

## 333 years of copper mining in the Røros region of the Mid-Scandic highlands Written sources versus natural archives

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The progression of industrial, rural and agrarian development is studied from sediment cores collected from two kettlehole lakes, Dokortjønna and Sandtjønna, in the vicinity of the mining town of Røros, focusing on the period 1645–1977. The results of palynological and geochemical analyses are compared with well-known historical documents to test whether the records from these natural archives match the documentary evidences. Vigorous forest clearance took place during the first 25 years of copper mining, but the evidence of escalating deforestation is less pronounced in the pollen diagram, probably due to the presence of long-distance tree (AP) pollen. On the other hand, the non-arboreal tree pollen (NAP) curves do reflect the dispersal of the agrarian plots fairly well. Forest regeneration is observed in the pollen record after the introduction of coal for use in the roasting ovens in 1877. Abrupt increases in Cu, Zn and Pb reflect air pollution and the commencement of ore roasting. The presence of cations and variations in their content mirrors the production of the copperworks and shifts in methods, and can be used here for dating purposes. A decrease in loss-on-ignition (LOI), with a delay of c. 50 years, serves as an indication of soil erosion caused by intensive land use. Sedimentation rates increased from 0.2 to 1.2 mm/yr. The source area for the sand was the field of sand-dunes (the Kvitsanden “desert”) formed during deforestation, possibly aided by vegetation damage caused by sulphuric fumes. The SO<sub>2</sub> emissions during periods of high production may have been >5 000 tonnes/yr.

*Keywords:* copper mining, palaeo-environment, human impact, deforestation, air pollution, geochemical parameters

### Introduction and historical review

The mining town of Røros, established in 1644, is situated in the county of Sør-Trøndelag in central Norway, 35 km west of the Swedish border (Fig. 1). It lies at the margin of a large undulating plateau (*Rørosvidda*) in the southern central part of the Scandic Mountains and is situated on a southwest-facing slope rising from a rather wide and flat valley bottom marked by the confluence of three main watercourses:

Glåma, Håelva and Hitterelva. The last-mentioned river was also decisive in determining the location of the *Bergstaden* (mining-town of Røros), as its discharge was sufficiently large to operate the bellows for the smelting works.

The aim of this paper is to describe and verify how the effects of 333 years of well-documented mining activities (involving land use, deforestation and pollution) can be traced from natural archives in the farming landscape associated with the mining community

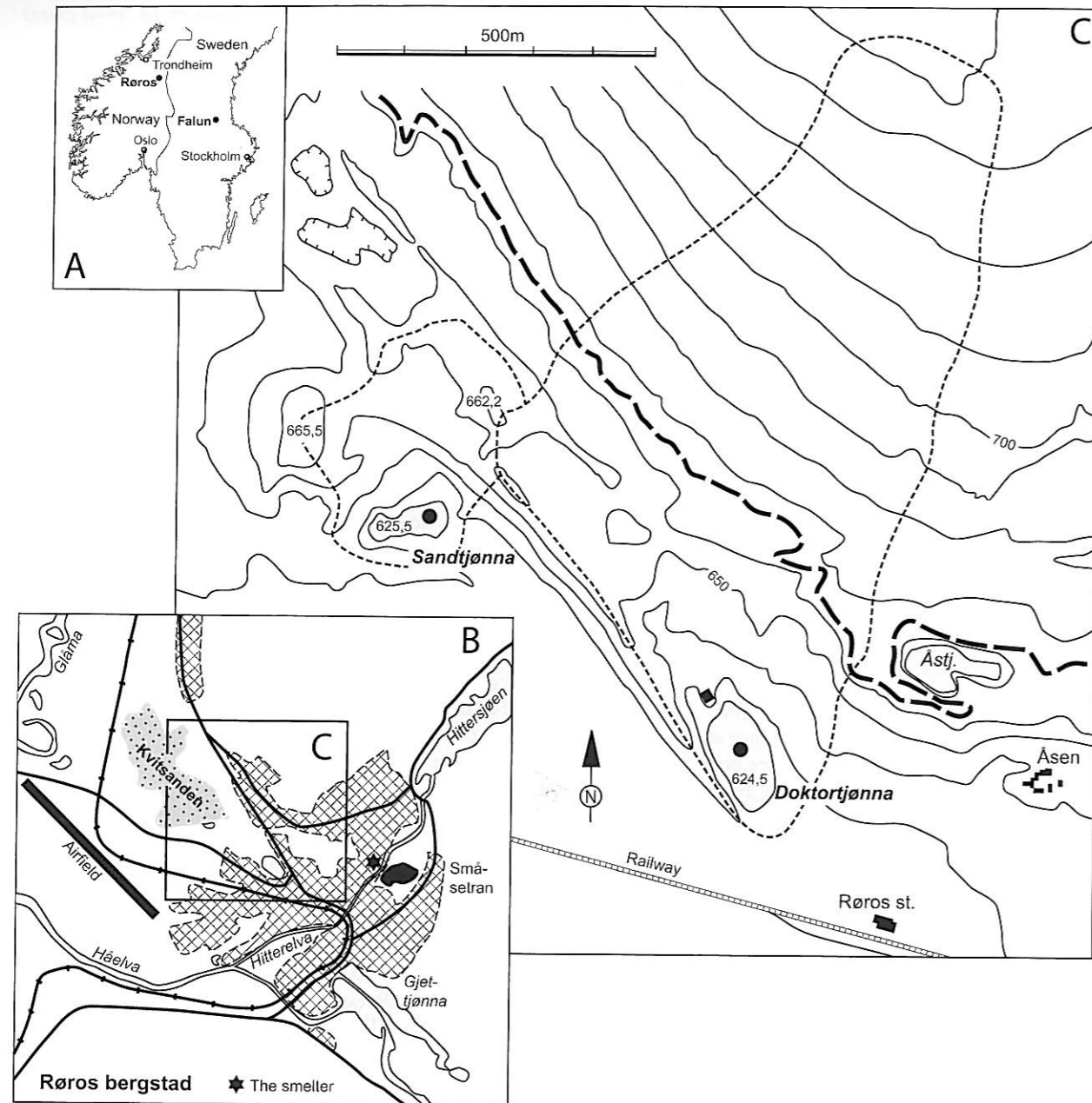


Figure 1. The key map, A, shows the location of the town of Røros in central Scandinavia. Map B shows the extent of the town, with major communication lines, the location of the smelter (★), and the environmentally protected area of Kvitsanden. The black area adjacent to the smelter represents the present extent of mine waste. The position of map C is framed. The catchment of Lake Dokortjønna is delimited with finely stippled lines on map C, and the sampling points are marked with black dots. The upper limit of glaciolacustrine sediments is marked with a heavy stippled line.

around the Røros township. To test this, sediments from two small lakes, Dokortjønna and Sandtjønna (Fig. 1c), lying within the agrarian area were analysed in terms of pollen, loss on ignition (LOI), grain size and geochemical parameters indicative of air pollution. Similar investigations in Central Sweden have

confirmed that lake sediments are reliable archives of pollution from metal smelters (Åström & Nylund 2000; Becker et al. 2001; Ek et al. 2001; Ek & Renberg 2001; Hammarlund et al. 2008). Prehistoric copper mining activities have also been reported in studies of blanket peats in the British Isles (Mighall et al.



Figure 2. A view of Røros in 1915, with the church to the left and the smokestack of the smelter (acting as a point source for pollution) close to it. Lake Dokortjønna is seen in the foreground. The farm of Åsen and its hayfields with adjacent barns (outhouses) are located on the slopes towards the town. Photo: Harald Pedersen (Røros Museum, archives).

2002) and France (Jouffroy-Bapicot et al. 2007). The results will be compared and matched with well-documented historical events in the town of Røros as recorded in local histories (Kvikne 1942, Øisang 1946), which are in turn based on works such as Schøning (1910), Brinchmann & Agerholt (1926), J. R. Prytz (1953) and archives and weekly internal accounts of the copperworks as compiled by Hiort (1886), Hiort, Krag & Aas (1903) and Voss (1911). The question to be answered is whether the impacts recorded in the natural archives are comparable in substance and time with the written sources.

Røros was designated a UNESCO World Heritage Site in 1980 on account of the considerable cultural treasures contained in its unique mining environment and its fine wooden architecture. In 1994 a group recommended that the site should be extended to include the historical industrial and farming landscape associated with the mining community in the surroundings of the town, "the Circumference", an area of radius

44 km and covering 5 000 km<sup>2</sup> (Larsen et al. 1994; Grytli 1996; Jones 1999). This extension plan has in effect been a subject of continuous debate since 1993 (Larsen et al. 1994; Sletten 2007a). As part of this process, the "Outhouse Project" was started in 1996, but its goal is only to renovate the buildings connected with the hayfields (Sletten 2007b). As pointed out by Daugstad (2001), the authorities are faced with a "multitude of challenges for integrated environmental management". We also hope that our paper can be a tool in this process.

#### Land-use history

The first human exploitation of this sub-alpine plateau was by Stone Age hunters, as revealed by several habitation sites, stray finds and pitfall traps, especially along the watercourses (Daugstad et al. 1999). Scattered permanent farms or summer farms existed in Røros and its immediate surroundings during the

Migration Period, the Viking Age and the Early Medieval Period, but these settlements were abandoned after the plague in 1349–50 (Sandnes 1971). Today only burial mounds, pitfall traps and traces of ancient summer farms and bloomery iron production are left (Daugstad et al. 1999). After the Reformation, but prior to the mining settlements created in 1644, there were only a few farms in the area (Kvikne 1942; Øisang 1946). One of these was Åsen (Figs. 1c, 2), now located on the edge of the town.

The discovery of copper ore in the region led in 1645 to the start of mining and metal production, which lasted until 1977 (Nissen 1976; Jones 1999). The number of inhabitants increased quickly, and so did the need for agricultural plots on the edge of the town, for the cultivation of both crops and hay, not least in order to provide winter fodder for the many draught animals needed in the mining community. Regular summer dairy farming also developed from the 18th century onwards. The community was thus based on a mixed economy, with a close link between mining and farming.

The roasting of the ore and further smelting produced large quantities of fumes that spread over the surrounding, and serious air pollution was reported in and around Røros, where the first smelter was built (Øisang 1946; Ødegaard 1984; Borgos 1994).

Large quantities of timber and charcoal were consumed in the production of copper (Ødegaard 1984; Espelund 1998), and rapid deforestation took place in and around the mining town. After only 10 years of operation, 250 000 m<sup>3</sup> of timber had been cut down in the vicinity (c. 30–50 km<sup>2</sup>) for fuel alone. The resulting lack of fuel forced the industry to move further out, and 15 new smelters were established, 10 of them within the projected extension to the World Heritage Site (Gjestland 1995). When the railway was completed in 1877, charcoal was replaced by coal and natural forest regeneration started.

#### Copper production and air pollution

Copper production rose slowly over the first 80 years to about 200 metric tonnes per year, but increased after 1730 to reach a peak of 600 t/yr in 1775, declining thereafter to about 350 t/yr. After 1888, when the smelting process was centralised to Røros and the Bessemer process was introduced, production increased once more, to about 700 t/yr. There was no production between 1920 and 1925, but on resumption it increased rapidly, with an exceptional record of

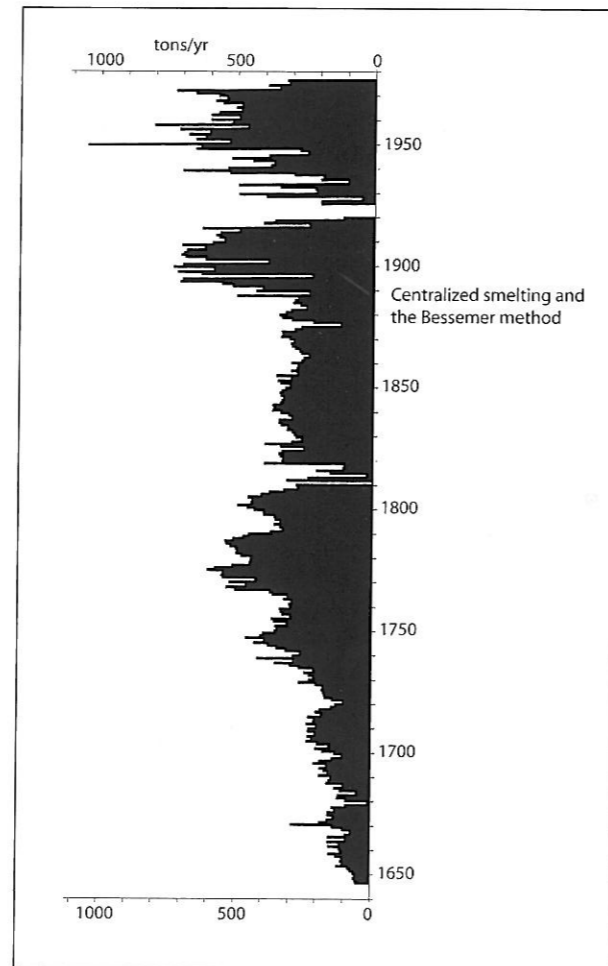


Figure 3. Annual copper production in tonnes per year (t/yr) during the 333 years of mining and smelting activities at Røros. Modified from Ødegaard (Røros Museum, archives).

1 000 t/yr in the late 1940s (Fig. 3). The works was finally closed in 1977.

Due to the high sulphur content of the ore, the first step in extracting the copper was an open-air roasting process where the sulphides were oxidised, releasing considerable amounts of SO<sub>2</sub>. Until 1850 this process was done outside the smelting works, close to the river Hitterelva. To remove all impurities (resulting in 98–99% pure copper), three oxidations and two reductions were needed. The reductions, yielding products such as Cu<sub>2</sub>S, FeS and slag, were performed inside the smelting works (Ødegaard 1984; Espelund 1998). In contrast to the smelting works at Falun and in Germany (Ødegaard 1984; Ek et al. 2001), the one at Røros already had a chimney before 1700, and therefore acted as a point source of air pollution. The damage to the vegetation was especially pronounced

after 1888, when the efficient Bessemer smelting process was introduced (Fig. 3). The SO<sub>2</sub> gas formed acid rain at times of high precipitation and low pressure, and damage to the vegetation and the hayfields that had developed parallel to the smelting works was soon reported (Borgos 1994).

The problem had become so serious after 1888 that the roasting process had to be closed down for the grass-growing season from 3rd May to 15th September each year. In 1905 the copperworks took over the most seriously damaged hayfields and paid the owners a small compensation. In addition, the company agreed to close down for a month in the summer every year to allow the inhabitants to move to their summer farms and hayfields. This scheme had the dual purpose of preventing emissions of SO<sub>2</sub> during the most favourable grass-growing season and enabling the workers to provide winter fodder (harvested by scything and mowing) for the draught animals and cows which were so essential to the community.

#### Environmental setting and site description

##### Geology

The basis for the mining industry in the Røros region was a system of strata-bound sulphide deposits in the complex of volcanic and sedimentary metamorphic rocks (Nilsen 1988; Nilsen & Wolff 1989). These abundant ore deposits, mainly associated with gabbros, contained zinc (ZnS), copper (CuFeS<sub>2</sub>) and lead (PbS) in varying proportions, with pyrite (FeS<sub>2</sub>) and pyrrhotite (FeS) also common. Copper (Cu) was the only metal extracted commercially during the entire production period, however, although zinc (Zn) is normally the dominant element in sulphide ores. The average Cu content of the ore was 2.7% and Zn 4.2–5%, with only small amounts of Pb (Bjerkgård et al. 1999).

Thick basal tills cover much of the region, and a major esker system runs through the town of Røros. The Kvitsanden dunes, regarded as the northernmost “desert” in Europe, are located on this esker. Glaciolacustrine sediments (fine sand and silt) occur sporadically below 665 m in the Glåma valley (Holmsen 1956; Reite 1997), see Figure 1c.

##### Climate

The climate at Røros is transitional between sub-oceanic and sub-continental, characterised by relatively low winter temperatures (a January mean of -11.2°C),

“high” summer temperatures (a July mean of +11.4°C) and little precipitation (a mean annual precipitation of 646 mm) (figures for the normal period 1961–1990, Aune 1993). Radiation fog is created in autumn and winter by cold air being forced down into the Hitterelva valley bottom through temperature inversion, and this also affected the distribution of air pollution.

##### Vegetation

Botanically, Røros lies in the boreal upland area at the transition between the middle and northern boreal vegetation zones, the latter being characterised by mires, birch woodland (*Betula pubescens*) and stunted coniferous woodland, here Scots pine (*Pinus sylvestris*) (Moen 1999). Agriculture is quite marginal owing to the short growing season (Borgos 1994), and this marginal position was further exacerbated by the escalating deforestation from 1645 onwards.

##### Catchment and lake description

*Lake Doktortjønna* is situated 624.5 m a.s.l. (Fig. 1c) and occupies a kettlehole on the margin of the modern urban area. It is located 400 m west of the farm of Åsen, among strips of former pastures, agricultural land and hayfields, and 800 m west of the smelting works. The lake measures 150×80 m and has a maximum water depth of 6.25 m. Its sediments were sampled down to 8.55 m. Lake Doktortjønna represents a small pollen source area, definable as a local and/or extra-local site (according to Jacobson & Bradshaw 1981). The catchment covers c. 51 ha, an inflow takes place by surface run-off from the till area, presumably augmented by a groundwater input from the esker bounding the basin to the west and north. The lake lacks an outlet and has subsurface drainage through the permeable river terrace sediments.

*Lake Sandtjønna* also occupies a small kettlehole, situated 625.5 m a.s.l., and is located some 600 m to the northwest on the same river terrace as Doktortjønna. The lake is less than half the size of Doktortjønna and the catchment that lies mainly within the glaciolacustrine sediments (fine sand and silt) occur sporadically below 665 m in the Glåma valley (Holmsen 1956; Reite 1997), see Figure 1c. There is no surface inflow, but considerable groundwater seepage takes place from the esker system, so that the effective catchment is larger than the topographic basin. The sampling point is shown in Figure 1c. Supplementary samples were obtained to date the commencement of sand movements, as the lake lies on the southern fringe of the “desert” of *Kvitsanden*.

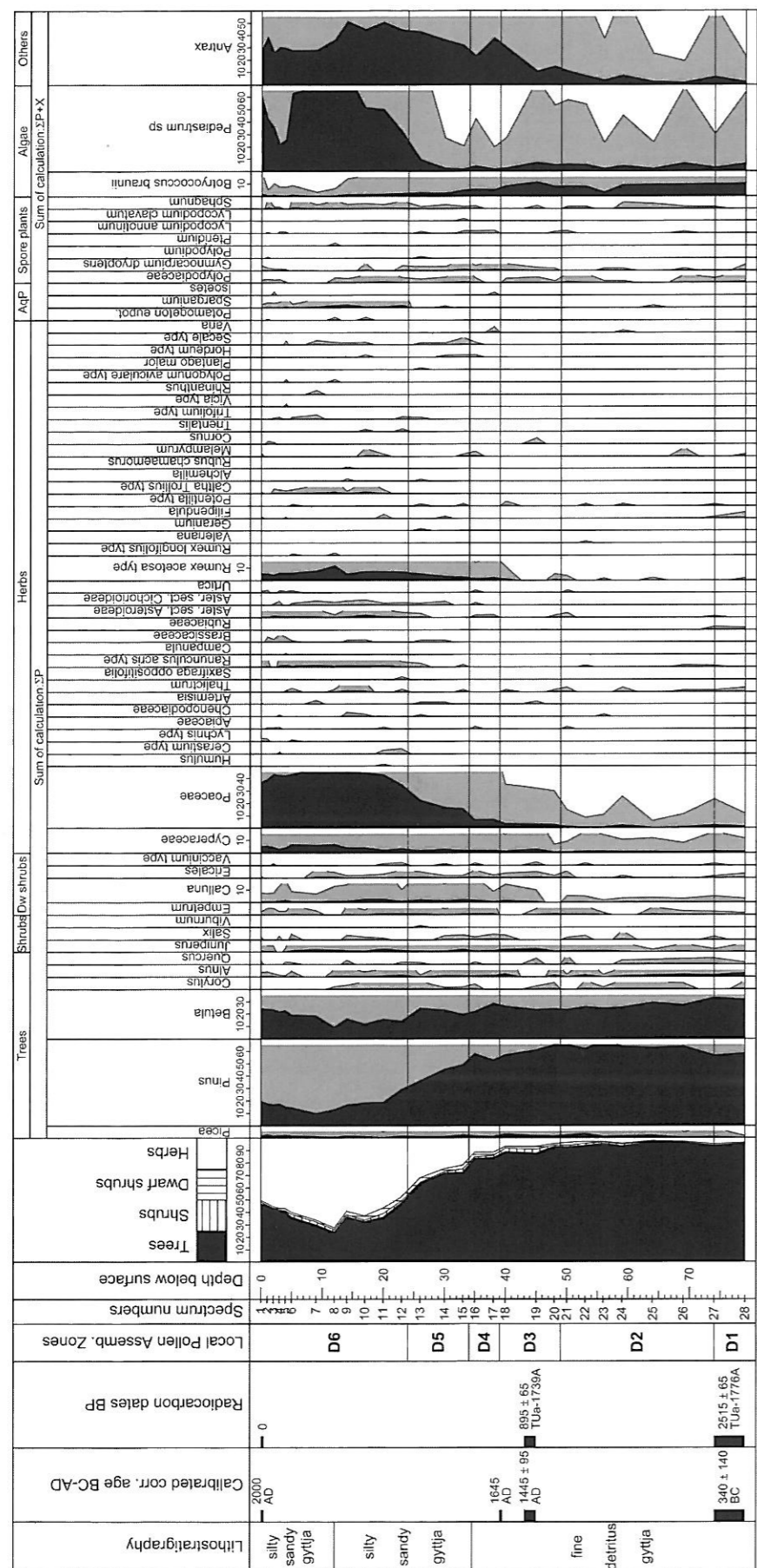


Figure 4. Percentage pollen diagram for Lake Doktortjøna. The black curves show pollen percentages and the grey curves have 10x magnification. Analysis: Lisbeth Prösch-Danielsen 1997-2004

Methods

Fieldwork was carried out during the wintertime in 1997, 2004 and 2005.

Pollen analyses

Material for pollen analysis and radiocarbon dating was obtained using a 75 mm diameter Russian corer. The pollen samples were prepared by the standard acetolysis method with HF treatment (Fægri & Iversen 1989) and the grains were identified with the aid of keys (Fægri & Iversen 1989) and reference material available in the Museum of Archaeology, Stavanger. The nomenclature follows Lid & Lid (1994). Microscopic charcoal particles larger than 25 µm and algae were also routinely counted.

The pollen data were processed and the percentage diagram (Fig. 4) drawn using the computer program CORE 2.0 (Narvik & Kaland 1994). The pollen sum, ΣP, used as a basis for the percentage calculations comprised only terrestrial pollen. Elsewhere the basis for the calculation was ΣP+X, where X is the constituent in question. The diagram defines the local pollen assemblage zones (LPAZs), numbered from the base upwards.

Sampling and sediment analyses

*Doktortjøna*: Samples for loss on ignition (LOI), grain size and geochemical analyses were collected from the upper 30 cm of the sediments with a gravity corer fitted with 44 mm internal diameter PVC tubes (Skogheim 1979). The 25 to 100 cm sediment depth interval was sampled with a modified Livingstone piston corer using PVC tubes with an internal diameter of 63 mm. The two cores were correlated visually (sand layers) and by reference to LOI and grain-size.

The cores were cut into 3 cm slices, except for the two uppermost samples, where the water content was high and 5 cm thick samples were extruded from the cores. The wet weight was determined and the samples dried at c. 40°C for at least 48 hrs. The dry samples were gently disaggregated in an agate mortar and stored in sealed plastic bags for further chemical analyses.

*Sandtjøna*: Samples were collected with a "Russian corer" of diameter 7.5 cm and length 75 cm. The core was cut into 4 cm slices, except for some thinner sand layers between the depths of 15 and 45 cm. The samples were treated as above.

Water content and loss on ignition (LOI)

Another set of samples were dried at 105°C for c.12 hrs and the water content determined. LOI was determined after ignition at 550°C for 2 hrs. LOI was calculated from the sum of mineral matter and ash.

Grain size

The ignited samples were wet-sieved through stainless steel sieves with mesh sizes of: 2, 1, 0.5, 0.25, 0.125 and 0.063 mm. The approximate distribution of silt fractions (<63 µm) was determined with a hydrometer.

Geochemistry

Samples for the geochemical analyses were sieved through a plastic screen with c. 0.25 mm openings. Metal cations except for lead (Pb) were determined with a slightly modified version of the method used by the Norwegian Geological Survey (Norsk Standard - NS 4770) in order to ensure comparability with similar earlier analyses from the region (Ottesen et al. 2000; Reimann et al. 2003). The dried samples were boiled in 7n HNO<sub>3</sub> for 3 hrs and analysed on an ICP-OES instrument (Thermo Jarrell Ash Corporation). Lead (Pb) was analysed with a Perkin-Elmer SIMAA6000

Table 1. Radiocarbon dates from Lake Doktortjøna, Røros, relevant to the present study. Calibrated ages AD/BC after Stuiver et al. (1998), OxCal v3.9, Bronk Ramsey (2003).

Lab. ref.	Material	Depth in cm	Uncal yr BP	Cal yr AD/BC	Average age, corrected for reservoir age:
TUa-1738A	Sandy silty gyttja	34.5–36.5	1305±85	AD 640–810	Not considered
TUa-1739A	Fine detrital gyttja	43.0–45.0	895±65	AD 1030–1220	AD 1425±95
TUa-1776A	Fine detrital gyttja	74.0–79.0	2515±65	800–520 BC	360±140 BC
TUa-2436A	Macroscopic plant fragments	100.0–105.0	3350±60	1730–1520 BC	Not corrected
TUa-1775A	Fine detrital gyttja	785.0–795.0 Another core	6765±75	5730–5560 BC	Not corrected

AAS instrument using a graphite furnace. The methods extract c. 90% of total Cu, c. 60% of total Zn and c. 25% of total Pb. The analyses were carried out at the Department of Plant and Environmental Sciences, Norwegian University of Life Sciences.

#### Radiocarbon dates

Three bulk samples of gyttja and one sample containing macroscopic plant fragments were picked out of the Doktortjønna cores for dating. The NaOH-soluble (A) fractions were dated by accelerator methods (AMS). The sample from a depth of 100–110 cm in the sediment was washed through a 1 mm sieve with distilled water in order to collect plant macrofossils. The dates are expressed in conventional <sup>14</sup>C years BP and calibrated according to Stuiver et al. (1998), OxCal v3.9 (Bronk Ramsey 2003), expressed in terms of a 68.2% confidence interval (Table 1). A reservoir age of approximately 300 years was estimated by comparing the <sup>14</sup>C date for TUA-1739A with the geochemical data. This will be discussed below.

#### Results and interpretations

Only the upper 80 cm of the cores will be discussed here, since this part gives sufficient background levels (pre-industrial) and describes the whole period of mining activities. The sediments below 80 cm are described in Daugstad et al. (1999).

#### Pollen analyses

The pollen diagram (Fig. 4) is divided into six local pollen assemblage zones (LPAZ D1–D6) with LPAZ D1 dating back to 6765±75 uncal. yr BP (TUA-1775A, Table 1).

#### LPAZ D1: prior to c. 340 BC (corrected age acc. to Table 1)

The AP (arboreal pollen) values (up to 95% ΣP) reflect a densely forested area. Pine (*Pinus sylvestris*) woodland dominated (60% ΣP) on minerogenic soils, while stands of birch (*Betula pubescens*) probably occurred around Doktortjønna. Birch twigs and bark were present in the sediment core from the lower part of this zone, and there is also evidence of stands of alder (*Alnus incana*). There is a continuous record of oak (*Quercus*) in the pollen spectra, i.e. the area belonged to the middle boreal vegetation zone, as is the situation today (def. Moen 1999). The algal flora is rather poor, indicating a scarcity of nutrients which persists

until the upper part of LPAZ D5.

#### LPAZ D2: from c. 340 BC–c. AD 1200

The area was still densely forested (AP 95%), with a dominance of pine (*Pinus sylvestris*) (65% ΣP) and birch (*Betula pubescens*) (30% ΣP) woodland. Pollen of alder (*Alnus incana*) and oak (*Quercus*), a warmth-demanding species, disappeared during this time interval, suggesting a colder climate. The lower border of the zone is defined by the immigration of spruce (*Picea abies*) into the area, the rational limit being set by pollen values >1% (Hafsten 1992). Nevertheless, the values never exceed 2–3% of ΣP and probably represent only locally scattered stands. Røros is situated nowadays between the two main spruce regions in Norway, the Mid-Norwegian province and the SE Norwegian province, which lies east of the Scandic Mountains.

Human presence in the Migration and Viking periods is revealed by ancient burial mounds and archaeological finds close to Røros. There is a small amount of evidence in the pollen diagram, although weak, that humans were altering the landscape at that early stage. This is seen in a gradual decrease in trees from a depth of c. 60 cm, an increase in charcoal particles and a peak in grasses (Poaceae), meadow-rue (*Thalictrum*), tormentil (*Potentilla*)-type pollen and *Varia*.

#### LPAZ D3: c. AD 1200–1645 (the establishment of the mining town of Røros)

This zone record a new period of forest clearance, estimated at approximately AD 1200, the Early Medieval Period. This is seen in a weak drop in AP followed by an increase in pollen types indicative of grassland and/or rough pasture, i.e. grasses (Poaceae), sedges (Cyperaceae), juniper (*Juniperus*), common sorrel (*Rumex acetosa* type), sunflower (Asteraceae), Apiaceae, stinging nettle (*Urtica* type) and meadow-rue (*Thalictrum* type). It has been verified that scything favours alpine meadow-rue (*Thalictrum alpinum*) in this area (Moen 1990; Gunnarsdottir & Høeg 2001). At the same time there is a small-scale rise in the curve for charcoal dust that demonstrates that the area had been permanently settled or at least was being used regularly for summer farming. This was followed by a period without any human interference in the vegetation, a plausible explanation for which might be the Black Death, which drastically reduced the population over large parts of Norway in 1349–50. According to written historical sources (Øisang 1946), the Røros area was resettled at the end of the 15th century, as is recorded at the LPAZ D3/D4 zone boundary in the pollen diagram. The

farm of Åsen was cleared later in the 16th century.

#### LPAZ D4: AD 1645 (establishment of the mining town of Røros) to c. AD 1690

The next deforestation step can be seen at the transition to LPAZ D4. The lower zone boundary coincides with a marked change in metal content (see below), which is correlated with the start of mining and ore roasting at the Røros smelting works in 1645. According to historical sources, the area had already become deforested for a distance of 25 km from the smelting works by 1670 (Øisang 1946), but no such dramatic forest clearance can be seen in the AP curves. The AP pollen types (mainly pine) most probably represent long-distance wind-borne transport. There is also a rise in charcoal dust particles (up to 38%) and of pollen types indicative of grassland and/or rough pasture. This is revealed especially by the curves for grasses (Poaceae) and common sorrel (*Rumex acetosa* type), which are present continuously from this point onwards up to the present time.

The increase in indicators of agriculture may point to a westward expansion of the farm of Åsen, but there is also another possible pollen source, as there is documentary evidence of a farming landscape that developed near the margin of the town immediately after the establishment of the smelting works (Borgos 1994; Borgos & Spangen 2001; Borgos pers. comm. 2006), which comprised small agricultural plots used for crops and hay production together with grazing land. It is not possible from pollen analyses, however, to determine whether these agricultural plots had reached the margins of Doktortjønna within the time interval in question.

#### LPAZ D5: c. AD 1690–1785

The transition to LPAZ D5 reflects a fourth deforestation step. A decrease in AP values to 50% ΣP is followed by an increase in charcoal dust particles and a further expansion of rough pasture and grassland communities. The lower zone boundary also corresponds to a shift in the lithostratigraphy from fine detrital gyttja to a silty, sandy gyttja. The abrupt decline in pine (*Pinus*) values and the overall low AP values can be explained as reflecting local as well as regional deforestation. Soil erosion with subsequent sand drifting accelerated with forest clearance and the bringing of large areas under cultivation. Cereal growing, including barley (*Hordeum*) and rye (*Secale*), is recorded throughout the zone and was also described in contemporary travel books (Suhm in Tronhiemske samlinger 1762; Breton 1975). The increase in a

combination of taxa such as grasses (Poaceae), sedges (Cyperaceae) (weak), common sorrel (*Rumex acetosa* type), buttercup (*Ranunculus acris* type), goosefoot (*Chenopodium* type), clover species (*Trifolium* type), pennie (*Artemisia*), meadow-rue (*Thalictrum*), Brassicaceae, *Geranium*, Queen of the meadow (*Filipendula*), lady's mantle (*Alchemilla*), sunflowers (Asteraceae sect. Asteroideae and A. sect. Cichorioideae) indicates land-use practices near Doktortjønna involving mowing and/or scything (Moen 1990; Gunnarsdottir & Høeg 2001; Øien & Moen 2001). It is well known that the managing director of the smelting works, Peder Hjort (1770/72–1789), laid out an agricultural plot close to Doktortjønna during this period.

Eutrophication of Lake Doktortjønna started in the upper part of the zone, as shown by the marked rise in the algal flora, with blooms of various *Pediastrum* species.

#### LPAZ D6: approx. AD 1785 to present time

This LPAZ is characterised by very low AP values (between 25 and 40%) and high values for charcoal dust particles, Poaceae (up to 50%) and other species indicative of grassland communities. In addition, *Pediastrum* sp. is well represented. Although the forest had been totally cleared in the area, AP values rose weakly in the second half of the LPAZ, estimated as commencing c.1880. This forest regeneration (reflected in the *Betula* curve) may be seen as a direct effect of introducing imported coal for use in the roasting furnaces in 1877 (Ødegaard 1984) instead of using the local pine and birch timber as fuel and for charcoal production.

The increasing proportion of pollen indicative of rough pasture and grassland communities indicates that this was the traditional type of local land-use practice within the Doktortjønna catchment, as indeed observed and documented by the geographer Gerhard Schøning in a travelogue from 1773–1775 (Schøning 1910). Agricultural plots were also cleared at Stormoen, southwest of the lake (Fig. 5). Eutrophication increases throughout this zone, probably due to a combination of air pollution and manuring of the agricultural plots.

#### Sediment properties

*Doktortjønna*: The sediment from below 80 cm up to 35 cm is a fine detritus gyttja with one thin sand layer at 62 cm (Fig. 6). The LOI is generally 50–60%, with c. 30% silt and clay (the clay content is very low, even when residues after ignition are included). Several fine

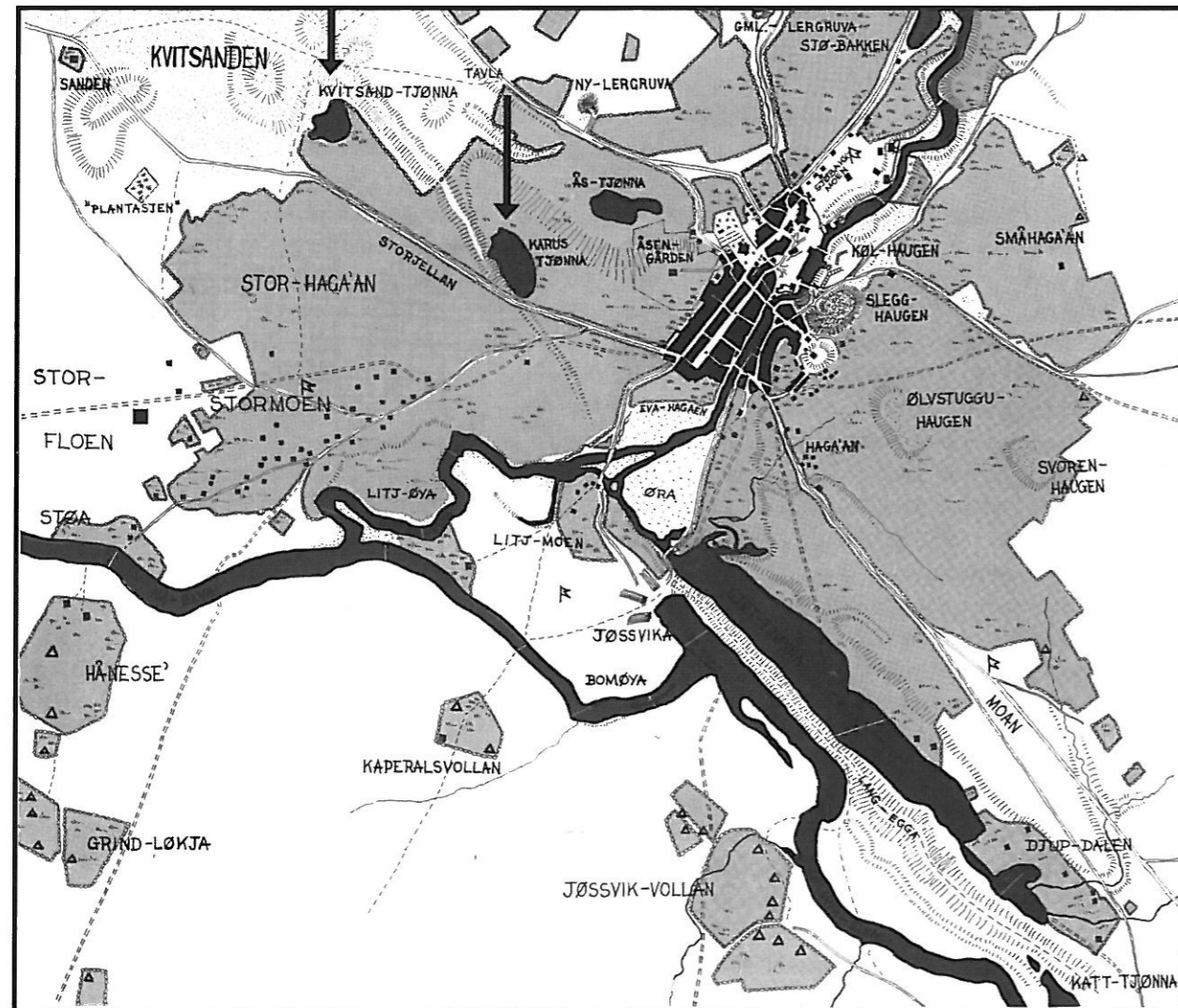


Figure 5. Map of Røros in 1810. The extent of the surrounding agricultural land and hayfields is shaded. Lake Doktortjønn and Lake Sandtjønn are marked with arrows. Røros Museum, archives, slightly modified.

sand layers are observed at depths from 35 cm up to 23 cm, and the LOI is reduced to less than 20%. Sand (mainly fine and very fine) increases to c. 10%. From c. 20 cm upwards the sediment is a fairly homogenous sandy-silty gytja, with c. 10% fine sand and with LOI increasing slowly to 20%.

**Sandtjønn:** The lower sediment unit, from c. 4 m up to 44 cm in depth, is an almost black fine-detritus gytja with a LOI of c. 90%, rapidly decreasing to c. 30% at the top of the gytja unit. Between 44 and 5 cm the sediment is almost pure sand (70–90% medium and fine sand). Two upward-fining sequences occur between 18 and 30 cm depth, indicating episodes of pronounced aeolian activity. There is an increase of up to c. 20% in LOI in the black sandy gytja of the

upper 5 cm (Fig. 6).

Both lakes seem to have had predominantly oxygenated bottom water for most of the time-span investigated, and some bioturbation may have occurred. Living *Chironomid* larvae were found in the top sediments of Lake Doktortjønn. Hydrogen sulphide was not recorded in the sediments from either of the lakes, but some black reduced layers were observed.

**Geochemistry**

**Doktortjønn:** the mean background values obtained from the sediments below 40 cm are: c. 30 ppm for Cu, c. 3 ppm for Pb and c. 152 ppm for Zn (Fig. 7). The background Cu values are comparable with

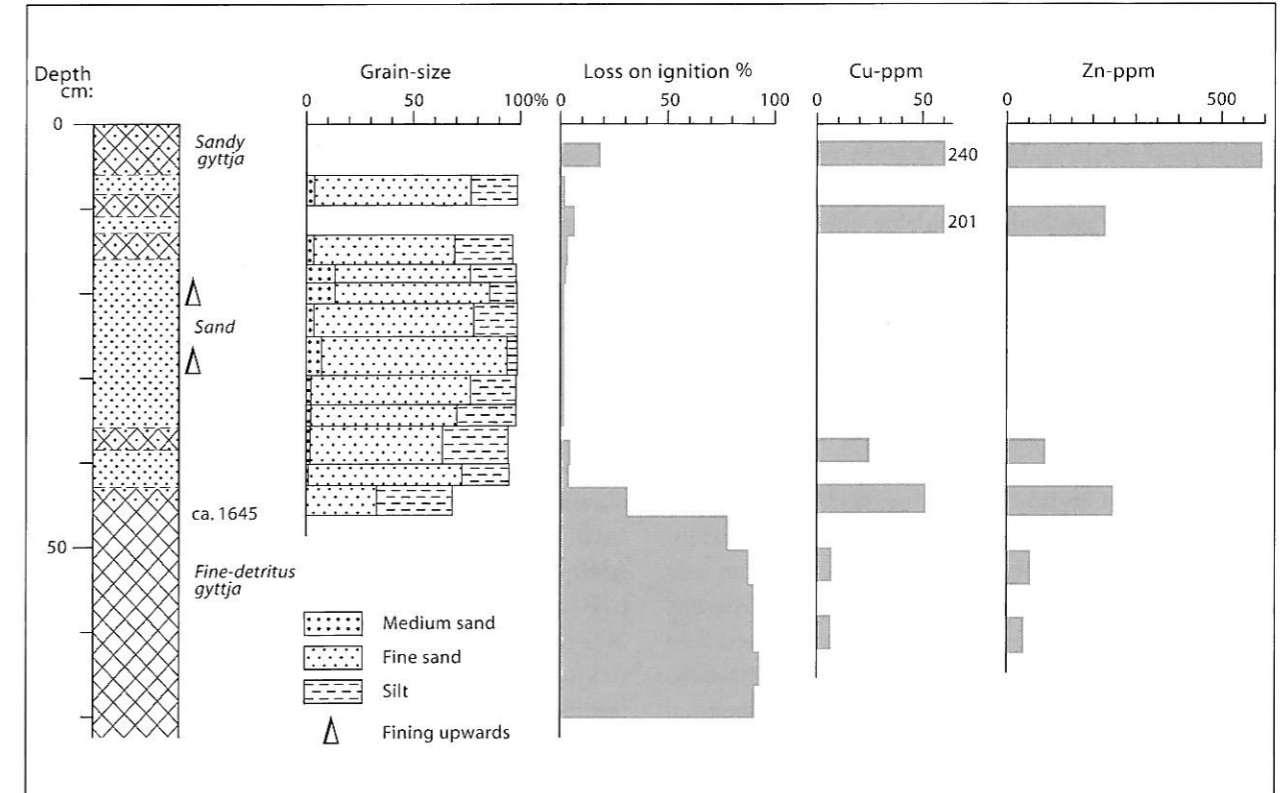


Figure 6. Sediment properties of Lake Sandtjønn: grain size, loss on ignition and acid-soluble Cu and Zn content.

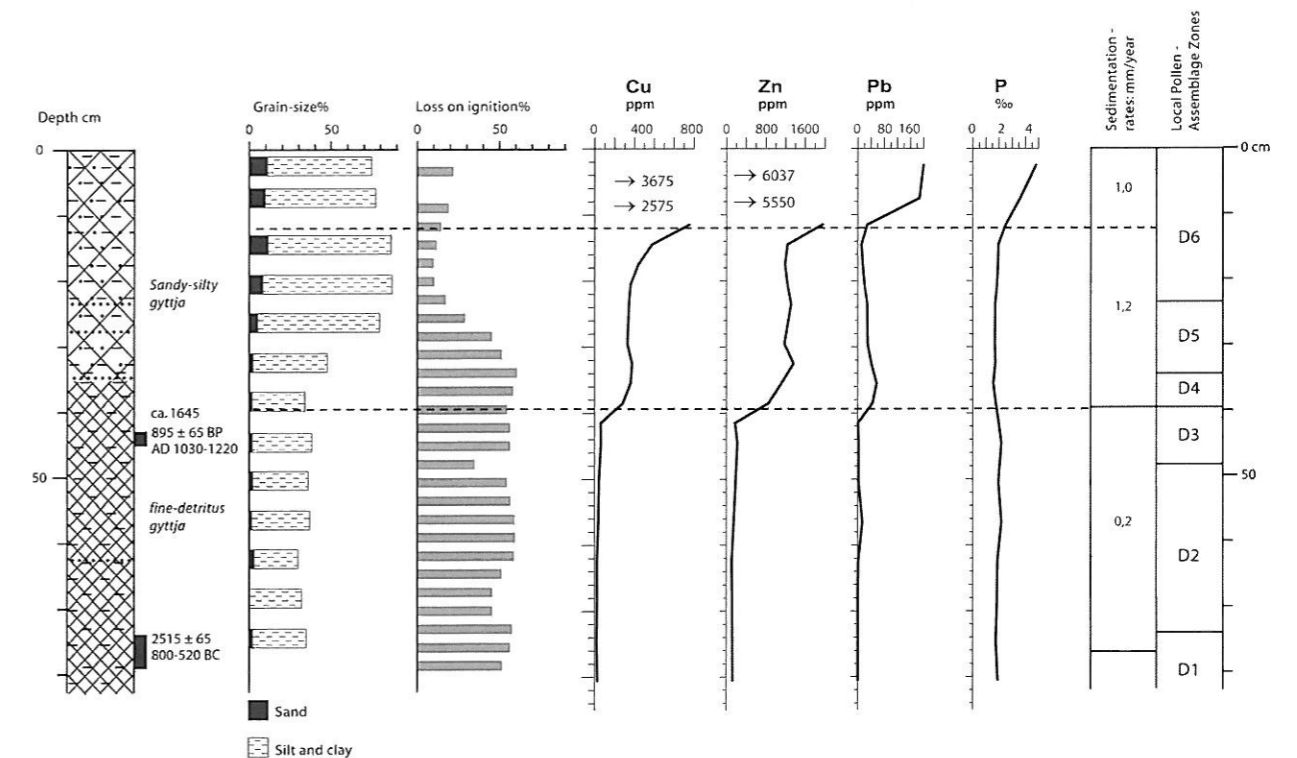


Figure 7. Sediment properties of Lake Doktortjønn: grain size, loss on ignition, selected chemical components (Cu, Zn, Pb, P) and rates of sedimentation. The right-hand column shows the Local Pollen Assemblage Zones (cf. Fig. 4).

average acid-soluble Cu in sub-soils of fluvial origin in the region, whereas Pb is lower and Zn higher than the regional sub-soil values (Ottesen et al. 2000).

The increases in Cu, Zn, and Pb in the 37–40 cm sample and up to a depth of 12 cm are c. 10-fold, whereas those recorded in the upper 12 cm of the sediments are 100, 65 and 38-fold for Cu, Pb and Zn, respectively. The P content is very low in most of the core, but increases in the uppermost part from 1.7 g/kg at a depth of 12 cm to 4.3 g/kg in the top sediment.

*Sandtjønnna:* The core was analysed for Cu and Zn only, to check the sediment level at which metal contamination increased (as a time marker). A sharp (c. 6-fold) increase in both metals occurs at 46 cm, accompanied by a decrease in LOI and an increase in sand (Fig. 6). The sample at 40–42 cm contains less metals, because of the high sand content, and the interval from 13 to 40 cm depth was not analysed because the sediments consist of nearly pure quartz-rich sand with practically no cation exchange capacity.

As in Doktortjønnna, we believe that the increase in metals was caused by the commencement of copper ore roasting. The average sedimentation rate in the polluted interval of the sediments in Sandtjønnna is c. 1.3 mm/yr. A higher rate than in Doktortjønnna seems reasonable because Sandtjønnna lies close to the source of sand.

The metal ion content is six to seven times lower in Sandtjønnna (c. 1 400 m from the smelter) than in Doktortjønnna (c. 800 m from the smelter), although the generally lower levels in Sandtjønnna are most likely attributable to differences in catchment properties. Sandtjønnna receives only groundwater from the large esker system, which is composed mainly of quartzitic and feldspathic sands with a very low ore mineral content. Doktortjønnna, on the other hand, receives surface run-off from the local phyllite-rich till, and some of the fall-out from the ore roasting may also have been washed into the lake from the much larger catchment.

#### *Chronology and rates of sedimentation in Lake Doktortjønnna*

As the air pollution was recorded in the sediments almost instantaneously, the 40 cm level may be considered a reliable time marker. We therefore assume that this level represents the year AD 1645, when ore roasting started, and that the terrestrial macro-sample at 100–105 cm depth (TUa-2436A) is accepted as an approximately correct age. Thus, the average

sedimentation rate for the pre-industrial period (between 40 and c. 102.5 cm sediment depth) is c. 0.2 mm/yr (Fig. 7).

The polluted sediments comprising the upper 40 cm are divided into two parts. The second increase in heavy metals, at a sediment depth of c. 12 cm, is assumed to represent the centralisation of ore roasting at the Røros smelter in 1888 with the introduction of the Bessemer process. The average sedimentation rate during the first period, from 1645 to 1888, was 1.2 mm/yr, whereas the upper 12 cm of sediment, representing the last 115–120 years, gives an average sedimentation rate of 1.0 mm/yr.

There is a discrepancy between the radiocarbon date obtained for a depth of 43–45 cm in the Doktortjønnna core (TUa-1739A) and the increase in heavy metals at c. 40 cm (Table 1, Fig. 7). The interval between these two in the core is 4 cm, representing approximately 200 years. Given the calculated average pre-industrial sedimentation rate, the <sup>14</sup>C date must be c. 300 years too old. Such a reservoir age for bulk samples is quite common (e.g. Ek & Renberg 2001). A similar reservoir age is also assumed to apply to the bulk date at 74–79 cm. The principal source of reservoir age error is likely to be old allochthonous material eroded and washed or blown into the lake, but other factors may also contribute (Geyh et al. 1998; Sensula et al. 2006). No sediment disturbances are visible.

Sample TUa-1738A, from a depth of 34.5–36.5 cm (AD 640–810), is certainly too old even with the calculated reservoir age, and it is not considered in this discussion (Table 1).

#### *Air and soil pollution*

Some of the airborne pollutants in the vicinity of Røros have accumulated in the humus layer of the soil profiles. Copper contents of up to 1 788 ppm have been reported in humus samples recovered less than 1.5 km from the Røros smelter (Låg 1976), a figure that is over 100 times higher than the regional topsoil values (Reimann et al. 2003) and indicates considerable heavy-metal pollution around Røros. Some of the humus-metal complexes may have been transported from the catchment by surface run-off in the course of time, and will have contributed to the very high heavy metal content of the Doktortjønnna sediments, particularly in the upper 10–12 cm. This increase is most likely to be related to the centralisation of ore roasting in Røros in 1888, and to the introduction of the Bessemer process.

As the soil in the cultivated plots was strongly

acidified by sulphuric fall-out, it had been necessary to apply organic manure (animal dung) to obtain reasonable grass harvests (Borgos 1994; Borgos & Spangen 2001). Animal dung contains phosphorous, but this application is only reflected in the upper 12 cm of the sediments in Doktortjønnna (Fig. 7). The distribution of algae (*Pediastrum* spp.) in the sediments nevertheless indicates eutrophication of the lake as early as c. 1750 (Fig. 4).

We have not had access to the complete dataset for ore production from the mines of the Røros region. But we can use the figures for between 1900 and 1945 (Øisang 1946) and choose 1910 as a year with average high production, c. 17 650 tonnes of ore. The average sulphur content of the ores from the region is c. 25% (Odd Nilsen pers. comm. May 2007), so that with an estimated release of up to 20% of the sulphur from the ore during production (cf. Ek et al. 2001), approximately 7 000 t of SO<sub>2</sub> may be said to have been released into the air in Røros in 1910.

This value is considered typical for the period between 1940 and 1970, whereas before 1880 emissions were about a half of that amount (see Fig. 3). Bjerkgård et al. (1999) have calculated from archive documents that about 6.5 Mt of ore were produced over the whole production period, which would imply that c. 2.5 Mt of SO<sub>2</sub> may have been emitted. Before 1888, however, the ore roasting took place at 13 different localities within and close to the extended World Heritage Site, and air pollution was spread over a large area. A considerable proportion of the air pollution probably occurred in the form of particulate emissions, which would account for the sediments containing Cu and Zn in proportions similar to their content in the ore.

#### *Conclusions*

This work focuses on the agrarian landscape situated next to the nucleus of the mining town of Røros, designated as an UNESCO World Heritage Site in 1980 by virtue of its unique wooden architecture. The natural archives contained in lake sediments point to close relationships between this mining town and its surrounding culturally dominated landscape, and suggested that the centre of Røros should not be looked upon as isolated in this respect.

The vegetation reconstructions for the Røros region over the last 2500 years reflect a change from open, pine-dominated forest to a completely deforested landscape. Five steps in forest clearance are recorded. Minor clearances are visible in the Migration–Viking Period time interval and later in the Early Medieval

Period, while forest clearance escalated after the start of mining and smelting operations in 1645 and the final step was recorded around 1690. During the first 25 years of copper production there is a delay between the historically documented forest clearance and its reflection in the pollen record, probably due to long-distance transport of tree pollen types (AP). The pollen diagrams also record signs of reforestation after the introduction of coal for use in the roasting furnaces in 1877. Otherwise, the pollen records, and especially the non-arboreal (NAP) pollen types, clearly show the close interdependence between the growth of the copperworks and the gradual extension of this unique agricultural landscape with its crops and hayfields.

Pollution from ore roasting is also clearly recorded in the sediments from Lake Doktortjønnna, in terms of abrupt increases in Cu, Zn and Pb. Since these were caused by aerosols, they would have been recorded in the sediments almost instantaneously, whereas the changes in grain size and LOI show a 40–60 years time lag and reflect a gradual response in the ecosystems around the lakes. The geochemical boundary in the sediment is regarded as a more reliable dating level than the radiocarbon dates, which are corrected for a reservoir age of 300 years in the bulk date. Thus, the geochemical results clearly demonstrate that airborne pollution brought about by human agency can be used as a marker horizon in lake sediments in order to detect mining activity.

Deforestation near the smelter was very rapid, and in addition the SO<sub>2</sub> fumes caused serious damage to the vegetation. This initiated aeolian transport of mineral particles into the lake. Our investigation confirms (as proposed by Holmsen 1942) that the dune-field (the “desert” of Kvitsanden), which is nowadays an environmentally protected area, was undoubtedly formed because of deforestation and possibly damage caused to the vegetation by sulphurous fumes from the smelter.

The effect of manuring, which added phosphorous to the grazing and hay-producing areas near Doktortjønnna, is only detected in the sediments representing the last 100–120 years. The sediments of Lake Doktortjønnna have proved to be a valuable tool for solving historical problems, and we hope that these lakes can be preserved as natural historical archives for future generations.

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