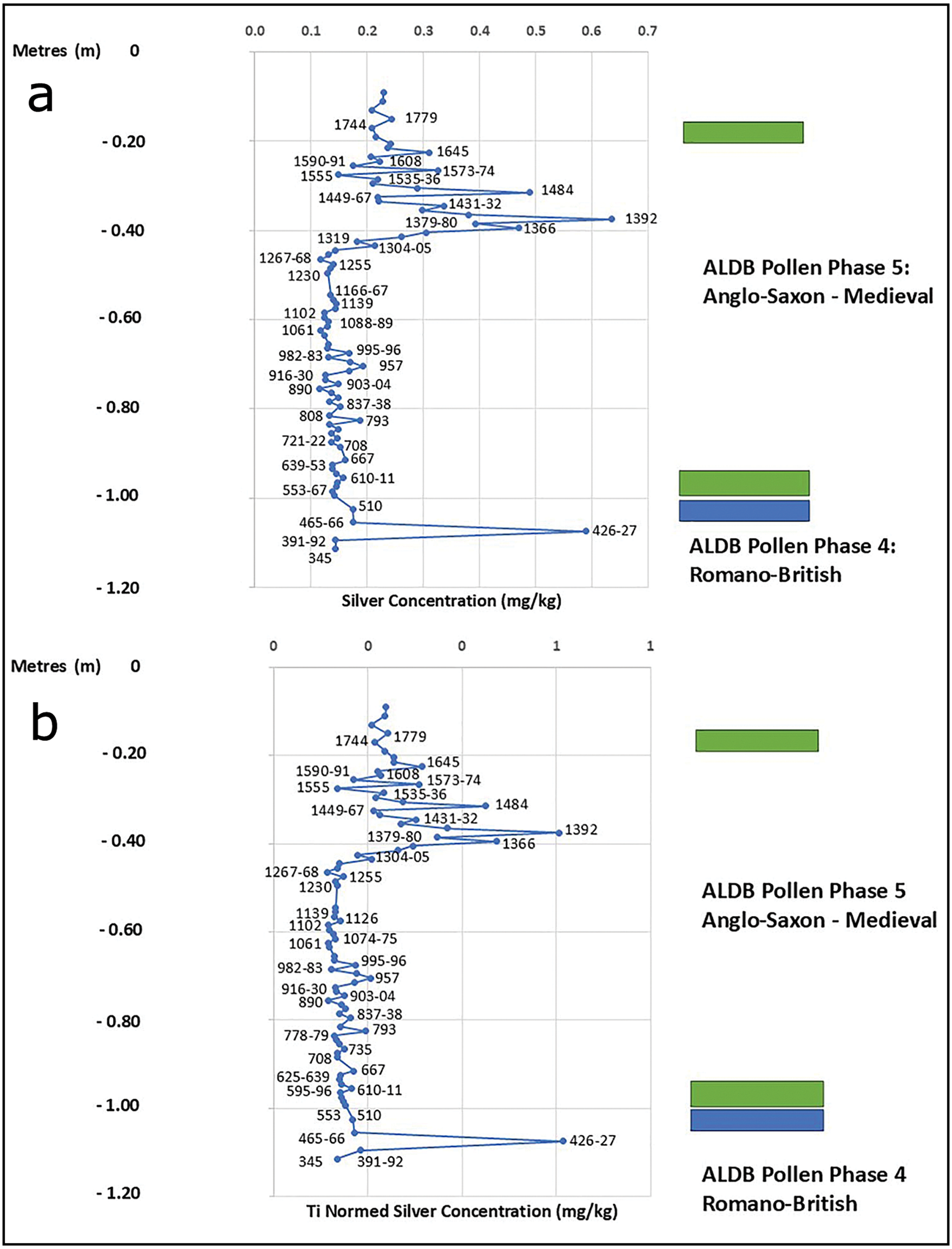

Figure 6. Chronological pattern of silver pollution in the Aldborough core: a) silver concentration; b) silver concentration normalised against titanium. See OSM 2c for dating error margins (figure by C.P. Loveluck & S. Chenery).

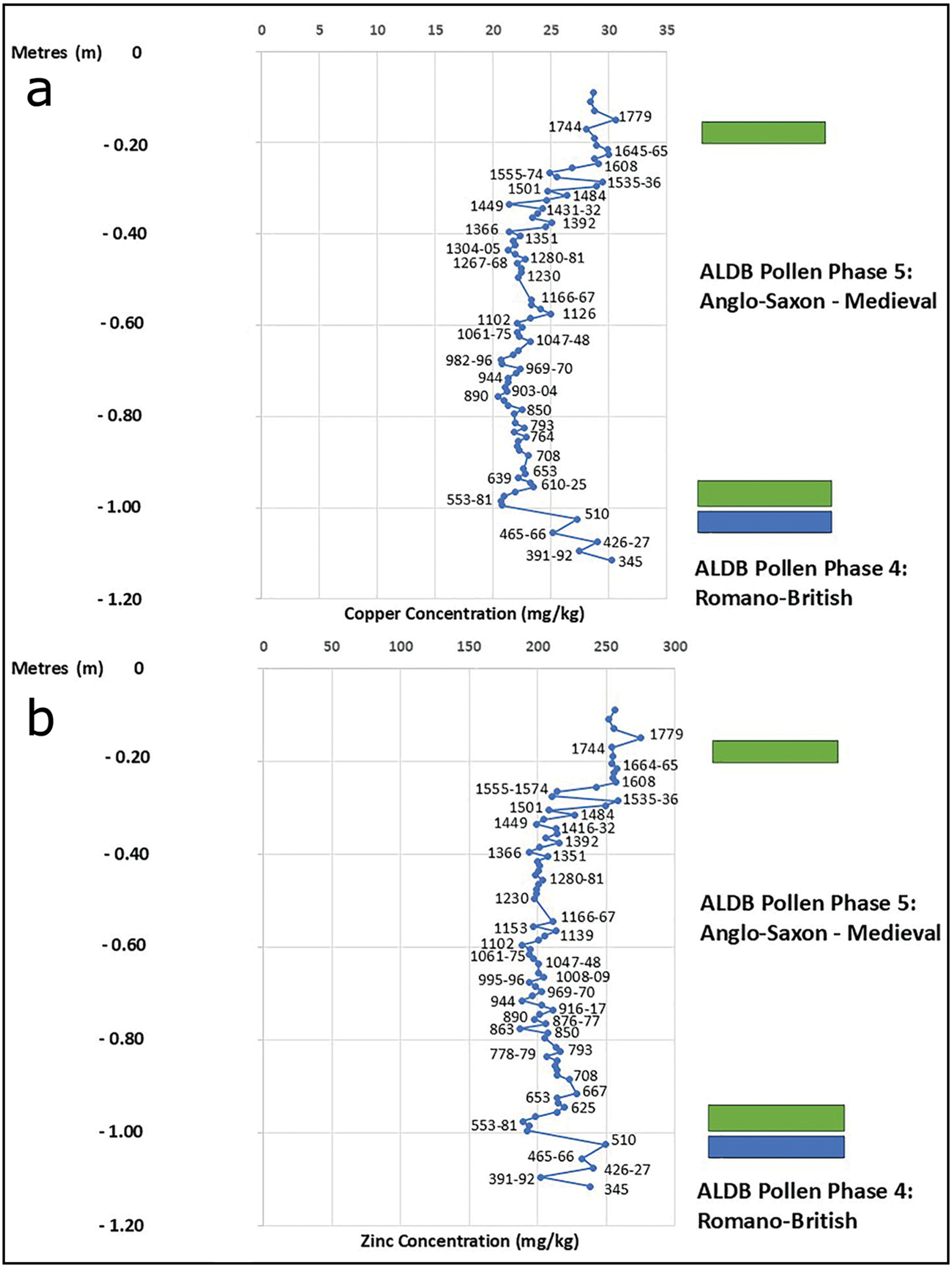

Figure 7. Chronological pattern of copper (a) and zinc (b) pollution in the Aldborough core. See OSM 2c for dating error margins (figure by C.P. Loveluck & S. Chenery).

(≥ 25mg/kg) and zinc (≥ 225mg/kg) between the late fourteenth to late eighteenth centuries and from the mid-fourth to early mid-sixth centuries (Figure 7). These close similarities may be due to the targeting of ores for specific purposes in different periods and changing scales of production. The late fourteenth to late eighteenth centuries in the model saw the highest levels of lead pollution. Therefore, the close tracking of copper, zinc and silver with lead during the periods noted above almost certainly reflects lead production and the unintentional metal pollution byproducts of smelting galena-lead ore.

The concentration data demonstrate that the smelting and working of iron were the principal metal-producing activities in the vicinity between the late Roman and modern periods. Figures 8 and 9a present the changing scale of iron and arsenic pollution through time. Both elements track each other closely, from around 1.025m–0.5m in the sediment core (between the early sixth and mid-thirteenth centuries in the model). From the mid-thirteenth to late eighteenth centuries and before the sixth century, arsenic does not follow iron levels and reflects an alternative anthropogenic influence: the smelting of arsenic-bearing galena. The close relationship between iron and arsenic from the sixth to mid-thirteenth centuries is typical of iron smelting centres, for example the Roman smelting centre at Magazzini, Elba, Italy (Becker *et al.* 2019: 9–11). Small quantities of copper and lead can also be released during smelting of iron but copper concentrations at Aldborough track lead and zinc, suggesting their combined release from the smelting of lead ores (Figures 5–7). Phosphorous also tracks iron and arsenic seemingly from the sixth to mid-thirteenth centuries (Figure 9b), marking the working of phosphoric iron at the height of iron production in the earlier Middle Ages (see below). Although, again, before the sixth century and after the mid-thirteenth century phosphorous tracks lead, zinc, copper and silver.

Bismuth levels were also highest from the late sixteenth to late nineteenth centuries (0.1m–0.255m) and elevated but with greater variation from the mid-fourth to early–mid-sixth centuries (1.115–1.025m) (OSM4). Bismuth is released through volcanic eruptions, coal-burning and the smelting of heavy metals (Kaspari *et al.* 2009: 9). The higher bismuth levels from the late sixteenth to late nineteenth centuries reflect a general increase in coal-burning, and the elevated levels between the fourth and sixth centuries probably relate to local coal burning for iron-smithing and possibly domestic heating at Aldborough, demonstrated at the excavated Roman metal-working complex.

Metals economy and societal contexts from the Early Modern to late Roman period

Lead production

Integrated analysis of lead pollution trends from the more closely dated section of the core (*c.* 1100–1700) showed close concurrence with historically documented levels of production and other environmental records. Overall, rises in levels of pollution track prosperity or sociopolitical stimuli, while falls often mark periods of warfare/political crisis and pandemics that limited production, transport and trade. The seventeenth- to eighteenth-century high point in lead production (Burt 1995) is evident in the pollution record (Figure 5b), and short-term falls in pollution in the mid-eighteenth and mid-

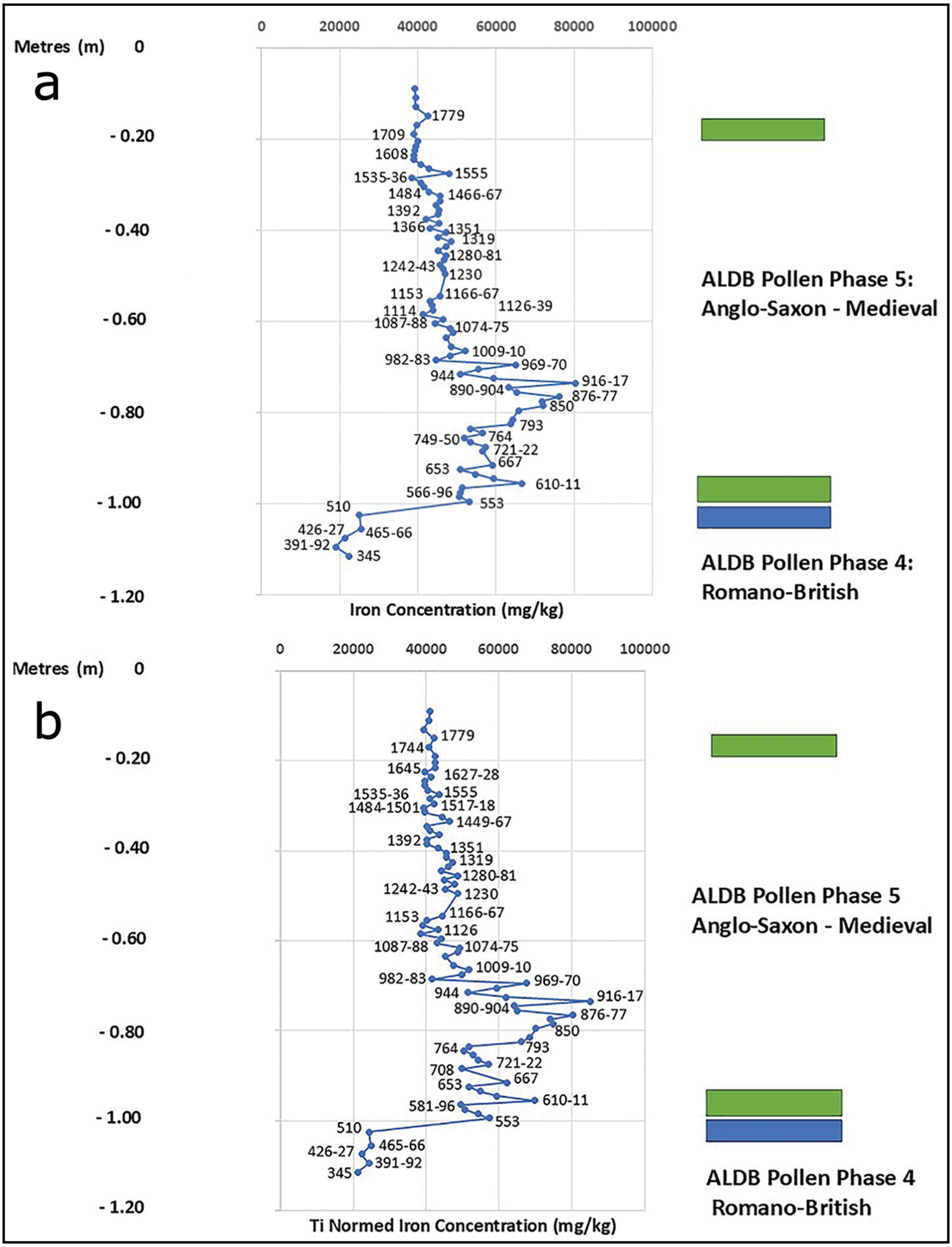

Figure 8. Chronological pattern of iron pollution in the Aldborough core: a) iron concentration; b) iron concentration normalised against titanium. See OSM 2c for dating error margins (figure by C.P. Loveluck & S. Chenery).

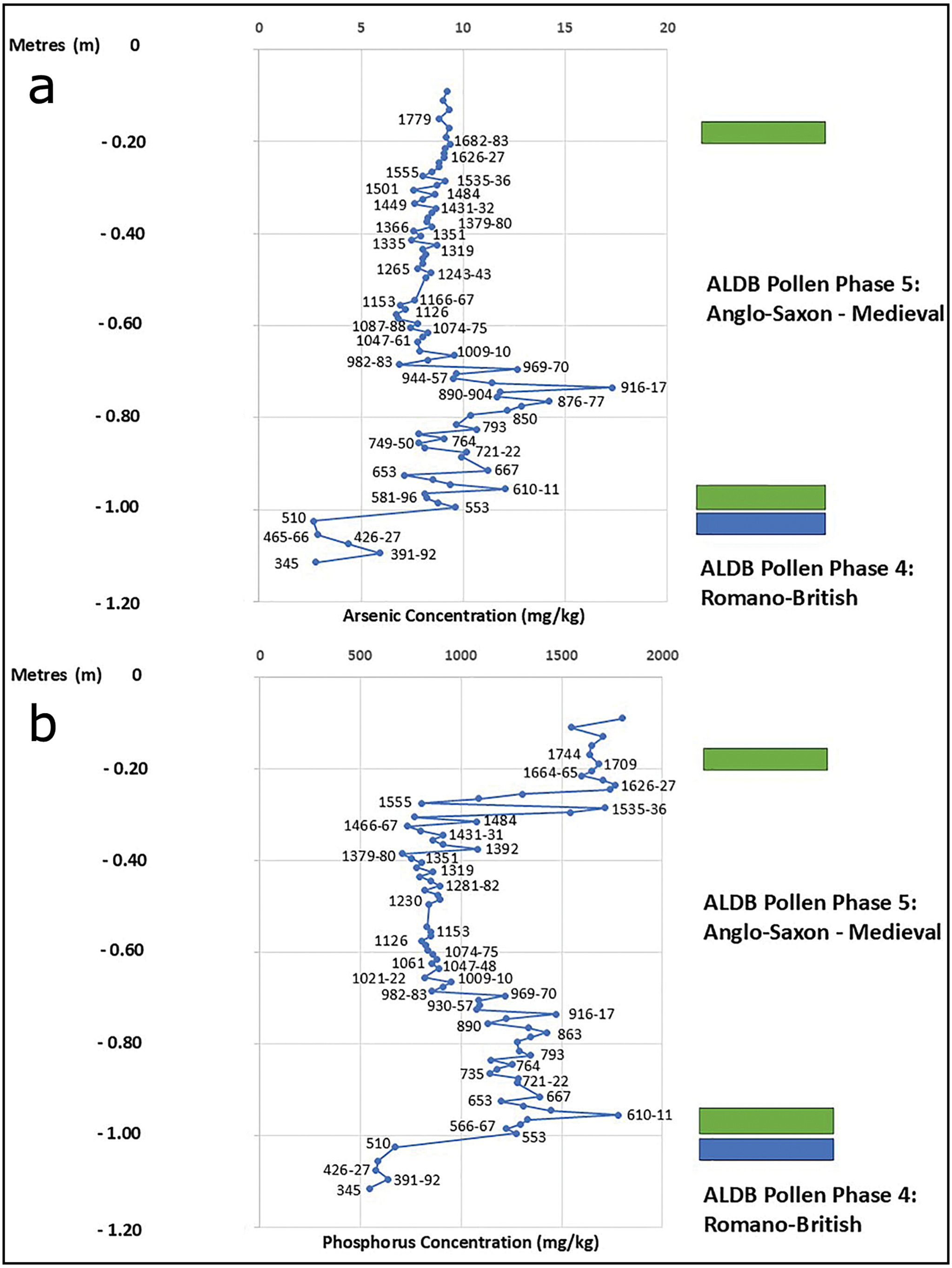

Figure 9. Chronological pattern of arsenic (a) and phosphorous (b) pollution in the Aldborough core. See OSM 2c for dating error margins (figure by C.P. Loveluck & S. Chenery).

seventeenth centuries coincide with the political crises of Jacobite advance through Yorkshire (1745) and Civil War campaigns impacting lead export from the Humber (1643–1644), and a plague outbreak in the region in 1645–1646 (Jennings 2018: 182; Slack 2000: 37–38). In the sixteenth century, the documented growth in lead production in the early reign of Henry VIII is reflected by a rise in pollution until *c.* 1535–1536 (see OSM2c for theoretical error margin), followed by sudden decrease after salvaged monastic lead depressed prices (Figure 5b). The trough at 1555 in the model could also reflect the impact of the 1557–1559 influenza epidemic—Yorkshire documented a 12.6 per cent population decrease between 1546 and 1563 (Moore 2010: 1058). Renewed lead, zinc and copper rises from the mid-sixteenth to early seventeenth centuries (Figures 5 & 7) probably reflect lead supply for Elizabeth I's French and Spanish wars, alongside commercial exports (Heap 2019: 10–11, 260–61).

Between the late thirteenth and late fifteenth centuries, there is also consilience between documented trends in lead production for Yorkshire and the Aldborough pollution record. Documented rises in Yorkshire production from *c.* 1370–1395 and 1420–1435 are probably reflected in lead, copper, zinc and silver peaks at Aldborough during the mid-to-late fourteenth and mid-fifteenth centuries in the model (Blanchard 2005: 1400). Similarly, a further peak in these elements in the mid-to-late fifteenth century may correspond with the recorded increase in lead exports from York and Hull in the 1460s–1490s (Kermode 1998: 332–45). A gradual rise in lead (and also zinc and copper) from the mid-thirteenth to early fourteenth centuries also correspond to the decades of castle-building by Edward I in Wales (Figures 5–7). The downturns in production attested in documentary sources *c.* 1310, 1345–1355 and 1457–1464 may also be reflected in the Aldborough lead, zinc and copper records in the early and middle decades of the fourteenth century and the mid-fifteenth century (Blanchard 2005: 1400–10; Figures 7, 8 & 9). Documented lead production in the Dales was already falling before plague struck in 1349–1350, reflected in the normalised lead plot (Figure 5b), unlike the Peak District where booming production collapsed in 1349 (Blanchard 2005: 1372). The downturn at Aldborough in the mid-fifteenth century likely reflects the impact of recession and plague outbreaks from 1457–1465—a near-identical collapse is recorded in the lead pollution record identified as British for 1460–1465 in the high-resolution Colle Gnifetti ice core, Switzerland (More *et al.* 2017: 217, S1, tab. S2).

Lead pollution patterns at Aldborough between the mid-twelfth and mid-thirteenth centuries also accord with textual records for the 'mine of Yorkshire'. There was a sustained rise in lead pollution between the mid-twelfth and early thirteenth centuries, prior to a sharp decline by the mid-thirteenth century. This matches the recorded production/revenue trend in the *Pipe Rolls* and high-resolution ice- and lake-core records of identified British pollution trends in the same decades (Brännvall *et al.* 1999: 4394; Blanchard 2005: 1400; More *et al.* 2017: 213; Loveluck *et al.* 2020: 476). At the margins of the better-dated section of the core, a twelfth-century low-point in lead pollution in 1139 (but see OSM2c for theoretical error margin) may reflect disruption caused by warfare in the reign of King Stephen (1135–1154) (Figure 5b). Another low point during the mid-eleventh century (at 1047–1061 in the titanium-normed lead record) possibly reflects the impact of the Norman Conquest, although this low point was reached from a general decline through the eleventh century, which may account for the absence of Yorkshire lead production in the *Domesday Book* (Figure 5b).

Prior to the mid-to-late eleventh century, the theoretical error margin in the age-depth model allows only the identification (with confidence) of major multi-decadal trends. Lead pollution declined steadily from the time of the Scandinavian kingdom of York (876–954), with only occasional rises in the later tenth century before further decline to the mid-eleventh century (Figure 5). However, there was a sustained peak in levels of lead pollution between the late eighth and mid-ninth centuries in the model, shown clearly in the normalised lead plot, and in small rises in silver and copper pollution byproducts (Figures 5b, 6b & 7). These largely coincide with the reign of Eanred of Northumbria (*c.* 810–841), which also overlaps with the earliest Pennine lead in Scandinavia, dating from *c.* 800–850 (Kershaw & Merkel 2023: 276). Prior to this, sustained relatively small-scale lead production is suggested only over several decades in the first half of the eighth century, and for short periods in the mid- and early seventh century (Figures 5b & 6b). The early-to-mid eighth-century rise spans the end of minting of the first Northumbrian regnal silver coinage (*sceattas*) by Aldfrith (685–705), and the minting of the series-Y Northumbrian *sceattas* by King Eadberht (738–757) (Booth 2000: 84–86). However, the small rise in silver pollution is insufficient to reflect any silver extraction to resource these coinages.

The final trends of note in the lead record relate to the period from the mid-fourth to early seventh century in the model. Perhaps surprisingly, the period from the mid-fourth to early-to-mid sixth century does not show total collapse in metal production after the withdrawal of Roman provincial administration *c.* 410. The normalised lead pollution record shows a small decline from an already low level from the later fourth to mid-fifth centuries (Figure 5b), overlapping with the end of imports of Pennine lead into Rhineland Germany by *c.* 400 (Durali-Mueller *et al.* 2007: 1566). However, there was a continuous small rise in lead pollution from the mid-fifth to mid-sixth centuries and a spike in silver pollution in the mid-fifth century (albeit only 0.6mg/kg), plus rises and falls in copper and zinc pollution (Figures 5, 6 & 7). This suggests small-scale lead smelting. However, the levels of silver, copper and zinc from the mid-fourth to early-to-mid sixth centuries were not accompanied by comparable trends in lead pollution, which raises the possibility of the preferential choice of ore for its higher silver and copper contents (Figures 5, 6 & 7). Following a peak in the early–mid-sixth century, the normalised lead record shows a sustained drop in production throughout the second half of the sixth century (Figure 5b). At this time, the levels of copper, zinc and silver pollution are also at their lowest for the past 1500 years (Figures 6 & 7).

Iron production

The pollution record shows that iron was the principal metal produced and worked in the vicinity of Aldborough from the Roman to Early Modern periods. Many of the trends in the lead record are also seen for iron and its smelting/smithing byproducts. Textual evidence for iron production and smithing is rare, despite the abundance of smithing-slag within the

Roman town. However, concurrence between the rise and fall of iron pollution and recorded sociopolitical events in the higher-resolution section of the core (*c.* 1100–1700) give us confidence to interpret some multi-decadal trends in earlier periods.

Like the higher-resolution lead record, short-term falls in iron pollution are seen in the mid-seventeenth and mid-eighteenth centuries (Figure 8b). There is also a sustained drop from the mid- to late sixteenth century, possibly reflecting the impact of the 1555–1557 influenza pandemic followed by a longer-term decline. A sustained gradual rise in iron pollution in the early sixteenth century is followed by a short drop *c.* 1535–1536 (but see OSM2c for theoretical error margin), possibly reflecting disruption caused by monastic dissolution, although the scale of decline was less than for lead. A sharper and deeper fall is seen in the mid-fifteenth century, as in the lead record, and likewise this could reflect documented economic recession and plague in this period (Blanchard 2005: 400–10). Iron pollution also exhibits a sharp drop in the mid-fourteenth century at *c.* 1351, one of the most tightly dated parts of the core (Figure 8b; OSM2c), possibly reflecting the impact of the 1349–1351 Black Death pandemic, not seen in lead because the Dales lead industry was in recession before 1349 (see above). Further consilience between iron and lead trends occurs in the twelfth and thirteenth centuries, with a rise in levels from the mid-twelfth to mid-thirteenth centuries.

Levels of iron pollution are orders of magnitude higher than lead for extended periods before 1100, where the dating error margin is wider. Nevertheless, key anthropogenic trends are evident. Iron pollution was higher between the early seventh and late tenth centuries than from the eleventh to eighteenth centuries; and from the late ninth to early tenth centuries in the model levels were more than double those of the later medieval and Early Modern periods (Figure 8b). This dramatic ninth-century increase in iron production is coincident with the smaller-scale rise in lead in its early decades (Figure 5b). Intensification of domestic production and exchange of raw materials, commodities and specialist goods during the early to mid-ninth century is a trend observable in settlements around the Humber, and more widely in England (Loveluck 2016: 562–64). Short-term sharp falls in iron pollution in the later ninth and mid-tenth centuries may reflect the immediate impacts of Scandinavian conquest in 876 and incorporation into the West Saxon kingdom of England in 954 (*The Anglo-Saxon Chronicle, D* manuscript; Swanton 1996: 113). However, by *c.* 1000, iron production had halved, falling to the levels seen in later periods.

The final trend of note is the marked early post-Roman rise in iron pollution from the early to mid-sixth century (Figure 8b), followed by a sharp fall during the second half of that century. Similar falls are seen in the levels of arsenic, normalised lead, zinc and copper across these decades, prior to recovery in the early seventh century (Figures 5b, 7 & 9a). The cause of this trend is uncertain, although ancient DNA research has demonstrated the presence of the Justinianic Bubonic plague in a mid-sixth-century grave in eastern England, and multiple pathogens seem to have caused a series of chronologically concentrated epidemics in north-west Europe from the 540s to the 590s (McCormick 2021: 74, 92–96).

Conclusions

Reconstruction of geoarchaeological history from the sediment core at Aldborough demonstrates the immense value of targeted coring in locations around historic metal-producing centres. Comparable detail in the analysis of their macro-economic outputs is not possible from site-based excavations alone. Detailed integration of different forms of evidence has shown considerable concurrence between the geoarchaeological pollution record and textual sources for levels of lead production from the mid-twelfth to eighteenth centuries AD and significant consilience with pollution patterns identified as British in origin in the Colle Gnifetti ice core (Swiss Alps) and in Swedish varved lake records. The agreement between these sources gives credence to the interpretation of pollution patterns of metals potentially linked to sociopolitical circumstances in the pre-twelfth-century parts of the core, where specific corroborating textual evidence is absent.

The results presented here substantially alter our perception of northern England in the immediate post-Roman period. Roman practices of metal production, comprising ore selection and use of coal are shown to have continued. Production/working of iron only declined slightly in the early to mid-fifth century before a continuous rise until the mid-sixth. This has fundamental significance for our understanding of metal production, specialisation and societal organisation *c.* 400–550, arguing against previously suggested total economic collapse (Fleming 2021: 126–31). Instead, a more nuanced narrative of 'islands' of surviving metal-producing communities is suggested. A similar continuity is seen among iron-producing communities in northern Gaul, at Vireux-Wallerand/Mont Vireux (Ardenne), Belgium, from the first to sixth centuries, and beyond (Lémant 1991: 149–55). Not surprisingly these key resources attracted the attention of emerging royal powers. From the ninth century, trends in large-scale iron- and lead-production at Aldborough may mark it as a royal centre and subsequent fluctuations track major economic phases and sociopolitical events. The fall across all metal production in the mid- to late sixth century may provide the first economic proxy for the impact of the Justinianic plague and other pathogens on north-eastern England.

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Data availability statement

All data are available in the OSM.

Online supplementary material (OSM)

To view supplementary material for this article, please visit https://doi.org/10.15184/aqy.2025.10175 and select the supplementary materials tab.

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