

Tracing a bog-iron bloomery furnace in an adjacent lake-sediment record in Ängersjö, central Sweden, using pollen and geochemical signals

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Received: 17 November 2015 / Accepted: 14 March 2016 / Published online: 28 March 2016
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Abstract Recent studies of bloomery sites in Sweden indicate the amount of iron produced with this early low-technology smelter was greater than previously thought, which implies greater economic importance. Little is known about the history of bloomery technology, not least the timeframe over which individual bloomeries were operated, as well as their impact on the landscape because of resource consumption and pollution. In this study we performed pollen and geochemical analyses of the lake-sediment record from Rörtjärnen, which is 120 m from the remains of a documented bloomery [one radiocarbon date: AD 1300–1435 (1 σ)], in Ängersjö, Hälsingland. A surface-soil transect shows a limited geochemical signal only within 20 m of the bloomery, and the sediment pollen record provides little direct evidence of an active bloomery and is consistent with other studied sites in the area linked to forest grazing or cultivation. Instead, we find major changes in sediment geochemistry during AD 800–1200,

centered on a unique peak in Pb at AD 1030–1060. These changes include, e.g., Si (biogenic) and P, together with changes in pollen (e.g., *Betula*, *Picea*, Cyperaceae), which together indicate disturbance in the forest and especially the adjoining fen. We attribute these changes to a period of bloomery-related activities predating the radiocarbon date of the charcoal from the bloomery, and suggest that date represents a late phase for the site.

Keywords Pollen · Geochemistry · Bloomery furnace · Iron production · Palaeolimnology

Introduction

Low-temperature bloomery furnace technology was the earliest method used for producing iron in Sweden and dates back to at least 700 BC (Magnusson 2015). The techniques used to construct bloomery furnaces changed through history in regards to shape and size, but the basic principal remained the same (Bentell 2015). They were constructed with the local resources that were available, but in general the furnace shaft was built with clay and stones with a bellows attached to the furnace and there was a pit at the bottom where the slag was collected. The amount of iron that potentially could be produced per run varied depending on the width and height of the furnace, from around 1 kg of iron up to 300 kg (Forenius and Hjärthner-Holdar 2013).

Bloomery iron was produced mainly from secondary iron minerals, such as limonite and goethite, which are formed when dissolved iron in groundwater is precipitated as iron oxyhydroxides when exposed to oxygen. These secondary iron minerals are found widely in Sweden in bogs, lake sediments and red-earth soils. These iron-rich

Communicated by M.-J. Gaillard.

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raw materials were first prepared by roasting before being used to produce iron. Over 7,000 sites with remains of bloomery furnaces or slag have been found and registered in Sweden (Swedish National Heritage Board database), mainly in central and southern Sweden in areas that were populated during the Iron and Middle Ages. These sites are regularly found close to locations where the raw material was gathered (e.g. Hyenstrand 1972).

The practice of producing iron with the bloomery process was widespread in Scandinavia and not specialized; that is, it was a common seasonal activity along with farming and animal husbandry (Magnusson 1986, 2015). It was previously thought that bloomery furnaces were used mainly to meet local needs for iron, for example, farming tools or weapons, as well as for limited trading, and that it was the eventual introduction of the iron blast furnace in the Middle Ages that was the main driver of the increasing production of iron that facilitated the increasing export of iron from Sweden. With the eventual development of blast furnaces it was possible to exploit waterpower to pump the bellows for the higher temperatures required to utilize ore from bedrock to produce iron. Although lake-sediment records hint at a possible earlier development (Karlsson et al. 2015), the oldest known blast furnace in Sweden was not established until the late 12th century at Lapphyttan (Magnusson 1985; Bindler et al. 2011). Thereafter during the 13th and 14th centuries blast furnaces were rapidly established throughout the ore-rich regions of central Sweden, mainly in the Bergslagen mining districts (Pettersen Jensen 2015). With the blast furnace iron production became a more specialized industry run by people with formal privileges, and manned by teams of workers. This new technology and its ability to produce larger quantities of iron vastly out-competed the bloomery furnace.

However, based on the large number of bloomeries and slag heaps documented in Sweden the total amount of iron that would have been produced greatly exceeds the estimates for the amount of iron needed to be self-sufficient during this time period (Forenius and Hjärthner-Holdar 2013; Berglund 2015). This greater level of production suggests there was already an ongoing export market for iron during early medieval times. This small-scale but seemingly widespread production of iron increases the interest in better understanding the history of bloomery furnaces as well as the early environmental impacts that would have followed along with their use due to resource consumption, environmental disturbance and possible pollution.

Most of the studies done on the remains of bloomery furnaces are archeological excavations, which provide important information on the technology used and how much iron may potentially have been produced. However, these investigations provide more limited information

about the timeframe over which a bloomery furnace may have operated. Only a smaller number of sites in Sweden have been dated, and the radiocarbon dates of charcoal or carbon trapped in slag that are available tell us only that a site was used at those discrete dated points in time. These isolated radiocarbon dates are difficult to interpret in terms of when a specific bloomery was first in operation and over what timeframe it may have operated. For example, in our study area in the parish of Ängersjö in Hälsingland, central Sweden, 15 bloomery furnaces have been documented, of which five have been dated, each with a single radiocarbon date from charcoal (Magnusson 1986). These five dates all fall in a calibrated range of AD 1300–1630, with the date from the bloomery associated with our study being the oldest, AD 1300–1435 (1 σ ; 560 ± 95 ^{14}C years BP). From one date we know only that a furnace was active at that one point in time, but this provides no knowledge about when it started or for how long it may have been active—does one date reflect a one-time operation or the last time the bloomery was used?

Multiproxy studies of lake-sediment and peat records that combine palaeoecology and geochemistry have been particularly useful in tracing the earliest history of mining in metallurgy in different areas of Europe (Monna et al. 2004; Baron et al. 2005; Jouffroy-Bapicot et al. 2007; Breitenlechner et al. 2010, 2013; Viehweider et al. 2015) and in Sweden specifically to trace the early history of iron blast furnaces (Bindler et al. 2011; Karlsson et al. 2015). In contrast to studying the establishment of blast furnaces at specific sites, which were set up along watercourses to exploit waterpower during the spring operation, bloomery furnaces were quite small scale, not operated continuously and were set up close to the resources exploited. Because the natural iron deposits used were local, there may not necessarily be a clear geochemical signature distinct from that found naturally in the surrounding soils and sediment. Furthermore, settlement and bloomery use were intertwined, and it is difficult to separate evidence of changes in forest cover and fire as being specifically related to forest grazing and agriculture or to small-scale bloomery operations (Pettersson et al. 2004; Segerström 2013). Despite the presence of at least 15 bloomery furnaces in the parish of Ängersjö, pollen and charcoal records from within the village and near two summer forest farms (Swedish, *fäbod*; analogous to shielings in the UK and *alpage* and *Almwirtschaft* in the Alps) outside of the village show changes similar to other palaeoecological records of early settlement and summer forest farms (Segerström 1997; Emanuelsson 2001; Lagerås 2007; Karlsson et al. 2010).

Our study site, the lake Rörtjärnen, is about 1 km to the west of the farms in Ängersjö, but only 120 m distant from one of the radiocarbon-dated bloomeries (Fig. 1). Between the bloomery site and the lake is a fen that contains visible

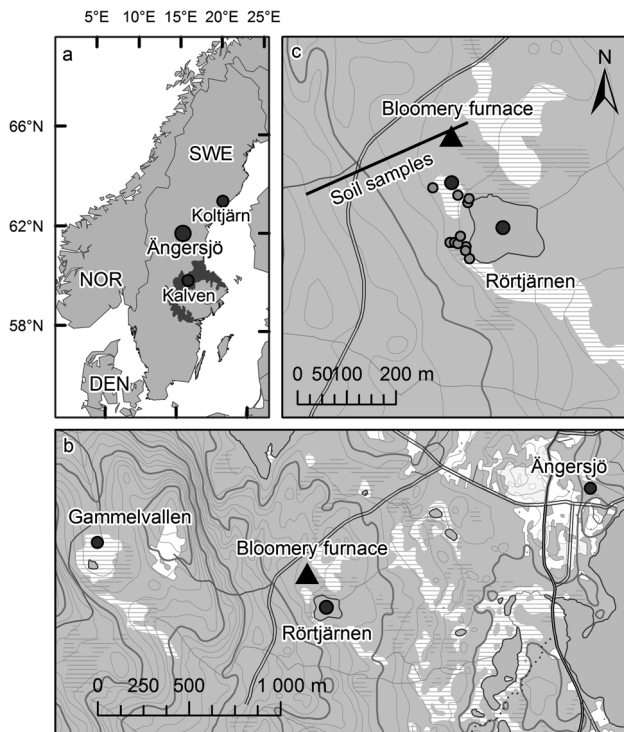


Fig. 1 **a** Map of Sweden with the study area Ängersjö and the location of two lakes discussed in the text, Koltjärnen and Kalven. The dark grey area in central Sweden shows the boundary of the historical Bergslagen ore-mining districts. **b** Location of the lake Rörtjärnen and the bloomery furnace, as well as the village of Ängersjö and the shieling site Gammelvallen where pollen records have previously been studied. **c** Map showing the bloomery furnace, location of soil-sample transect, the mires around the lake and the peat coring sites, and the coring site in Rörtjärnen

deposits of bog iron, which was likely the raw material for the bloomery. Given that we know a bloomery was operated close to the lake, our first question was, how well is a known bloomery furnace reflected in the sediment record of a nearby lake? Should we be able to identify signals in the sediment record that we could specifically associate with the bloomery, our second question was, could we identify or infer the timeframe over which the bloomery operated? To address these questions we combined pollen analysis with geochemistry, which included multi-element wavelength dispersive X-ray fluorescence spectroscopy (WD-XRF), mercury, and carbon and nitrogen analysis.

Site description and methods

Rörtjärnen (61°58′35″N, 14°50′49″E) is a small lake (1.5 ha, 5.5 m depth) situated 1 km west of Ängersjö, which is a remote village in an upland area (400 m a.s.l.) in Hälsingland, central Sweden (Fig. 1). The boreal forest landscape in this area is characterized primarily by blocky,

uneven glacial till with some exposed bedrock in elevated areas and in lower lying areas extensive patches of mires (fens). 120 m to the north of the lake is the site of a small bloomery furnace with slag (now heavily disturbed following blowdown of a dead spruce rooted through the slag pile). In the Swedish National Heritage Board registry the site is listed as object RAA Ängersjö 28:1 (see also Magnusson 1986). Several metres from the bloomery site is a groundwater-fed section of a fen, where bog iron was likely excavated, which connects to the main body of the fen (~4 ha) that drains toward the west. This fen is separated from Rörtjärnen by a narrow deposit of till overlying bedrock. Two small, connected fens (~0.8 ha), fed by groundwater draining out from the till, adjoin the lake on its NW and SW shore and floating *Sphagnum* mats occupy the entire fringe of the lakeshore. Although there is now a small ditch from the NE corner of the lake, drainage is mainly through seepage through a fen along the east side of the lake.

A sediment profile was collected from Rörtjärnen in February 2002 using a freeze corer (Renberg 1981) for the uppermost, unconsolidated sediment (0–65 cm depth) and a Russian peat corer (1 m length, 8 cm diameter) for the more consolidated sediment below. The freeze core and the first 1 m long Russian core were matched together into a single 103 cm long profile based on the field-measured overlap and later fine-tuning using visible characteristics and the geochemical data in the overlapping sections. The cores were sliced into 1 cm sections, freeze-dried and homogenized before further analysis.

Two samples of macrofossils (mixture of needles and seeds from *Picea abies*) in the sediment core were radiocarbon dated at Tandem Laboratory, Uppsala University, Sweden. An age-depth model for the sediment core (Fig. 2) was created using Clam 2.2 (Blaauw 2010) and IntCal13. The age-depth model (smooth spline) is based on the two radiocarbon dates and the peak in lead (Pb) at 7 cm that we assign to the peak in emissions c. AD 1970, which compensates for the lower compaction in surface sediments (Maier et al. 2013). To test and validate the model we included independent chronological markers, which are plotted passively in Fig. 2. One date is the establishment of *Picea abies* in central Sweden, $2,800 \pm 250$ BP (Giesecke 2005), and the others are three well-dated features of the historical Pb pollution curve derived from varved sediment records from central and northern Swedish lakes (Brännvall et al. 1999; Bindler et al. 2011): (1) Roman Pb peak, dated to AD 80; (2) an initial medieval peak AD 1200; and (3) a rapid increase in Pb AD 1500, with an uncertainty of ± 50 years for each date. The radiocarbon dates for the five dated bloomeries in the Ängersjö area were calibrated to calendar years using OxCal 4.2 (Bronk Ramsey 2009).

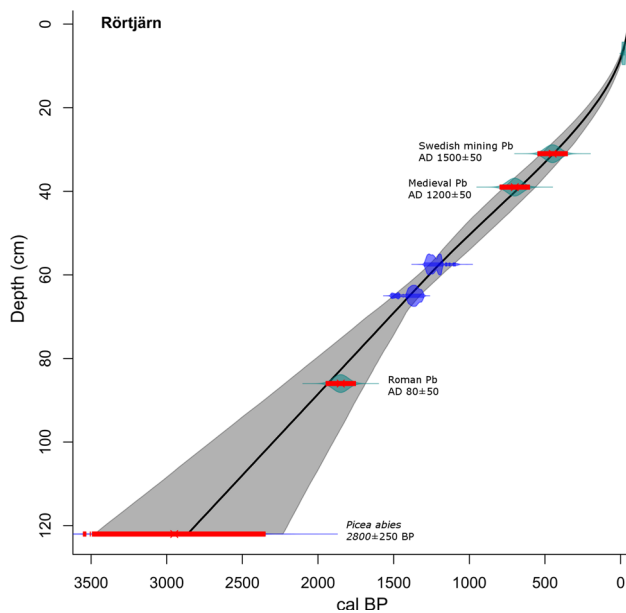


Fig. 2 Age depth-model of the lake-sediment record from Rörtjärnen in Ängersjö, Sweden. Two radiocarbon dates and the lead emission peak, c. AD 1970, were used with a smooth-spline setting in Clam 2.2 (Blaauw 2010). Independent chronological markers are plotted passively (marked in red as ‘outliers’): 122 cm, establishment of *Picea abies* in central Sweden, approximately $2,800 \pm 250$ BP (Giesecke 2005); 86 cm, Roman Pb peak, AD 80 ± 50 ; 39 cm, medieval Pb peak, AD 1250 ± 50 ; and 31 cm, peak from Swedish mining, AD 1500 ± 50 , which are derived from varved sediment records, particularly Kalven and Koltjärnen (Brännvall et al. 1999; Bindler et al. 2011)

Pollen analysis ($n = 68$) was done for every second sample down to 31 cm depth, every cm from 31 to 68 cm and every second sample thereafter to 98 cm depth. The samples were prepared following the standard procedure in Moore et al. (1991). For each sample a total of 600–800 pollen grains were counted and each species is presented as a percentage of the total terrestrial pollen count. Reference pollen slides and the general keys of Beug (1961), Moore and Webb (1978) and Moore et al. (1991) were used to identify pollen types and the nomenclature for pollen types follows Moore et al. (1991). Pollen diagrams were created using Tilia (Grimm 1991, 2004) and the data are plotted on the depth scale of the sediment profile. Smear slides with fresh sediment were examined further down in the sediment to identify at which depth the establishment of *Picea abies* occurred (122 cm). This second Russian core was correlated with the first based on field depths and visual characteristics.

Major and trace elements in the powdered samples were measured using wavelength dispersive X-ray fluorescence spectroscopy (WD-XRF) after the samples were lightly ground with mortar and pestle (see Rydberg (2014) for a full description of methods, including accuracy and

precision). A total of 77 samples in the depth range 0–103 cm were analyzed. Mercury was analyzed using thermal desorption atomic absorption spectrometry (Perkin–Elmer SMS100). Accuracy and precision of replicate analyses and standard reference materials were within $\pm 5\%$. Carbon ($n = 49$) and nitrogen ($n = 30$) contents were analyzed using a Perkin–Elmer 2400 series II CHNS/O-analyzer in CHNS-mode. Replicate analyses were within $\pm 1\%$ for C and $\pm 10\%$ for N. Carbon:nitrogen (C/N) ratios are presented as the atomic ratio. Stable isotopes of Pb ($^{206}\text{Pb}/^{207}\text{Pb}$) were measured in a small sub-set of samples using ICP-MS following a nitric acid extraction at the Institute of Environmental Sciences, Technische Universität Braunschweig. Accuracy of the isotope measurements was supported by analyses of IAEA SL-1, with a measured $^{206}\text{Pb}/^{207}\text{Pb}$ ratio of 1.220 ± 0.003 ($n = 10$) versus a reported value of 1.217 (Farmer et al. 2002).

To assess the geochemical fingerprint of the bloomery emissions we collected 10 soil samples in 2012 from 10 locations along a 250 m transect across the bloomery furnace site with two of the sample locations immediately next to the furnace (Fig. 1). The soil was collected using a sharpened steel cylinder (2 cm diameter) and the organic humus layer and the uppermost 2 cm of mineral soil were divided into separate samples. After freeze-drying the samples were ground in a Retsch swing mill and then analyzed using WD-XRF. The concentrations for Fe, Pb and Zn were normalized with Zr, which is the least leachable element in soil (Hodson 2002) and rescaled to 0–1 ($x' = (x - x_{\min}) / (x_{\max} - x_{\min})$) when plotting the data. In the autumn of 2015 we also collected peat samples in the fen sections adjoining the lake along the western side to determine whether the peat geochemistry could explain some of the major changes in geochemistry observed in the sediment—particularly for Si. A 150 cm deep peat profile (40 cm monolith and 3 overlapping 50 cm Russian peat cores) was collected from the fen adjoining the lake on the NW and bulk peat samples (10–60 cm depth) from 11 additional locations (Fig. 1). Samples were dried at $35\text{ }^\circ\text{C}$, ground and analyzed using WD-XRF.

To summarize the sediment geochemical data and to identify major changes in composition, we performed a principal component analysis (PCA; SPSS v.22) after transforming the data to z-scores. The concentration data and the initial PCA indicated a gradual long-term linear trend in the data driven by declining Si concentrations and increasing concentrations of almost all other elements. To compensate for the influence of this long-term trend, the data were detrended prior to the final PCA. For the PCA we excluded Pb because changes in Pb are driven almost exclusively by external factors (i.e. pollution deposition; cf. Bindler 2011) and we were interested in how Pb relates to the local environmental changes indicated by the PCA. We also excluded the surface sediments (0–10 cm), which

represent the past ca. 100 year and because some of the largest changes in geochemistry occur in these surface sediments, which would include, for example, modern clear-cut forestry. C, N and Hg are not included because these data are discontinuous, but these are presented in relation to the principal components. Detrending the data before the PCA also allows us to apply a changepoint analysis, which can be used to identify statistically the maximum likelihood and location of discrete changes in noisy time/depth series (Gallagher et al. 2011).

Results

Age-depth model

The results of the radiocarbon dating are presented in Table 1. The age-depth model (Fig. 2) is supported by the appearance of *Picea abies* at 122 cm depth, and also—as discussed further later—by the fact that the main patterns and timing of changes in Pb concentrations over the past 2,200 years are consistent with well-dated Pb records from central and northern Sweden, such as a small peak AD 80, and peaks AD 1200 and 1500 (Fig. 3: Brännvall et al. 1999; Bindler et al. 2011). These independent chronological markers are plotted passively in the age-depth model shown in Fig. 2.

In the Results and Discussion sections we present and discuss the data in relation to the best-fit age from the model (as well as including the sediment depth); however, this is not the true age and the 95 % confidence range of the model spans from ±10 to 145 years for each sample (Fig. 2). The variance in the age range for each sample is low (±10 to 80) during the most important period for our study from AD 500 to 1500.

Pollen

Forest cover and composition

Arboreal pollen dominates the pollen record (Fig. 4), where *Pinus sylvestris* is the dominant fraction, comprising

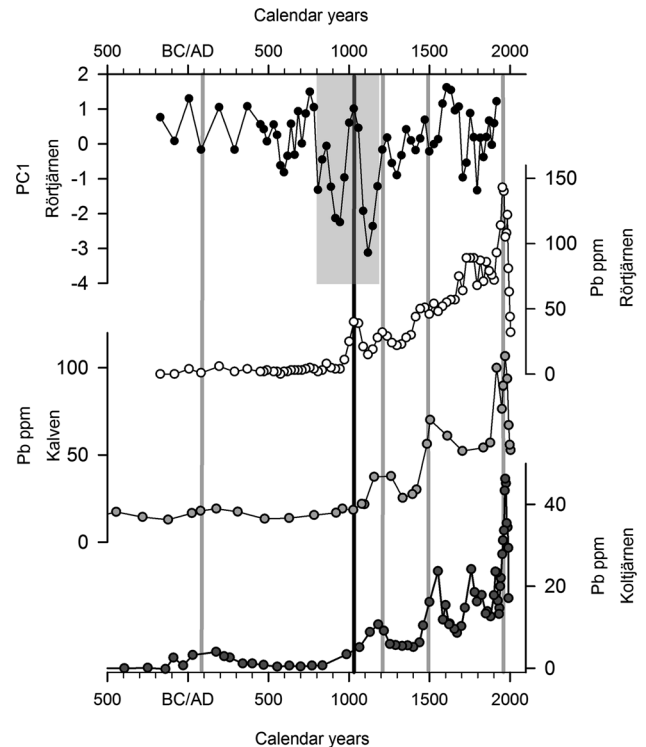


Fig. 3 First principle component of Rörtjärnen’s geochemistry, showing the main period of disturbance (the vertical grey-shaded area indicates the key period of disturbance, AD 800–1200), together with Pb concentrations in the lake-sediment records from Rörtjärnen and two varved sediment records—Kalven in central Sweden (Bindler et al. 2011) and Koltjärnen in northern Sweden (Brännvall et al. 1999). All lakes show the well-established peaks in Pb ca. AD 80, 1250 and 1500 (vertical grey lines) for lakes from central to northern Sweden, whereas Rörtjärnen also shows a unique peak (black line) occurring AD 1030–1060, centered in the disturbance phase

30–70 % of the total terrestrial pollen. The total sum for arboreal pollen is about 95 % from 100 BC until AD 1440 (98–32 cm), when it declines to 90 % and eventually to a minimum value of 80 % AD 1970 (7 cm). Clear changes occur within the arboreal assemblage over the 2,100-year study period. *Picea abies*, which became established in the region about 2,800 BP (Giesecke 2005), first appears in smear slides at 122 cm depth, and in our counted section

Table 1 Radiocarbon dating and calibration of macrofossils from Rörtjärnen

Depth (cm)	Sample	Lab-id	¹⁴ C year BP	Cal year AD (2 σ)	Probability distribution
56–59	Needles (<i>Picea abies</i>) and seeds	Ua-20,499	1,295 ± 45	650–778	0.939
				791–807	0.019
				811–826	0.015
				840–863	0.026
64–66	Needles (<i>Picea abies</i>) and seeds	Ua-20,500	1,485 ± 45	430–492	0.142
				513–516	0.004
				529–651	0.854

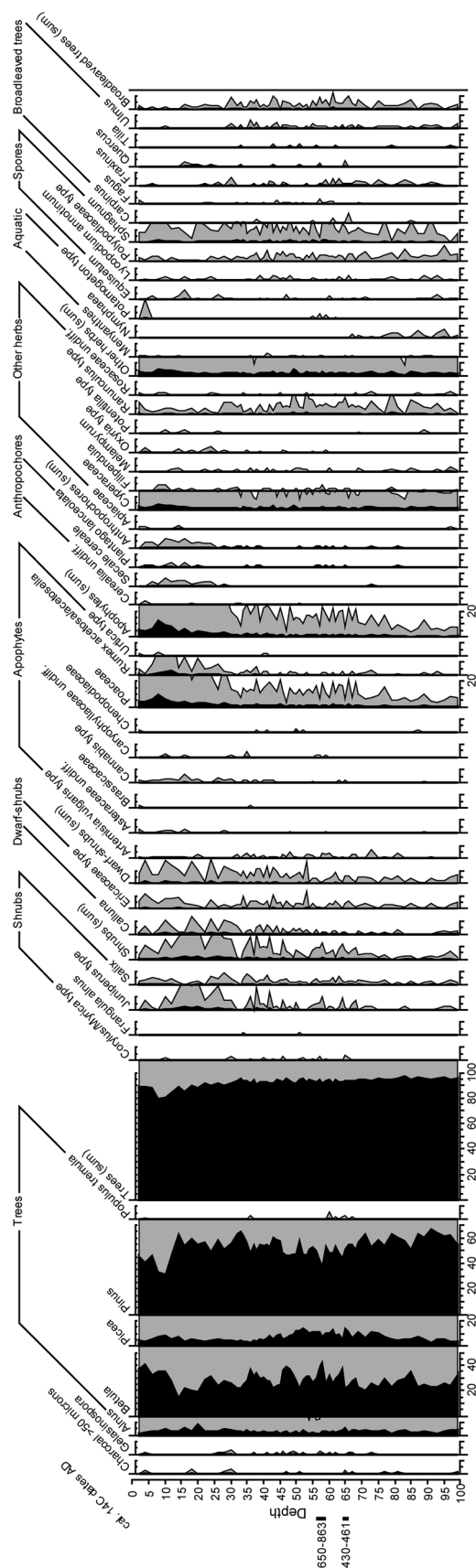


Fig. 4 Pollen diagram from Rörtjärnen in Ängersjö, Sweden. Pollen types and charcoal are shown in *black* as the percentage (grey = 10 × exaggeration) of the total amount of terrestrial pollen in each sample. Data are shown on a depth scale with the radiocarbon-dated levels marked to the *left*

increases from 4 % at 100 BC (98 cm) to an average of 10 % during the period AD 500–1200 (68–40 cm).

Betula represents typically about 26 % of the terrestrial pollen during 100 BC to AD 1360 (98–35 cm), but excursions to higher values (30–40 %) occur c. AD 600, 730–760 and a longer period during 970–1060 (63, 56–57, 48–45 cm depth, respectively), which are also identified in the inferred changepoint model. This latter period is linked particularly to a decline in *Picea* below 10 % (also identified in the changepoint model, c. AD 1010), which has persisted until the present. *Betula* is a primary colonizer following disturbance, and the strong negative relationship between *Betula* and the other three main tree species (*Pinus*, *Picea* and *Alnus*), with an r^2 -value of 0.95 prior to AD 1200 and 0.77 afterwards, indicates periods of forest disturbance.

Forest grazing and cultivation

The share of pollen from apophytes—natural plants that are favored by human disturbance—is low and stable (0.7 ± 0.3 %) prior to AD 330 (76 cm), as is the case also for shrub-type vegetation (0.3 ± 0.2 %) and herbs (2.5 ± 0.8 %). Thereafter, from AD 330 to 1500 (76–29 cm) the apophytes increase to 1.5–3 % (mainly Poaceae and *Rumex* spp.), and increase further again after AD 1580 (27 cm) with a peak of 13 % AD 1970 (7 cm). Shrub-type vegetation is about twofold higher from AD 1060 (45 cm).

There are no arable soils immediately surrounding Rörtjärnen and consequently pollen indicators of cultivation (anthropochores), such as *Cerealia*-type pollen, would have to represent land use closer to the village of Ängersjö where, for example, *Secale cereale* was cultivated. Anthropochores occur in isolated and irregular intervals from the first appearance of a single pollen grain of *S. cereale* c. AD 400 (72 cm) with a few occurrences of *Plantago lanceolata* and *Cerealia*-type pollen until AD 1580 (27 cm) where anthropochore pollen is continuously present, but in low abundance (≤ 1 %). During the past two centuries (AD 1820–1970, 17–7 cm) the total share of tree pollen declines below 90 %, with a corresponding increase in apophyte (4–13 %) and anthropochore (≥ 0.3 %) pollen.

Charcoal particles and other changes in the pollen record

Charcoal particles were found in only 10 isolated levels in the sediment record and the share of particles was very low

($\leq 0.2\%$). This would indicate that fires of any type, whether natural or human related, occurred infrequently or at some distance from the lake. *Gelasinospora*, a fungus that grows on charcoal and dung, is nonexistent until AD 400 (72 cm) and occurs in a bit less than half the samples until 1630 (25 cm) with increased levels at AD 760 (56 cm), 970 (48 cm), 1,060 (45 cm) and 1,530 (29 cm), which coincide with the periods of elevated *Betula* pollen.

The abundance of Cyperaceae ($1.5 \pm 0.4\%$) remains stable until AD 940–970 (49–48 cm), when it increases briefly to 3 %, with a small peak occurring again in AD 1150 (3.3 %, 42 cm). Both of these small increases are identified in the inferred changepoint model.

Soil and peat geochemistry

The organic surface soil samples at the bloomery site show the highest ratios of Pb, Zn and Fe in relation to Zr with declining trends with increased distance. At around 10 m east and 30 m west from the site the ratios are similar to the sample 250 m away from the bloomery furnace (Fig. 5). The Fe concentration in the sample closest to the furnace is 16 % while samples further away than 10 m are in the range 0.5–0.8 %. Zinc and Pb concentrations vary more than Fe but the highest levels are found within 5 m of the furnace (Zn 80 ppm and Pb 44 ppm) compared to samples further away (Zn 34–50 ppm and Pb 25–34 ppm). The concentrations of Fe in the mineral soil samples collected at the bloomery site are also greater (2.8–3.4 %) than locations further away along the transect (0.4–1.1 %). Both Pb (20–25 ppm) and Zn (23–26 ppm) are slightly higher in mineral soils at the bloomery than further away (Pb 16–21 ppm and Zn 11–17 ppm). The samples show varying ratios of trace element to Zr ratios across the sampled transect with the general pattern that the samples at the bloomery-furnace site show enriched amounts of Fe, Pb and Zn. The soil transect cannot be considered a definitive measure of the geochemical footprint of the bloomery because of the generations of forestry that have taken place

at this site. However, the short distance indicated by the geochemistry is supported by experimental work by Hörnberg and Liedgren (2012), who determined the footprint for charcoal particles from Sami hearth fires is ≤ 40 m.

In the peat core from a lawn area in the fen (Fig. 1; Table 2), Si concentrations are $1.2 \pm 0.2\%$ in the uppermost 20 cm consisting mainly of fresh/undecomposed *Sphagnum*, and $0.5 \pm 0.2\%$ in the lowermost Sect. (56–140 cm depth). From 20 to 56 cm depth, Si concentrations are higher, $4.2 \pm 1.7\%$ (i.e., up to 13 % total dry weight as SiO_2). The Si/Al ratio is quite low in the deeper layers, ≤ 1.3 , whereas in the upper 56 cm the ratios are in the range 10–30, indicating that much of the Si is biogenic Si (Peinerud et al. 2001). In the 11 bulk peat samples, Si concentrations are mostly higher, 2–14 % (7–30 % as SiO_2), as are Si/Al ratios, 3–40.

Sediment geochemistry

For the sediment geochemical analyses we present both the main changes in individual elements and their associations within the principal component analysis (PCA), which places each element in the context of what is happening with the sediment matrix as a whole (Figs. 6, 7). The sediment from Rörtjärnen is composed mainly of organic matter (24–30 % C; ~ 43 –53 % as organic matter) and Si (13–25 %; ~ 28 –53 % as SiO_2). There is an overall long-term decline in Si concentrations in the sediment record from values $>20\%$ in deeper sediments to ~ 13 –15 % in more recent sediments (excluding the top 10 cm, where there is a peak of 23.4 % at 5 cm, ca. AD 1978). Consequently, other major elements (e.g. Al from 1.5 to 1.9 %) as well as most of the trace elements (e.g. Sr from 28 to 48 ppm) show an opposite, gradual long-term increasing trend, and as noted in the methods section, this long-term trend has been removed from the PCA.

For the sediment from 170 BC to AD 1930 (103–10 cm depth) there are 4 principal components (PC1–4), which account for 50, 15, 9 and 6 % of the total variance in the geochemistry (79 % combined). The first principal component, PC1, separates Si with a negative loading (79 % of its total variance) from most other elements, which have positive loadings and include Ca, Sr, Al, Fe, Co, Mg, S, V and Cl ($\geq 50\%$), as well as the main fraction of Ba, Mn and Br (45–40 %), and a smaller fraction of Ni and Zn (28 and 23 %). Because Si is decoupled from other elements derived from aluminosilicates minerals, we infer that the majority of the Si is biogenic Si, which is supported by direct measurements of biogenic Si in similar peatland-connected boreal forest lakes (Meyer-Jacob et al. 2015). Thus, this PC reflects primarily the relative proportions of biogenic Si versus other components including lithogenic

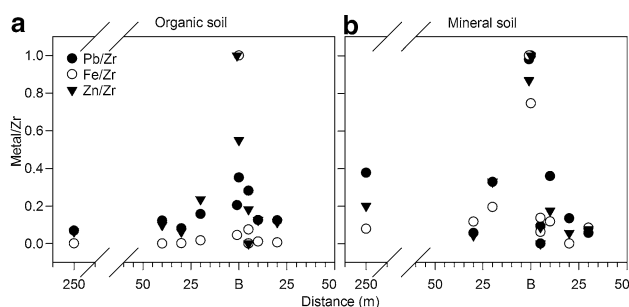


Fig. 5 Rescaled (0–1) ratios of Pb, Fe and Zn versus Zr in the organic top soil (a) and the upper mineral soil (b) plotted against distance away (to the west and east) from the bloomery furnace (b)

Table 2 Geochemistry of the peat profile from the fen (average values for 0–20, 20–56 and 56–140 cm depth) and the bulk samples (10–60 cm depth) from 11 additional locations in the fen

Sample	Al %	Si %	Si/Al	P ppm	S %	Ti ppm	Fe %	Pb ppm
Peat profile from fen (NW corner of lake)								
0–20 cm	0.091	1.16	17	294	0.068	16	0.266	2
20–56 cm	0.320	4.23	15	707	0.240	94	0.413	9
56–140 cm	0.774	0.52	1	946	0.297	222	0.462	3
Spatial survey: bulk samples 10–60 cm depth								
B1	0.237	3.59	15	734	0.262	81	0.365	10
B2	0.304	11.80	39	641	0.314	125	0.720	7
B3	0.406	4.66	11	693	0.286	122	0.319	5
B4	0.431	4.95	11	785	0.326	140	0.397	11
B5	0.453	1.88	4	946	0.373	122	1.727	15
B6	0.918	13.99	15	960	0.523	135	0.267	7
B7	1.094	2.78	3	1,186	0.587	132	0.176	2
B8	0.731	9.58	13	870	0.807	85	0.142	2
B9	1.305	10.56	8	1,112	0.647	370	0.273	6
B10	0.354	6.93	20	663	0.739	143	0.865	6
B11	0.396	3.17	8	598	0.731	85	0.210	3

Sites B1–4 and the profile are from the area at the NW corner of the lake, and sites B5–11 from the SW corner (see Fig. 1)

elements (e.g. Al), organically bound elements (e.g. Cl, Br) and trace metals (e.g. Mn, Zn).

The main features of PC1 (Figs. 6, 7), which are identified clearly in the changepoint analysis, are generally stable and positive scores from 170 BC to AD 800 (103–54 cm), two periods with negative scores during AD 810–975 (54–48 cm) and AD 1090–1180 (44–41 cm), and mostly positive scores from AD 1235 onwards (39 cm upwards) similar to sediment deposited prior to AD 810. These two periods with negative scores are driven by an increase in Si to values >20 % and corresponding declines in other elements.

The main elements associated with PC2 (15 % of total variance) are large positive loadings for P (83 %) and Zn (37 %) as well as smaller positive loadings for Cl, Br and Mn (21–17 %) and small negative loadings for V, Ni and S (32–21 %). The main pattern for PC2 is negative sample scores but with an increasing trend up to AD 620 (>62 cm), positive scores during AD 620–1470 (62–31 cm) but with large fluctuations during AD 915–1180 (50–41 cm), followed by declining scores towards similar values as those during the first period. The changepoint analysis identifies the same major fluctuations during AD 915–1180 for PC2 as those for PC1. During this phase P, for example, fluctuates nearly twofold from 660 to 1,150 ppm and back to 650 ppm.

The C/N ratio of the sediment is mainly in the range 16–19 with a few isolated excursions to lower values (10–15), and there is no significant correlation of PC2 with C ($R^2 = 0.19$) or CN ratios ($R^2 = 0.07$), which indicates limited changes in the relative amount and the source of the

organic matter (i.e. terrestrial versus aquatic) associated with this PC. We infer that PC2 reflects mainly changes in the quality of the organic matter—mainly its degree of decomposition—deposited at the lake bottom, and that this organic material is derived primarily from the adjoining mires and *Sphagnum* mats along the shoreline. Variations in Hg, most notably the elevated values at AD 1000–1060 (47–45 cm; 120 ppb), follow PC2 from 170 BC until AD 1440 ($R^2 = 0.65$, 103–28 cm), whereafter Hg remains elevated and later increases in recent sediments (AD 1980–2000, 4–1 cm) to 300 ppb while PC2 scores decline. From the late 15th century there is an association between regional Hg pollution and the expansion of mining in Bergslagen (Bindler et al. 2012).

The third and fourth components of the PCA (9 and 6 % of the total variance, respectively) are related mainly to a positive loading on PC3 for Ti (58 %) with minor positive loadings for Br and Ba (17 %) and minor negative loadings for Zn, Mn and Ni (20–17 %), and only Na (86 %) is assigned to PC4. What these two components may signify specifically in terms of environmental processes is uncertain.

The Pb record

Lead concentrations are quite low in the lowermost sediment up to AD 730 (103–57 cm) with values ≤ 4 ppm, but with a small peak of 6 ppm c. AD 190 (83 cm), which is clearly discernible also as a small enrichment in Pb (PbEF 2.5). There is a peak in Pb occurring AD 1030–1060 (46–45 cm) with 40 ppm (PbEF 15) and increases that

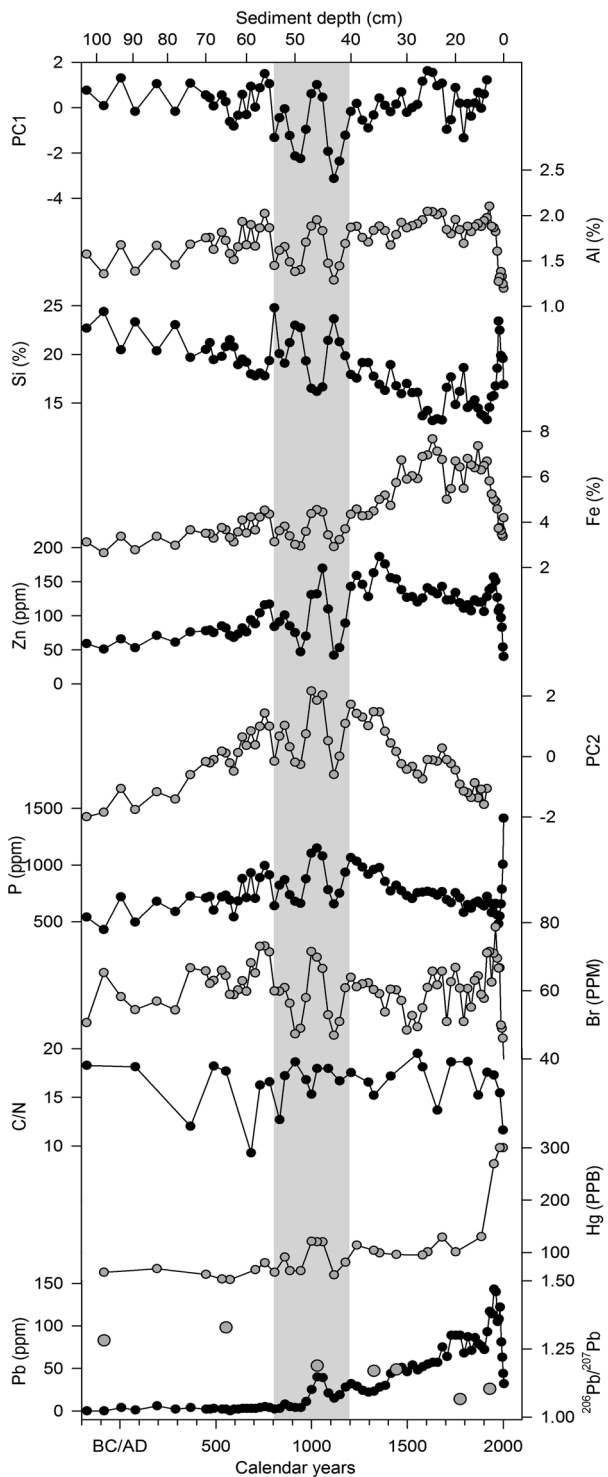


Fig. 6 Selected geochemical data (Al, Si, Fe, Zn, P, Br, C/N atomic ratio, Hg, Pb and $^{206}\text{Pb}/^{207}\text{Pb}$) and the two first principle components (PC1 and PC2) of the geochemical data from the sediment record for Rörtjärnen in Ängersjö, Sweden

occur AD 1235 (30 ppm, PbEF 11), 1470 (50 ppm, PbEF 20) and 1770 (90 ppm, PbEF 30). With the exception of the Pb peak occurring AD 1030–1060 (46–45 cm), these

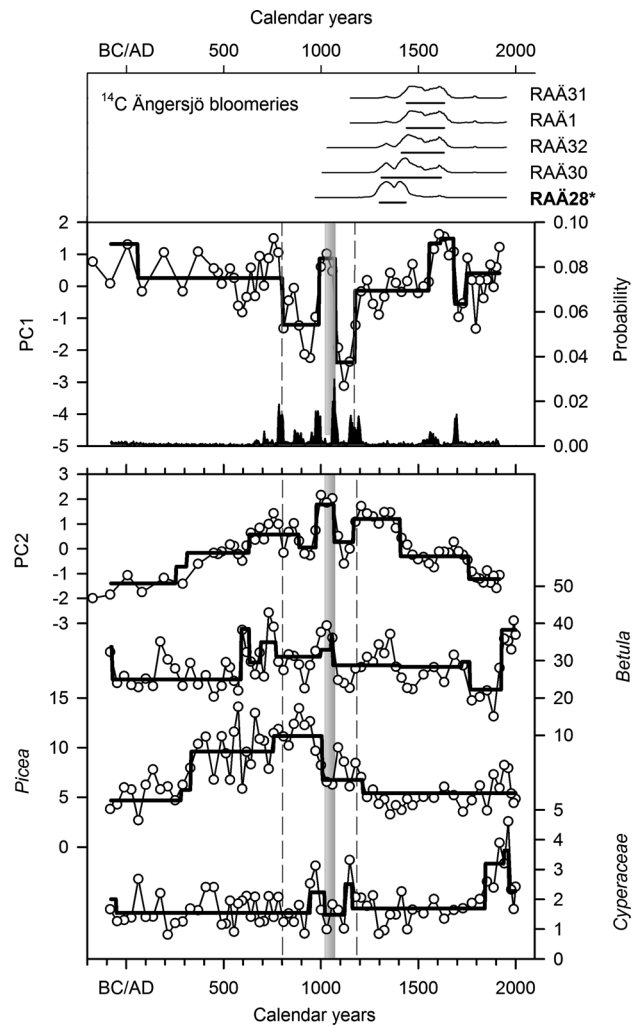


Fig. 7 Changepoint modeling of the data for PC1, PC2, *Betula*, *Picea* and *Cyperaceae*. *Open circles* show the z-scores for the geochemical data and pollen percentages for the vegetation, whereas the *thick black lines* show the maximum likelihood for the data and the locations of the inferred changepoints. In the *uppermost panel* for PC1 the data shows an example of the output of the probability modeling that defines the changepoints in the data time series. The *vertical dashed lines* indicate the main disturbance phase, AD 800–1200, and the *shaded grey area* indicates the peak disturbance indicated by Pb and each of the changepoint models. The *panel at the top* shows the calibrated dates (OxCal 4.2) for the one charcoal sample dated at each of the five bloomeries in the Ängersjö area (Magnusson 1986); RAÄ28* is the bloomery close to Rörtjärnen. Both the full probability distributions and the $1 - \sigma$ range are shown

changes in Pb concentration are consistent with the overall evolution of regional atmospheric pollution, which is exemplified by a comparison to the varved lake-sediment records from Kalven, 225 km to the south of Rörtjärnen, and Koltjärnen, 225 km to the north (Fig. 3), which both show a small Roman-Pb peak AD 80, increasing concentrations beginning during the late 900 s and peaks in concentration occurring AD 1200 and 1500 (Brännvall et al.

1999; Bindler 2011), where the latter date reflects an expansion of mining in Bergslagen. The consistency in the timing of these peaks provides independent support for the age-depth model, but of importance here is the distinct peak in Pb in Rörtjärnen during AD 1030–1060 (46–45 cm) that is unique to Rörtjärnen. Furthermore, this distinctive Pb peak is centered in the disturbance period indicated by the first two components of the PCA. As a passive variable in the PCA, Pb is not significantly correlated to any of the PC's because Pb changes mainly in relation to external factors (i.e. atmospheric pollution) and not due to changes within the lake or its catchment.

The $^{206}\text{Pb}/^{207}\text{Pb}$ isotope ratio at 80 BC (98 cm) is 1.281 and increases to 1.328, AD 550 (65 cm), where the latter value is characteristic of pre-anthropogenic lake sediments and soil C-horizon samples in Sweden (Bindler 2011). The lower value 80 BC may reflect some small addition of long-range atmospherically transported Pb pollution; Pb isotopes are generally more sensitive to small changes in sources not readily detectable through concentrations (Brännvall et al. 1999). The $^{206}\text{Pb}/^{207}\text{Pb}$ isotope ratios at AD 1030 (46 cm), 1325 (36 cm) and 1445 (32 cm) are ~ 1.169 – 1.188 , which are generally characteristic of long-range atmospheric sources. Buried peat would also accumulate an atmospheric signal over time, because mires derive much of their Pb also through atmospheric deposition; for example, peat accumulated from c. 3,000 BP onwards in southern Sweden has isotope ratios <1.2 due to long-range atmospheric transport of pollutant Pb from mainland Europe (Bindler et al. 1999; Klaminder et al. 2003). Thus it is not possible in the AD 1030 sample, for example, to distinguish re-mobilized Pb from peat from atmospherically deposited Pb. The ratio in Rörtjärnen decreases further to 1.065–1.103 from AD 1680 onwards (19 and 10 cm), which indicates an additional source of atmospheric Pb from Swedish ore (Johansson and Rickard 1984, 1985; Bindler and Rydberg 2015).

Discussion

The pollen record from Rörtjärnen displays a general pattern over the past 2200 years that is consistent with the history of land use and settlement established for Ängersjö in a previous paleoecological study of peat records from the village and outlying summer forest farms (Karlsson et al. 2010). On its own there is no obvious evidence—especially the low and infrequent occurrence of charcoal particles—to specifically indicate an active bloomery close to the lake.

Pollen from apophytes increases from AD 300—albeit in low concentrations. The increase is mainly in Poaceae and *Rumex* spp., which increase due to the effects of forest

grazing. *Juniperus* and *Calluna* also increase, indicating some opening of the dense forest canopy would have occurred—although the landscape is still dominated by forest as indicated by the high percentage of arboreal pollen. Isolated occurrences of anthropochore pollen (such as *Secale cereale*) and weeds (such as *Plantago*) are found as early as AD 200, but are not continuously present as a group until AD 1270. The isolated occurrence of anthropochores at Rörtjärnen from AD 200 is consistent with the beginning of cultivation in the village of Ängersjö, where the pollen record from the village shows continual evidence of cultivation from AD 200–400 onwards. The general pattern and low pollen percentages in Rörtjärnen are the same as those Karlsson et al. (2010) found for the summer forest grazing sites at Gammelvallen (1 km E of Rörtjärnen) and Öjingsvallen (7 km SE of Rörtjärnen).

Changes in arboreal pollen in the sediment from Rörtjärnen are also quite similar to the general trends from Gammelvallen. However, *Picea* had increased at Gammelvallen to 25–30 % before a steep decline between the 8th and 13th centuries, and the shifts between *Betula* and *Pinus/Picea* are more pronounced. In contrast to the pollen record from Gammelvallen, as well as from Ängersjö and the summer forest farm at Öjingsvallen, charcoal particles occur only discontinuously in the sediment record of Rörtjärnen, which would suggest fewer fires close to the lake. The lower, more limited occurrence of charcoal particles would seemingly preclude the prior existence of a bloomery, were there not physical evidence of such a site near the lake. The environmental impact of bloomeries blends into those associated with the general land-use changes occurring with settlement, which is consistent with iron-making as just one part of the seasonal cycle of activities on a farm (Magnusson 1986).

Unlike the pollen record, which reflects vegetation dynamics mainly within about a 1 km radius of a small forest lake (Hjelle and Sugita 2012), the main component of the geochemical record reflects events directly connected to or in the lake itself. The primary feature of the geochemical record is a distinct period of disturbance from AD 800 until 1200, which is observed in the two main principal components (PC1 and 2; Fig. 7). The changes in these two components unambiguously indicate an environmental disturbance physically connected to Rörtjärnen, which significantly altered the main geochemical composition of the material delivered to the lake bottom. PC1 indicates two short, but distinct periods of increased Si, AD 810–975 and AD 1090–1180, which coincide with increases in Cyperaceae pollen as indicated by the changepoint models. From this we can infer that these pulses of Si (and corresponding declines in elements related to mineral matter, such as Al) are due to an input of biogenic Si, such as from phytoliths but also diatoms, from the adjacent fens

along the western shore. That the fens are a source of biogenic Si is conceptually supported by the concentrations and elevated Si/Al ratios measured in the peat. Cyperaceae pollen could be co-transported from the fens, but could also increase with regrowth of sedges in response to disturbance.

PC2 indicates a change in the quality of the organic matter, which has a higher P content in particular and which includes elevated concentrations of Zn and Hg. Peatland disturbance is known to release P (Pinder et al. 2014), and studies of, for example, collapsing hummocks in a sub-arctic mire in northernmost Sweden show that loss of peat organic matter to adjoining surface waters also releases organically bound Hg (Rydberg et al. 2010). PC2 and particularly P already begin to change from AD 400, which coincides with the first occurrence of anthropochore pollen in Rörtjärnen and more generally the Ängersjö area (Karlsson et al. 2010) and the beginning of a decline in total sum of tree pollen from 96 to 94 %. Similar to PC1, we infer that the changes in PC2 during the broader period AD 600–1400 are driven by organic material entering Rörtjärnen from the adjoining fens (i.e. more-decomposed peat). Excluding the less-decomposed surface peat in the profile taken near the head of the fen, the deeper layers (20–140 cm) and the bulk samples have P concentrations in the range of 600–1200 ppm. Because the fen and *Sphagnum* mats along the lakeshore would naturally dominate as a source of organic matter to the lake, an increased input from either of these sources cannot be seen in the C and N data. The start of this period, AD 600 as indicated by PC2, occurs along with an increase in *Betula* from 30 to 40 % (and appearance of individual pollen grains of *Populus* and *Corylus*) and a decline in *Picea* and *Pinus*. Given the pollen evidence for human presence in the area, we can speculate this initial forest disturbance and the observed changes in the sediment geochemistry (i.e. PC2) have a common connection to human activities.

Of specific importance to our study questions is that, centered in the middle of this period of disturbance indicated by PC1 and PC2, there is a brief, well-defined peak in Pb during AD 1030–1060. Excluding this one peak, the 2200-year Pb record is otherwise very consistent with the long-term pattern of atmospheric Pb pollution found in lakes from Bergslagen and further to the north in Sweden (Brännvall et al. 1999; Bindler 2011). Coinciding with this Pb peak is a pronounced and permanent decline in *Picea* from >10 to 6 % together with another peak in *Betula* to ~40 %, which would indicate cutting of *Picea* and regrowth of *Betula*. The change-point models for PC1, PC2, *Betula*, *Picea* and Cyperaceae each identify this point in the sediment record as a period of change (Fig. 7).

Espelund (2006) has suggested that *Pinus* and *Picea* were preferred for early iron making in Scandinavia rather

than *Betula* because of the higher resin content. This same decline in *Picea* and peak in *Betula* occurs at Gammalvallen, 900 m to the west, and also in a low-resolution peat record taken 20 m from the bloomery furnace, but in that core there is also a clear increase in charcoal particles (Emanuelsson 2001). Based on only one bulk radiocarbon date (AD 1450–1820) in that peat core and a cross-correlation of that pollen record with our sediment record, the *Picea* decline and a more-pronounced spike in *Betula* pollen probably correspond to the same 11th century decline in *Picea* occurring in both Rörtjärnen and Gammalvallen, which is realistic given the short distance (≤ 1 km) between the three sites. The temporal connection between the pollen changes in both the sediment and peat records and the charcoal in the peat record provide a connection to the operation of the bloomery.

Because there is a sustained occurrence of charcoal in the peat core but not in our lake-sediment record, we suggest that changes in the geochemistry in the sediment record from Rörtjärnen do not reflect activities at the bloomery 120 m further away, but rather activities immediately connected to the lake. The soil transect, although hundreds of years have gone by and the geochemical fingerprint from the bloomery would be weakened in the soil, also suggests a rather limited deposition footprint from the bloomery, which would be unlikely to reach the lake.

After AD 1200, the sediment record does not indicate the same degree of disturbance as during the previous 400 years; rather the changes in geochemistry as well as pollen are more consistent with the general changes in land use taking place in the Ängersjö area indicated by previous work (Karlsson et al. 2010). *Picea* declines further to <4 % by c. AD 1350, which coincides with the more established record of bloomeries in the area (Magnusson 1986), and from AD 1500 total tree pollen declines systematically, which coincides with the more systematic expansion of agriculture in the village.

Evidence in the sediment record from Rörtjärnen for a bloomery furnace?

In answer to our main question, how well is a known bloomery with one age date of AD 1300–1435 (560 ± 95 ^{14}C year BP; Magnusson 1986) reflected in the palaeoecological and geochemical record of an adjacent lake, the brief answer is that this bloomery is not specifically reflected in the sediment record. Based on the pollen data alone there is insufficient evidence to suggest an active bloomery near the lake—not least the lack of charcoal particles. The pollen data are similar to the general pattern of forest disturbance and land use observed for summer forest farms elsewhere in central Sweden. Unexpectedly, we instead find evidence in the geochemical record of an

earlier human-related disturbance centered around the date AD 1030–1060, which is supported by observed changes in the pollen record—such as the combination of increased Si and Cyperaceae pollen that bracket this Pb peak. We suggest this period of disturbance, AD 800–1200, is related to an exploitation of the fens connected to Rörtjärnen. Analyses of the geochemistry of peat from the adjoining fens show these could be a source for the increases in biogenic Si in the sediment record, as indicated by elevated Si/Al ratios in both the peat and sediment.

We can answer our second question if we reframe it more generally: can we identify or infer the timeframe over which a bloomery or bloomeries were in operation near the lake? The geochemical record indicates a distinct period of disturbance connected to Rörtjärnen spanning the period from AD 800 to 1200, and more broadly during AD 600 to 1400. When the pollen data are re-evaluated in light of the observed changes in sediment geochemistry, there are changes in vegetation coherent with the timing of the indications of catchment disturbance, such as the increases in both Cyperaceae and Si and especially the almost 50 % decline in *Picea* with the Pb peak occurring AD 1030–1060. From this combination of pollen and geochemical data it is reasonable to speculate that the fens adjoining Rörtjärnen were exploited for bog iron for processing in a bloomery. Because bloomeries were used off and on and often rebuilt, we suggest the individual radiocarbon dates of charcoal from the five Ängersjö bloomery sites including ours, which fall within a limited time range of AD 1300–1630, reflect a late use for these sites rather than the period over which each was actively used. From the sediment record we infer bloomery-related activities—i.e., extraction of bog iron—began certainly by AD 1030–1060, but already by AD 800.

Acknowledgments We would like to thank Hanna Staland for her contributions to the pollen analysis and Ingemar Renberg for assistance during sediment coring. This research was funded by grants from the Umeå Center for Environmental Research (CMF) and the Swedish Research Council (2011–3638).

References

- Baron S, Lavoie M, Ploquin A, Carignan J, Pulido M, De Beaulieu JL (2005) Record of metal workshops in peat deposits: history and environmental impact on the Mont Lozère Massif, France. *Environ Sci Technol* 39:5,131–5,140. doi:10.1021/es0481651
- Bestell L (2015) Vad slaggvarpen berättar: om tillverkning av koppar och järn innan och under medeltiden i Europa. In: Berglund B (ed) *Järnet och Sveriges medeltida modernisering*. Jernkontoret, Stockholm, pp 259–298
- Berglund B (2015) *Järnet och Sveriges medeltida modernisering*. Jernkontoret, Stockholm
- Beug HJ (1961) *Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete*. Fischer, Stuttgart
- Bindler R (2011) Contaminated lead environments of man: reviewing the lead isotopic evidence in sediments, peat, and soils for the temporal and spatial patterns of atmospheric lead pollution in Sweden. *Environ Geochem Health* 33:311–329. doi:10.1007/s10653-011-9381-7
- Bindler R, Rydberg J (2015) Revisiting key sedimentary archives yields evidence of a rapid onset of mining in the mid-13th century at the Great Copper Mountain, Falun, Sweden. *Archaeometry*. doi:10.1111/arc.12192
- Bindler R, Brännvall M-L, Renberg I, Emteryd O, Grip H (1999) Natural lead concentrations in pristine boreal forest soils and past pollution trends: a reference for critical load models. *Environ Sci Technol* 33:3,362–3,367
- Bindler R, Segerström U, Pettersson Jensen I-M et al (2011) Early medieval origins of iron mining and settlement in central Sweden: multiproxy analysis of sediment and peat records from the Norberg mining district. *J Archaeol Sci* 38:291–300. doi:10.1016/j.jas.2010.09.004
- Bindler R, Yu RL, Hansson S, Classen N, Karlsson J (2012) Mining, metallurgy and the historical origin of mercury pollution in lakes and watercourses in Central Sweden. *Environ Sci Technol* 46:7,984–7,991. doi:10.1021/e5300789q
- Blaauw M (2010) Methods and code for ‘classical’ age-modelling of radiocarbon sequences. *Quat Geochronol* 5:512–518. doi:10.1016/j.quageo.2010.01.002
- Brännvall M-L, Bindler R, Renberg I, Emteryd O, Bartnicki J, Billström K (1999) The Medieval metal industry was the cradle of modern large-scale atmospheric lead pollution in northern Europe. *Environ Sci Technol* 33:4,391–4,395
- Breitenlechner E, Hilber M, Lutz J, Kathrein Y, Unterkircher A, Oeggel K (2010) The impact of mining activities on the environment reflected by pollen, charcoal and geochemical analyses. *J Archaeol Sci* 37:1,458–1,467. doi:10.1016/j.jas.2010.01.006
- Breitenlechner E, Goldenberg G, Lutz J, Oeggel K (2013) The impact of prehistoric mining activities on the environment: a multidisciplinary study at the fen Schwarzenbergmoos (Brixlegg, Tyrol, Austria). *Veget Hist Archaeobot* 22:351–366
- Bronk Ramsey C (2009) Bayesian analysis of radiocarbon dates. *Radiocarbon* 51:337–360
- Emanuelsson M (2001) Settlement and land-use history in the central Swedish forest region: the use of pollen analysis in interdisciplinary studies. *Acta Universitatis Agriculturae Sueciae: Silvestria* 223. Swedish University of Agricultural Sciences, Umeå
- Espelund A (2006) Pit Metallurgy? *Metallurgija* 12:155–164
- Farmer JG, Eades LJ, Atkins H, Chamberlain DF (2002) Historical trends in the lead isotopic composition of archival *Sphagnum* mosses from Scotland (1838–2000). *Environ Sci Technol* 36:152–157
- Forenius S, Hjärthner-Holdar E (2013) *Berättelser från markerna: en antologi om järn, skog och kulturarv*. Bergslagens medeltidsmuseum, Norberg
- Gallagher K, Bodin T, Sambridge M, Weiss D, Kylander M, Large D (2011) Inference of abrupt changes in noisy geochemical records using transdimensional changepoint models. *Earth Planet Sci Lett* 311:182–194. doi:10.1016/j.epsl.2011.09.015
- Giesecke T (2005) Holocene dynamics of the southern boreal forest in Sweden. *Holocene* 15:858–872. doi:10.1191/0959683605hl859ra
- Grimm EC (1991) *Tilia v. 2.0.b.4*. Illinois State Museum, Research and Collections Center, Springfield
- Grimm EC (2004) *Tilia Graph v. 2.0.2*. Illinois State Museum, Research and Collections Center, Springfield
- Hjelle KL, Sugita S (2012) Estimating pollen productivity and relevant source area of pollen using lake sediments in Norway:

- how does lake size variation affect the estimates? *Holocene* 22:313–324. doi:[10.1177/0959683611423690](https://doi.org/10.1177/0959683611423690)
- Hodson ME (2002) Experimental evidence for mobility of Zr and other trace elements in soils. *Geochim Cosmochim Acta* 66:819–828. doi:[10.1016/S0016-7037\(01\)00803-1](https://doi.org/10.1016/S0016-7037(01)00803-1)
- Hörnberg G, Liedgren L (2012) Charcoal dispersal from alpine Ställo hearths in sub-arctic Sweden: patterns observed from soil analysis and experimental burning. *Asian Cult Hist* 4:29–42
- Hyenstrand Å (1972) Järnframställning i randbygd och problemet i järnbärrarland: en kartografisk studie. *Jernkontorets forskning H 6*. Jernkontoret, Stockholm
- Johansson Å, Rickard D (1984) Isotopic composition of Phanerozoic ore leads from the Swedish segment of the Fennoscandian shield. *Miner Depos* 19:249–255
- Johansson Å, Rickard D (1985) Some new lead isotope determinations from the Proterozoic sulfide ores of Central Sweden. *Miner Depos* 20:1–7
- Jouffroy-Bapicot I, Pulido M, Baron S et al (2007) Environmental impact of early palaeometallurgy: pollen and geochemical analysis. *Veget Hist Archaeobot* 16:251–258. doi:[10.1007/s00334-006-0039-9](https://doi.org/10.1007/s00334-006-0039-9)
- Karlsson H, Emanuelsson M, Segerström U (2010) The history of a farm-shieling system in the central Swedish forest region. *Veget Hist Archaeobot* 19:103–119. doi:[10.1007/s00334-009-0231-9](https://doi.org/10.1007/s00334-009-0231-9)
- Karlsson J, Segerström U, Berg A, Mattielli N, Bindler R (2015) Tracing modern environmental conditions to their roots in early mining, metallurgy, and settlement in Gladhammar, southeast Sweden: vegetation and pollution history outside the traditional Bergslagen mining region. *Holocene* 25:944–955. doi:[10.1177/0959683615574586](https://doi.org/10.1177/0959683615574586)
- Klaminder J, Renberg I, Bindler R, Emteryd O (2003) Isotopic trends and background fluxes of atmospheric lead deposition in N Europe: analyses of three ombrotrophic bogs from south Sweden. *Glob Biogeochem Cycles* 17:1,019–1,028. doi:[10.1029/2002GB001921](https://doi.org/10.1029/2002GB001921)
- Lagerås P (2007) The ecology of expansion and abandonment. Medieval and post-medieval land-use and settlement dynamics in a landscape perspective. Riksantikvarieämbetet, Stockholm
- Magnusson G (1985) Lapphyttan: an example of medieval iron production. In: *Medieval iron in society*. Papers presented at the symposium in Norberg May 6–10, 1985. *Jernkontorets Forskning H 34*. Jernkontoret and Riksantikvarieämbetet, Stockholm, pp 21–60
- Magnusson G (1986) Lågteknisk järnhantering i Jämtlands län [Bloomery iron production in the county of Jämtland, Sweden]. *Jernkontorets bergshistoriska skriftserie 22*. Jernkontoret, Stockholm
- Magnusson G (2015) Järnet och Sveriges medeltida modernisering. *Jernkontoret*, Stockholm
- Maier DB, Rydberg J, Bigler C, Renberg I (2013) Compaction of recent varved lake sediments. *Gff* 135:231–236
- Meyer-Jacob C, Tolu J, Bigler C, Yang H, Bindler R (2015) Early land use and centennial scale changes in lake-water organic carbon prior to contemporary monitoring. *Proc Natl Acad Sci* 112:6,579–6,584
- Monna F, Petit C, Guillaumet J-P et al (2004) History and environmental impact of mining activity in Celtic Aeduan territory recorded in a peat bog (Morvan, France). *Environ Sci Technol* 38:665–673. doi:[10.1021/es034704v](https://doi.org/10.1021/es034704v)
- Moore PD, Webb JA (1978) *An illustrated guide to pollen analysis*. Wiley, Chichester
- Moore PD, Webb JA, Collinson ME (1991) *Pollen analysis*, 2nd edn. Blackwell Scientific, Oxford
- Peinerud EK, Ingri J, Ponter C (2001) Non-detrital Si concentrations as an estimate of diatom concentrations in lake sediments and suspended material. *Chem Geol* 177:229–239
- Pettersson Jensen I-M (2015) *Järnet och Sveriges medeltida modernisering*. Jernkontoret, Stockholm
- Pettersson G, Karlsson S, Risberg J, Mådal-Runebjer E (2004) Soil chemistry, vegetation history and human impact at the Late Holocene iron production site of Åskagsberg, western Sweden. *J Nordic Archaeol Sci* 14:101–113
- Pinder KC, Eimers MC, Watmough SA (2014) Impact of wetland disturbance on phosphorus loadings to lakes. *Can J Fish Aquat Sci* 71:1,695–1,703. doi:[10.1139/cjfas-2014-0143](https://doi.org/10.1139/cjfas-2014-0143)
- Renberg I (1981) Improved methods for sampling, photographing and varve-counting of varved lake sediments. *Boreas* 10:255–258
- Rydberg J (2014) Wavelength dispersive X-ray fluorescence spectroscopy as a fast, non-destructive and cost-effective analytical method for determining the geochemical composition of small loose-powder sediment samples. *J Paleolimnol* 52:265–276. doi:[10.1007/s10933-014-9792-4](https://doi.org/10.1007/s10933-014-9792-4)
- Rydberg J, Klaminder J, Rosén P, Bindler R (2010) Climate driven release of carbon and mercury from permafrost mires increases mercury loading to sub-arctic lakes. *Sci Total Environ* 408:4,778–4,783
- Segerström U (2013) Skogen runt blåsterugnen RAÄ 1, Ängersjö, Hälsingland. Den lågteknologiska järnproduktionens miljöpåverkan. In: Pettersson Jensen I-M, Berg Nilsson L, Karlsson C (eds) *Berättelser från markerna*. En antologi om järn, skog och kulturarv. Bergslagens medeltidsmuseum, Norberg, pp 203–216
- Segerström U (1997) Long-term dynamics of vegetation and disturbance of a southern boreal spruce swamp forest. *J Veget Sci* 8:295–306. doi:[10.2307/3237359](https://doi.org/10.2307/3237359)
- Viehweider B, Lutz J, Oeggel K (2015) Late-Holocene land use changes caused by exploitation in the mining region of Kitzbühel (Tyrol, Austria). *Veget Hist Archaeobot* 24:711–729